U.S. Department of Transportation
Federal Highway Administration

ACOUSTICS AND YOUR ENVIRONMENT

THE BASICS OF SOUND AND HIGHWAY TRAFFIC NOISE

A VIDEO PRODUCTION

DTS-34-HW966-LR1

Final Report
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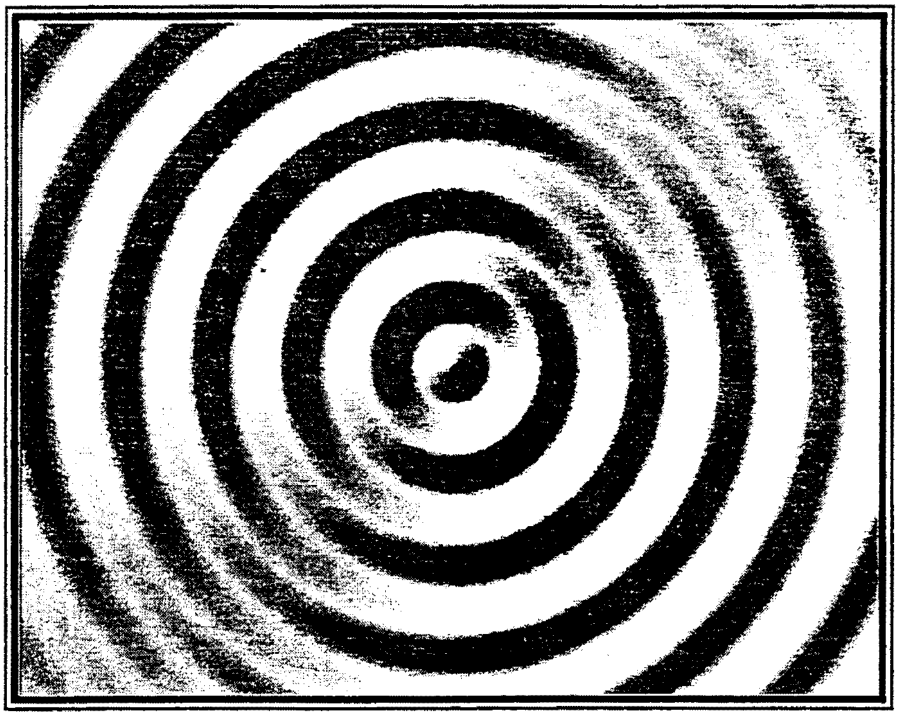

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U.S. Department of Transportation
Federal Highway Administration

Memorandum

Subject: INFORMATION: Highway Traffic Noise

Date: MAR 1 1999

From: Chief, Environmental Analysis Division

Reply to Attn. of: HEP-40

To: Division Administrators

We have had many requests to develop an educational tool to present the fundamentals of sound and highway traffic noise. The Volpe National Transportation Systems Center (VNTSC), Acoustics Facility, in support of the FHWA, has produced a video entitled, "Acoustics and Your Environment - the Basics of Sound and Highway Traffic Noise." The video is approximately 48 minutes long and has two nearly equal parts. It is intended for an audience that desires a thorough, detailed explanation of the subject matter, e.g., traffic noise analysts or residents immediately adjacent to a proposed noise barrier.

Part 1 covers the basics of sound, including the following topics:

- Sound waves,
- Frequency,
- Noise,
- Sound pressure level,
- Sound perception, and
- Noise descriptors.

Part 2 covers the basics of highway traffic noise, including the following topics:

- Highway traffic noise,
- Source/path/receiver,
- Sound sources,
- Noise effects, and
- Sound propagation.

We hope the attached video will be useful to FHWA field offices and State Departments of Transportation (DOTs). The attached copy of the script for the video should be valuable as a source reference for the fundamentals information. Along with a copy of this memorandum, one copy of the video and script is being distributed directly by the VNTSC to all State DOTs.

If you have any questions concerning the video, you may contact Bob Armstrong or Steve Ronning at (202) 366-2073 or (202) 366-2078, respectively.

James M. Shrouds

James M. Shrouds
Chief, Environmental Analysis Division

2 Attachments

cc: Resource Center Directors

PREFACE

This letter report includes the narration for the acoustics video produced by the Federal Highway Administration in association with the Volpe Center Acoustics Facility and Out of the Box Productions. The narrator's words are extracted from the video script that covers the basics of acoustics with a specific focus on highway traffic noise. Keep in mind that the video itself contains animations, illustrations, and actual footage; only minimal graphics are presented herein.

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PART I, WHAT IS ACOUSTICS?

I'd like to start by defining acoustics.

Acoustics is the science of sound, including its production, transmission, and effects. Applications of acoustics include: medical ultrasonics, underwater acoustics, architectural acoustics, active or passive noise control, nondestructive evaluation, environmental noise, and many, many more.

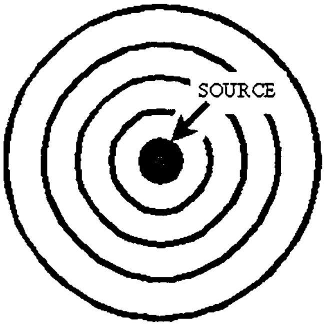
It is the application of environmental noise produced by highway traffic that will be discussed here, starting with the basics of sound.

What is Sound?

Understanding acoustics requires the understanding of sound. **Sound** is a vibratory disturbance created by a moving or vibrating source. As the source moves or vibrates, surrounding atoms or molecules are temporarily displaced from their normal configurations thus forming a disturbance that moves away from the sound source.

(video includes animation of waves propagating away from a source)

In order to better understand *sound* waves, it is first useful to study this animated representation of waves.



In this demonstration, the sphere in the middle pulsates in and out at equal intervals forming waves that propagate away from the sphere or the source.

One way to picture this type of wave is by imagining yourself tapping your finger on the surface of water; as you tap, waves propagate away from your finger in a circular pattern.

Now we're going to look at a snapshot in time of the wave animation in order to get a better understanding of wave parameters.

For simplicity, the outward propagating waves can be approximated with the trigonometric sine function.

The pattern of this sine wave repeats itself periodically.

The **wavelength** of these waves, represented by the Greek letter lambda, is defined as the repetition length. As a wave propagates through an unchanging medium, its wavelength remains constant.

Another parameter of a wave is its amplitude. The **amplitude** determines the strength of the wave. Greater disturbances at the source lead to greater strengths during propagation. For sound waves, a higher amplitude equates to a higher volume.

Waves also have an associated frequency. **Frequency**, abbreviated with a lower case f, is defined as the number of cycles of repetition per second. In other words, frequency is the number of wavelengths that have passed by a stationary point in one second's time.

The unit of frequency used here is called hertz abbreviated Hz. It is defined as the cycles of the wave per second.

$$f = \textbf{cycles/second} = \textbf{hertz (Hz)}$$

When the number of hertz exceeds 1,000 it is common to write the amount in units of kilohertz. For example, 1,000 Hz = 1 kHz.

Frequency is inversely proportional to wavelength. An equation relating the two parameters is $c_o = f\lambda$, where c_o is the speed of sound in the medium. In air at a temperature of 20° Celsius, the speed of sound is 343 meters per second or 1125 feet per second.

This equation implies that longer wavelengths are associated with lower frequencies, and shorter wavelengths are associated with higher frequencies.

Sound can have a single frequency component as we earlier illustrated, or it can have multiple frequency components at varying amplitudes thus making each sound distinctive; this type of sound is **complex**. Most real life sounds are complex.

For convenience, the frequency components of a complex sound source are very often studied in terms of octave or fractional octave bands.

These bands each cover a range of frequencies and are referred to by the center frequency of the band. When a sound is complex, it can be called broadband because it encompasses many frequency bands.

For **octave-band analysis**, the entire frequency spectrum is divided into one-octave bands; a list of these bands is shown in the table. The center frequency of each band is one octave higher than the previous band.

Notice the center frequencies' associated wavelengths. For the frequency of 31.5 Hz the wavelength in air is 10.89 m or 35.72 ft and for the frequency of 8,000 Hz the wavelength is 0.04 m or 0.14 ft.

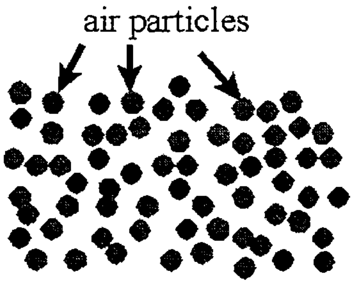
octave bands

center frequency (Hz)	**associated wavelength in air at 20° C**	**range (Hz)**
31.5	10.89 m, 35.72 ft	22.4-45
63	5.44 m, 17.86 ft	45-90
125	2.74 m, 9.00 ft	90-180
250	1.37 m, 4.50 ft	180-355
500	0.69 m, 2.25 ft	355-710
1000	0.34 m, 1.13 ft	710-1400
2000	0.17 m, 0.56 ft	1400-2800
4000	0.09 m, 0.28 ft	2800-5600
8000	0.04 m, 0.14 ft	5600-11200

Sound Waves

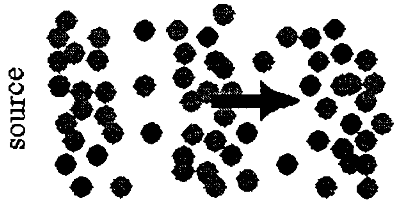
We've used animation to help describe various wave parameters. Now that these parameters have been explained, let's look at a demonstration of how ***sound* waves** operate.

Sound waves must propagate through some medium since it is the medium's particles that support the wave. The example medium here is air.



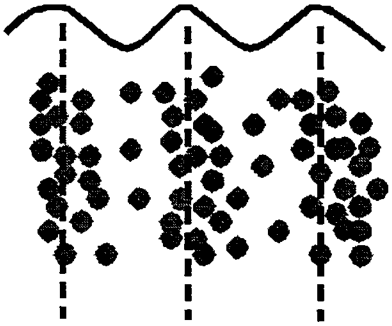
Now a source is introduced on the left side; it is producing a pure tone or single frequency sound wave in the air.

The air particles are displaced as the waves propagate away from the source. The particles themselves are just oscillating back and forth, but it can be seen that the sound waves are propagating outward.



As the air particles bunch up this forms a high positive amplitude area and when they are most spread apart this forms an area of high negative amplitude. In their undisturbed configurations, the particles represent an area of zero amplitude. The amplitudes correspond to a change in pressure from its ambient value; this is termed the acoustic pressure.

A sine wave is again shown to better understand the wave parameters. Notice how the darker areas of the acoustic wave line up with the peaks of the sine wave.



We have now defined wave parameters including frequency and have illustrated the important characteristics of sound waves. The discussion has focused on the sound *source.* It is also important to understand the ***receiver* of the sound**.

As an example, sound waves travel through the air and interact with the human ear.

Perfect human hearing lies in the range of approximately 20 to 20,000 Hz. Frequencies below 20 Hz and above 20 kHz are heard by other living creatures but not by humans. 20-20,000 Hz is called the audible sound range.

Infrasound includes frequencies below 20 Hz, and ultrasound includes frequencies above 20 kHz.

In order to connect frequencies with sounds we recognize, let us first listen to the piano. A piano covers a frequency range of 55 to 8,360 Hz.

A middle C is at 262 Hz.

Human conversation is also recognizable. Nearly all information in human speech is contained in the frequency range of 200 to 6,000 Hz.

It should also be noted that human hearing is most sensitive between about 1 and 6.3 kHz.

Noise

Now that we better understand sound, it is suitable to introduce a more subjective part of sound, noise. Although sound can be measured as a physical quantity, noise requires the judgment of a human listener.

Noise is defined as any unwanted sound. Unwanted sound may be defined differently depending on the listener.

However, several types of noise are understood to be objectionable; these types include highway traffic – this type of noise will be discussed later in this presentation, loud machinery or tools, and aircraft.

A better understanding of noise involves quantifying its perception. Physical measurements of the strength of the wave are explained first followed by perceptual measurements.

Pressure vs. Sound Pressure Level

We talked before about the amplitude of a wave. The amplitude of a sound wave can be quantified by measuring the associated pressure disturbance. In other words, we need to measure the change in pressure from its ambient value; again, this change in pressure is termed the **acoustic pressure**.

Sound can be represented in terms of a physical unit of pressure; one such unit is pascals, abbreviated **Pa**, a unit widely used in the acoustics community. Acoustic pressure amplitudes can range from the hundred *thousandths* to the hundred *thousands* in pascals.

Because of the wide range of amplitudes encountered when measuring pressure, it has become convenient and customary to plot the pressure data on the more compact logarithmic scale.

On this scale, the unit is the decibel, abbreviated **dB**, and now instead of plotting the acoustic pressure you plot the **sound pressure level**.

The equation for converting pressure to sound pressure level, abbreviated SPL, is

$$\mathrm{SPL} = 10\log_{10}\left(\frac{p}{p_{\mathrm{ref}}}\right)^2;$$

in this equation, p is a time-averaged pressure and p_{ref} is the reference pressure, a quantity that depends on the medium in which the sound wave is propagating.

In water, $p_{\mathrm{ref}} = 1 \times 10^{-6}$ Pa = 1 μPa. In air $p_{\mathrm{ref}} = 20$ μPa; this is the pressure value which represents the threshold of unimpaired human hearing for a 1 kHz tone, in other words, the quietest audible sound at that frequency.

To get an idea of how pressure and sound pressure level relate, here is an example calculation where air is the supporting medium.

We have an acoustic pressure level of 0.036 pascals. The sound pressure level is then calculated to be about 65 decibels. This is the approximate sound pressure level for normal conversation.

$$\mathbf{SPL} = \mathbf{10\log_{10}}\left(\frac{\mathbf{0.036\ Pa}}{\mathbf{20\ \mu Pa}}\right)^2$$
$$= \mathbf{65\ dB}$$

Here are other examples of sound levels starting with a very quiet sound and working our way up.

A quiet suburban neighborhood will exhibit an average sound level of about 40 decibels.

A gas lawnmower 31 meters or 100 feet away will create a sound level of approximately 75 decibels.

A diesel truck 15 meters or 50 feet away traveling at highway speeds will achieve a maximum level of 85 decibels.

A jet aircraft at an altitude of 305 meters or 1000 feet will create a maximum level of about 90 decibels.

The threshold of pain for humans is between 130 and 140 decibels.

Combining Sound Pressure Levels

The sound pressure level is often represented by a capital L. We will now use L to help explain the combining of sound pressure levels.

When you need to add sound pressure levels it is *not* a simple matter of algebraically adding the numbers. 80 dB + 80 dB does not equal 160 dB! As explained earlier in the presentation, the decibel scale is logarithmic; therefore, to **combine decibel values**, each must be converted to a linear scale, added, and then converted back to a logarithmic scale. Here, L_1, L_2, up to L_n represent the n sound levels that are to be combined.

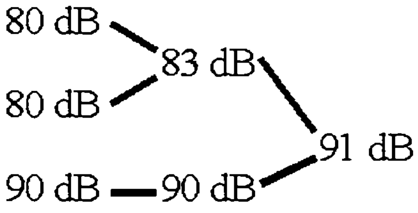
$$L_{\mathrm{total}} = \mathbf{10\log_{10}}\left(\mathbf{10}^{L_1/10} + \mathbf{10}^{L_2/10} + \cdots + \mathbf{10}^{L_n/10}\right)$$

For applications requiring only integer decibel accuracy it is also possible to apply some simple steps to calculate an **approximate total sound pressure level**.

First find the decibel difference between two sound pressure levels. You then add an adjustment factor to the higher of the two sound pressure levels. If the dB difference is 0 or 1 then you add 3 dB, 2 or 3 you add 2 dB, and between or equal to 4 and 9 you add 1 dB. If the difference is 10 dB or greater you can safely ignore the lower level source; under these conditions, the higher level source is said to "mask" the lower one.

decibel value difference	**add to higher value**
0, 1	3 dB
2, 3	2 dB
4 to 9	1 dB
≥ 10	0 dB

Here's an example combining three sound pressure levels. The typical procedure is to combine the smallest values first then work your way up. So, we start by combining the 80-dB levels. Their difference is zero so we add 3 dB to 80 dB to get 83 dB. Then the difference of 83 dB and 90 dB is 7, so we add 1 dB to 90 dB for a grand total of 91 dB.



Perception of Sound

Now that we understand how to quantify sound, we can move on to its perception.

A sound's **loudness** is a subjective rather than an objective description of noise; it all depends on how the sound is perceived for a particular individual. When researchers determined there was a need to find a relationship between the sound pressure level of a noise and its subjective loudness, several experiments were performed. As a result of extensive human testing, objective descriptors of loudness were constructed and applied to human perception.

When the sound pressure level increases or decreases, some humans in a normal living environment can detect a loudness change if the sound pressure level is altered by 3 dB or more. A change of 1 or 2 dB will usually go unnoticed. A 5-dB change, on the other hand, can be easily detected by most people. Also, sound will be perceived as being twice as loud if the decibel level increases by 10 dB or half as loud if decreased by 10 dB, and it is common to perceive a 20 dB change as four times as loud or one quarter as loud.

sound level change	**descriptive change in perception**
+20 dB	four times as loud
+10 dB	twice as loud
+5 dB	readily perceptible increase
+3 dB	barely perceptible increase
0 dB	reference
-3 dB	barely perceptible reduction
-5 dB	readily perceptible reduction
-10 dB	half as loud
-20 dB	one quarter as loud

(video plays audio clips of sound at a level of 60 dB then 70 dB)

Here's an example of a sound becoming twice as loud. We start with the first sound, complex noise.

And here's the second sound, the same audio clip but at a different sound level.

The second audio clip should sound twice as loud as the first; there was a 10-dB difference. Listen to the sounds again.

We can also look at human perception of sound according to frequency.

Remember from before that the audible sound range for humans is from 20 to 20,000 Hz. Even though perfect human hearing lies in this range, we do not hear equally well at all frequencies.

Earlier it was stated that human hearing is most sensitive in the range of about 1,000 to 6,300 Hz.

To describe sound levels in a manner which closely approximates normal human hearing, the actual sound level measurement is modified by applying A weighting. **A weighting** is a response function that spans the audible frequency range. This weighting assigns to each frequency a "weight" that is related to the sensitivity of the ear at that frequency; frequencies to which the human ear is less sensitive are weighted less than those to which the ear is more sensitive. The A-weighting curve emphasizes frequencies in the 1,000 to 6,300 Hz range and de-emphasizes frequencies out of that range.

This is the A-weighting plot in tabular form for octave bands. For each center frequency shown, a dB adjustment value is given. For example, for the 125 Hz octave band, a -16.1 dB adjustment should be applied. The 500 Hz band requires a -3.2 dB adjustment; the 1,000 Hz band, which can be thought of as the reference frequency for A weighting, has no adjustment; and the 2,000 Hz band requires a +1.2 dB adjustment in sound pressure level.

octave band adjustments

frequency (Hz)	**A-weighting adjustment (dB)**
31.5	-39.4
63	-26.2
125	-16.1
250	-8.6
500	-3.2
1000	0
2000	+1.2
4000	+1.0
8000	-1.1

A sound pressure level with A weighting applied is often stated in units of **dB(A)**.

The A-weighted sound level is the most widely used measure of environmental noise and is internationally accepted.

Noise Descriptors

Noise can be a steady continuous sound or it may tend to fluctuate between intensely loud and quieter periods. An example of the latter is the noise produced by road traffic; it peaks with the passage of a heavy truck and will have quiet intervals when there is little or no traffic.

Because of the large array of noises and the need to understand them from different perspectives, there are several ways to describe noise. Many noise descriptors are available where each is appropriate for particular circumstances.

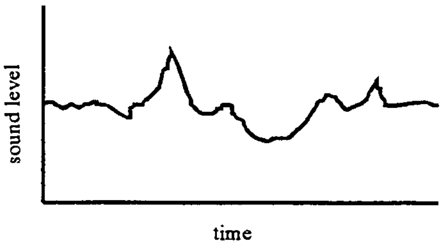
A general noise descriptor is one we have already spoken about, the A-weighted sound level. The symbol for this descriptor is L_A.

More specific descriptors are the sound exposure level, the maximum sound level, the hourly equivalent sound level, the day-night average sound level, the community noise equivalent level, and the 10-percentile exceeded sound level. While all of these A-weighted noise descriptors can be applied to highway traffic noise, the equivalent sound level and the 10-percentile exceeded sound level are most often used for traffic noise analysis.

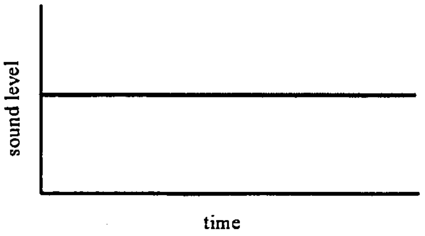
L_{AE}, $L_{A(F,S)mx}$, L_{Aeq1h}, L_{dn}, L_{den}, L_{10}

L_{Aeq1h}, called the hourly equivalent sound level, is essentially the average A-weighted sound level occurring during a one hour period.

To illustrate the equivalent sound level, we are first showing you the sound pressure level recorded at one location over time. This time history reveals peaks and dips caused by loud and quiet sounds during the time period.



Now applying the L_{Aeq1h} noise descriptor, the sound pressure level averages, and the plot flattens out. This sound descriptor should be applied to continuous sounds, such as relatively dense highway traffic.



The other noise descriptor we will discuss is L_{10}, the A-weighted 10-percentile exceeded sound level; it is the sound pressure level exceeded 10 percent of a specific time period. Here is an example: say 50 samples were taken during a period of time. You extract the highest 10 percent of the sound pressure levels, which in this case would be 5 samples. The 5th highest sound pressure level is the 10-percentile exceeded sound level.

PART II, HIGHWAY TRAFFIC NOISE

In the first part of this video we discussed the basics of acoustics and reviewed some common noise descriptors which can be applied to highway traffic noise.

Now we are going to move on to the acoustics involved in highway traffic noise. This includes the noise **source**, or the vehicles driving on the highway; the **receiver** of the noise, or the people in near-by communities; and the **propagation path** of the sound as it travels from the source to the receiver.

Sound Source

Let's first talk about the sound source. We'll describe two basic sound source types and their relationship to highway traffic noise.

A **point source** is defined as a source that is essentially concentrated at a single point from which noise propagates outward in all directions. In other words, sound radiates *spherically* from a point source.

The sound levels measured from a point source decrease at a rate of 6 dB per doubling of distance. This is a decrease due to spherical spreading.

A **line source** radiates sound *cylindrically.*

It can be composed of multiple point sources arranged on a line located at a perpendicular distance relative to the observer.

The sound levels measured from a line source decrease at a rate of 3 dB per doubling of distance. This is a decrease due to cylindrical spreading.

Two theoretical sound source types have been described, but what about actual noise generated from a highway. Well, we can consider highway traffic noise as a line source or as point sources, depending on the traffic density and the listener's proximity to the highway.

Individual vehicles act as point sources.

Categorizing vehicles into several different groups is important to predicting noise levels. Vehicles are typically divided into these categories: **automobiles**, which includes all vehicles having two axles and four tires, designated primarily for transportation of nine or fewer passengers or for transportation of cargo; **medium trucks**, which includes all cargo vehicles with two axles and six tires; **heavy trucks**, which includes all cargo vehicles with three or more axles; **buses**, which includes all vehicles having two or three axles and are designated for transportation of nine or more passengers; and **motorcycles**, which includes all vehicles with two or three tires with an open-air driver and/or passenger compartment.

In general, the loudest vehicles are in the heavy truck category. As an example, at a distance of 15 meters (50 feet), a single heavy truck traveling at normal highway speeds can produce a maximum sound level of around 85 dB(A).

The quietest vehicles are in the automobile category. For the same conditions as the example heavy truck, the maximum sound level of the automobile is around 75 dB(A).

The major noise sources in vehicles are, for trucks, the exhaust stack, and for all vehicles, the engine and tire/pavement interaction.

The sound levels of individual vehicle noise are influenced by how fast the vehicle is traveling.

Whereas individual vehicles are here considered as point sources, highway traffic can be considered a line source; it is composed of several vehicles or point sources closely spaced. A community is a sufficient distance from the highway to see highway traffic as a line noise source. This implies that for highway traffic noise, the sound decreases, due to cylindrical spreading, at a rate of 3 dB per doubling of distance away from the road.

Receiver of Sound

Highway noise studies are born out of concern for people. **People exposed to highway noise** include those who live, go to school, or work in surrounding communities or people who actually work on the highway itself. The concern lies in their safety and well-being.

The most obvious negative effect of noise is physical damage of hearing. Transportation noise levels experienced by communities and the general public, however, are normally not high enough to produce hearing damage.

Other effects are the interference of noise with certain activities, such as sleeping, relaxation, study, or conversation. Although most interruptions by highway noise can be considered merely annoying, some may be considered dangerous.

An example of this is the inability to hear warning signals or verbal warnings in situations involving workers next to a noisy highway.

Less obvious, but nevertheless real, are the stress effects of noise. There is ample evidence that noise can cause stress and thus may be a contributor to stress-related diseases such as anxiety or heart disease.

Sound Propagation Path – Meteorological Effects

The path the sound takes when traveling from the source to a receiver can be quite complicated when taking into account ground reflections, obstructions, and meteorological effects. The received sound level depends heavily on these parameters.

We can start by talking about a **simple propagation path**, the path going directly from the source to a receiver. Besides geometrical spreading which causes the sound level to decrease as it propagates toward the receiver, the propagation medium itself can possess inherent losses. Atmospheric absorption is the attenuation of sound during its passage through air. For propagation distances related to highway measurements, this attenuation is only significant at very high frequencies, greater than 5,000 Hz; it is, in general, small compared to attenuation caused by other propagation mechanisms and can usually be neglected.

Meteorological conditions can also affect the direct propagation path; these conditions include vertical temperature and wind gradients.

In general, daytime weather conditions permit the ground to be heated by solar radiation. The air nearest the ground is warmest becoming progressively cooler with increasing height. This is called a temperature lapse.

The speed of sound increases with increasing temperature; this causes sound rays to bend upward away from the earth. In turn, the noise level at the receiver decreases.

At night the ground usually cools by radiation faster than the surrounding atmosphere thus causing the air temperature to become warmer with increasing height. This is called a temperature inversion.

Under these conditions the sound rays bend downward toward the earth. For this case, the noise level increases at the receiver.

Besides the refraction due to temperature gradients, wind can also cause the sound to deviate from a straight path. When sound is propagating upwind the ray paths curve upward as with a temperature lapse, decreasing the received noise level, and when sound is propagating downwind the ray paths curve downward as with a temperature inversion, increasing the received noise level.

The importance of meteorological effects is that sound may reach the receiver with greater intensity if it is refracted downward toward the earth and with less intensity if the sound is refracted upward away from the earth than in cases where meteorological effects are negligible. It should be noted that while atmospheric conditions can have major effects on propagation of sound over distances greater than about 100 meters or 300 feet, typical highway studies are performed within 100 meters distance from the highway, in areas where the meteorological effects would be less severe. As for some other meteorological conditions, effects of fog and precipitation are generally negligible. On the other hand, atmospheric turbulence, which can be generated by moving vehicles or heated pavement, can potentially cause fluctuations in received sound levels or can reduce soft ground attenuation, the next topic of discussion.

Sound Propagation Path – Ground Reflections

In addition to a simple path from the source to a receiver, sound can also reflect off the ground during propagation. The **ground reflected wave** can interfere with the direct, nonreflected wave to produce a net increase or decrease in sound pressure level.

Increases in sound pressure level can be attributed to an **acoustically hard ground** such as asphalt or water located between the source and the receiver. For practical highway applications, measurements have shown a 1 to 2 dB increase for the first and second row residences adjacent to the highway. It should be noted that theory indicates that in certain situations greater increases are possible.

An **acoustically soft ground**, such as grassland, plowed earth, or snow, can cause a significant broadband attenuation (except at low frequencies). As a general rule of thumb, for each doubling of distance the soft ground effect attenuates the sound pressure level at the receiver by 1.5 dB. This extra attenuation applies only to incident angles of 20 degrees or less. For greater angles, the ground becomes a good reflector and can be considered acoustically hard.

Another consideration when discussing ground reflections is the terrain geometry. Sound may encounter terrain that is not flat, but rather terrain with small hills.

For a downwardly curving ground the sound rays stray away from the ground's surface.

For an upwardly curving ground the sound rays are forced to encounter the ground's surface.

Sound Propagation Path – Obstructions

We have so far discussed several aspects of the sound propagation path and have now arrived at the last topic covered in this presentation, obstructions in the propagation path.

Natural terrain features, such as hills and dense woods, as well as man-made features, such as buildings and walls, obstruct the sound path between source and receiver and in most cases reduce or attenuate noise levels for nearby receivers. The amount of attenuation provided by these objects depends on the size of the object and frequency content of the associated noise source.

– Constructed noise barriers

The term **noise barrier** refers to any large object that blocks the line of sight between source and receiver, including the ground itself if it protrudes upward through the line of sight. A noise barrier is commonly a **wall** or **earth berm** specifically constructed for the purpose of noise reduction. This type of obstruction is the most commonly used traffic noise abatement measure.

When sound encounters a barrier, there are three possible paths it takes: diffracted over or around the barrier, transmitted through the barrier, or reflected by the barrier.

The **diffracted sound** is the most important path that reaches the receiver located on the other side of the noise barrier. This is the sound that "bends" over the top of the barrier into the barrier's "noise shadow." The frequency content of the sound is important. As discussed earlier, there is a direct relationship between the frequency and wavelength of sound. Lower frequencies have longer wavelengths and higher frequencies have shorter ones. As a result, diffraction is not uniform over all frequencies. Longer wavelengths that approach the barrier height easily bend over the top of the barrier right down to the receiver, whereas shorter wavelengths bend just slightly over the top not reaching the receiver. Therefore, it follows that more low frequency sounds reach the receiver.

Diffraction also occurs around barrier ends. In these instances it is usually only important for receivers close to the end of a barrier.

The "**noise shadow**" behind a barrier is not very well defined, much different than a shadow in optics; when *light* hits a barrier there is a well defined region of darkness or light absence behind the barrier. For *sound*, the shadow must be considered an area of noise reduction rather than an area of noise absence. The "deeper," or closer to the base of the barrier, a receiver is positioned in the shadow zone the greater the associated barrier attenuation.

Barrier attenuation is usually represented by the more standardized term barrier insertion loss. **Barrier insertion loss** is defined as the sound level at a given receiver before the construction of a barrier minus the sound level at the same receiver after the construction of the barrier.

barrier insertion loss (IL) = $L_{\text{before}} - L_{\text{after}}$

The construction of a barrier usually results in a partial loss of soft-ground attenuation, a loss apparent when compared to the no-barrier case. This is due to the barrier forcing the sound to take a higher path relative to the ground plane. Physically, barrier insertion loss is the net effect of barrier diffraction, combined with this partial loss of soft-ground attenuation.

Another way sound from the source can reach the receiver on the other side of the barrier is by a rather direct, although obstructed, path.

When the incident sound hits the barrier, some of the acoustical energy can be transmitted through the barrier material and continue to the source.

The amount of transmission depends upon factors relating to the barrier material such as the weight, stiffness, or loss factors; the angle of incidence of sound; and frequency spectrum of sound.

The amount of sound reduction during transmission is called the **transmission loss**. Typically, the transmission loss improves with increasing weight of the material. Most common materials used in barrier construction provide a transmission loss of 20 dB or better.

For materials such as concrete or masonry blocks the transmission loss values are more than sufficient, exceeding 30 dB. In other words, the sound energy transmitted through these barriers is reduced by 30 dB, rendering it effectively negligible when compared with the diffracted sound. As a general rule, the transmitted sound must be at least 10 dB lower as compared to the diffracted sound in order for it to be ignored.

The remaining noise is either absorbed by the noise barrier material or reflected.

The ability of a barrier's surface to absorb incident sound energy is characterized by its **Noise Reduction Coefficient**, abbreviated NRC. Noise Reduction Coefficient values are based on an average of absorption coefficients at individual frequencies and theoretically range from 0 to 1, 0 indicting that the surface is totally reflective (or that there is no absorption) and 1 indicating that the material is totally absorptive. NRC values for an absorptive barrier generally range from 0.6 to 0.9.

A reflective barrier surface can cause noise to affect receivers on the opposite side of the highway. It is a common perception among such communities to hear a difference in the sound after the barrier is installed.

Although theory indicates greater increases for a single reflection, practical highway measurements commonly show a 1 to 2 dB increase in sound pressure level from the no-barrier case due to the sound reflected off the opposing barrier. Such increases can be considered typical for the first and second row residences. While this increase may not be readily perceptible, residents on the opposite side of the highway may perceive a change in the quality of the sound; the signature of the reflected sound may differ from that of the source due to a change in frequency content upon reflection.

If we have parallel barriers instead of just a barrier on one side of the highway, the situation becomes much more complicated.

For **parallel barriers** sound may reflect back and forth across the roadway many times before ultimately progressing outwards toward nearby receivers. The multiple reflections increase the sound level at nearby receivers and can reduce insertion loss provided by either wall alone by 2-6 dB. As an example, a barrier that achieves a 10 dB insertion loss may realize only a 4-8 dB insertion loss if a parallel barrier is placed on the opposite side of the highway.

The reduction in barrier effectiveness due to multiple reflections from parallel barriers or retaining walls is called parallel-barrier degradation.

Research has shown that as a general rule, if the ratio of roadway width to average height of the parallel barriers is 10:1 or greater, the parallel barrier degradation is less than 3 dB. Remember that decibel changes less than 3 are typically not perceivable.

Solutions to parallel barrier degradation include: 1) applying absorbing material to the face of the barrier and 2) tilting the barrier out, away from the highway. When tilting a barrier, one must consider tall structures on the opposite side of the highway so as not to adversely affect them with the reflected sound.

Several design considerations need to be addressed when constructing a barrier. Following is a brief discussion of some of the acoustical design parameters.

As a general rule, a wall that **breaks the line of sight** between source and receiver provides 5 dB attenuation; thereafter, you can achieve about 0.5 dB attenuation per incremental foot of height or 1.5 dB attenuation per meter.

Breaking the line of sight with a barrier and getting the 5 dB reduction is simple; with this you can achieve a 68 percent reduction in acoustic energy which equates to a 30 percent reduction in loudness. The actual insertion loss for such a barrier could be less than 5 dB because of the partial loss of acoustically soft ground attenuation as discussed earlier.

barrier noise reduction	**feasibility**
5 dB	simple
10 dB	attainable
15 dB	very difficult
20 dB	nearly impossible

It is also usually quite feasible to achieve a 10 dB reduction using walls or berms of reasonable height; here you would get a 90 percent reduction in acoustic energy and a loudness reduction of 50 percent.

Greater barrier noise reductions are not so easily attainable. A 15-dB reduction would be very difficult and a 20-dB reduction would be nearly impossible. Noise barriers are usually designed with an *insertion loss* goal of 10 dB in mind.

Remember that insertion loss includes the barrier reduction and the partial loss of ground attenuation. Actual barrier insertion losses of between 6 and 8 dB are quite common. Also, keep in mind that a barrier will provide no insertion loss until its attenuation exceeds any loss of excess ground attenuation due to construction of the barrier.

– *Rows of houses*

Besides obstructions that are specifically constructed for noise abatement, other large objects can interfere with sound propagation. Specifically, we are referring here to rows of buildings or large areas of dense foliage.

Buildings refer to houses, offices, apartments, and other similar structures. For **rows of buildings**, the amount of noise reduction varies with building sizes, their spacing, and site geometry.

Typically 4.5-5.0 dB attenuation is attainable for the 1st row of buildings, and an additional 1.5 dB for each subsequent row, up to a maximum of about 10 dB.

To get an idea of how gaps or openings between buildings in a row can affect the amount of insertion loss, here are some percentages and the corresponding dB reduction.

If 40-65 percent of the 1st row is occupied by buildings, the expected insertion loss will be about 3 dB. For 65-90 percent, the insertion loss will be about 5 dB. Lastly, for percentages greater than 90, the buildings will provide attenuation comparable to that of a barrier of similar height.

– *Foliage*

In addition to constructed noise barriers and rows of buildings, areas of **dense foliage** can provide attenuation.

Such attenuation is caused by sound scattering into the sky from trunks and limbs, affecting the middle frequencies, and leaves, affecting very high frequencies. Sound absorption by leaves is generally not substantial.

In addition, some low frequency attenuation results from ground attenuation within the wooded area, where the roots of underbrush produce acoustically absorptive soft ground.

To achieve any substantial amount of attenuation due to foliage, such as trees and bushes, foliage must be at least 30 meters (100 feet) deep (in other words, a strip of 30 meter width) and dense enough to block the line-of-sight between source and receiver.

Further, the foliage area should have a height that extends 5 meters (16 feet) above the line of sight.

Typically, as much as 5 dB attenuation is attainable.

If the foliage area is doubled in width to 60 meters (200 feet) or extended beyond that, a reduction of 10 dB, but no greater, is attainable.

Theoretically, using foliage to reduce the noise in communities surrounding highways is appealing. However, foliage of sufficient width and density to reduce noise is not usually found along highways. **Vegetation** planted as part of a highway project will not provide noise abatement.

Wrap up

This presentation has highlighted some of the basics of acoustics and highway traffic noise. Of course, many details beyond what was covered here must be taken into account to accurately describe the sound in our communities. There are ongoing studies in this field of acoustics, and we can look forward to progress in years to come.

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