2. BASIC NOISE CONCEPTS

This chapter discusses the basic concepts of transit noise which provide background for Chapters 3 through 6, where transit noise is computed and assessed. The Source-Path-Receiver framework sketched in Figure 2-1 is central to all environmental noise studies. Each transit **source** generates close-by noise levels, which depend upon the type of source and its operating characteristics. Then, along the propagation **path** between all sources and receivers, noise levels are reduced (attenuated) by distance, intervening obstacles and other factors. And finally at each **receiver**, noise combines from all sources to interfere, perhaps, with receiver activities. This chapter contains an overview of this Source-Path-Receiver framework. Following this overview is a discussion of transit-noise descriptors.

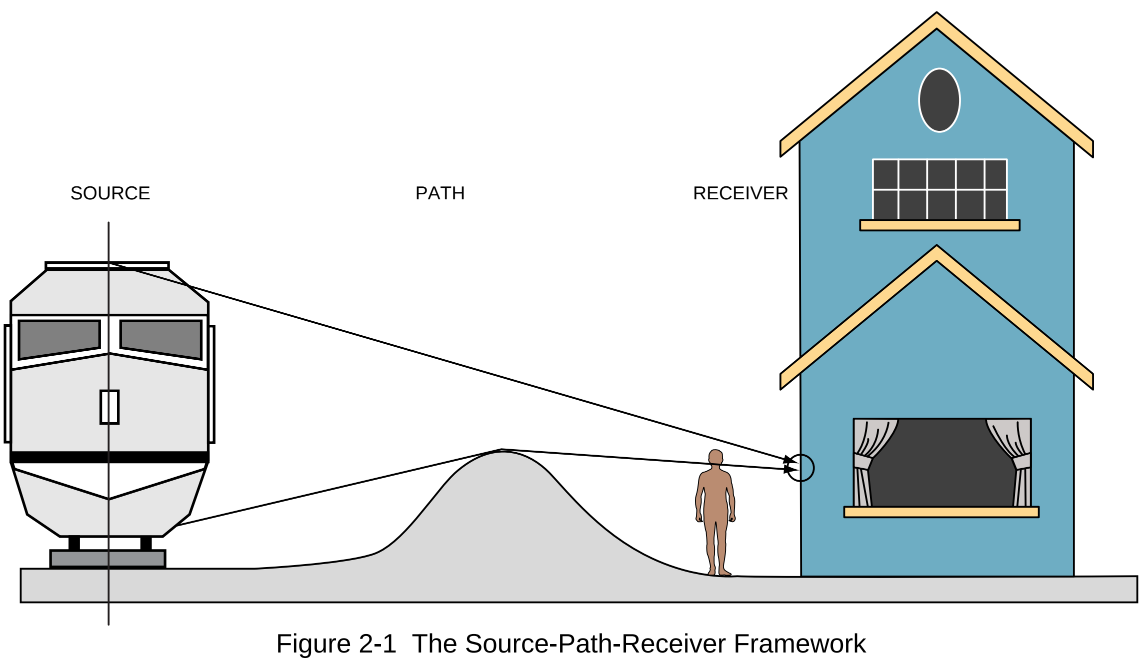


Figure 2-1 The Source-Path-Receiver Framework

In brief, this chapter contains:

- An overview of transit **sources**: a listing of major sources, plus some discussion of noise-generation mechanisms (Section 2.1)
- An overview of noise **paths**: a discussion of the various attenuating mechanisms on the path between source and receiver (Section 2.2)
- An overview of **receiver** response to transit noise: a discussion of the technical background for transit-noise criteria and the distinction between absolute and relative noise impact (Section 2.3)
- A discussion of the **noise descriptors** used in this manual for transit noise (Section 2.4)

2.1 SOURCES OF TRANSIT NOISE

This section discusses major characteristics of the sources of transit noise. Transit noise is generated by transit vehicles in motion. Vehicle propulsion units generate: (1) whine from electric control systems and traction motors that propel rapid transit cars, (2) diesel-engine exhaust noise, from both diesel-electric locomotives and transit buses, (3) air-turbulence noise generated by cooling fans, and (4) gear noise. Additional noise of motion is generated by the interaction of wheels/tires with their running surfaces. Tire noise from rubber-tired vehicles is significant at normal operating speeds. The interaction of steel wheels and rails generates three types of noise: (1) rolling noise due to continuous rolling contact, (2) impact noise when a wheel encounters a discontinuity in the running surface, such as a rail joint, turnout or crossover, and (3) squeal generated by friction on tight curves.

Figure 2-2 illustrates typical dependence of source strength on vehicle speed for two types of transit vehicles. Plotted vertically in this figure is a qualitative indication of the maximum sound level during a passby. In the figure, speed dependence is strong for electric-powered transit trains because wheel/rail noise dominates, and noise from this source increases strongly with increasing speed. On the other hand, speed dependence is less for diesel-powered commuter rail trains, particularly at low speeds where the locomotive exhaust noise dominates. As speed increases, wheel-rail noise becomes the dominant noise source and diesel- and electric-powered trains will generate similar noise levels. Similarly, but not shown, speed dependence is also strong for automobiles, city buses (two-axle) and non-accelerating highway buses (three-axle), because tire/pavement noise dominates for these vehicles; but it is not significant for accelerating highway buses where exhaust noise is dominant.

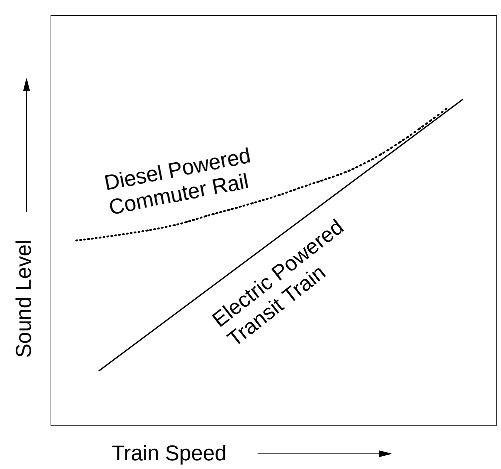


Figure 2-2 Example Sound Level Dependence on Speed

For transit vehicles in motion, close-by sound levels also depend upon other parameters, such as vehicle acceleration and vehicle length, plus the type/condition of the running surfaces. For very high-speed rail vehicles, air turbulence can also be a significant source of noise. In addition, the guideway structure can also radiate noise as it vibrates in response to the dynamic loading of the moving vehicle.

Noise is generated by transit vehicles even when they are stationary. For example, auxiliary equipment often continues to run even when vehicles are stationary – equipment such as cooling fans on motors, radiator fans, plus hydraulic, pneumatic and air-conditioning pumps. Also, transit buses are often left idling in stations or storage yards. Noise is also generated by sources at fixed-transit facilities. Such sources include ventilation fans in transit stations, in subway tunnels, and in power substations, equipment in chiller plants, and many activities within maintenance facilities and shops.

Table 2-1 summarizes sources of transit noise, separately by vehicle type and/or type of facility. Prodecures for computing close-by noise levels for major sources as a function of operating parameters such as vehicle speed are given in Chapters 5 and 6.

Table 2-1 Sources of Transit Noise

Vehicle or Facility	Dominant Components	Comments
Rail Rapid Transit (RRT), or Light Rail Transit (LRT) on exclusive right-of-way	Wheel/rail interaction and guideway amplification	Depends on condition of wheels and rails.
	Propulsion system	When accelerating and at higher speeds.
	Brakes	When stopping.
	Auxiliary equipment	When stopped.
	Wheel squeal	On tight curves.
	In general	Noise increases with speed and train length.
Light Rail Transit (LRT) in mixed traffic	Wheel squeal	On tight curves.
	Auxiliary equipment	When stopped.
	Horns and crossing bells	At grade crossings.
	In general	Lower speeds mean less noise than for RRT and LRT on exclusive right-of-way.
Commuter Rail	Diesel exhaust	On diesel-hauled trains.
	Cooling fans	On both diesel and electric-powered trains.
	Wheel/rail interaction	Depends on condition of wheels and rails.
	Horns and crossing gate bells	At grade crossings.
	In general	Noise is usually dominated by locomotives.
Low and Intermediate Capacity Transit	Propulsion systems, including speed controllers	At low speeds.
	Ventilation systems	At low speeds.
	Tire/guideway interaction	For rubber-tired vehicles, including monorails.
	Wheel/rail interaction	Depends on condition of wheels and rails.
	In general	Wide range of vehicles: monorail, rubber-tired, steel wheeled, linear induction. Noise characteristics depend upon type.

Table 2-1 Sources of Transit Noise (continued)		
Vehicle or Facility	**Dominant Components**	**Comments**
Diesel Buses	Cooling fans	While idling.
	Engine casing	While idling.
	Diesel exhaust	At low speeds and while accelerating.
	Tire/roadway interaction	At moderate and high speeds.
	In general	Includes city buses (generally two axle) and commuter buses (generally three axle).
Electric Buses and Trackless Trolleys	Tire/roadway interaction	At moderate speeds.
	Electric traction motors	At moderate speeds.
	In general	Much quieter than diesel buses.
Bus Storage Yards	Buses starting up	Usually in early morning.
	Buses accelerating	Usually near entrances/exits.
	Buses idling	—
	In general	Site specific. Often peak periods with significant noise.
Rail Transit Storage Yards	Wheel squeal	On tight curves.
	Wheel impacts	On joints and switches.
	Wheel rolling noise	—
	Auxiliary equipment	Throughout day and night. Includes air-release noise.
	Coupling/uncoupling	—
	Signal horns	—
	In general	Site specific. Often early morning and peak periods with significant noise.
Maintenance Facilities	Signal horns	—
	PA systems	—
	Impact tools	—
	Car/bus washers/driers	—
	Vehicle activity	—
	In general	Site specific. Considerable activity throughout day and night, some outside.
Stations	Automobiles	Patron arrival/departure, especially in early morning.
	Buses idling	—
	P.A. systems	—
	Locomotive idling	At commuter rail terminal stations.
	Auxiliary systems	At terminal stations and layover facilities.
	In general	Site specific, with peak activity periods.
Subways	Fans	Noise through vent shafts.
	Buses/trains in tunnels	Noise through vent shafts.
	In general	Noise is not a problem.

2.2 PATHS OF TRANSIT NOISE, FROM SOURCE TO RECEIVER

This section contains a qualitative overview of noise-path characteristics from source to receiver, including attenuation along these paths. Equations for specific noise-level attenuations along source-receiver paths appear in Chapters 5 and 6.

Sound paths from source to receiver are predominantly through the air. Along these paths, sound reduces with distance due to (1) divergence, (2) absorption/diffusion and (3) shielding. These mechanisms of sound attenuation are discussed below.

Divergence. Sound levels naturally attenuate due to distance, as shown in Figure 2-3. Plotted vertically is the attenuation at the receiver, relative to the sound level 50 feet from the source. As shown, the sound level attenuates with increasing distance. Such attenuation, technically called "divergence," depends upon source configuration and source-emission characteristics. For sources grouped closely together (called point sources), attenuation with distance is large: 6 decibels per doubling of distance. Point sources include crossing signals along rail corridors, PA systems in maintenance yards and other closely grouped sources of noise. For vehicles passing along a track or roadway (called line sources), divergence with distance is less: 3 decibels per doubling of distance for L_{eq} and L_{dn}, and 3 to 6 decibels per doubling of distance for L_{max}. In Figure 2-3, the line source curve separates into three separate lines for L_{max}, with the point of departure depending on the length of the line source. These three noise descriptors – L_{eq}, L_{dn} and L_{max} – are discussed in Section 2.4. Equations for the curves in Figure 2-3 appear in Chapter 6.

Absorption/Diffusion. In addition to distance alone, sound levels are further attenuated when sound paths lie close to freshly-plowed or vegetation-covered ground. Plotted vertically in Figure 2-4 is this additional attenuation, which can be as large as 5 decibels as close in as several hundred feet. At very large distances, wind and temperature gradients sometimes modify the ground attenuation shown here; such variable atmospheric effects are not included in this manual because they generally occur beyond the range of typical transit-noise impact. Equations for the curves in this figure appear in Chapter 6.

Shielding. Sound paths are sometimes interrupted by man-made noise barriers, by terrain, by rows of buildings, or by vegetation. Most important of these path interruptions are noise barriers, one of the best means of mitigating noise in sensitive areas. A noise barrier reduces sound levels at a receiver by breaking the direct line-of-sight between source and receiver with a solid wall (in contrast to vegetation, which hides the source but does not reduce sound levels significantly). Sound energy reaches the receiver only by bending (diffracting) over the top of the barrier, as shown in Figure 2-5, and this diffraction reduces the sound level at the receiver.

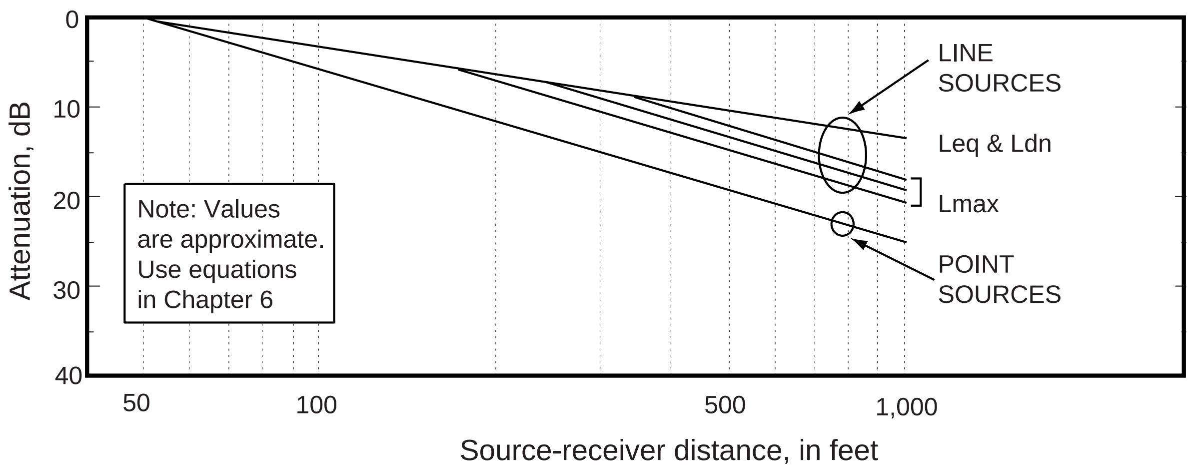


Figure 2-3 Attenuation due to Distance (Divergence)

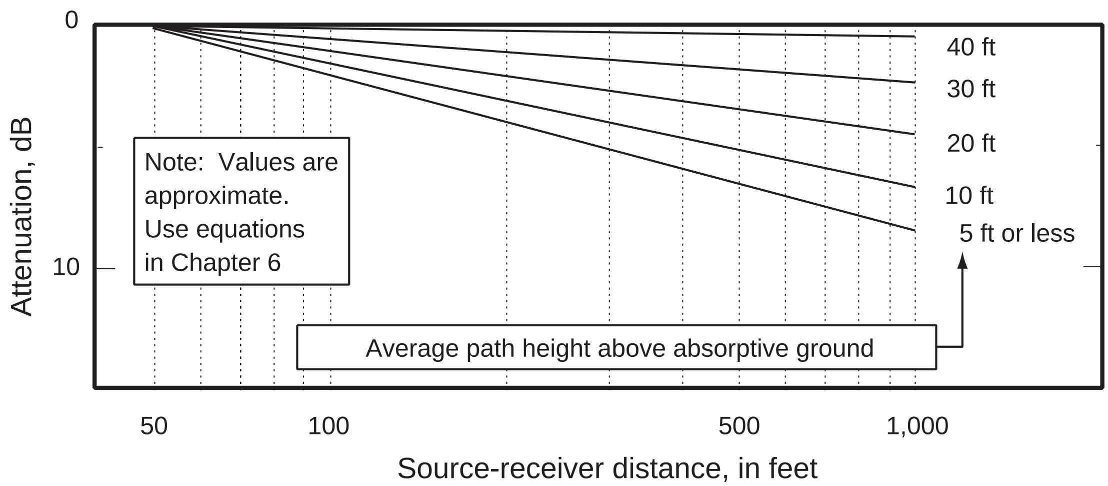


Figure 2-4 Attenuation due to Soft (Sound-Absorptive) Ground

Sound barriers for transportation systems are typically used to attenuate noise at the receiver by 5 to 15 decibels, depending upon barrier height, length, and distance from both source and receiver. Barriers on structure, very close-in to the source, sometimes provide less attenuation than do barriers slightly more distant from the source, due to reverberation (multiple reflections) between the barrier and the body of the vehicle. However, this reverberation is often offset by increased barrier height, which is easy to obtain for such close-in barriers, and/or acoustical absorption on the source side of the barrier. Acoustical absorption is included as a mitigation option in Chapter 6. Equations for barrier attenuation, plus equations for other sound-path interruptions, also appear in Chapter 6.

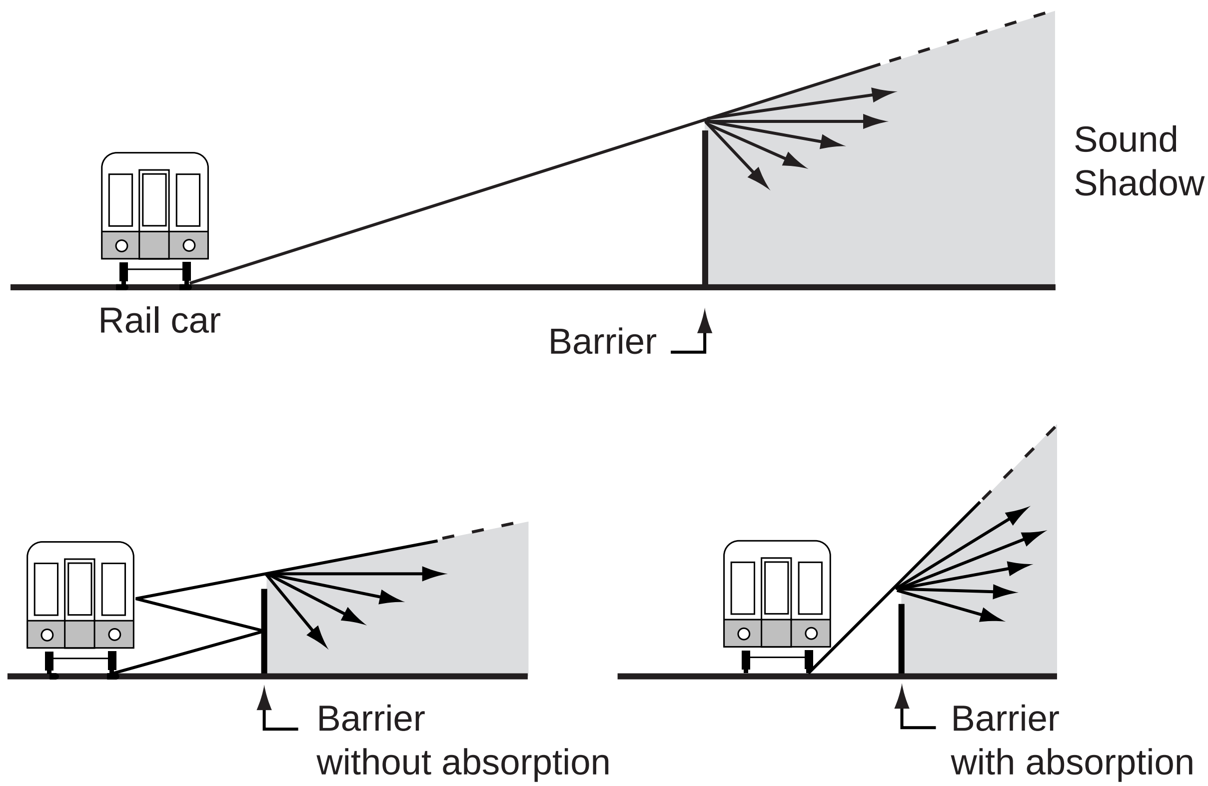


Figure 2-5 Noise Barrier Geometry

Sometimes a portion of the source-to-receiver path is not through the air, but rather through the ground or through structural components of the receiver's building. Discussion of such ground-borne and structure-borne propagation is included in Chapter 7.

2.3 RECEIVER RESPONSE TO TRANSIT NOISE

This section contains an overview of receiver response to noise. It serves as background information for the noise-impact criteria in Chapter 3.

Noise can interrupt ongoing activities and can result in community annoyance, especially in residential areas. In general, most residents become highly annoyed when noise interferes significantly with activities such as sleeping, talking, noise-sensitive work, and listening to radio or TV or music. In addition, some land uses, such as outdoor concert pavilions, are inherently incompatible with high noise levels.

Annoyance to noise has been investigated and approximate dose-response relationships have been quantified by the Environmental Protection Agency (EPA).[1][2] The selection of noise descriptors in this manual is largely based upon this EPA work. Beginning in the 1970s, the EPA undertook a number of research and synthesis studies relating to community noise of all types. Results of these studies have been widely published, and discussed and refereed by many professionals in acoustics. Basic conclusions of these studies have been adopted by the Federal Interagency Committee on Noise, the Department of Housing and Urban Development (HUD), the American National Standards Institute, and even internationally.[3][4][5][6] Conclusions from this seminal EPA work remain scientifically valid to this day.

Figure 2-6 contains a synthesis of actual case studies of community reaction to newly introduced sources of noise in a residential urban neighborhood.[2] Plotted horizontally in the figure is the new noise's excess above existing noise levels. Both the new and existing noise levels are expressed as Day-Night Sound Levels, L_{dn}, discussed in Section 2.4. Plotted vertically is the community reaction to this newly introduced noise. As shown in the figure, community reaction varies from "No Reaction" to "Vigorous Action," for newly introduced noises averaging from "10 decibels below existing" to "25 decibels above existing." Note that these data points apply only when the stated assumptions are true. For other conditions, the points shift to the right or left somewhat.

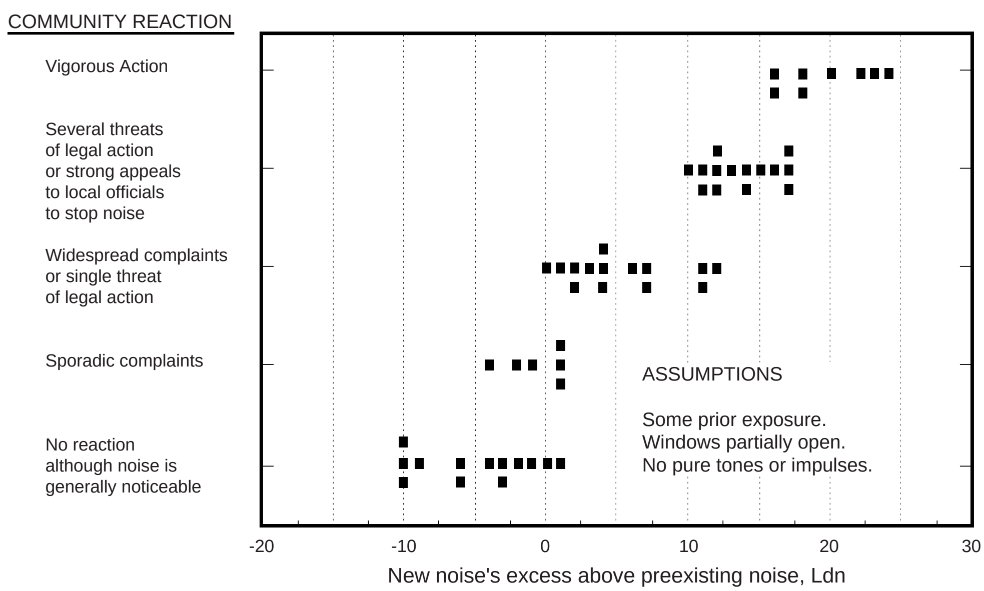


Figure 2-6 Community Reaction to New Noise, Relative to Existing Noise in a Residential Urban Environment

In a large number of community attitudinal surveys, transportation noise has been ranked among the most significant causes of community dissatisfaction. A synthesis of many such surveys on annoyance appears in Figure 2-7.[7][8] Plotted horizontally are different neighborhood noise exposures. Plotted vertically is the percentage of people who are *highly annoyed* by their particular level of neighborhood noise. As shown in the figure, the percentage of high annoyance is approximately 0 percent at 45 decibels, 10 percent around 60 decibels and increases quite rapidly to approximately 70 percent around 85 decibels. The scatter about the synthesis line is due to variation from community to community and to some wording differences in the various surveys. A recent update of the original research, containing several additional railroad, transit and street traffic noise surveys, added confirmation to the shape of the original Schultz curve.[9]

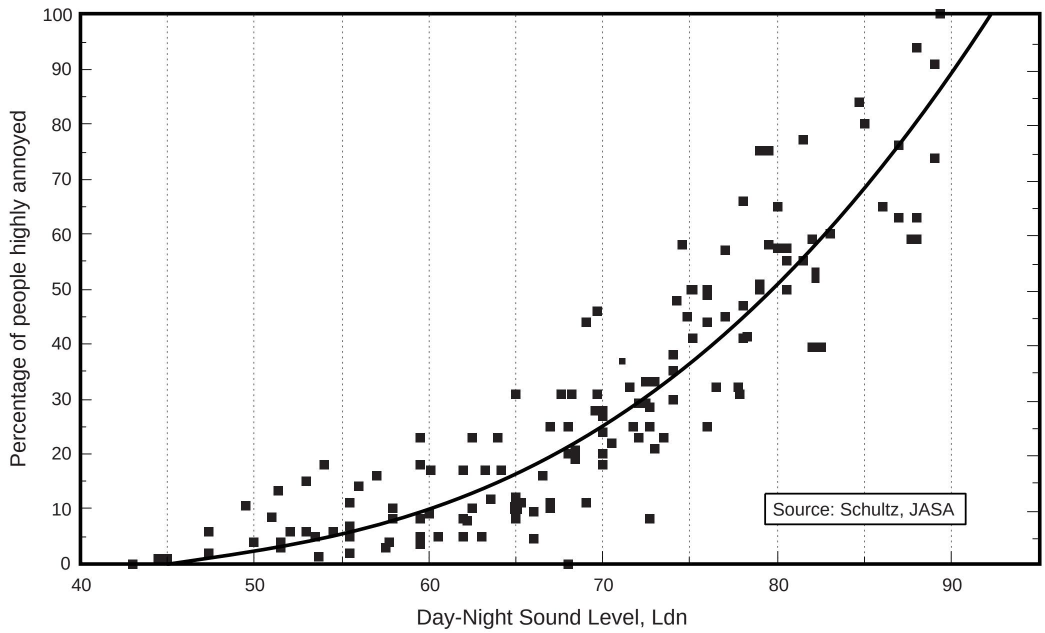


Figure 2-7 Community Annoyance Due to Noise

As indicated by these two figures, introduction of transit noise into a community may have two undesirable effects. First, it may significantly increase existing noise levels in the community, levels that residents have mostly become accustomed to. This effect is called "relative" noise impact. Evaluation of this effect is "relative" to existing noise levels; relative criteria are based upon noise increases above existing levels. Second, newly introduced transit noise may interfere with community activities, independent of existing noise levels; it may be simply too loud to converse or to sleep. This effect is called "absolute" noise impact, because it is expressed as a fixed level not to be exceeded and is independent of existing noise levels. Both these effects, relative and absolute, enter the assessment of transit noise impact in Chapters 4, 5 and 6. These two types of impact, relative and absolute, are merged into the transit noise criteria of Chapter 3.

2.4 DESCRIPTORS FOR TRANSIT NOISE

Environmental noise generally derives, in part, from a conglomeration of distant noise sources. Such sources may include distant traffic, wind in trees, and distant industrial or farming activities, all part of our daily lives. These distant sources create a low-level "background noise" in which no particular individual source is identifiable. Background noise is often relatively constant from moment to moment, but varies slowly from hour to hour as natural forces change or as human activity follows its daily cycle. Superimposed on this low-level, slowly varying background noise is a succession of identifiable noisy events of relatively brief duration. These events may include single-vehicle passbys, aircraft flyovers, screeching of brakes, and other short-term events, all causing the noise level to fluctuate significantly from moment to moment.

It is possible to describe these fluctuating noises in the environment using single-number descriptors. To do this allows manageable measurements, computations, and impact assessment. The search for adequate single-number noise descriptors has encompassed hundreds of attitudinal surveys and laboratory experiments, plus decades of practical experience with many alternative descriptors.

This manual uses the following single-number descriptors for transit-noise measurements, computations, and assessment:

The *A-weighted Sound Level*, which describes a receiver's noise at any moment in time.

The *Maximum Level* (L_{max}) during a single noise event.

The *Sound Exposure Level (SEL)*, which describes a receiver's cumulative noise exposure from a single noise event.

The *Hourly Equivalent Sound Level* ($L_{eq}(h)$), which describes a receiver's cumulative noise exposure from all events over a one-hour period.

The *Day-Night Sound Level* (L_{dn}), which describes a receiver's cumulative noise exposure from all events over a full 24 hours, with events between 10pm and 7am increased by 10 decibels to account for greater nighttime sensitivity to noise.

This section illustrates all of these noise descriptors, in turn, and describes their particular application in this manual. Emphasized here are graphic illustrations rather than mathematical definitions to help the reader gain understanding and to see the interrelationships among descriptors.

2.4.1 A-weighted Sound Level: The Basic Noise Unit

The basic noise unit for transit noise is the A-weighted Sound Level. It describes a receiver's noise at any moment in time and is read directly from noise-monitoring equipment, with the "weighting switch" set on "A." Figure 2-8 shows some typical A-weighted Sound Levels for both transit and non-transit sources.

As is apparent from Figure 2-8, typical A-weighted Sound Levels range from the 30s to the 90s, where 30 is very quiet and 90 is very loud. The scale in the figure is labelled "dBA" to denote the way A-weighted Sound Levels are typically written, for example, 80 dBA. The letters "dB" stand for "decibels" and refer to the general strength of the noise. The decibel is a unit of level which denotes the ratio between two quantities that are proportional to power. When used to describe sound level, the number of decibels is 10 times the logarithm (to the base 10) of the ratio (p^2/p_{ref}^2), where p is the sound pressure (in micro-pascals) and p_{ref} is a reference pressure (20 micro-pascals). The letter "A" indicates that the sound has been filtered to reduce the strength of very low and very high-frequency sounds, much as the human ear does. Without this A-weighting, noise-monitoring equipment would respond to events people cannot hear, events such as high-frequency dog whistles and low-frequency seismic disturbances. On the average, each A-weighted sound level increase of 10 decibels corresponds to an approximate doubling of subjective loudness.

A-weighted sound levels are adopted here as the basic noise unit because: (1) they can be easily measured, (2) they approximate our ear's sensitivity to sounds of different frequencies, (3) they match attitudinal-survey tests of annoyance better than do other basic units, (4) they have been in use since the early 1930s, and (5) they are endorsed as the proper basic unit for environmental noise by nearly every agency concerned with community noise throughout the world.

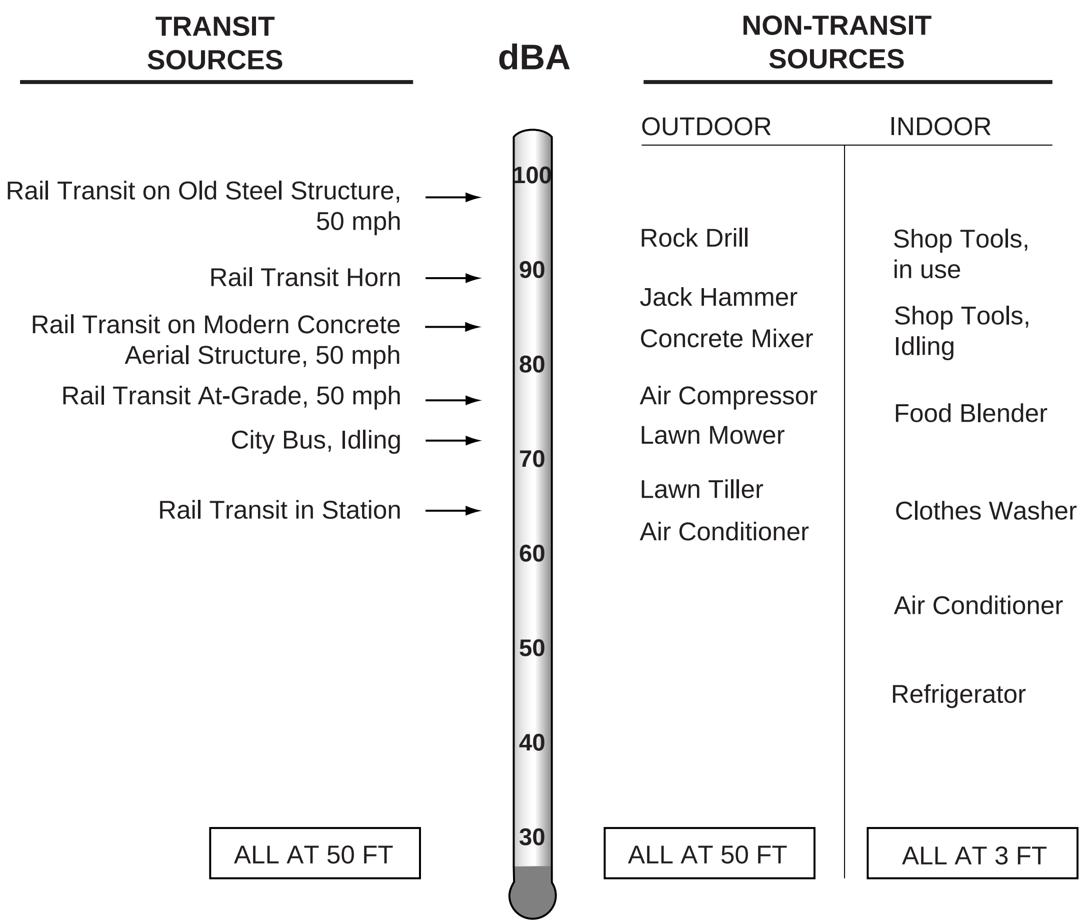


Figure 2-8 Typical A-Weighted Sound Levels

2.4.2 Maximum Level (L_{max}) During a Single Noise Event

As a transit vehicle approaches, passes by, and then recedes into the distance, the A-weighted sound level rises, reaches a maximum, and then fades into the background noise. The maximum A-weighted sound level reached during this passby is called the Maximum Level, abbreviated here as "L_{max}." For noise compliance tests of transient sources, such as moving transit vehicles under controlled conditions with smooth wheel and rail conditions, L_{max} is typically measured with the sound level meter's switch set on "fast." However, for tests of continuous or stationary transit sources, and for the general assessment of transit noise impact, it is usually more appropriate to use the "slow" setting. When set on "slow," sound level meters ignore some of the very-transient fluctuations, which are unimportant to people's overall assessment of the noise. L_{max} is illustrated in Figure 2-9, where time is plotted horizontally and A-weighted sound level is plotted vertically.

Noise guidelines published by the American Public Transit Association (APTA) have been used for a number of years to assess the noise impact of rail transit projects.(10) For moving trains, the APTA guidelines are based on L_{max} during a vehicle passby. They are directed toward conventional rail rapid transit projects and cover all aspects of such systems. Because L_{max} is commonly used in vehicle-noise specifications and because it is commonly measured for individual vehicles, equations are included in Appendices D and E to convert between L_{max} and the cumulative descriptors discussed below. However, L_{max} is not used as the descriptor for transit environmental noise impact assessment for several reasons. L_{max} ignores the number and duration of transit events, which are important to people's reaction to noise, and cannot be totalled into a one-hour or a 24-hour cumulative measure of impact. Moreover, the L_{max} is not conducive to comparison among different transportation modes. For example, noise descriptors used in highway noise assessments are L_{eq} and L_{10}, the noise level exceeded for 10 percent of the peak hour.

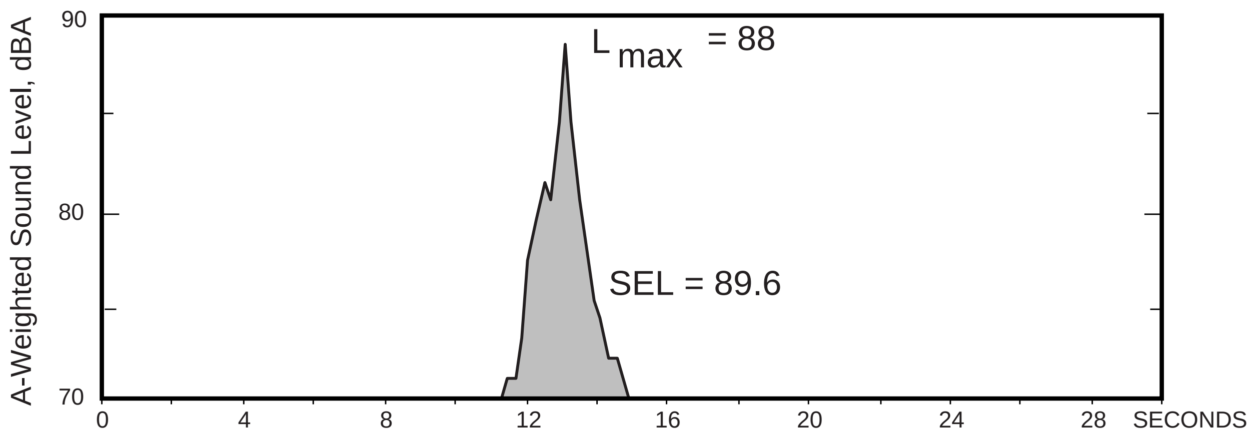


Figure 2-9 Typical Transit-Vehicle Passby

2.4.3 Sound Exposure Level (SEL): The Cumulative Exposure from a Single Noise Event

Shaded in Figure 2-9 is the noise "dose" during a transit-vehicle passby. This dose represents the total amount of sound energy that enters the receiver's ears (or the measurement microphone) during the vehicle passby. Figure 2-10 shows another noise event – this one within a fixed-transit facility as a transit bus is started, warmed up, and then driven away. For this event, the noise dose is large due to *duration*.

The quantitative measure of the noise dose for single noise events is the Sound Exposure Level, abbreviated here as "SEL" and shaded in both these figures. The fact that SEL is a cumulative measure means that (1) louder events have greater SELs than do quieter ones, and (2) events that last longer in time have greater SELs than do shorter ones. People react to the duration of noise events, judging longer events to be more annoying than shorter ones, assuming equal maximum A-Levels. Mathematically, the Sound Exposure Level is computed as:

$$\text{SEL} = 10\log_{10}\begin{bmatrix}\text{Total sound energy}\\ \text{during the event}\end{bmatrix}$$

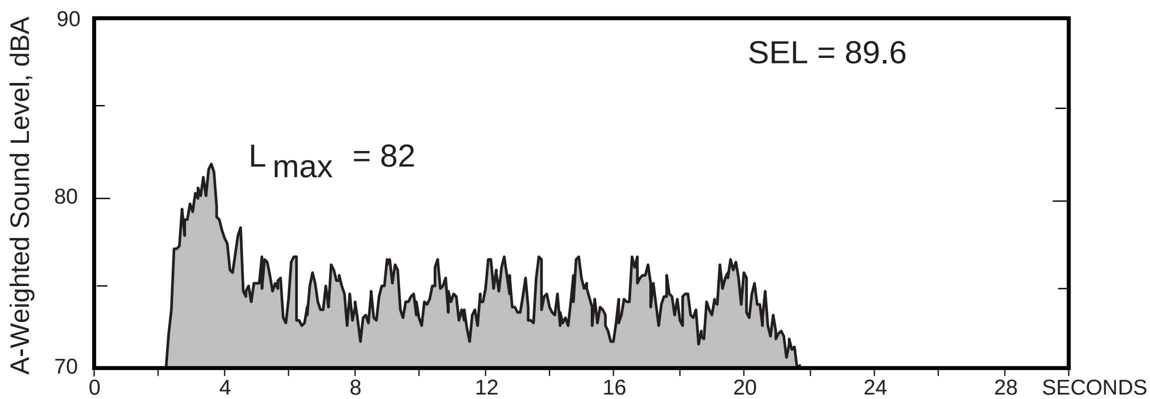


Figure 2-10 Typical Fixed-Facility Noise Event

Figure 2-11 repeats the previous time histories, but with a stretched vertical scale. The stretched scale corresponds to sound "energy" at any moment in time. Mathematically, sound energy is proportional to 10 raised to the (L/10) power, that is, $10^{(L/10)}$. The vertical scale has been stretched in this way because noise doses are "energy" doses. Only in this way do the shaded zones properly correspond to the noise doses that underlie the SEL. Note that the shaded zones in the two frames have equal numerical areas, corresponding to equal SELs for these two very different noise events.

Each frame of the figure also contains a tall, thin shaded zone of one-second duration. This tall zone is another way to envision SELs. Think of the original shaded zone being squeezed shorter and shorter in time, while retaining the same numerical area. As its duration is squeezed, its height must increase to keep the area constant. If an SEL shading is squeezed to a duration of one second, its height will then equal its SEL value; mathematically, its area is now $10^{(L/10)}$ times one second. Note that the resulting height of the squeezed zone depends both upon the L_{max} and the duration of the event -- that is, upon the total area under the original, time-varying A-Level. Often this type of "squeezing" helps communicate the meaning of SELs and noise doses to the reader.

SEL is used in this manual as the cumulative measure of each single transit-noise event because unlike L_{max}: (1) SEL increases with the duration of a noise event, which is important to people's reaction, (2) SEL

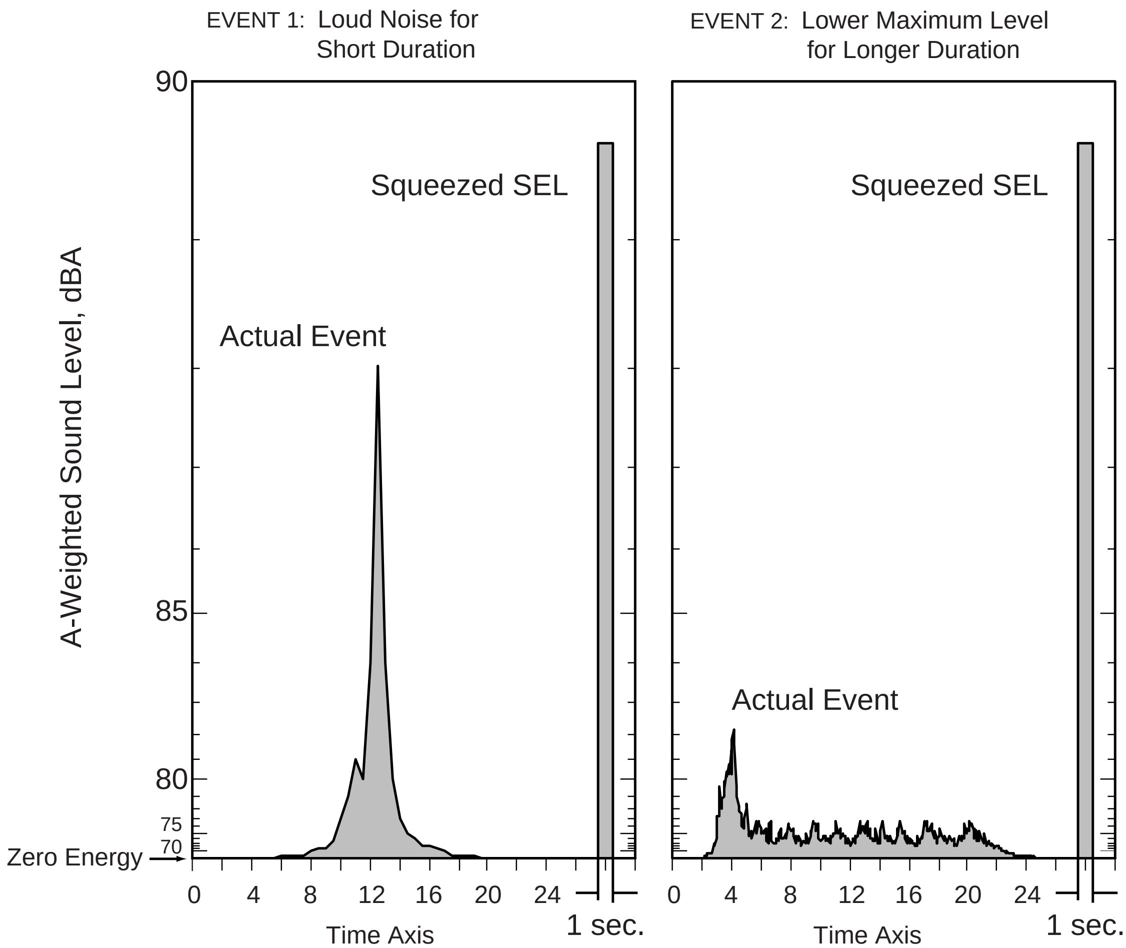


Figure 2-11 An "Energy" View of Noise Events

therefore allow a uniform assessment method for both transit-vehicle passbys and fixed-facility noise events, and (3) SEL can be used to calculate the one-hour and 24-hour cumulative descriptors discussed below.

2.4.4 Hourly Equivalent Sound Level (L_{eq}(h))

The descriptor for cumulative one-hour exposure is the Hourly Equivalent Sound Level, abbreviated here as "L_{eq}(h)." It is an hourly measure that accounts for the moment-to-moment fluctuations in A-weighted sound levels due to all sound sources during that hour, combined. Sound fluctuation is illustrated in the upper frame of Figure 2-12 for a single noise event such as a train passing on nearby tracks. As the train approaches, passes by, and then recedes into the distance, the A-weighted Sound Level rises, reaches a maximum, and then fades into the background noise. The area under the curve in this upper frame is the receiver's noise dose over this five-minute period.

The center frame of the figure shows sound level fluctuations over the one-hour period that includes the five-minute period from the upper frame. Now the area under the curve represents the noise dose for one hour. Mathematically, the Hourly Equivalent Sound Level is computed as:

$$L_{eq}(hour) = 10 \log_{10} \begin{bmatrix} \text{Total sound energy} \\ \text{during one hour} \end{bmatrix} - 35.6$$

Sound energy is totalled here over a full hour; it accumulates from all noise events during that hour. Subtraction of 35.6 from this one-hour dose converts it into a time average, as explained in Section 2.4.6. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total noise dose would enter the receiver's ears. This type of average value is "equivalent" in that sense to the actual fluctuating noise.

A useful, alternative way of computing L_{eq} due to a series of transit-noise events is:

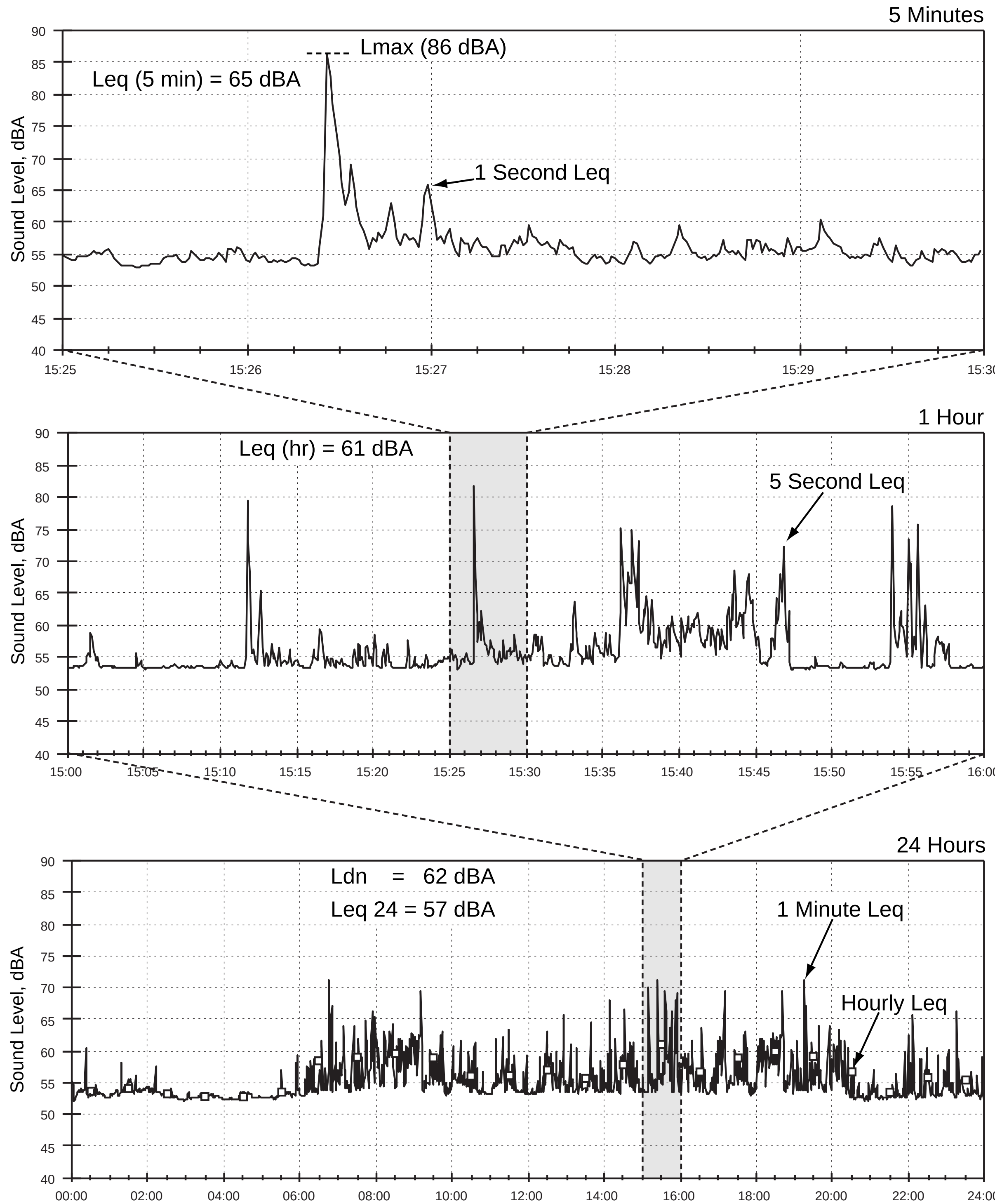
$$L_{eq}(hour) = 10 \log_{10} \begin{bmatrix} \text{Energy Sum of} \\ \text{all SELs} \end{bmatrix} - 35.6$$

This equation concentrates on the cumulative contribution of individual noise events, and is the fundamental equation incorporated into Chapters 5 and 6.

The bottom frame of Figure 2-12 shows the sound level fluctuations over a full 24-hour period. It is discussed in Section 2.4.5.

Figure 2-13 shows some typical hourly L_{eq}'s, both for transit and non-transit sources. As is apparent from the figure, typical hourly L_{eq}'s range from the 40s to the 80s. Note that these L_{eq}'s depend upon the number of events during the hour and also upon each event's duration, which is affected by vehicle speed. Doubling the number of events during the hour will increase the L_{eq} by 3 decibels, as will doubling the duration of each individual event.

Hourly L_{eq} is adopted here as the measure of cumulative noise impact for non-residential land uses (those not involving sleep) because: (1) L_{eq}'s correlate well with speech interference in conversation and on the telephone – as well as interruption of TV, radio and music enjoyment, (2) L_{eq}'s increase with the duration of transit events, which is important to people's reaction, (3) L_{eq}'s take into account the number of transit events over the hour, which is also important to people's reaction, and (4) L_{eq}'s are used by the Federal Highway Administration in assessing highway-traffic noise impact. Thus, this noise descriptor can be used for comparing and contrasting highway, transit and multi-modal alternatives. L_{eq} is computed for the loudest facility hour during noise-sensitive activity at each particular non-residential land use. Section 2.4.6 contains more detail in support of L_{eq} as the adopted descriptor for cumulative noise impact for non-residential land uses.



Typical A-weighted Sound Level Variation over a 24-Hour Period

Figure 2-12 Example A-Weighted Sound Level Time Histories

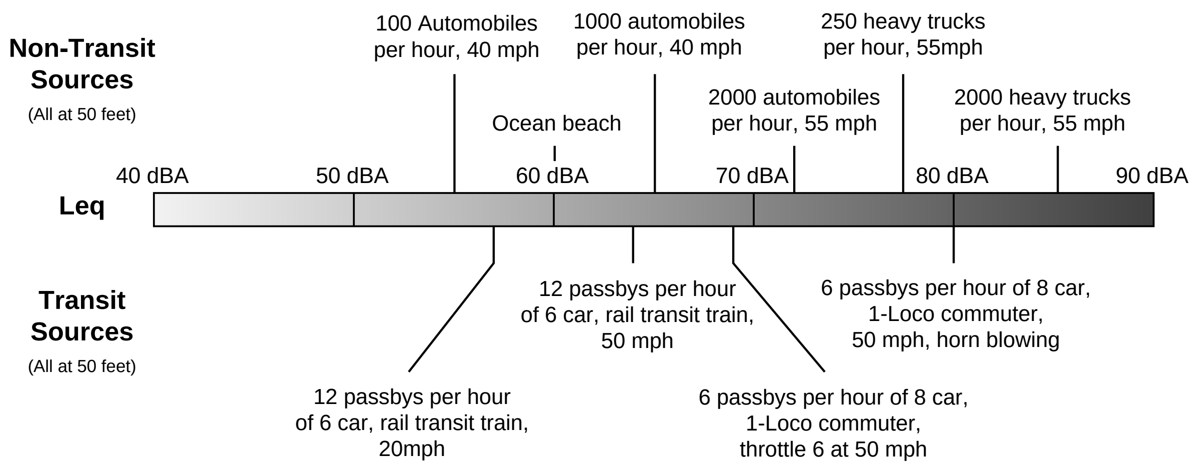


Figure 2-13 Typical Hourly L_{eq}'s

2.4.5 Day-Night Sound Level (L_{dn}): The Cumulative 24-Hour Exposure from All Events

The descriptor for cumulative 24-hour exposure is the Day-Night Sound Level, abbreviated here as "L_{dn}." It is a 24-hour measure that accounts for the moment-to-moment fluctuations in A-Levels due to all sound sources during 24 hours, combined. Such fluctuations are illustrated in the bottom frame of Figure 2-12. Here the area under the curve represents the receiver's noise dose over a full 24 hours. Note that some vehicle passbys occur at night in the figure, when the background noise is less. Mathematically, the Day-Night Level is computed as:

$$L_{dn} = 10 \log_{10} \begin{bmatrix} \text{Total sound energy} \\ \text{during 24 hours} \end{bmatrix} - 49.4$$

where nighttime noise (10pm to 7am) is increased by 10 decibels before totalling.

Sound energy is totalled over a full 24 hours; it accumulates from all noise events during that 24 hours. Subtraction of 49.4 from this 24-hour dose converts it into a type of "average," as explained in Section 2.4.6. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total noise dose would enter the receiver's ears.

An alternative way of computing L_{dn} from twenty-four hourly L_{eq}'s is:

$$L_{dn} = 10 \log_{10} \begin{bmatrix} \text{Energy sum of} \\ \text{24 hourly } L_{eq}\text{s} \end{bmatrix} - 13.8$$

where nighttime L_{eq}'s are increased by 10 decibels before totalling, as in the previous equation.

L_{dn} due to a series of transit-noise events can also be computed as:

$$L_{dn} = 10 \log_{10}\left[\begin{matrix}\text{Energy sum of}\\ \text{all SELs}\end{matrix}\right] - 49.4$$

assuming that transit noise dominates the 24-hour noise dose. Here again, nighttime SELs are increased by 10 decibels before totalling. This last equation concentrates upon individual noise events, and is the equation incorporated into Chapters 5 and 6.

Figure 2-14 shows some typical L_{dn}'s, both for transit and non-transit sources. As is apparent from the figure, typical L_{dn}'s range from the 50s to the 70s – where 50 is a quiet 24-hour period and 70 is an extremely loud one. Note that these L_{dn}'s depend upon the number of events during day and night separately – and also upon each event's duration, which is affected by vehicle speed.

L_{dn} is adopted here as the measure of cumulative noise impact for residential land uses (those involving sleep), because: (1) L_{dn} correlates well with the results of attitudinal surveys of residential noise impact, (2) L_{dn}'s increase with the duration of transit events, which is important to people's reaction, (3) L_{dn}'s take into account the number of transit events over the full twenty-four hours, which is also important to people's reaction, (4) L_{dn}'s take into account the increased sensitivity to noise at night, when most people are asleep, (5) L_{dn}'s allow composite measurements to capture all sources of community noise combined, (6) L_{dn}'s allow quantitative comparison of transit noise with all other community noises, (7) L_{dn} is the designated metric of choice of other Federal agencies (Department of Housing and Urban Development (HUD), Federal Aviation Administration (FAA), Environmental Protection Agency (EPA)) and also has wide acceptance internationally. Section 2.4.6 contains more detail in support of L_{dn} as the adopted descriptor for cumulative noise impact for residential land uses.

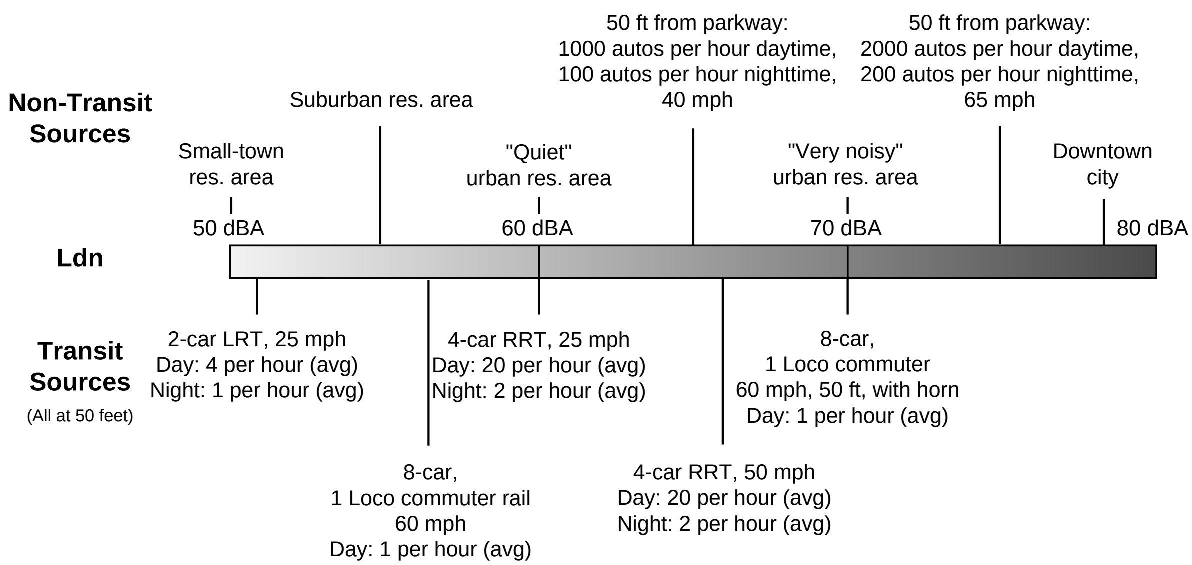


Figure 2-14 Typical L_{dn}'s

2.4.6 A Noise-Dose Analogy for L_{eq} and L_{dn}

In Figure 2-12 (page 2-16), the area under the curves represent noise "doses." An analogy between rainfall and noise is sometimes helpful to further explain these noise doses.

The one-hour noise dose in the middle frame of the figure is analogous to one hour of rainfall; that is, the total accumulation of rain over this one-hour period. Note that every rain shower increases the one-hour rain dose. Also, note that heavier showers increase the dose more than do lighter ones, and longer showers increase the dose more than do shorter ones. The same is true for noise: (1) every transit event increases the one-hour noise dose; (2) loud events increase the noise dose more than do quieter ones; and (3) events that stretch out longer in time increase the noise dose more than do shorter ones.

The moment-to-moment A-level is like the moment-to-moment rate at which the rain is falling. Arithmetically, if this rain rate is measured in "inches of rain per second," then a constant rain rate of 0.001 inches/second, times 3600 seconds in an hour, will total to a one-hour dose of 3.6 inches of rain. This arithmetic appears in the upper center of Table 2-2. Analogously in the upper right, a constant A-level of 60 dBA, plus $10\log_{10}(3600)$, will total to a one-hour noise dose of 95.6. In spite of the logarithmic complication, the analogy holds: a constant A-level (or rain rate), increased by the number of seconds in an hour, yields the one-hour noise dose (or rain dose). In the table, the noise arithmetic is repeated in energy terms, where the analogy is even more direct.

This arithmetic can also be done in reverse, leading to "averages" of the type used for L_{eq} and L_{dn}. This reverse arithmetic appears at the bottom of the table. A total hourly rain dose of 3.6 inches, divided by 3600 seconds, yields an average rain rate of 0.001 inches per second. Similarly, a one-hour noise dose of 95.6, minus $10\log_{10}(3600)$, yields an average A-level of 60 dBA. In other words, a fluctuating noise with a one-hour dose of 95.6 decibels can be "replaced" with an average A-Level of 60 dBA, to yield the same one-hour dose. The actual fluctuating noise and the average 60-dBA noise are "equivalent"; they yield the same total one-hour noise dose. This is the concept behind the word equivalent in the abbreviation "L_{eq}." The same analogy holds for the 24-hour rain dose and the 24-hour noise dose that leads to L_{dn}. Here, however, nighttime A-Levels are increased by 10 decibels before totaling into the 24-hour dose, and the number of seconds involved is 86,400.

Unfortunately, the word "average" leaves many people with the impression that the maximum levels which attract their attention are being devalued or ignored. They are not. Just as all the rain that falls in the rain gauge in one hour counts toward the total, all sounds are included in the one-hour noise dose that underlies L_{eq} and in the 24-hour noise dose that underlies L_{dn}. None of the noise is being ignored, even though the L_{eq} and L_{dn} are often numerically lower than many maximum A-Levels. Their noise doses include all transit events, all noise levels that occur during their time periods -- without exception. Every added event, even the quiet ones, will increase these noise doses, and therefore increase L_{eq} and L_{dn}.

Neither the L_{eq} nor the L_{dn} is an "average" in the normal sense of the word, where introduction of a quiet event would pull down the average. Furthermore, just as in watering a field or garden, scientific evidence strongly indicates that total noise dose is the truest measure of noise impact. Neither the moment-to-moment rain rate nor the moment-to-moment A-level is a good measure of long-term effects.

Table 2-2 Rainfall Analogy with Noise Dose		
Computation	**Rain**	**Noise**
DOSE	Dose = Rate × Duration = (0.001 inches/sec) × (3600 sec) = 3.6 inches of rain	Dose = Level + 10 log (Duration) = 60 + 10 log (3600) = 60 + 35.6 = 95.6 dB *Or in Energy Terms:* Dose = $10^{(L/10)}$ × Duration = $10^{(60/10)}$ × Duration = 1,000,000 × 3600 = 3,600,000,000 and 10 log (Dose) = 95.6 dB
AVERAGE	Average = Dose ÷ Duration = (3.6 inches) ÷ (3600 sec) = 0.001 inches/sec	Average = Dose − 10 log (Duration) = 95.6 − 10 log (3600) = 95.6 − 35.6 = 60.0 dB *Or in Energy Terms:* Average = (Energy Dose) ÷ Duration = $10^{(95.6/10)}$ ÷ 3600 = 3,630,780,548 ÷ 3600 = 1,008,550 and 10 log (1,008,550) = 60.0 dB

Why not just compute transit noise impact on the basis of the highest L_{max} of the day? – for example, as "loudest L_{max} equals 90 dBA?" If that were done, then there would be no difference in noise impact between a main trunk line and a suburban branch line; one passby per day would be no better than 100 per day, if the loudest level remained unchanged. Clearly such a reduction in number-of-passbys is a true benefit, so it should reduce the numerical measure of impact. It does with L_{eq} and L_{dn}, but not with L_{max}. In addition, if assessments were made just on the loudest passby, then one passby at 90 dBA would be worse than 100 passbys at 89 dBA. Clearly this is not true. Both L_{eq} and L_{dn} increase with the number of passbys, while L_{max} does not. Both the L_{eq} and the L_{dn} combine the number of passbys with each passby's L_{max} and duration, all into a cumulative noise dose, with mathematics that "make sense" from an annoyance point of view. L_{eq} and L_{dn} mathematics produce results that correlate well with independent tests of noise annoyance from all types of noise sources.

In terms of individual passbys, here are some characteristics of both the L_{eq} and the L_{dn}:

When passby L_{max}'s increase: → Both L_{eq} and L_{dn} increase

When passby durations increase:	→	Both L_{eq} and L_{dn} increase
When the number of passbys increases:	→	Both L_{eq} and L_{dn} increase
When some operations shift to louder vehicles:	→	Both L_{eq} and L_{dn} increase
When passbys shift from day to night:	→	L_{dn} increases

All of these increases in L_{eq} and L_{dn} correlate to increases in community annoyance.

2.4.7 Summary of Noise Descriptors

In summary, the following noise descriptors are adopted in this manual for the computation and assessment of transit noise:

The **A-weighted Sound Level,** which describes a receiver's noise at any moment in time. It is adopted here as the basic noise unit, and underlies all the noise descriptors below.

The **Maximum Level (L_{max})** during a single noise event. The L_{max} descriptor is not recommended for transit noise impact assessment, but because it is commonly used in vehicle-noise specifications and because it is commonly measured for individual vehicles, equations are included in Appendices D and E to convert between L_{max} and the cumulative descriptors adopted here.

The **Sound Exposure Level (SEL),** which describes a receiver's cumulative noise exposure from a single noise event. It is adopted here as the primary descriptor for the measurement of transit-vehicle noise emissions, and as an intermediate descriptor in the measurement and calculation of both L_{eq} and L_{dn}.

The **Hourly Equivalent Sound Level (L_{eq}(h)),** which describes a receiver's cumulative noise exposure from all events over a one-hour period. It is adopted here to assess transit noise for non-residential land uses. For assessment, L_{eq} is computed for the loudest transit facility hour during the hours of noise-sensitive activity.

The **Day-Night Sound Level (L_{dn}),** which describes a receiver's cumulative noise exposure from all events over a full 24 hours. It may be thought of as a noise dose, totaled after increasing all nighttime A-Levels (between 10pm and 7am) by 10 decibels. Every noise event during the 24-hour period increases this dose, louder ones more than quieter ones, and ones that stretch out in time more than shorter ones. L_{dn} is adopted here to assess transit noise for residential land uses.

REFERENCES

1. Environmental Protection Agency, "Impact Characterization of Noise Including Implications of Identifying and Achieving Levels of Cumulative Noise Exposure," Task group 3, Henning von Gierke, Chairman, Report NTID 73.4, Washington DC, 27 July 1973.

2. Environmental Protection Agency, "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety," Report No. 550/9-74-004, Washington DC, March 1974.

3. Federal Interagency Committee on Urban Noise, "Guidelines for Considering Noise in Land Use Planning and Control," a joint publication of the Environmental Protection Agency, the Department of Transportation, the Department of Housing and Urban Development, the Department of Defense, and the Veterans Administration, Washington DC, June 1980.

4. Department of Housing and Urban Development, "Environmental Criteria and Standards of the Department of Housing and Urban Development, 24 Code of Federal Regulations Part 51; 44 Federal Register 40861, Washington DC, 12 July 1979.

5. American National Standards Institute, "American National Standard: Compatible Land Use With Respect to Noise," Standard S3.23-1980, New York NY, May 1980.

6. International Standards Organization, "Assessment of Noise with Respect to Community Response," Recommendation R-1996, Geneva, 1971.

7. Theodore J. Schultz, "Noise Rating Criteria for Elevated Rapid Transit Structures," U.S. Department of Transportation Report No. UMTA-MA-06-0099-79-3, Washington DC, May 1979.

8. Theodore J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," Journal of the Acoustical Society of America, Vol. 63, No. 8, August 1978.

9. S. Fidell, D.S. Barber, and T.J. Schultz, "Updating a Dosage-Effect Relationship for the Prevalence of Annoyance Due to General Transportation Noise," Journal of the Acoustical Society of America, Vol. 89, No. 1, January 1991.

10. American Public Transit Association, "1981 Guidelines for Design of Rapid Transit Facilities," Rapid Transit Committee, 1981.