Technical Noise Supplement

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Instead, it is the generally accepted threshold of the best human hearing. SPLs in negative decibel ranges are inaudible to humans. On the other extreme, the decibel scale can go much higher than shown in Table 2-5. For example, gunshots, explosions, and rocket engines can reach 140 dBA or higher at close range. Noise levels approaching 140 dBA are nearing the threshold of pain. Higher levels can inflict physical damage on such things as structural members of air and spacecraft and related parts. Section 2.2.1.1 discusses the human response to changes in noise levels.

Table 2-5. Typical Noise Levels

Common Outdoor Activities	Noise Level (dBA)	**Common Indoor Activities**
	110	Rock band
Jet flyover at 1,000 feet		
	100	
Gas lawnmower at 3 feet		
	90	
Diesel truck at 50 feet at 50 mph		Food blender at 3 feet
	80	Garbage disposal at 3 feet
Noisy urban area, daytime		
Gas lawnmower, 100 feet	**70**	Vacuum cleaner at 10 feet
Commercial area		Normal speech at 3 feet
Heavy traffic at 300 feet	**60**	
		Large business office
Quiet urban daytime	**50**	Dishwasher in next room
Quiet urban nighttime	**40**	Theater, large conference room (background)
Quiet suburban nighttime		
	30	Library
Quiet rural nighttime		Bedroom at night, concert hall (background)
	20	
		Broadcast/recording studio
	10	
	0	

Snow & Ice Control Operations

Caltrans

California Department of Transportation

Maintenance Program

Mission Statement

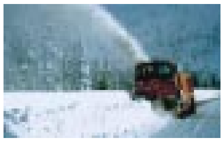
The Maintenance Program's mission is to protect public safety and preserve California's Highway System by maintaining and repairing the system and responding to emergencies so travelers and goods reach their destination safely and efficiently.

Values

- Our workforce
- Customer's time
- Teamwork
- Customer's opinions and needs
- Financial resources
- Our commitments
- Commerce and the economy
- The environment
- Continuous improvement/quality
- Innovation

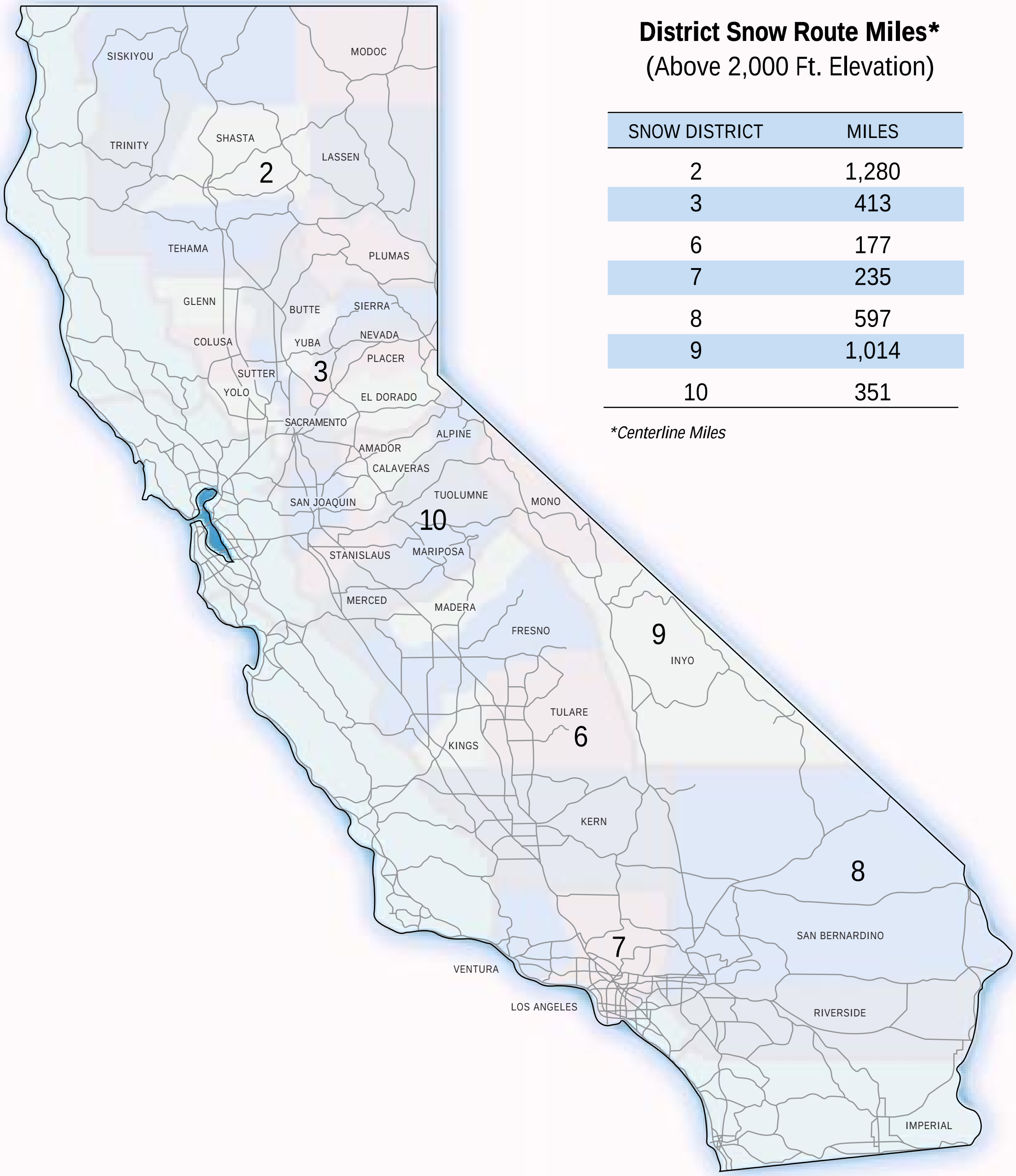
CALIFORNIA DEPARTMENT OF TRANSPORTATION

SNOW & ICE CONTROL OPERATIONS



Caltrans

Caltrans Snow Districts



District Snow Route Miles*
(Above 2,000 Ft. Elevation)

SNOW DISTRICT	MILES
2	1,280
3	413
6	177
7	235
8	597
9	1,014
10	351

**Centerline Miles*

Introduction

The California Department of Transportation (Caltrans) has been given statutory authority for the planning, design, construction, operation, and maintenance of California's State Highway System. A key component of the maintenance of certain highways is the control of snow and ice. Caltrans maintenance forces strive to provide a safe travel way during winter conditions while keeping traffic delays to a minimum. However, Caltrans must also consider the environmental issues of snow and ice control activities. Compounding this is the traveling public's expectation that high levels of service are to be maintained, even though a route is subject to snow and ice conditions.

The large geographical area that comprises the State of California includes many different climate zones. Consequently, motorists from warmer and drier parts of the state may be unprepared for the challenges of driving in the snow during the winter.

This booklet will describe various aspects of Caltrans' methods of controlling snow and ice on mountainous highways.

Caltrans Snow and Ice Policy

The following is Caltrans' official policy on snow and ice removal from state highways:

"Snow removal and ice control shall be performed as necessary in order to facilitate the movement and safety of public traffic and shall be done in accordance with the best management practices outlined herein with particular emphasis given to environmentally sensitive areas."[1]

Rotary snow plow

[1] *Adopted July 1992. Outlined in Caltrans Report to the Legislature in response to Chapter 318, Statutes of 1991 (Hauser), "The Use of Deicing Chemicals on California State Highways" July, 1992.*

Chain Control Operations

These signs are typical, although in some areas the speed limit sign is not included.

Snow and ice control is important on every mountainous route within California; however, certain routes carry heavy seasonal recreational traffic as well as high volumes of truck traffic. These routes require extensive snow-fighting activity to keep open during heavy snow storms. This can be compounded by the fact that many motorists driving in these areas expect to be able to drive the same way they do in the summer. Also, many motorists are reluctant to pull off the traveled way and "chain-up."

Long traffic queues are not uncommon during storms on major transportation routes to and from recreational areas. In areas where traffic congestion has become a major factor in travelers' safety and snow removal efforts, provisions have been made to "meter" traffic. Traffic metering is performed at lower elevations below the snow line during chain control operations. Metering controls the volume of traffic during peak periods over snow routes, allowing smooth flow of traffic and maximum snow removal effort. The metering is conducted where food, fuel, and restrooms are available to temporarily delayed motorists.

Caltrans has defined the following chain control designations for various road conditions during snow storms:

R1a (Modified R1) Chains required for single axle drive vehicles with trailers.

R1 Chains required, except for autos or pickups with snow tires.

R2 Chains required, except for vehicles with four-wheel drive and snow tires on four wheels. (Must *carry* chains.)

R3 Chains required; no exceptions. (Note: R3 conditions are rare — the road is usually closed prior to this designation.)

The illustrations at left show the typical signs used by Caltrans for the chain requirements described above.

CHAIN CONTROL REQUIREMENTS

It is Caltrans' responsibility to determine and post chain requirements. California Vehicle Code specifies and defines "Tire Traction Devices." Traditionally, these devices have been made of steel chain.

Studded tires, while legal for use on highways during winter months, do not qualify as an approved "Tire Traction Device."

Winter traffic

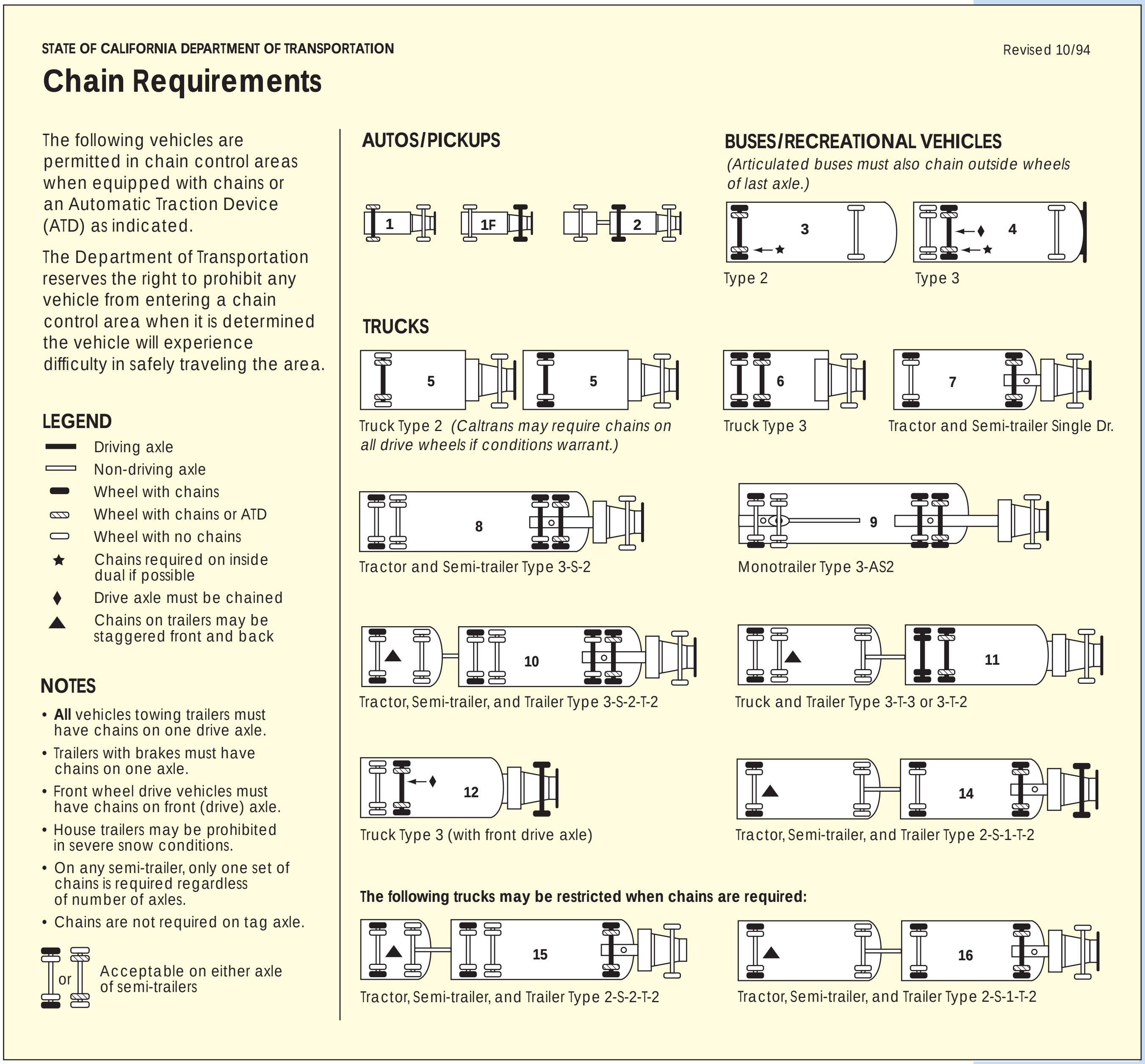
Cable type chains are approved in California when used per the proper application (see Figure 1). However, during extreme conditions, large trucks using cable chains may be held until conditions permit safe travel.

Cars and pickup trucks equipped with mud and snow tires (as alternative traction devices) are acceptable during R1 chain control conditions.

Four-wheel drive vehicles one ton and smaller with snow tires (as alternative traction devices) on all four wheels are acceptable during R2 chain control conditions.

Truckin' on the east slope of the Sierra Nevadas

Figure 1

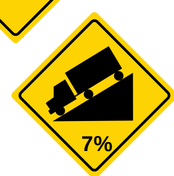


During R1 or R2 conditions, all vehicles including four-wheel drives that are pulling trailers must chain at least one drive axle. If the trailer is equipped with brakes, one of the trailer's braked axles must be chained also.

To aid truck drivers in the proper chaining of their vehicles, Caltrans provides the chain requirement chart to drivers at most weigh stations leading to mountainous areas.

On most major routes Caltrans provides personnel to check all vehicles at chain control points. On other routes the regulatory signs are deployed by Caltrans personnel, then left unattended.

Chain controls are generally used during snowstorms and usually end soon after the end of the storm. However, with sunshine, the snow and ice pack will begin to melt resulting in slush on the pavement that is difficult to negotiate without tire chains. Isolated shady spots can remain frozen well into the day and can be effectively treated with light applications of deicing salt or salt substitute and sand, thereby allowing chain controls to be dropped.



Due to restricted tire clearances and poor traction, certain types of vehicles present a challenge to chain control personnel at the check points. These include single drive trucks pulling double trailers, commercial auto carriers, three-axle tractors with single drive and newer front wheel drive vehicles that are restricted from chain use per their owner manuals. These vehicles are often held or may be turned back until road conditions improve.

Many motorists are unfamiliar with driving in snow and ice conditions and are likely to drive too fast for the conditions.

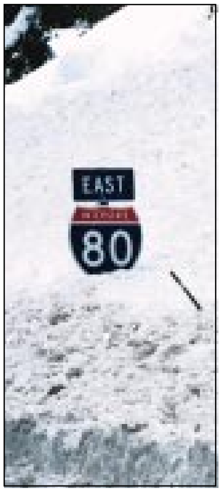
Caltrans reserves the right to prohibit any vehicle or combination that it deems unsafe from traveling inside a chain control area.

Certain sections of low traffic volume mountainous routes (i.e., State Routes 4, 120, 108, and others) are closed during the winter season because Caltrans has made the determination that safety concerns coupled with low traffic demands do not justify the high cost of keeping these routes open during the winter.

Carving a path through the Sierra Nevada mountains

Clearing the Roadway Surface

Caltrans utilizes snowplows and motor graders for clearing snow from the roadway surface. Deicing salt is the primary agent for ice melting and breaking the bond between the snow pack and the pavement. Abrasives, such as sand or volcanic cinders, are spread in order to provide better vehicle traction. In some areas salt is applied separately from abrasives in order to better control the location and application rate. This has proven to significantly reduce the amount of salt used.



District directors are responsible for the judicious use of salt and other chemicals for snow and ice control. Through operator training and usage logs, the Department has significantly reduced the amount of applied deicing salt. Without the use of an effective deicer such as salt, Caltrans would need to require more frequent and extended use of chains by motorists travelling mountainous routes in the winter. The use of chains, which requires lower vehicle operating speeds, combined with the operational problems presented by motorists stopping on the traveled way to install chains, significantly reduces the capacity of the highway. Another problem faced is that chain use on mountain highways contributes to pavement wear and deterioration of ride quality.

Lake Tahoe basin

The control of ice and snow on mountainous routes involves balancing the needs of the travelling public, traffic and personal safety, and the protection of the environment.

ENVIRONMENTAL CONCERNS

Although there is by no means a consensus of opinion among experts as to the magnitude of damage caused by the application of deicing salt, it is believed that deicing salt does cause some vegetation damage, as well as bridge deck and vehicle underbody corrosion.

In recognizing the potential for these kinds of harmful effects, Caltrans has implemented a reduced salt-use policy dated October 1989 and required the transportation districts to develop specific route by route plans. In the winter of 1989/90, Caltrans reduced salt usage by 62 percent statewide as compared to the previous winter. This was made possible by the combination of a mild winter and improved control of the application frequency of deicing salt.

The State of Nevada Department of Transportation, in cooperation with Caltrans, retained a private research firm to study the impacts of roadway deicing salts on vegetation within the Lake Tahoe Basin. This study, published in 1990, concluded that of 5,450 trees observed along the Lake Tahoe Basin highways within both Nevada and California, 15 percent of the trees were salt-affected. The majority of the damaged trees surveyed showed evidence of disease, bark beetle infestation and the effects of four years of drought.[2]

In addition, there is concern that deicing salt could be degrading local water supply sources in the Lake Tahoe Basin. In this regard, the Lahontan Water Quality Control Board issued board Order No. 6-89-139A directing Caltrans to perform water quality testing of certain Lake Tahoe area streams on a regular basis.[3] Caltrans annually reports back to the Lahontan Water Quality Control Board.

Another environmental concern is the usage of sand and its effects on air quality following storm conditions. Dust from airborne particulate matter is generated by vehicles driving over drying sand.

Caltrans has implemented several programs including immediate sweeping of sand deposited during a storm and the application of hydroscopic materials to the sand to attract moisture and eliminate dust from high-speed traffic. Both of these practices have proven to be effective. Caltrans is continually searching for materials, and improved operational practices to lessen the effects to the environment from our snow removal operations.

ALTERNATIVE MATERIALS

Caltrans, in response to the requirements of Assembly Concurrent Resolution 96 (Waters), evaluated several alternatives to deicing salt during the winter of 1989/90. In a report to the members of the California Legislature,[4] Caltrans reported that it had been testing two major alternative deicers, calcium magnesium acetate (CMA) and magnesium chloride. A summary of the results of the testing of these two materials follows:

Calcium Magnesium Acetate (CMA)

CMA was utilized on various routes subject to heavy snowfall in Mono County in District 9. In addition, it was tested in small amounts on test sections in Northern and Central California. During these tests, it was found that CMA was less effective than salt for deeper snow packs and does not penetrate the pack as rapidly as salt, which results in a delay in the melting of ice

[2] "Roadside Erosion Control and Revegetation Needs Associated With the Use of Deicing Salt Within the Lake Tahoe Basin," Resource Concepts, Inc. (September 1990)

[3] "Report for Monitoring Program per Board Order 89-139A,Æ" Lahontan Water Quality Control Board, California Department of Transportation (February 14, 1990)

[4] "Evaluation of Deicing Substitutes on Certain Routes During the 1989-90 Snow Season," California Department of Transportation (July 3, 1990)

and snow pack, particularly at temperature below 24 degrees F. CMA does, however, change the consistency of the snow pack so that it is easier to plow.

CMA can cause respiratory distress and eye irritation for personnel required to handle it, thereby necessitating the use of protective gear. CMA costs about $600 to $700 per ton as compared to salt which costs less than $50 per ton. Another problem with CMA is that it typically needs to be spread at about 1-1/2 times the rate of salt to be effective.

Magnesium Chloride

Magnesium chloride was tested on a 5-1/2 mile section of Interstate 80 near Donner Summit. At the end of storms, bare pavement was achieved more uniformly than with salt. Magnesium chloride was found to be as effective at lower temperatures as salt. Magnesium chloride, being a liquid, can be applied in a more uniform manner than granular salt, but must be kept in storage tanks. One of the drawbacks of magnesium chloride use is the fact that it should not be used on the travel way when snow pack is over 1/4 inch in depth. Applications on pack over that depth have caused the road surface to become slippery due to fast melting followed by re-freezing, necessitating additional sanding and magnesium chloride treatments to eliminate the problem.

Slip-in sanding boxes in storage

Liquid magnesium chloride appears to be a viable substitute for salt; however, it has been shown to be most effective as an anti-icer at lower elevations where frost has been a problem. Its residual effects in these areas makes it easy to apply pre-storm with re-applications not needed for several days.

Caltrans is planning to continue the use of liquid magnesium chloride, and other alternative deicers, in an effort to reduce the use of salt.

Caltrans anticipates that deicing salt will still be needed in the future, even with the use of alternative deicers, because of its cost-effectiveness and the low environmental impact in most areas of use. Caltrans districts will judiciously use salt for snow and ice control; by balancing the need to protect the environment with providing the best service to our customers.

Snow and Ice Control Equipment

Although deicing materials (salt, magnesium chloride, etc.) are useful in the control of snow and ice, snowplows and motor graders are often required to clear snow and ice from the roadway surface. Rotary snow plows are necessary to move snow off the travel way in large quantities and clear storage areas. Although equipment and methods vary according to local conditions, the following is a brief description of Caltrans equipment used to control snow and ice.

Caltrans typically uses four-, five-, and ten-cubic yard capacity trucks with push plows.

In some areas, Caltrans crews utilize trucks with wing plows that enable clearing a wide area (up to 22 feet) in a single pass. The wing plow is hydraulically extended from the side of the truck by the operator. Most trucks with plows also have the ability to spread salt or sand while plowing. Most truck-mounted plows operate at about 30-35 mph. Trucks equipped with these plows cost about $40 per hour to operate including operator.

Caltrans also uses motor graders to a large degree. Motor graders used for snow and ice removal have both front and moldboard blades which enable then to plow wide areas. Motor graders can apply considerable downward pressure (with the moldboard blade) which makes them very effective at cutting hard snow/ice pack. In areas with large snowfall amounts or that have miles of snow pack conditions, the motor grader is the operations "workhorse." They push huge quantities of snow and remove snow pack from the travel way. However, great care needs to be used by the operator, as they can cause significant damage to flexible pavements if not closely monitored. With the advances of all-wheel drive and articulated units into our service fleets, the speed and efficiency of these units have become remarkable. These advances have also increased operator comfort and control, essential for long

Rotary snow plow blowing snow

shifts and slippery roads. Due to the slower speed that they work at, they do tend to slow traffic down as it maneuvers around them. On most multi-lane highways, motor graders work in teams of two or three, staggered to allow traffic to maneuver through them, to avoid traffic back ups. Serrated blades have been used in some areas on the moldboard with success for the removal of stubborn ice and snow pack. Motor graders cost about $60 per hour to operate.

Rotary snowplows are used to blow piles and windrows of snow left by plowing out of the snow storage areas, as well as cutting through deep snow. Several of our larger rotaries have the ability to remove up to 5,000 tons of snow per hour. Rotary plows also have the ability to direct the snow blown out of the chute away from fixed objects, such as roadside signs. The rotary plows operate at a much slower speed than truck-mounted plows and motor graders (about 3-5 mph). Rotary plows cost about $120 an hour to operate.

SNOW REMOVAL PERSONNEL MANAGEMENT

Due to the seasonal nature of snow and ice control operations, Caltrans employs a large number of temporary employees. In addition to these seasonal employees, some members of other maintenance area crews are called on to assist in these operations. In rural areas, some districts use dormitories built along major routes to provide food and housing for employees that are temporarily assisting with snow removal activities. Some temporary staff members are local residents; others stay at local motels. Crews from non-snow areas of California are utilized to assist in many areas to fortify local snow crews.

Roadeo events

Equipment Roadeo

One method of enhancing Caltrans' snow-crew training program is the Equipment Roadeo. This competitive event, which is held annually, promotes safety and professionalism in snow removal operations. Events include: tire chain installation / removal; detailed vehicle pre-trip inspection; operation of plow trucks, motor graders and front-end loaders on an event course.

Caltrans districts conduct local qualifying events with finalists competing at the annual statewide Roadeo. Although contestants must use their personal time for these events, Caltrans feels that the friendly competition will improve operator performance and professionalism as well as foster “esprit de corps.” Recently, Caltrans' top operators have performed well at the National Roadeo held in Colorado, including several first place finishes in 1998.

COMMUNICATIONS

In order to provide motorists with current information on highway conditions, Caltrans updates the California Highway Information Network (CHIN) phone numbers 24 hours a day.

ROAD CONDITIONS

Within California

1-800-427-7623 (ROAD)

Outside California

916-445-7623

Caltrans also provides up-to-date highway information on the Internet at the following address: http://www.dot.ca.gov/hq/roadinfo.

In order to provide motorists with current information, district maintenance personnel report current conditions to the district dispatch office, which in turn informs the Headquarters Maintenance Communications Office. In addition to CHIN and the Internet, Caltrans uses Highway Advisory Radios (HAR) along many routes to provide motorists with local road and traffic information. There are also Changeable Message Signs (CMS) permanently located along many routes to advise motorists of current conditions. Portable CMS are also used at strategic locations as needed, to advise of road and traffic conditions.

WEATHER FORECASTING

Caltrans relies on storm forecasts from the National Weather Service, various sources on the internet, and a few contracted weather forecasters. District dispatchers advise maintenance crews of impending snowstorms via telephone or radio and follow with a facsimile (FAX) of the entire forecast. Some maintenance superintendents and supervisors telephone the National Weather Service directly in order to share information concerning local conditions. Weather information via contracted satellite service is also utilized. This service provides, real-time radar, satellite, and written weather updates via satellite link. This type of service has been very reliable for reception of weather information when weather conditions have caused power and telephone outages. These types of real-time information systems have enabled snow crew supervisors to more accurately predict the timing and nature of storm cells. This enables more precise control of deicer application timing, as well as determining appropriate staffing levels, chain controls and traffic management while a storm passes through the area.

In some areas, Road Weather Information Systems (RWIS) are available to provide local pavement and atmospheric data.

Road Weather Information System

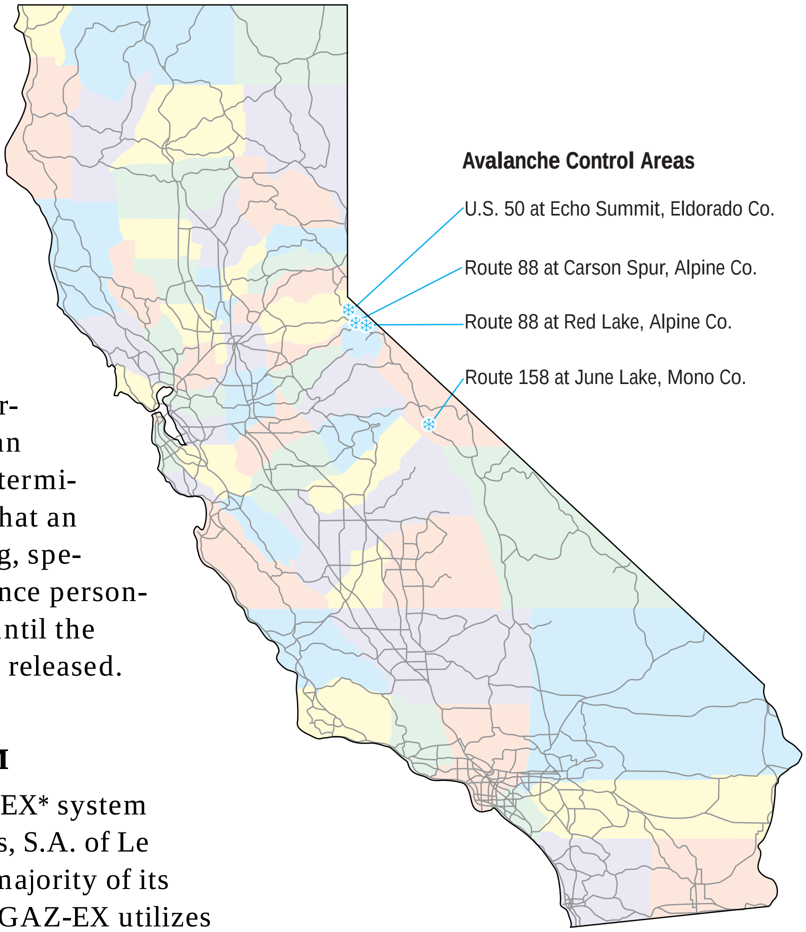
ENFORCEMENT

Caltrans has the responsibility for determining when chain controls are necessary, informing motorists of the requirements, and inspecting vehicles for conformance to the requirements. The enforcement of the chain requirements is the responsibility of the California Highway Patrol (CHP). The CHP often will station a unit (an officer and vehicle) at the chain control point. In addition, CHP units may patrol the section of the route under chain control restriction. The California Vehicle Code specifies a basic fine for violation of chain control requirements. Additionally, local jurisdictions may add additional court costs and fees.

In addition to enforcing chain requirements, the CHP also aids Caltrans in assuring the expeditious and orderly flow of traffic through the chain control area. Caltrans has the authority to set reduced speed limits of either 40, 35, 30, or 25 miles per hour, whichever is found most appropriate for the prevailing conditions.[5] The enforcement of posted speed limits within the chain control area is a CHP responsibility.

Avalanche Control Areas

Avalanches pose a substantial threat to the safety of the traveling public and Caltrans maintenance workers. To control avalanches, Caltrans or their advisors perform snow surveys in known avalanche areas to determine the likelihood of an avalanche. Once the determination has been made that an avalanche is threatening, specially trained maintenance personnel close the highway until the avalanche can be safely released.



THE GAZ-EX SYSTEM

Caltrans uses the GAZ-EX* system developed by Schippers, S.A. of Le Touvet, France for the majority of its avalanche control. The GAZ-EX utilizes

[5] *California Vehicle Code Section 22363.*

**GAZ-EX is a trademark of Schippers S.A.*

stored propane and oxygen piped into a fixed cannon located in an avalanche starting zone, directing a blast toward the ground. The system is remote controlled and is considered to be more effective and have a higher factor of safety than any other currently available system. These units have been placed throughout the state to control areas that have had historical avalanche problems.

LoCAT* commercially made artillery guns are available as a back up to the GAZ-EX system. The LoCAT units are replacements for the outdated U.S. military 75 mm recoilless rifles that were retired from active duty with Caltrans in 1997. The LoCAT system utilizes compressed air to propel a seven-pound explosive payload to the target area. We are continually looking for lower cost, more effective solutions to avalanche control to improve operational safety and productivity.

In some parts of the state, for close range avalanche control work, a low-pressure inert gas propelled projectile is fired from the Avalauncher.** This device has limited range, but is simple to operate at a relatively low cost.

The last resort in our avalanche control arsenal is the deployment of explosive hand charges. This operation is very time consuming and requires trained and certified personnel. These hand-charging operations often take place during the most extreme conditions on the snow laden cornice areas over looking the highways. Dedicated employees apply their special skills in hand throwing these charges to release avalanches in areas where other methods are not effective or available.

GAZ-EX avalanche control cannon

LoCAT avalanche control system

*LoCAT is a trademark of SSE, Inc.

**Avalauncher is a trademark of Avalanche Control Systems.

Improvements in Snow and Ice Control

Caltrans is always looking for new methods and equipment to improve its snow and ice control operations.

The use of traffic sensing equipment, such as pavement loops, in the travel corridors leading to the mountains could provide important traffic data to chain control points. This data could be useful to manage traffic entering a chain control area, allowing for more efficient plowing and traffic movement.

Wire-guidance systems embedded in the pavement on sections of highways that experience winter closures are being used and evaluated. These systems enable snow plow operators to safely reopen the closed road by indicating the plow truck's location on the snow-buried roadway.

A Global Positioning System (GPS) vehicle guidance system is currently being installed and tested in several places in the state. One of these systems will be evaluated on Interstate 80 over Donner Summit to see if it has value in assisting motorists and snow removal equipment while driving and working in poor visibility.

In a related application, a structure called a "jet roof" is installed on the top of a ridge near Carson Pass on Route 88. The "jet roof" alters the wind patterns that normally blow across the ridge area creating dangerous snow cornices. If not prevented, these cornices can suddenly give way in an avalanche of snow onto the highway below.

Currently under development is a system to measure snow removal level of service. Caltrans believes that by consistently measuring we can implement performance-based adjustments to personnel, equipment, and materials. Cost savings, improved service to our customers, and safer winter travel are the goals of this program.

Close-up of jet roof *(above)*; Jet roof array above Carson Pass *(below)*

Conclusion

The maintenance of California's highways is increasingly challenged in that higher public expectations and increasing traffic are complicating operations.

Motor grader at work

In order to maintain satisfactory levels of service, Caltrans must strive for maximum effectiveness from its crews, equipment and materials. The snow and ice control program is no exception.

Caltrans will strive to incorporate new products and techniques into snow and ice control. Increased training opportunities for snow and ice control personnel and improvements in traffic management and information systems will maximize the utilization of provided resources while protecting the safety of the traveling public, maintenance personnel and the environment.

References

1. *Maintenance Manual*, Volume One, California Department of Transportation (June 1998)

2. *Snow Fence Guide*, Strategic Highway Research Program (October 1991)

3. *The Use of Deicing Chemicals on California State Highways*, Caltrans Report to the Legislature in Response to Chapter 318, Statutes of 1991 (Hauser)

4. *Evaluation of Deicing Substitutes on Certain Routes During the 1989-90 Snow Season*, California Department of Transportation, Report to the Legislature as Required by Resolution Chapter 157, Statutes of 1989 (ACR 96 Waters) July 1990

5. *Roadside Erosion Control and Revegetation Needs Associated With the Use of Deicing Salt Within the Lake Tahoe Basin*, Resource Concepts, Inc. (September 14, 1990)

6. *California Vehicle Code*, California Department of Motor Vehicles

For More Information

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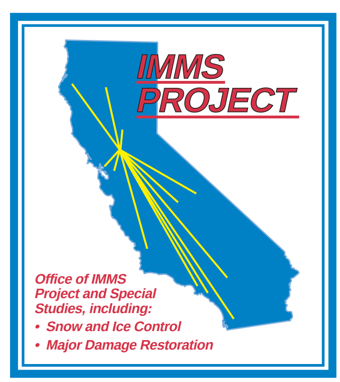
http://www.ca.gov.hq/roadinfo



Listen to the Signs

In all weather conditions, Caltrans highway workers need your help. Always remember:

- Slow down when passing a work area. Stay alert and leave enough time for travel. Pay attention to the signs.
- Be careful. Just like you, Caltrans workers want to return home safely tonight.
- Maintain control of your vehicle. Stay focused on the job at hand – driving safely.
- Obey all warning signs and watch for equipment. Workers may be nearby.
- NEVER drive while under the influence of drugs or alcohol.

Caltrans

Road Conditions

Within California
1-800-427-7623 (ROAD)

Outside California
916-445-7623

Callers can use a touch-tone phone for recorded messages on road conditions. After dialing, enter the route number and touch the pound sign (#).

California Relay Service
TTY 1-800-735-2929

Internet Access
http://www.dot.ca.gov

For information while in Western Nevada – from Reno, Sparks, Carson City, North and South Shore Lake Tahoe

(702) 831-6677

Gray Davis, *Governor*
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Transportation- and Construction-Induced Vibration Guidance Manual

California Department of Transportation
Environmental Program
Environmental Engineering
Noise, Vibration, and Hazardous Waste Management Office

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Bender Vibration and Overpressure Calculation (per Caltrans 2004)

Vibration

K= 100 Charge Wt= 30
Ave Normal Confinement K = 100
Highest Normal Confinement K = 240
Sinking Cut K = 330 to 420

Distance	Calc'd PPV
150	0.501
225	0.262
300	0.165
750	0.038
1000	0.024
1250	0.017
1500	0.013
1850	0.009
2000	0.008
2250	0.007
2550	0.005
3450	0.003
4400	0.002
5150	0.002
6200	0.001
7200	0.001

Air Blast

K= 0.75
K=0.75 for probable
K=2.4 for maximum

Distance	Calc'd PSI	Calc'd dB
150	0.00715	127.8
225	0.00440	123.6
300	0.00311	120.6
750	0.00104	111.1
1000	0.00073	108.1
1250	0.00056	105.7
1500	0.00045	103.8
1850	0.00035	101.7
2000	0.00032	100.8
2250	0.00028	99.6
2550	0.00024	98.3
3450	0.00017	95.2
4400	0.00012	92.6
5150	0.00010	91.0
6200	0.00008	89.1
7200	0.00007	87.5

Report of Conversation

Conversation Type: Phone conversation
Lindsay Christensen contacted Charles Emmett

Client:	Hauge Brueck Associates
Job:	Homewood Ski Resort EIR/EIS
Project/Task Number:	[Click and type project and task number]

Date:	March 30, 2010		
Time:	[Click and type time]		
Contact:	Charles Emmett Air Quality and Noise Principal Planner Tahoe Regional Planning Agency		
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ICF Employee:	Lindsay Christensen Air Quality and Noise Specialist Sacramento, CA		
Phone:	916-737-3000	Ext:	231-7614
Subject:	**Discussion of noise impacts in Plan Areas where ambient noise currently exceeds TRPA thresholds**		

Question: What constitutes a significant impact in a Plan Area where the ambient noise levels are already in exceedance of TRPA thresholds?

- In a Plan Area where existing ambient noise exceeds TRPA thresholds, an impact would be considered significant if the project would result in *any* increase in noise.
- Noise should be mitigated to existing noise levels, but does not need to be mitigated to 1982 levels.

(2)

NTID300.1

NOISE FROM CONSTRUCTION EQUIPMENT AND OPERATIONS, BUILDING EQUIPMENT, AND HOME APPLIANCES

DECEMBER 31, 1971

Prepared by

BOLT, BERANEK AND NEWMAN
under
CONTRACT 68-04-0047

for the

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Office of Noise Abatement and Control
Washington, D.C. 20460

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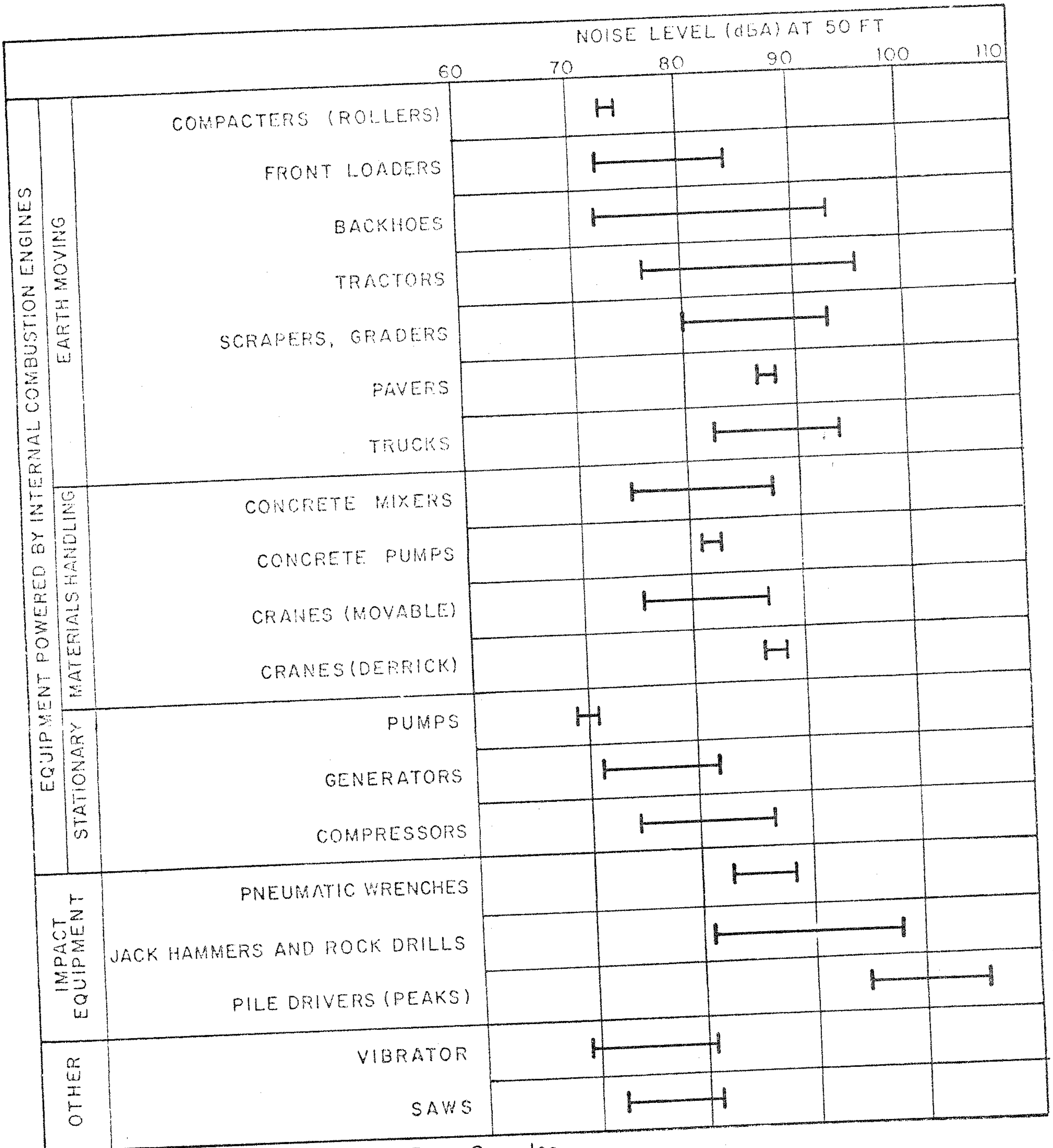


Note: Based on Limited Available Data Samples

FIG. 1. CONSTRUCTION EQUIPMENT NOISE RANGES.

building equipment (compactors, scrapers, graders, pavers, etc.). Internal combustion engines are used for propulsion (either on wheels or tracks) and for powering working mechanisms (buckets, arms, trenchers, etc.). Engine power varies from about 50 hp to over 600 hp. Engine noise typically predominates, with exhaust noise usually being most significant and with inlet noise and structural noise being of secondary importance. Other sources of noise in this equipment include the mechanical and hydraulic transmission and actuation systems, and cooling fans (often very significant). Typical operating cycles may involve one or two minutes of full-power operation, followed by three or four minutes at lower power.

Noise levels at 50 ft from earthmoving equipment range from about 73 to 96 dB(A). The greatest and most direct potential for noise abatement here lies in quieting the engine by use of improved mufflers.

Engine-powered materials-handling equipment such as cranes, derricks, concrete mixers, and concrete pumps, is used in a more-or-less fixed location; mobility of this equipment over the ground is not part of its major work cycle. Although noise from the working process (such as the clanking of aggregate in the concrete mixing bin) often is the most "identifiable" noise component, the dominant source of noise generally is the prime mover. Noise levels at 50 ft range from about 75 to 90 dB(A). The greatest potential abatement for noise again lies in engine quieting, with treatment of power transmission and working mechanisms being of secondary importance.

Stationary equipment, such as pumps, electric power generators and air compressors, generally runs continuously at relatively constant power and speed. Noise levels at 50 ft range

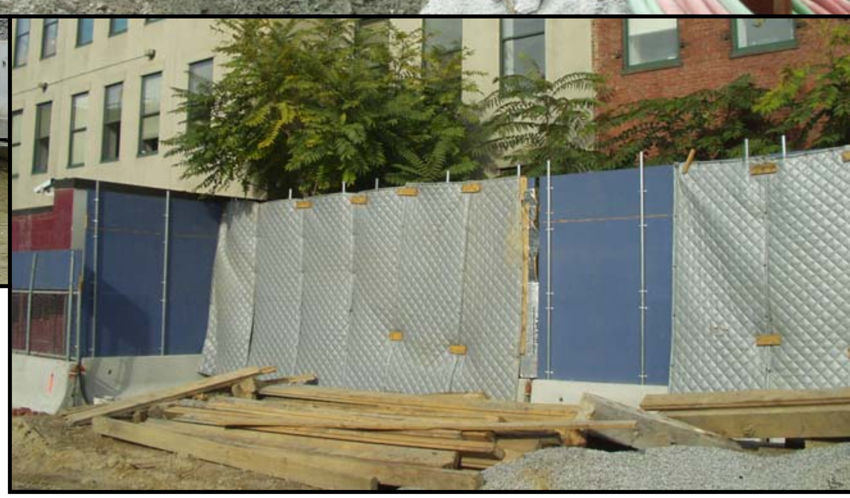
U.S. Department
of Transportation

**Federal Highway
Administration**

FHWA
Roadway Construction Noise Model
User's Guide

FHWA-HEP-05-054
DOT-VNTSC-FHWA-05-01

Final Report
January 2006



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Cambridge, MA 02142

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13. ABSTRACT (Maximum 200 words)

The Roadway Construction Noise Model (RCNM) is the Federal Highway Administration's (FHWA) national model for the prediction of construction noise. Due to the fact that construction is often conducted in close proximity to residences and businesses, construction noise must be controlled and monitored to avoid impacts on surrounding communities. In addition to community issues, excessive noise can threaten a construction projects' progress. Each project needs to balance the community's need for peace and quiet with the contractor's need to progress the work.

During the Central Artery/Tunnel (CA/T) project in Boston, Massachusetts, the project's noise control program developed the Construction Noise Control Specification 721.560, the most comprehensive noise specification ever developed in the United States. As part of the CA/T project noise control program, a construction noise prediction spreadsheet was developed. Because the CA/T prediction tool can benefit other state and local governments, the FHWA developed the RCNM, which is based on the noise prediction calculations and equipment database used in the CA/T prediction spreadsheet. The RCNM provides a construction noise screening tool to easily predict construction noise levels and determine compliance with noise limits for a variety of construction noise projects of varying complexity.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS – WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup ©	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS – WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

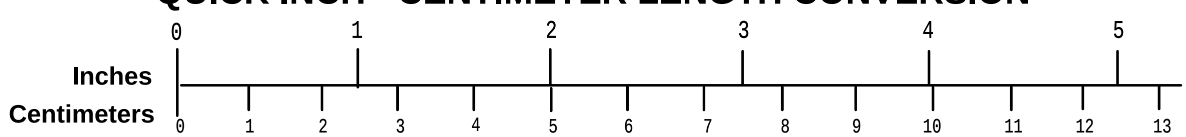
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286.

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1 Introduction

The Roadway Construction Noise Model (RCNM) is the Federal Highway Administration's (FHWA) national model for the prediction of construction noise. Due to the fact that construction is often conducted in close proximity to residences and businesses, construction noise must be controlled and monitored to avoid impacts on surrounding communities. In addition to community issues, excessive noise can threaten a construction project's progress. Each project needs to balance the community's need for peace and quiet with the contractor's need to progress the work.

The Central Artery/Tunnel (CA/T) project in Boston, Massachusetts, which began in the early 1990s, is the largest urban construction project ever conducted in the United States. Its noise control program developed the Construction Noise Control Specification 721.560, the most comprehensive noise specification ever developed in the United States [1]. As part of the CA/T project noise control program, a construction noise prediction spreadsheet was developed [2]. Because the CA/T prediction tool can benefit other state and local governments, the FHWA developed the RCNM, which is based on the noise prediction calculations and the equipment database used in the CA/T prediction spreadsheet. The RCNM provides a construction noise screening tool to easily predict construction noise levels and to determine compliance with noise limits for a variety of construction noise projects of varying complexity.

2 Background

The RCNM is a national model based on the noise calculations and extensive construction noise data compiled for the CA/T Project. The basis for the national model is a spreadsheet tool developed in support of the CA/T project [2]. The CA/T predictions originated from Environmental Protection Agency (EPA) noise level work [3] and an Empire State Electric Energy Research Corp. Guide [4] which utilizes an "acoustical usage factor" to estimate the fraction of time each piece of construction equipment is operating at full power (i.e., its loudest condition) during a construction operation. Table 1 presents a construction equipment noise database compiled through the CA/T project [2]. This database is used to predict construction noise within the RCNM. The noise levels listed represent the A-weighted maximum sound level (Lmax), measured at a distance of 50 feet from the construction equipment.

Table 1. CA/T equipment noise emissions and acoustical usage factors database.

CA/T Noise Emission Reference Levels and Usage Factors					
filename: EQUIPLST.xls					
revised: 7/26/05		Acoustical	Spec 721.560	Actual Measured	No. of Actual
	Impact	Use Factor	Lmax @ 50ft	Lmax @ 50ft	Data Samples
Equipment Description	**Device ?**	**(%)**	**(dBA, slow)**	**(dBA, slow)**	**(Count)**
				(samples averaged)	
All Other Equipment > 5 HP	No	50	85	-- N/A --	0
Auger Drill Rig	No	20	85	84	36
Backhoe	No	40	80	78	372
Bar Bender	No	20	80	-- N/A --	0
Blasting	Yes	-- N/A --	94	-- N/A --	0
Boring Jack Power Unit	No	50	80	83	1
Chain Saw	No	20	85	84	46
Clam Shovel (dropping)	Yes	20	93	87	4
Compactor (ground)	No	20	80	83	57
Compressor (air)	No	40	80	78	18
Concrete Batch Plant	No	15	83	-- N/A --	0
Concrete Mixer Truck	No	40	85	79	40
Concrete Pump Truck	No	20	82	81	30
Concrete Saw	No	20	90	90	55
Crane	No	16	85	81	405
Dozer	No	40	85	82	55
Drill Rig Truck	No	20	84	79	22
Drum Mixer	No	50	80	80	1
Dump Truck	No	40	84	76	31
Excavator	No	40	85	81	170
Flat Bed Truck	No	40	84	74	4
Front End Loader	No	40	80	79	96
Generator	No	50	82	81	19
Generator (<25KVA, VMS signs)	No	50	70	73	74
Gradall	No	40	85	83	70
Grader	No	40	85	-- N/A --	0
Grapple (on backhoe)	No	40	85	87	1
Horizontal Boring Hydr. Jack	No	25	80	82	6
Hydra Break Ram	Yes	10	90	-- N/A --	0
Impact Pile Driver	Yes	20	95	101	11
Jackhammer	Yes	20	85	89	133
Man Lift	No	20	85	75	23
Mounted Impact Hammer (hoe ram)	Yes	20	90	90	212
Pavement Scarafier	No	20	85	90	2
Paver	No	50	85	77	9
Pickup Truck	No	40	55	75	1
Pneumatic Tools	No	50	85	85	90
Pumps	No	50	77	81	17
Refrigerator Unit	No	100	82	73	3
Rivit Buster/chipping gun	Yes	20	85	79	19
Rock Drill	No	20	85	81	3
Roller	No	20	85	80	16
Sand Blasting (Single Nozzle)	No	20	85	96	9
Scraper	No	40	85	84	12
Shears (on backhoe)	No	40	85	96	5
Slurry Plant	No	100	78	78	1
Slurry Trenching Machine	No	50	82	80	75
Soil Mix Drill Rig	No	50	80	-- N/A --	0
Tractor	No	40	84	-- N/A --	0
Vacuum Excavator (Vac-truck)	No	40	85	85	149
Vacuum Street Sweeper	No	10	80	82	19
Ventilation Fan	No	100	85	79	13
Vibrating Hopper	No	50	85	87	1
Vibratory Concrete Mixer	No	20	80	80	1
Vibratory Pile Driver	No	20	95	101	44
Warning Horn	No	5	85	83	12
Welder / Torch	No	40	73	74	5

3 The RCNM

The RCNM is a computer program used to assess construction noise impacts. The computer on which it is installed should be equipped with the Microsoft Windows 98 or newer operating system (OS) and 192 MB or more of random access memory (RAM). The display should be set to 1024 x 768 pixels or greater, and the computer should carry the Adobe Acrobat 4.0 or newer software.

The RCNM allows the estimation of three key metrics of interest: Lmax, Leq, and L10 at receptor locations for a construction operation that can include up to 20 pieces of equipment. RCNM allows for user-defined construction equipment and user-defined noise limit criteria. The two main uses of the RCNM are to allow typical computer users to: 1. easily predict noise emissions from construction equipment, and 2. determine a construction work plan’s compliance with noise criteria limits. A variety of construction work scenarios can be created quickly, allowing the user to determine the impact of changing construction equipment and adding/removing the effects of shielding due to noise mitigation devices such as barriers.

3.1 RCNM Main Page

The RCNM consists of one main display page with Input Data and Results sections, shown in Figure 1.

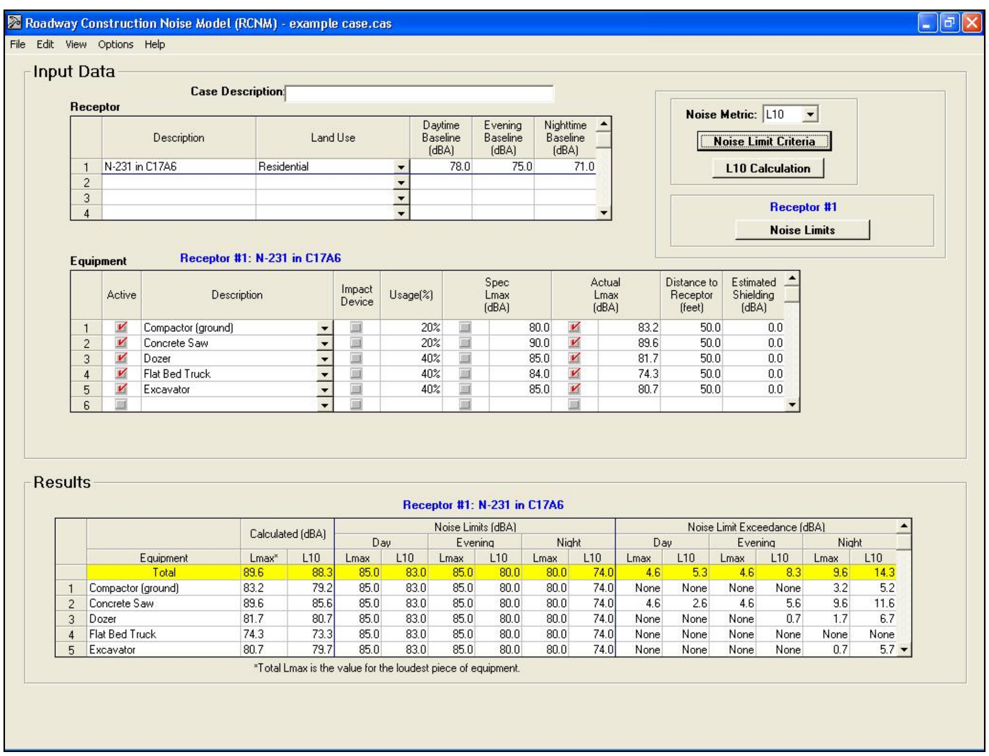

Figure 1. The RCNM main page

Several command buttons and pull-down menus allow the user to modify the input data before results are calculated by the model.

3.1.1 File Menu

The <File> menu, shown in Figure 2, contains items that allow the user to create, open, and save a case, export the results of a case, and exit the program.

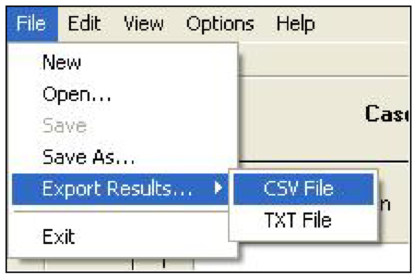

Figure 2. <File> Menu

- <New> creates a new case. If a case is currently open, the user is prompted to save it before closing.
- <Open…> allows the user to open an existing case file ([name].cas).
- <Save> saves the case with the current filename. If this is a new case, the user is asked for a new filename ([name].cas).
- <Save As…> The user is asked for a filename for a new case ([name].cas) and saves the case with that filename.
- <Export Results> prompts the user to save the case results for the current or all receptors to a comma separated value (CSV) file with the following naming convention: [name].csv. This type of file is easily read into a spreadsheet program. The user can also save the case results to a text file (TXT), which saves the results to a space-separated text format with the following naming convention: [name].txt.
- <Exit> closes the application. If changes have been made to the open case, the user is asked if he/she would like to save the case.

3.1.2 Edit Menu

The <Edit> menu, shown in Figure 3, allows the user to copy and paste data, delete data, and undo changes.

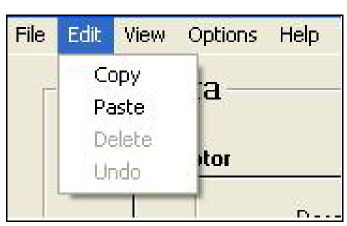

Figure 3. <Edit> Menu

- <Copy> lets the user copy into a clipboard the contents of a single cell or an entire line from an RCNM dialogue box.
- <Paste> lets the user copy the contents of the clipboard into a single cell or an entire line of an RCNM dialogue box.
- <Delete> lets the user delete from the case a receptor or piece of equipment selected in the receptor or equipment dialogue box.
- <Undo> lets the user revert the RCNM one step to where it was before the latest change was made.

3.1.3 View Menu

The <View> menu, shown in Figure 4, allows the user to focus in <Zoom +> on either the Input Data or Results section of the RCNM's main page. To activate Zoom +, click on Zoom + and guide the spyglass + icon to either Input Data or Results and single-click.

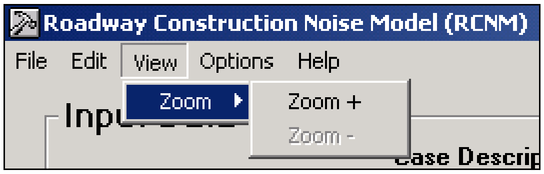

Figure 4. <View> Menu

To deactivate Zoom + and go back to the full RCNM screen, click on Zoom – and guide the spyglass – icon to the Input Data or Results section that has been maximized on the screen.

3.1.4 Options Menu

The <Options> menu, shown in Figure 5, allows the user to modify the equipment list and change the case's units of measure from feet to meters.

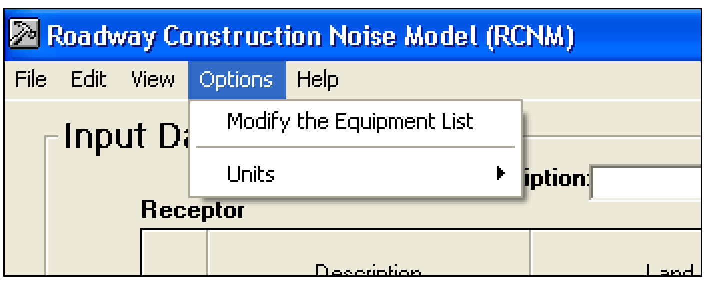

Figure 5. <Options> menu

The <Options> menu allows the user to add new types of equipment to the equipment list. The equipment list modification dialogue box, shown in Figure 6, allows the user to specify a user-defined piece of equipment and add it. The user can specify the following data: whether the equipment is an impact device, the equipment's usage factor[1], and the equipment's Lmax level (spec and/or actual[2]). The user can also delete equipment that's been added by selecting it and clicking the delete button. The default equipment cannot be modified, but it may be deleted entirely from the case by selecting it and clicking the delete button. Selecting the default button restores the default equipment list (from the CA/T Project) and eliminates any user-defined equipment.

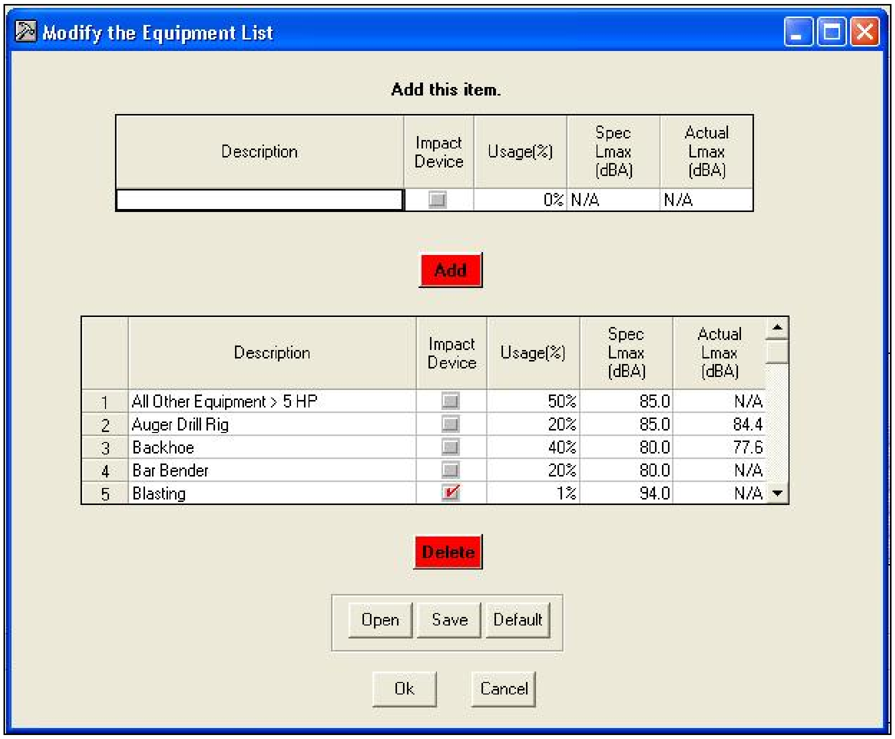

Figure 6. Equipment list modification dialogue box

Data for user-defined pieces of equipment may be saved to an equipment file ([name].equ), along with all other equipment in the current list, including default equipment. This file may be opened in other cases to incorporate these pieces of equipment.

The <Options> menu, as shown in Figure 7, also allows the user to change the case's units of measure from feet to meters or from meters to feet. The only input data affected by this tool are the Distance to Receptor values.

[1] Usage factor is the percentage of time during a construction noise operation that a piece of construction equipment is operating at full power. In the case of construction blasting, the equipment gives a very short duration blast, and can be quantified by using a 1% usage factor in the RCNM to allow for some prediction. Never use a usage factor of zero because the log of zero causes a mathematical impossibility. The usage factor term only affects the computation of Leq and L10. The usage factor does not enter into the equation when calculating the more important term for blasting, that being the Lmax.

[2] "Spec" refers to noise levels stated in noise specifications, and "Actual" refers to Lmax values measured at 50 ft from the equipment.

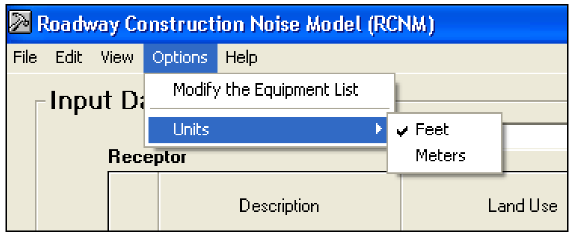

Figure 7. Units modification pull-down menu

3.1.5 Help Menu

The <Help> Menu loads for the user the RCNM User's Guide in Portable Document Format (PDF). This PDF is searchable by key word using the Adobe Acrobat Edit / Find search tool.

3.2 Input Data

The user is required to input receptor data and equipment data before a case can be processed. The user is advised to type in some summary comments about the case in the Case Description dialogue box before inputting data. Also, in order to determine noise limit exceedance values, the user can input noise limit criteria.

3.2.1 Receptors

Multiple receptors may be input for a case, but only one receptor may be processed at a time. The name of the highlighted receptor chosen for processing appears in blue type above the Equipment input dialogue box and the Noise Limits command button (see Figure 1). The user specifies the receptors for a study by entering information into the Receptors input box in the main window of the RCNM. The user is required to enter the receptor name, land use, daytime baseline L10 or Leq, evening baseline L10 or Leq, and nighttime baseline L10 or Leq. The baseline levels indicate the sound level at a receptor before any construction noise contributions. Baseline levels are only necessary if the desired noise criteria limits are based on *relative* increases in noise level. If the desired noise criteria limits are *absolute* noise levels, then the user should insert a placeholder number other than zero.

When entering information for more than one receptor, it may be desirable to copy information already entered. An entire receptor row may be highlighted and copied to another row, where copying multiple rows requires the selection of the same number of rows when pasting (this same functionality also applies to editable cells). Note: Entire rows may be selected by clicking on the row number.

Again, the RCNM will only calculate results for the receptor displayed in blue type in the Input Data portion of the main page. The results for other receptors may be displayed by selecting the desired receptor in the Receptor window; to select a receptor, click in any cell in the row. Up to 100 receptors may be included in any case. Information for receptors is saved in the case file ([name].cas).

3.2.2 Equipment

Core equipment noise data are stored in the RCNM and are accessible by a pull-down menu in the main page, as in Figure 8.

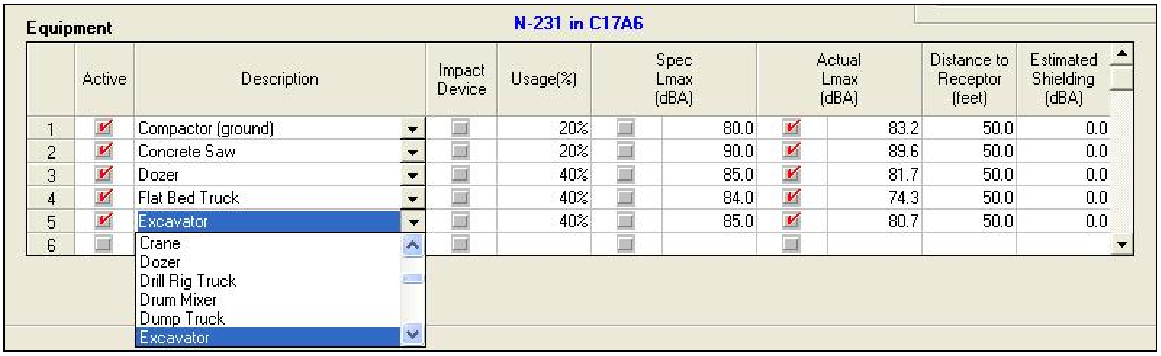

Figure 8. Equipment dialogue box, with pull-down menu shown

As discussed in Section 3.1.4, new pieces of equipment may be added to a case and saved in an equipment file ([name].equ). When the user-defined equipment file is opened through the <Options> / <Modify the Equipment List> menu, user-defined equipment will appear in the equipment pull-down menu. The user activates and inactivates chosen equipment types by ticking and unticking the "Active" checkbox. The user is required to specify:

1. The type of reference emission levels to use ("Spec", if applicable, or "Actual", [the default is "Actual"]);
2. Distance to Receptor – that is, the distance between each type of equipment and the receptor being analyzed (the default distance is 50 feet); and
3. Estimated Shielding (in dBA) associated with each type of equipment (can leave the default value of 0.0 when not considering shielding). **NOTE: A Best Practices document is presented in Appendix A showing how to determine Estimated Shielding using several Rules of Thumb developed from experience at the CA/T project.**

When entering information for more than one piece of equipment, it may be desirable to copy information already entered. An entire equipment row may be highlighted and copied to another row, where copying multiple rows requires the selection of the same number of rows when pasting (this same functionality also applies to editable cells). Note: Entire rows may be selected by clicking on the row number.

The user may analyze up to 20 pieces of equipment at one time, and they may be included in any combination of different or identical equipment types.

3.2.3 Noise Metric and Noise Limit Criteria

While a case is open, the user can choose a noise metric (for baseline levels, noise limits, and calculated results) and enter the noise limit criteria for a local area. The user may edit the Lmax and L10 or Leq day, evening, and night noise limit criteria for a residential, commercial, or industrial area. Daytime, evening, and nighttime may represent any time periods the user wishes, but they are typically defined as 7 AM to 6 PM, 6 PM to 10 PM, and 10 PM to 7 AM, respectively. The criteria, used together with the baseline sound levels, define the noise limits for each receptor. CA/T Noise Limit Criteria are used as a default [1], but users may input their own criteria. The RCNM offers a metric pull-down menu and two or three command buttons to the right of the Receptor input dialogue box.

- Metric Pull-Down Menu

A pull-down menu allows the user to choose between the L10 or Leq metric, as in Figure 9. The chosen metric represents that used for the baseline levels, noise limits, and calculated results. For the noise limits and calculated results, Lmax values are also included.

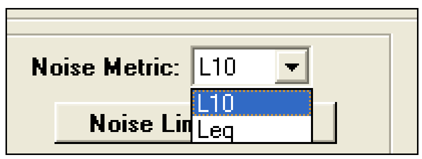

Figure 9. Noise Metric pull-down menu

- Noise Limit Criteria Pop-up Dialogue Box

A pop-up dialogue box allows the user to specify Noise Limit Criteria information for an area being studied in a case, as in Figure 10. The flexibility of the Noise Limit Criteria allows RCNM users to incorporate criteria based on local noise ordinances and baseline levels measured for each receptor.

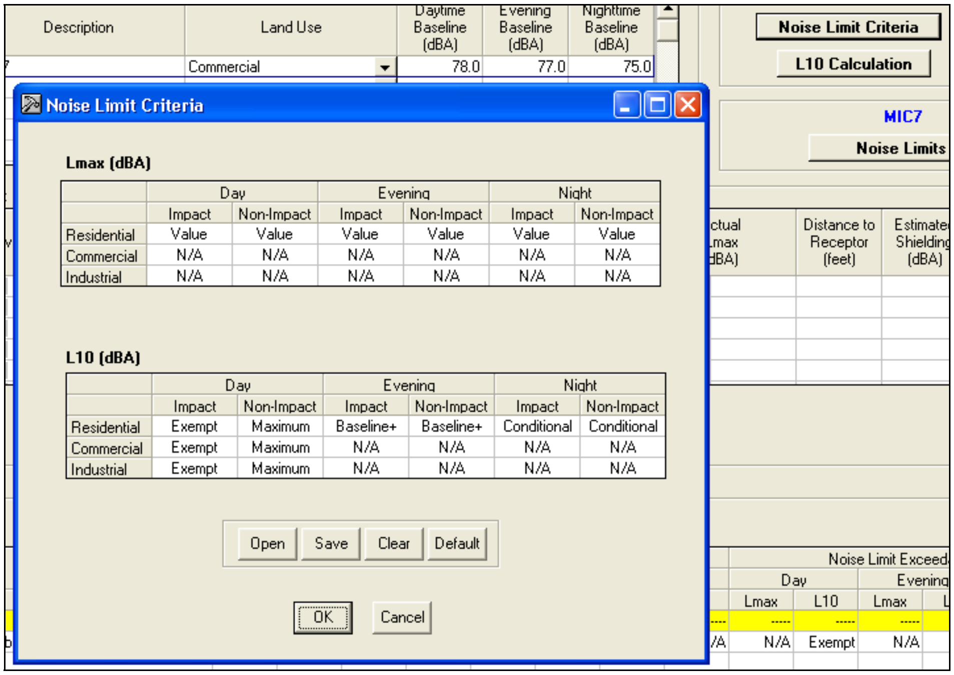

Figure 10. Noise Limit Criteria pop-up dialogue box

The user may populate this dialogue box with Noise Limit Criteria information derived from CA/T Construction Noise Control Spec. 721.560 [1] by clicking on the "Default" command button and clicking "Yes" when asked to load information from the default file, which is stored in the RCNM (see Table 2).

Table 2. Default Noise Limit Criteria

	Daytime (7 AM to 6 PM)		Evening (6 PM to 10 PM)		Nighttime (10 PM to 7 AM)	
Land Use	**L10 Limit (dBA)**	**Lmax Limit (dBA)**	**L10 Limit (dBA)**	**Lmax Limit (dBA)**	**L10 Limit (dBA)**	**Lmax Limit (dBA)**
Residential	maximum of 75 and baseline + 5 for non-impact* and exempt for impact**	85 for non-impact and 90 for impact	baseline + 5	85	if baseline <70 then baseline +5; if baseline ≥70 then baseline + 3	80
Commercial	maximum of 80 and baseline + 5 for non-impact and exempt for impact	N/A	N/A	N/A	N/A	N/A
Industrial	maximum of 85 and baseline+5 for non-impact and exempt for impact	N/A	N/A	N/A	N/A	N/A

* Non-impact equipment is equipment that generates a constant noise level while in operation.

** Impact Equipment is equipment that generates impulsive noise. Impulse Noise is defined as noise produced by the periodic impact of a mass on a surface, of short duration (generally less than one second), high intensity, abrupt onset and rapid decay, and often rapidly changing spectral composition.

Otherwise, the user may clear any information present in the dialogue box and specify new data in each cell. Clicking on the "Clear" command button will prompt the user to set all the cells in the dialogue box to Not Applicable (N/A), as in Figure 11. By clicking "Yes," the user will populate all cells with N/A; by clicking "No," the dialogue box will return to the data present before the user clicked "Clear."

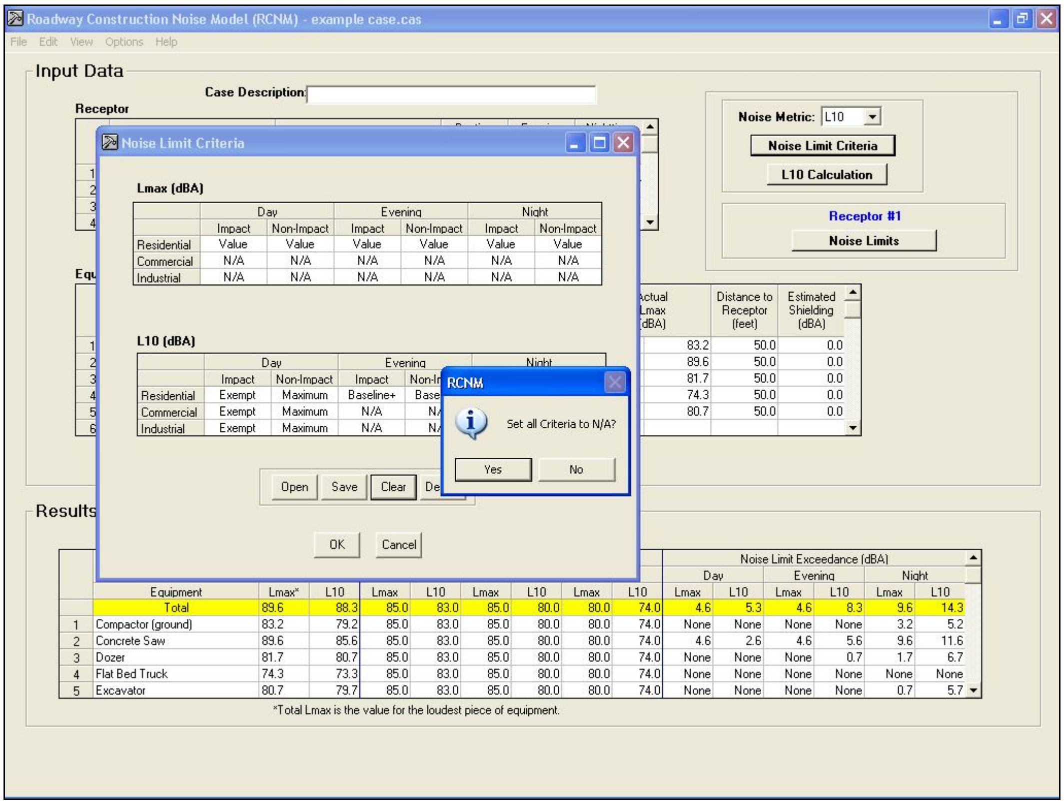

Figure 11. The Noise Limit Criteria "Clear" command button

Clicking on any cell in the Noise Limit Criteria dialogue box reveals a Noise Limit Criteria pull-down menu. Click on this pull-down menu to access the six options, as in Figure 12.

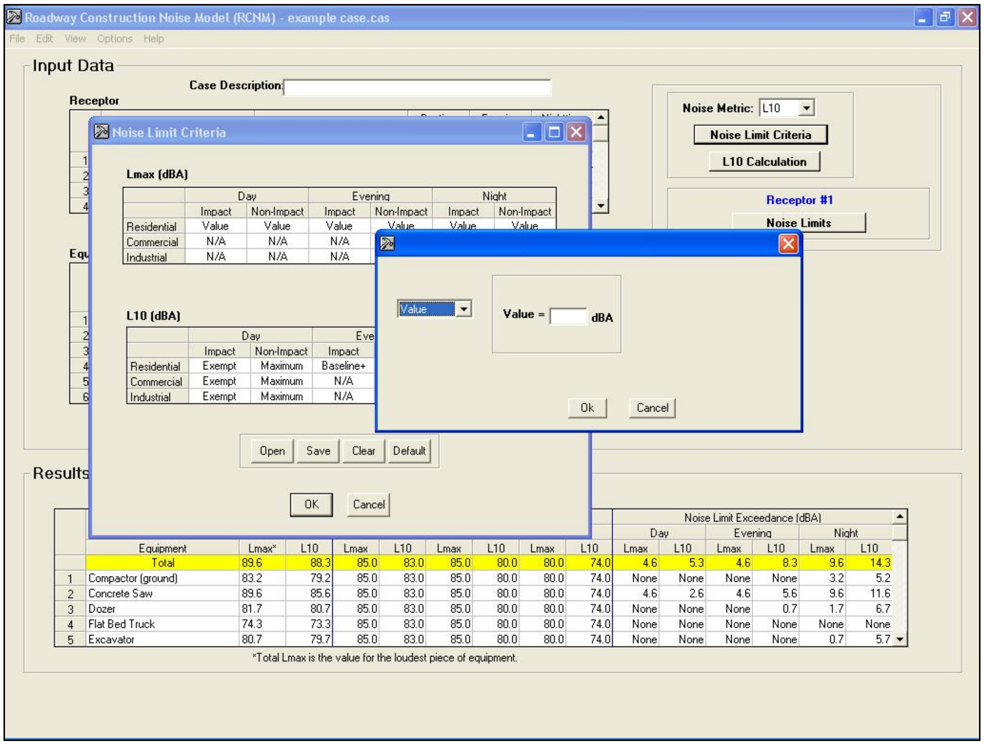

Figure 12. Noise Limit Criteria pull-down menu

Through these six options, the user specifies what Noise Limit Criteria changes, if any, are desirable in each cell. The six cell options are:

i. Exempt (for the specified metric and land use, the equipment is exempt from noise limits)
ii. N/A (for the specified metric and land use, the equipment does not have applicable noise limits)
iii. Value (user is prompted to enter a value for which the noise level should not exceed), as in Figure 13:

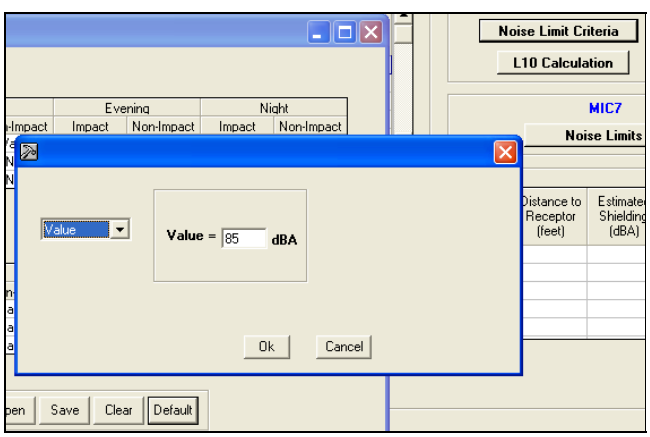

Figure 13. Noise Limit Criteria "Value" dialogue box

iv. Maximum (set value for which a noise level should not exceed to the maximum of two possible levels: A user-defined level or the Baseline level plus some user-defined increment), as in Figure 14:

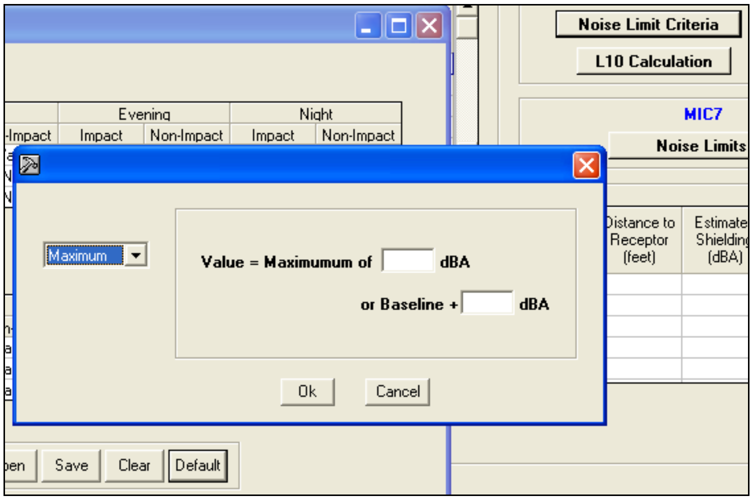

Figure 14. Noise Limit Criteria "Maximum" dialogue box

v. Baseline + (set value for which a noise level should not exceed to the Baseline level plus some user-defined increment), as in Figure 15:

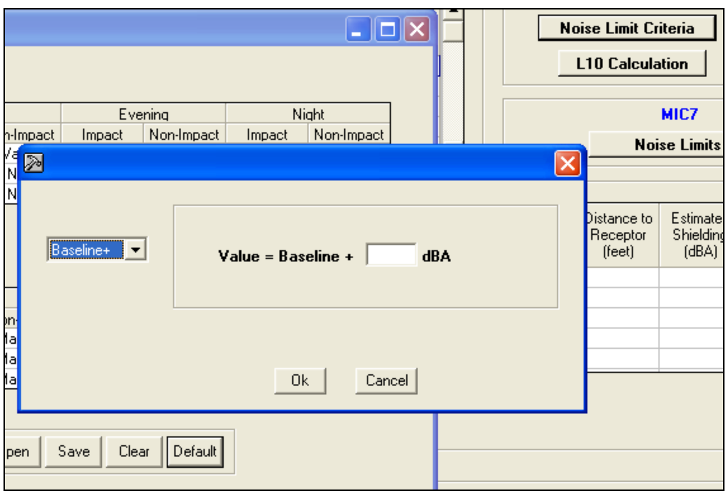

Figure 15. Noise Limit Criteria "Baseline +" dialogue box

vi. Conditional (set conditional value for which a noise level should not exceed; the user is prompted to enter the following information: 1. a comparison value, i.e., "If Baseline < [value], then …"; 2. an increment value to add to the baseline level if the baseline level is *less than* the comparison value; 3. an increment value to add to the baseline level if the baseline level is *greater than or equal to* the comparison value), as in Figure 16:

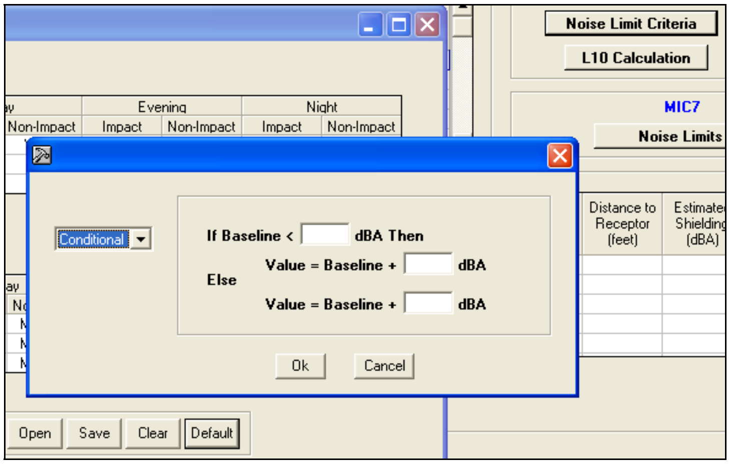

Figure 16. Noise Limit Criteria "Conditional" dialogue box

To see the current value of a cell, simply hold the mouse pointer over the cell. Once the user has specified values for all the cells in the Noise Limit Criteria dialogue box, these criteria can be saved in a criteria file ([name].cri) by clicking on the "Save" command button. The user will be prompted to give the criteria file a name. These criteria can thereafter be loaded into any case by clicking on the "Open" command button.

The user returns to the Noise Limit Criteria dialogue box by clicking "Ok", and returns to the case by clicking "Ok" again.

- L10 Calculation (this button is present if the L10 metric is chosen)

By clicking on the "L10 Calculation" command button, the user can specify the adjustment factor used to calculate L10, as in Figure 17. By clicking the "Default" command button, the user automatically calls for an adjustment factor of 3 dBA, a value empirically derived from extensive CA/T Project data [2].

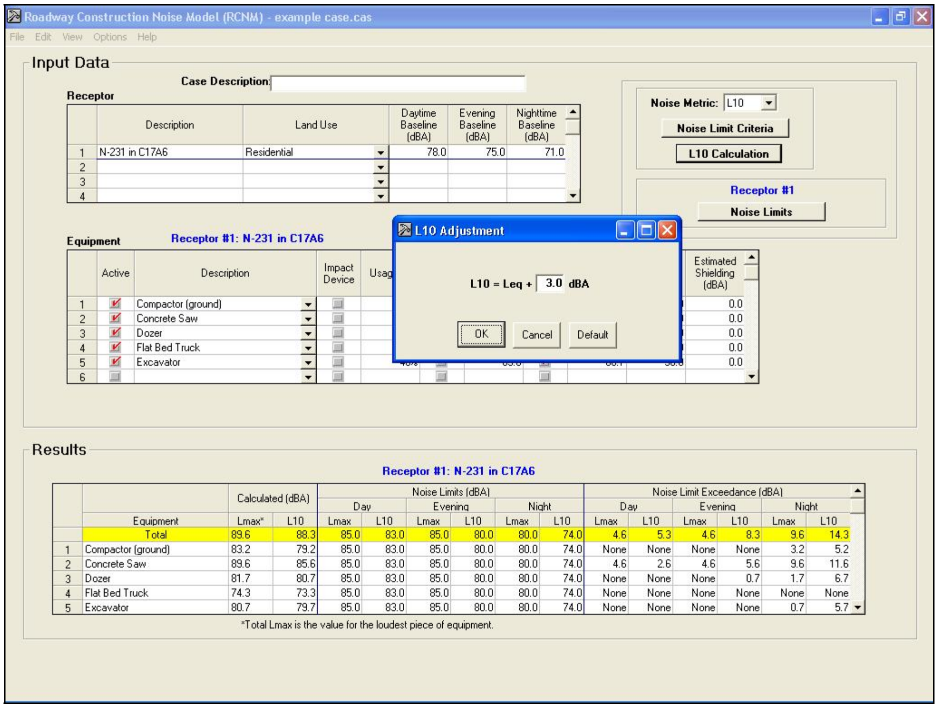

Figure 17. L10 Adjustment dialogue box

- Noise Limits

The "Noise Limits" command button opens a display window that looks exactly like the "Noise Limit Criteria" dialogue box, except that it is not editable, and the only button in the opened window is "Ok". The values in the cells are based on the criteria set in the Noise Limit Criteria window and the baseline levels for the selected receiver, as in Figure 18. (If a receiver is not selected, the dialogue box is unavailable for viewing.)

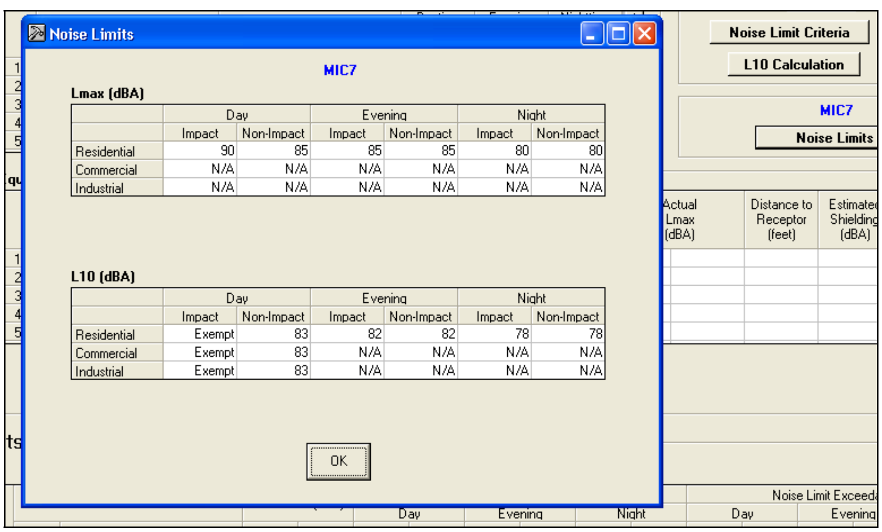

Figure 18. Noise Limits display window

Again, these limits may be changed by the user through the Noise Limit Criteria data entry window.

4 Results

Once the data for one receptor and up to 20 pieces of equipment have been specified in the Input Data portion of the main screen, the RCNM will automatically calculate the Results readout displayed in the bottom portion of the main screen, as in Figure 19. Any changes to the Input Data will automatically cause the RCNM to update the Results. The results for only one receptor will be displayed at a time; results for other receptors can be displayed by selecting the desired receptor in the Receptor window (click in any cell in the desired receptor row). Results for up to 100 receptors can be saved in a case. If Noise Limit Criteria information has been specified, the corresponding results (limits and exceedance values) will be updated as well.

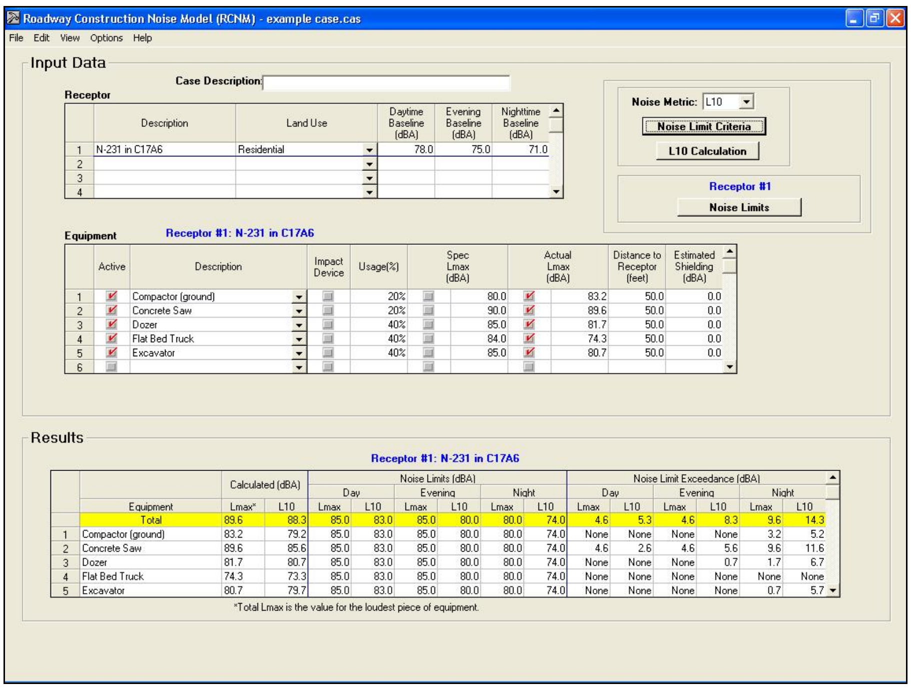

Figure 19. The RCNM main-page Results display

If there is insufficient input data for RCNM to compute a result, then a "Check Input Data" button will appear in the middle of the screen. Clicking on this button will provide the user with an indication of what additional input data are required.

The Results are presented in a read-only spreadsheet that contains the following fields, all applicable to the selected receptor:

- Equipment – the name/description of the equipment type
- Calculated Lmax – the calculated Lmax value for the equipment type. This is calculated from the "Spec" or "Actual" equipment Lmax, distance, and estimated shielding.

- Calculated Leq or L10 – the calculated Leq or L10 value (depending on what is selected in the Noise Metric pull-down menu) for the equipment type. This is calculated from the Calculated Lmax values, equipment usage factors, and selected adjustment factor.
- Day Lmax Noise Limit – the daytime Lmax noise limit for the equipment type.
- Day Leq or L10 Noise Limit – the daytime Leq or L10 noise limit for the equipment type.
- Evening Lmax Noise Limit – the evening Lmax noise limit for the equipment type.
- Evening Leq or L10 Noise Limit – the evening Leq or L10 noise limit for the equipment type.
- Night Lmax Noise Limit – the nighttime Lmax noise limit for the equipment type.
- Night Leq or L10 Noise Limit – the nighttime Leq or L10 noise limit for the equipment type.
- Day Lmax Noise Limit Exceedance – the daytime Lmax noise limit exceedance for the equipment type. If the criteria limit was not exceeded, the value is "None".
- Day Leq or L10 Noise Limit Exceedance – the daytime Leq or L10 noise limit exceedance for the equipment type. If the criteria limit was not exceeded, the value is "None".
- Evening Lmax Noise Limit Exceedance – the evening Lmax noise limit exceedance for the equipment type. If the criteria limit was not exceeded, the value is "None".
- Evening Leq or L10 Noise Limit Exceedance – the evening Leq or L10 noise limit exceedance for the equipment type. If the criteria limit was not exceeded, the value is "None".
- Night Lmax Noise Limit Exceedance – the nighttime Lmax noise limit exceedance for the equipment type. If the criteria limit was not exceeded, the value is "None".
- Night Leq or L10 Noise Limit Exceedance – the nighttime Leq or L10 noise limit exceedance for the equipment type. If the criteria limit was not exceeded, the value is "None".

The user may scroll down to view equipment results that are not visible, or the <View> / <Zoom +> menu may be used to zoom in on the Results display only (see Section 3.1.3). There is a row at the top of the Results display, highlighted in yellow, that calculates the total for all equipment combined. This row is always visible during scrolling of the Results spreadsheet. (Calculations for totals are explained in Section 5.3.)

Again, users may export a case's input information and results to a comma separated value (CSV) report file ([name].csv) by choosing the <Export Results> option from the <File> menu. The user can also save the case results to a text file (TXT), which saves the results to a space-separated text format ([name].txt). Results may be saved for a single receptor or all receptors in the case.

5 Calculations in the RCNM

The RCNM uses the primary equation described in the CA/T Construction Noise Control Specification 721.560 [1] for the construction noise calculations.

5.1 Metric Calculation

LmaxCalc = selected_Lmax – 20log(D/50) - shielding (1)

where

selected_Lmax is the "Spec" or "Actual" maximum A-weighted sound level at 50 ft., listed in Table 1 for all pieces of equipment, in dBA,
D is the distance between the equipment and the receptor, in feet,
shielding is the insertion loss of any barriers or mitigation, in dBA (see Appendix A).

Leq = LmaxCalc + 10log(U.F.%/100) (2)

where

U.F.% is the time-averaging equipment usage factor, in percent (see footnote 1 on p 7).

L10 = Leq + 3 dBA adjustment factor (3)

The RCNM calculates L10 by adding 3 dBA to the Leq, where the 3 dBA default L10 adjustment factor was empirically derived by comparing extensive CA/T construction noise data. This adjustment factor may be changed in the RCNM at the user's discretion.

5.2 Exceedance Calculation

Daytime Lmax Exceedance = LmaxCalc – Daytime Lmax Limit (4)

Daytime Leq or L10 Exceedance = Leq or L10 – Daytime Leq or L10 Limit (5)

Evening Lmax Exceedance = LmaxCalc – Evening Lmax Limit (6)

Evening Leq or L10 Exceedance = Leq or L10 – Evening Leq or L10 Limit (7)

Nighttime Lmax Exceedance = LmaxCalc – Nighttime Lmax Limit (8)

Nighttime Leq or L10 Exceedance = Leq or L10 – Nighttime Leq or L10 Limit (9)

5.3 Totals Calculation

The Total values in the Results section are determined in the following manner:

1) Total Leq = 10*log(Σ (individual equipment Leq values[3]))
2) Total L10 = 10*log(Σ (individual equipment L10 values[3]))
3) Total Lmax = Maximum among individual equipment Lmax values
4) Total noise limits and limit exceedances:
    a. Determine whether or not total is impact or non-impact
        i. If all the equipment is non-impact, label the total as non-impact.
        ii. If all the equipment is impact, label the total as impact.
        iii. If the equipment is mixed non-impact and impact, label the total as non-impact.
    b. Determine total noise limits and limit exceedances the same way as with individual pieces of equipment (see Section 5.2), only use the calculated total sound levels (Total Leq or Total L10) and the impact or non-impact label according to the criteria specified in i through iii.

[3] The Leq and L10 levels are energy averages.

6 References

[1] Construction Noise Control Specification 721.560, Central Artery/Tunnel Project, Massachusetts Turnpike Authority, Boston, MA, 2002.

[2] Thalheimer, Erich. "Construction Noise Control Program and Mitigation Strategy at the Central Artery/Tunnel Project". Noise Control Engineering Journal, Vol. 48, No. 5, pp 157-165, September - October 2000.

[3] "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety", Environmental Protection Agency, ONAC 550/9-74-004. Washington, DC, March 1974.

[4] "Power Plant Construction Noise Guide". Bolt, Beranek, and Newman Inc. and Empire State Electric Energy Research Corp., Report No. 3321. New York, NY May 1977.

Appendix A: Best Practices for Calculating Estimated Shielding for Use in the RCNM

This Appendix presents some simplified shielding factors for use in the RCNM. These suggestions are "rules of thumb" based on experience gathered by CA/T construction noise experts working in the field [2].

1) If a noise barrier or other obstruction (like a dirt mound) just barely breaks the line-of-sight between the noise source and the receptor, use 3 dBA.

2) If the noise source is completely enclosed OR completely shielded with a solid barrier located close to the source, use 8 dBA. If the enclosure and/or barrier has some gaps in it, reduce the effectiveness to 5 dBA.

3) If the noise source is completely enclosed AND completely shielded with a solid barrier located close to the source, use 10 dBA.

4) If a building stands between the noise source and receptor and completely shields the noise source, use 15 dBA.

5) If a noise source is enclosed or shielded with heavy vinyl noise curtain material (e.g., SoundSeal BBC-13-2" or equivalent), use 5 dBA.

6) If dilapidated windows are replaced with new acoustical windows, or quality internal or exterior storm sashes, use an incremental improvement of 10 dBA for an overall Outside-to-Inside Noise Reduction (OINR) of 35 dBA.

7) If work is occurring deep inside a tunnel using the "top-down" construction method (i.e. cover the tunnel work with concrete roadway decks to allow surface traffic and then excavate underneath the roof deck), use 12 dBA.

TRANSIT NOISE AND VIBRATION IMPACT ASSESSMENT

FTA-VA-90-1003-06 **May 2006**

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Federal Transit Administration

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13. ABSTRACT (Maximum 200 words)

This report is the second edition of a guidance manual originally issued in 1995 which presents procedures for predicting and assessing noise and vibration impacts of proposed mass transit projects. All types of bus and rail projects are covered. Procedures for assessing noise and vibration impacts are provided for different stages of project development, from early planning before mode and alignment have been selected through preliminary engineering and final design. Both for noise and vibration, there are three levels of analysis described. The framework acts as a screening process, reserving detailed analysis for projects with the greatest potential for impacts while allowing a simpler process for projects with little or no effects.

This updated guidance contains noise and vibration impact criteria that are used to assess the magnitude of predicted impacts. A range of mitigation measures are described for dealing with adverse noise and vibration impacts. There is a discussion of noise and vibration during the construction stage and also discussion of how the technical information should be presented in the Federal Transit Administration's environmental documents. This guidance will be of interest not only to technical specialists who conduct the analyses but also to transit agency staff, federal agency reviewers, and members of the general public who may be affected by the projects.

14. SUBJECT TERMS

Transit noise and vibration analysis, noise and vibration impact criteria, noise and vibration mitigation measures, environmental impact assessment, National Environmental Policy Act compliance.

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PREFACE

This guidance manual on transit noise and vibration impact assessment is an updated edition of a document originally published in 1995. The manual details the procedures for producing accurate impact assessments for proposed federally-funded mass transit projects and discusses ways of reducing excessive noise and vibration caused by projects. While the manual is intended primarily for acoustics professionals who conduct the analyses as part of the environmental review process, it is written for a broader audience. Sections on noise and vibration fundamentals and a glossary of terms allow lay readers to gain a better understanding of one of the more technical subjects covered in the Federal Transit Administration's environmental documents.

The revisions in this manual are based on practitioners' experience in using the procedures and on developments that have occurred in this field over the past decade. The basic procedures for prediction and impact assessment remain the same; however, changes have been made throughout the document to clarify the procedures and to add new content. Some of the more significant changes involve: inclusion of noise reference levels for several new transit modes; fuller explanation of how to handle multimodal highway/transit projects; methods for assessing locomotive horn noise at grade crossings; expanded discussion of noise and vibration mitigation measures including costs; refined vibration impact criteria expressed in one-third octave bands for Detailed Analysis; and more examples on how to use the General Noise Assessment procedures for different types of transit projects.

This updated guidance manual supersedes the original document and should be used for addressing noise and vibration impacts for all construction projects seeking funding from FTA. For the great majority of projects, the results obtained from application of the methods described in this manual will not depart significantly from results obtained from the old manual. This document is also available in the Planning and Environment section of FTA's Web site (www.fta.dot.gov).

1. INTRODUCTION

1.1 PURPOSE

Noise and vibration assessments are key elements of the environmental impact assessment process for mass transit projects. Experience has shown that noise and vibration are among the major concerns with regard to the effects of a transit project on the surrounding community. A transit system is of necessity placed near population centers and often causes significant noise and vibration at nearby residences and other sensitive types of land use.

This manual provides guidance for preparing and reviewing the noise and vibration sections of environmental documents. In the interest of promoting quality and uniformity in assessments, the manual will be used by project sponsors and consultants in performing noise and vibration analyses for inclusion in environmental documents. The manual sets forth the methods and procedures for determining the level of noise and vibration impact resulting from most federally-funded transit projects and for determining what can be done to mitigate such impact. Since the methods have been developed to assess typical transit projects, there will be some situations not explicitly covered in this manual. The exercise of professional judgment may be required to extend the basic methods in these cases.

1.2 THE ENVIRONMENTAL REVIEW PROCESS

The Federal Transit Administration (FTA) provides capital assistance for a wide range of mass transit projects – from completely new rail rapid transit systems to bus maintenance facilities and vehicle purchases. The extent of environmental analysis and review will depend on the scope and complexity of the proposed project and the associated environmental impacts. FTA's environmental impact regulation classifies the most common projects according to the different levels of environmental analysis required, ranging from an environmental impact statement (EIS) to little or no environmental documentation (categorical exclusion). FTA's environmental impact regulation is codified in Title 23, Code of Federal Regulations, Part 771.[(1)*]

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[*]References are located at the end of each chapter.

Environmental Impact Statements. Large fixed-guideway projects, such as heavy rail, light rail, commuter rail and automated guideway transit systems, normally require environmental impact statements, including an in-depth noise and vibration assessment. While there may be exceptions to the EIS requirement, in the great majority of cases new rail starts or extensions to existing systems involve significant environmental effects in the context of the National Environmental Policy Act (NEPA). Because they are located in dense urban areas, noise and vibration impacts are a frequent concern; thus it is likely that for the major infrastructure projects requiring an EIS, the most detailed treatment of noise and/or vibration impacts will also be required.

There are other projects as well which may require a detailed analysis of noise and vibration impacts even if an EIS is not required to comply with NEPA. These could be bus/high-occupancy-vehicle (HOV) lanes built on existing highways or construction of certain bus or rail terminals and storage and maintenance facilities. If the project is proposed to be located in or very close to a sensitive area or site, it is prudent to use the most detailed procedures contained in the manual to predict noise and/or vibration levels since this will provide the most reliable basis for considering measures to mitigate excessive noise/vibration at a specific site.

Categorical Exclusions. At the other extreme is a host of smaller transit projects which normally do not cause significant environmental impacts and do not require noise and vibration assessment. These projects are listed as "categorical exclusions" in FTA's environmental regulation, meaning that FTA has determined that there are no significant environmental impacts for those types of projects and no environmental document is required. Examples are: vehicle purchases; track and railbed maintenance; installation of maintenance equipment within the facility, etc. Section 771.117(c) contains a list of transit projects predetermined to be categorical exclusions.

Other types of projects may also qualify as categorical exclusions, for example, certain transit terminals, transfer facilities, bus and rail storage and maintenance facilities (see 23 CFR 771.117(d)). These projects usually involve more construction and a greater potential for off-site impacts. They are presented in the regulation with conditions or criteria which must be met in order to qualify for categorical exclusion. The projects are reviewed individually by FTA to assure that any off-site impacts are properly mitigated. Depending on the proposed project site and the surrounding land use, a noise and vibration assessment may be needed even though the project may ultimately qualify as a categorical exclusion. The screening process in Chapters 4 and 9 will be helpful in pointing out potential noise and vibration concerns and the general assessment procedures may then be used to define the level of impact.

Environmental Assessments. When a proposed project is presented to FTA, if it is uncertain whether the project requires an EIS or qualifies as a categorical exclusion, FTA will direct the project sponsor to prepare an environmental assessment (EA). Generally, an EA is selected (rather than trying to process the project as a categorical exclusion) if the FTA reviewer feels that several types of impacts need further investigation, for example, air quality, noise, wetlands, historic sites, traffic, etc. An EA is a relatively brief environmental study which helps determine the magnitude of the impacts that will likely be caused by the project. If, during the analysis, it appears that any impacts are significant, an EIS will be prepared. If the analysis shows that none of the impacts is significant or if mitigation measures are incorporated in the project to adequately deal with adverse impact, the EA will fully document this and serve as the basis for a Finding of No Significant Impact issued by FTA. It is important to note that when mitigation measures are relied on, they must be described in detail in the EA since FTA's finding is based on the inclusion of these measures in the project.

FTA's environmental regulation does not list typical projects that require EA's. An EA may be prepared for any type of project if uncertainty exists about the magnitude or extent of the impacts. Experience has shown that most of the EA's prepared for transit projects require an assessment of noise impacts.

1.3 NOISE AND VIBRATION ANALYSIS IN PLANNING AND PROJECT DEVELOPMENT

Major capital investment projects are developed initially from a comprehensive transportation planning process conducted in metropolitan areas (see 23 CFR 450.300). The metropolitan planning process includes the consideration of social, economic, and environmental effects of proposed major infrastructure improvements. However, at this stage, environmental effects are usually considered on a broad scale, for example, overall development patterns, impact on greenspace, and regional air quality. Noise and vibration assessments are not typically done at the systems planning stage since the proposed infrastructure improvements lack the necessary detail.

Once the need for a major capital investment in a corridor is established in the metropolitan transportation plan, the task then becomes identifying the transit mode and alignment best suited for the corridor. If FTA capital investment funds will be pursued, the project sponsor must perform an "alternatives analysis."[(2)] Often combined with a Draft EIS, the alternatives analysis presents information on benefits, costs, and impacts of alternative strategies for meeting the need for new capacity. Usually, several alternatives ranging in cost will be evaluated. If environmental impacts of the alternatives will be assessed, noise and, to a lesser extent, vibration are primary issues. The screening and general assessment procedures described in this manual are well-suited to compare and contrast noise/vibration effects among different modes and alignments. In fact, the general assessment procedures were developed partly to respond to this need. In addition, they can be used for any specific project where the screening procedure indicates potential for impact and the project sponsor wants a relatively quick assessment of the level of impact.

If the results of the alternatives analysis justify further development of a major capital investment, FTA will approve entry of the proposed project into preliminary engineering. During preliminary engineering, the environmental review process is completed. With the mode and alignment determined, the impact assessment at this stage focuses on the locally preferred alternative for a major capital investment. The detailed analysis procedures for noise can be used to produce the most accurate estimates of noise impact for the proposed project. The detailed procedures should be used as the basis for reaching any decisions on the need for noise reduction measures and the types of measures that are appropriate for the project.

After the NEPA process is completed for a major project, federal funding for final design may be granted. If vibration impacts were identified during preliminary engineering, a detailed analysis of vibration impact may be conducted during final design. Final design activities will produce the geotechnical information needed to refine the impact assessment and allow the most detailed consideration of vibration control measures, if needed. Even for smaller transit projects, if vibration impact is predicted in a general assessment, vibration mitigation measures should only be specified after a detailed analysis has been done. Detailed vibration analysis is best accomplished during final design of the project.

Once the project enters construction, there may still be a need for noise or vibration analysis in some circumstances. Large construction projects in densely populated residential areas may require noise monitoring to make sure that agreed-upon noise limits are not exceeded. Vibration testing may be needed in the final stages of construction to determine whether vibration control measures are having the predicted effect.

Considering that transit projects must be located amid or very close to concentrations of people, noise and vibration impacts can be a concern throughout the planning and project development phases. This manual offers the flexibility to address noise and vibration at different stages in the development of a project and in different levels of detail depending on the types of decisions that need to be made.

There are three levels of analysis which may be employed, depending on the type and scale of the project, the stage of project development, and the environmental setting. The technical content of each of the three levels is specified in the body of this document, but a summary of each level is given in the following paragraphs:

- **Screening Procedure:** Identifies noise- and vibration-sensitive land uses in the vicinity of a project and whether there is likely to be impact. It also serves to determine the noise and vibration study areas for further analysis when sensitive locations are present. The screening process may be all that is required for many of the smaller transit projects which qualify as categorical exclusions. When noise/vibration-sensitive receivers are found to be present, there are two levels of quantitative analysis available to predict impact and assess the need for mitigation measures.

- **General Assessment:** Identifies location and estimated severity of noise and vibration impacts in the noise and vibration study areas identified in the screening procedure. For major capital investments, the General Assessment provides the appropriate level of detail to compare alternative modes and alignments in alternatives analysis. It can be used in conjunction with established highway noise prediction procedures to compare and contrast highway, transit and multimodal alternatives. Before basic decisions have been reached on mode and alignment in a corridor, it is not prudent to conduct the most detailed level of noise and vibration analysis. For smaller transit projects, this level is used for a closer examination of projects which show possible impacts as a result of screening. For many smaller projects, this level may be sufficient to define impacts and determine whether mitigation is necessary.

- **Detailed Analysis:** Quantifies impacts through an in-depth analysis usually only performed for a single alternative. Delineates site-specific impacts and mitigation measures for the preferred alternative in major investment projects during preliminary engineering. For other smaller projects, Detailed Analysis may be warranted as part of the initial environmental assessment if there are potentially severe impacts due to close proximity of sensitive land uses.

The three levels of noise and vibration assessment are described in the chapters which follow.

1.4 ORGANIZATION OF THE MANUAL

The guidance manual is divided into two parts, noise and vibration. Each part has parallel organization according to the following subjects:

Noise/Vibration

- Basic Concepts
- Criteria
- Screening Procedure
- General Assessment
- Detailed Analysis

Construction Noise/Vibration

Documentation

Appendices

- Glossary
- Background for Transit Noise Impact Criteria
- Receiver Selection
- Existing Noise Determination
- Noise Source Level Determination
- Maximum Noise Level Computation

REFERENCES

1. U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Environmental Impact and Related Procedures," Final Rule, 52 Federal Register 32646 -32669; August 28, 1987 (23 Code of Federal Regulations 771).

2. U.S. Department of Transportation, Federal Transit Administration, “Major Capital Investment Projects,” Final Rule, 65 Federal Register 76863-76884; December 7, 2000 (49 CFR Part 611).

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 primer on the fundamentals of noise characteristics.

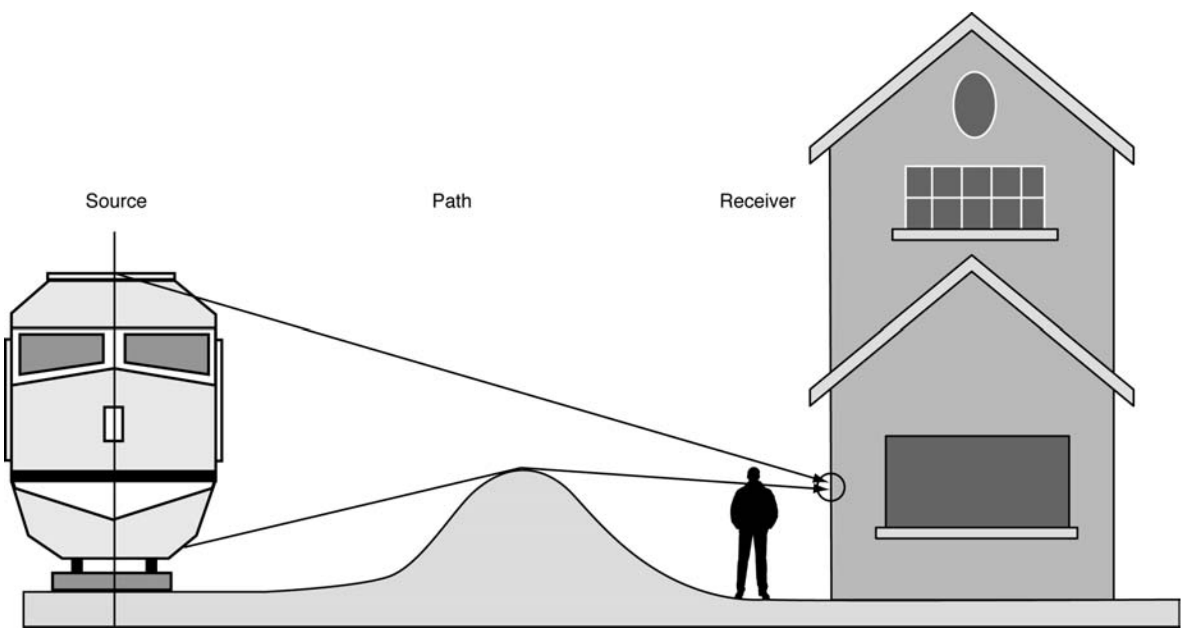


Figure 2-1. The Source-Path-Receiver Framework

In brief, this chapter contains:

- A primer on the fundamentals of noise characteristics (Section 2.1)
- An overview of transit **sources**: a listing of major sources, plus some discussion of noise-generation mechanisms (Section 2.2)
- An overview of noise **paths**: a discussion of the various attenuating mechanisms on the path between source and receiver (Section 2.3)
- 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 2.4)
- A discussion of the **noise descriptors** used in this manual for transit noise (Section 2.5)

2.1 FUNDAMENTALS OF NOISE

Noise is generally considered to be unwanted sound. Sound is what we hear when our ears are exposed to small pressure fluctuations in the air. There are many ways in which pressure fluctuations are generated, but typically they are caused by vibrating movement of a solid object. This manual uses the terms 'noise' and 'sound' interchangeably since there is no physical difference between them. Noise can be described in terms of three variables: amplitude (loud or soft); frequency (pitch); and time pattern (variability).

Amplitude. Loudness of a sound depends on the amplitude of the fluctuations above and below atmospheric pressure associated with a particular sound wave. The mean value of the alternating positive and negative pressure fluctuations is the static atmospheric pressure, not a useful descriptor of sound. However, the effective magnitude of the sound pressure in a sound wave can be expressed by the "root-mean-square" (rms) of the oscillating pressure measured in Pascals, a unit named after Blaise Pascal a 17th century French mathematician. In calculation of the 'rms', the values of sound pressure are squared to make them all positive and time-averaged to smooth out variations. The 'rms' pressure is the square root of this time-averaged value.

The quietest sound that can be heard by most humans, the "threshold of hearing," is a sound pressure of about 20 microPascals, and the loudest sounds typically found in our environment range up to 20 million microPascals. Because of the difficulty in dealing with such an extreme range of numbers, acousticians use a compressed scale based on logarithms of the ratios of the sound energy contained in the wave related to the square of sound pressures instead of the sound pressures themselves, resulting in the "sound pressure level" in decibels (dB). The 'B' in dB is always capitalized because the unit is named after Alexander Graham Bell, a leading 19th century innovator in communication. Sound pressure level (L_p) is defined as:

$$L_p = 10 \log_{10} (p^2_{rms} / p^2_{ref}) = 20 \log_{10} (p_{rms} / p_{ref}) \text{ dB, where } p_{ref} = 20 \text{ microPascals.}$$

Inserting the range of sound pressure values mentioned above results in the threshold of hearing at 20 microPascals at 0 dB and a typical loudest sound of 20 million microPascals is 120 dB.

Decibel Addition. The combination of two or more sound pressure levels at a single location involves 'decibel addition' or the addition of logarithmic quantities. The quantities that are added are the sound energies (p^2_{rms}). For example, a doubling of identical sound sources results in a 3 dB increase, since:

$$10 \log_{10} (2 p^2_{rms} / p^2_{ref}) = 10 \log_{10} (p^2_{rms} / p^2_{ref}) + 10 \log_{10} (2) = 10 \log_{10} (p^2_{rms} / p^2_{ref}) + 3.$$

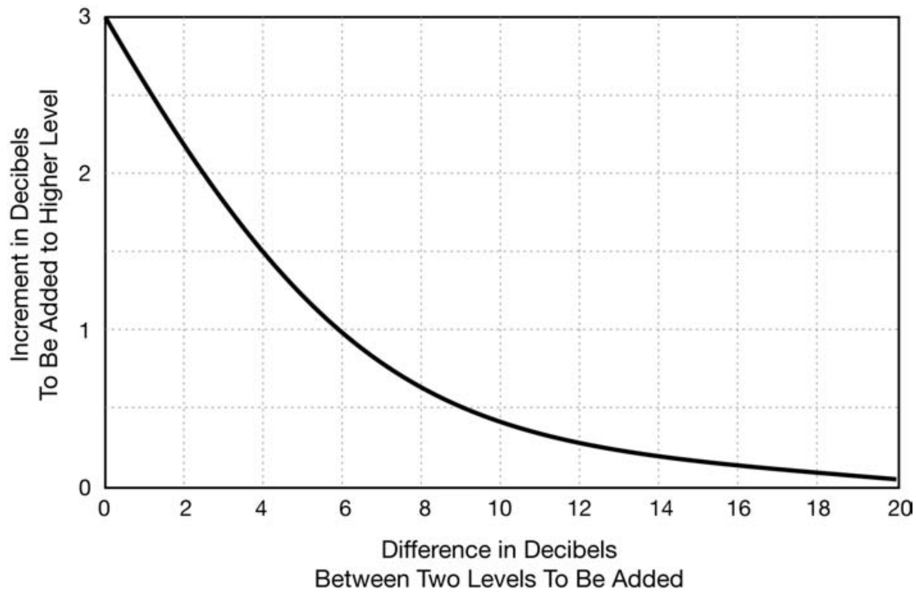


Figure 2-2. Graph for Approximate Decibel Addition

For example, if the noise from one bus resulted in a sound pressure level of 70 dB, the noise from two buses would be 73 dB. Figure 2.2 provides a handy graph that can be used to add sound levels in decibels. For example, if two sound levels of 64 dB and 60 dB are to be added, the difference in decibels between the two levels to be added is 4 dB. The curve intersects the "4" where the increment to be added to the higher level is "1.5." Therefore the sum of the two levels is 65.5 dB.

Frequency. Sound is a fluctuation of air pressure. The number of times the fluctuation occurs in one second is called its frequency. In acoustics, frequency is quantified in cycles per second, or Hertz (abbreviated Hz), named after Heinrich Hertz, a famous 19^{th} century German physicist. Some sounds, like whistles, are associated with a single frequency; this type of sound is called a "pure tone." Most often, however, noise is made up of many frequencies, all blended together in a spectrum. Human hearing covers the frequency range of 20 Hz to 20,000 Hz. If the spectrum is dominated by many low frequency components, the noise will have a characteristic like the rumble of thunder. The spectrum in Figure 2-3 illustrates the full range of acoustical frequencies that can occur near a transit system. In this example, the noise spectrum was measured near a train on a steel elevated structure with a sharp curve. This spectrum has a major low frequency peak centered around 80 Hz. Although not dominant in this example, frequencies in the range of 500 Hz to 2000 Hz are associated with the roar of wheel /rail noise. However a strong peak above 2000 Hz is associated with the wheel squeal of the train on the curve.

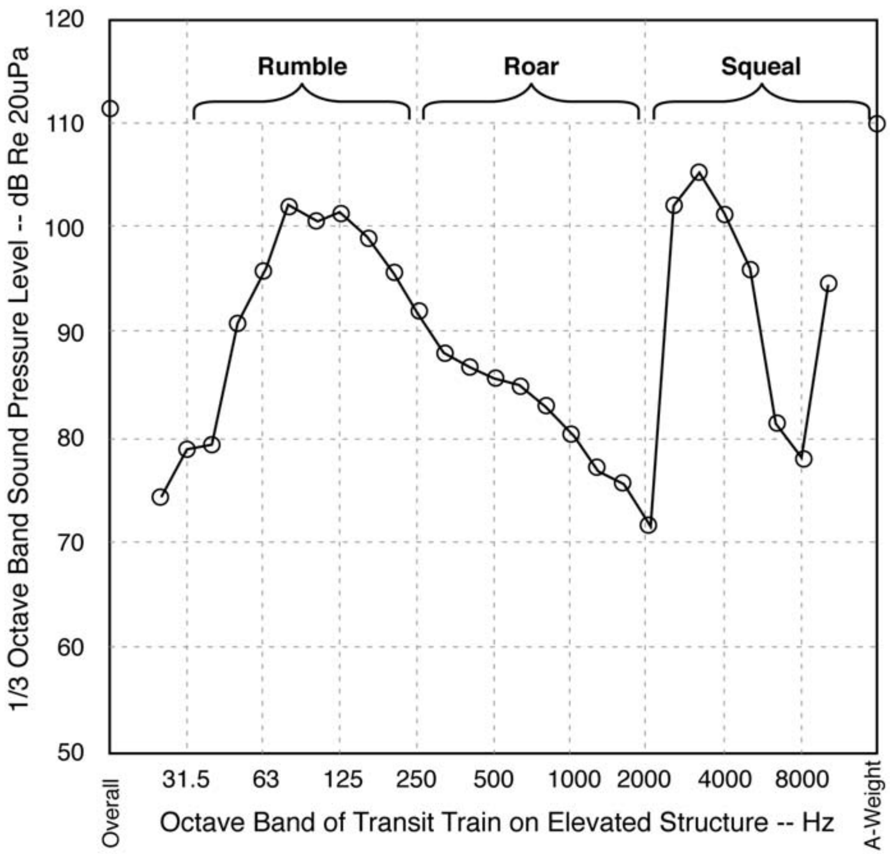


Figure 2-3. Noise Spectrum of Transit Train on Curve on Elevated Structure

Our human hearing system does not respond equally to all frequencies of sound. For sounds normally heard in our environment, low frequencies below 250 Hz and very high frequencies above 10,000 Hz are less audible than the frequencies in between. Acoustical scientists measured and developed frequency response functions that characterize the way people respond to different frequencies. These are the so-called A-, B- and C-weighted curves, representing the way people respond to sounds of normal, very loud and extremely loud sounds, respectively. Environmental noise generally falls into the “normal” category so that the A-weighted sound level is considered best to represent the human response. The A-weighted curve is shown in

Figure 2-4. This curve shows that sounds at 50 Hz would have to be amplified by 30 dB to be perceived equally as loud as a sound at 1000 Hz at normal sound levels.

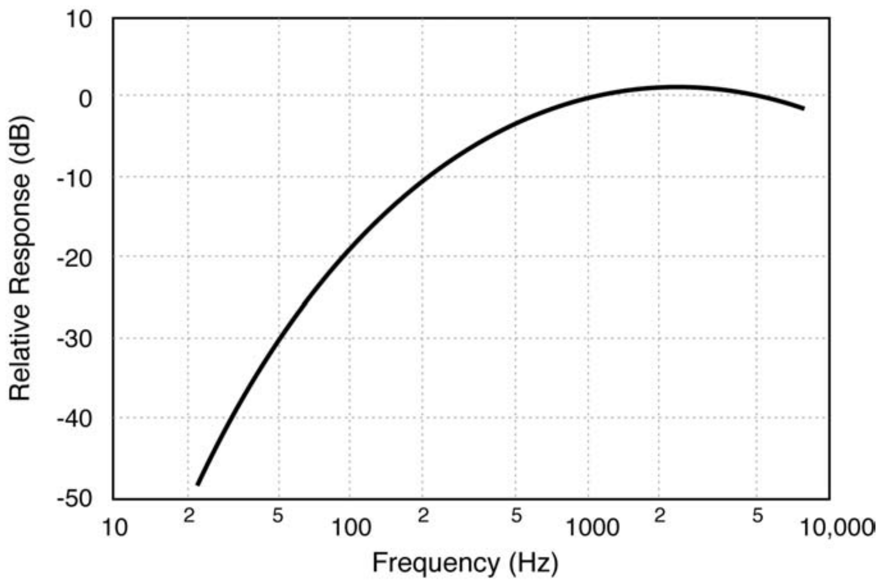


Figure 2-4. A-weighting Curve

Low frequencies are associated with long wavelengths of sound. Conversely, high frequencies are the result of short wavelengths. The way in which frequency and wavelength of sound waves are related is the speed of sound. The relationship is:

$$f\lambda = c, \text{ where}$$

f = frequency in cycles per second (Hz)
λ = wavelength in feet, and
c = speed of sound in feet per second.

The speed of sound in air varies with temperature, but at standard conditions is approximately 1000 feet per second. Therefore, according to the equation, a frequency of 1000 Hz has a wavelength of 1 foot and a frequency of 50 Hz has a wavelength of 20 feet.

The scale of these waves explains in part the reason humans perceive sounds of 1000 Hz better than those of 50 Hz – the wavelengths are similar to the size of the receiver's head. Waves of 20 feet in length at 50 Hz are house-sized, which is why low-frequency sounds, such as those from idling locomotives, are not deterred by walls and windows of a home. These sounds transmit indoors with relatively little reduction in strength.

Time pattern. The third important characteristic of noise is its variation in time. 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.

2.2 SOURCES OF TRANSIT VEHICLE 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 2-5 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

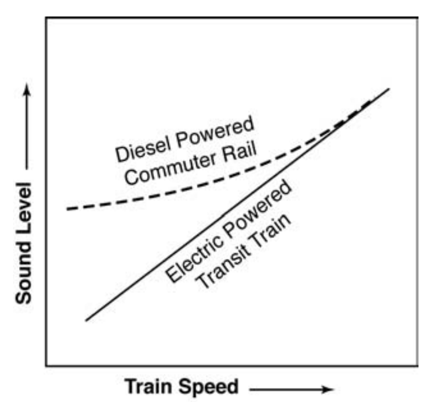


Figure 2-5. Example Sound Level Dependence on Speed

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. 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.

Transit vehicles are equipped with horns and bells for use in emergency situations and as a general audible warning to track workers and trespassers within the right-of-way as well as to pedestrians and motor vehicles at highway grade crossings. Horns and bells on the moving transit vehicle, combined with stationary bells at grade crossings can generate noise levels considered to be extremely annoying to nearby residents.

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. Procedures 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 and horns at grade crossings.
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.
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.

Table 2-1. Sources of Transit Noise (continued)

Vehicle or Facility	**Dominant Components**	**Comments**
Bus Storage Yards	Buses starting up	Usually in early morning.
	Buses accelerating	Usually near entrances/exits.
	Buses idling	Warm-up areas
	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	On tangent track
	Auxiliary equipment	Throughout day and night. Includes air-release noise.
	Coupling/uncoupling	On storage tracks
	Signal horns	Throughout yard site
	In general	Site specific. Often early morning and peak periods with significant noise.
Maintenance Facilities	Signal horns	Throughout facility
	PA systems	Throughout facility
	Impact tools	Shop buildings
	Car/bus washers/driers	Wash facility
	Vehicle activity	Throughout facility
	In general	Site specific. Considerable activity throughout day and night, some outside.
Stations	Automobiles	Patron arrival/departure, especially in early morning.
	Buses idling	Bus loading zone
	P.A. systems	Platform area
	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.

2.3 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 2-6. 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 2-6, 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 2.5. Equations for the curves in Figure 2-6 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 2-7 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.

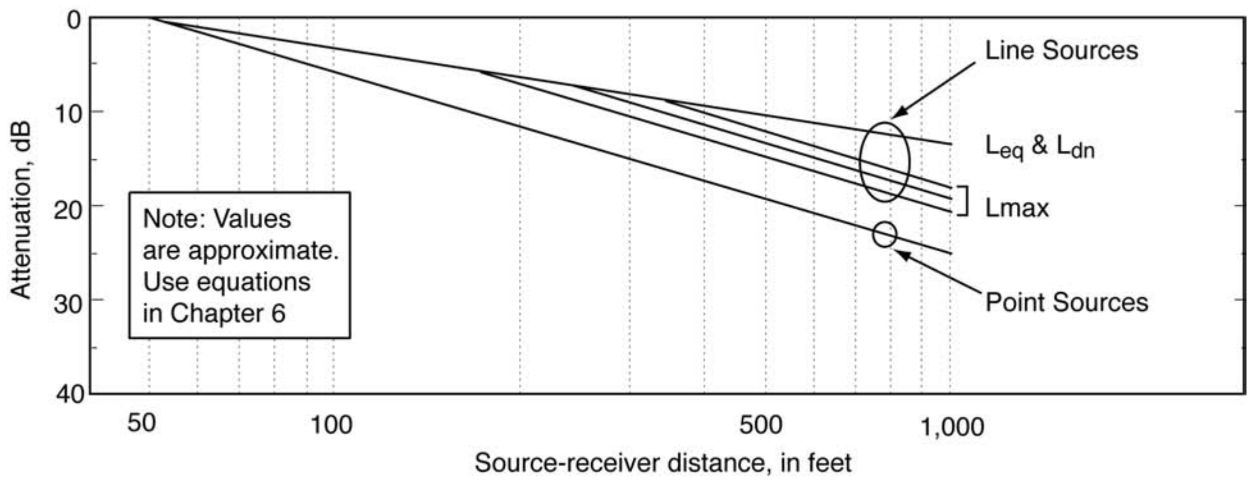


Figure 2-6. Attenuation due to Distance (divergence)

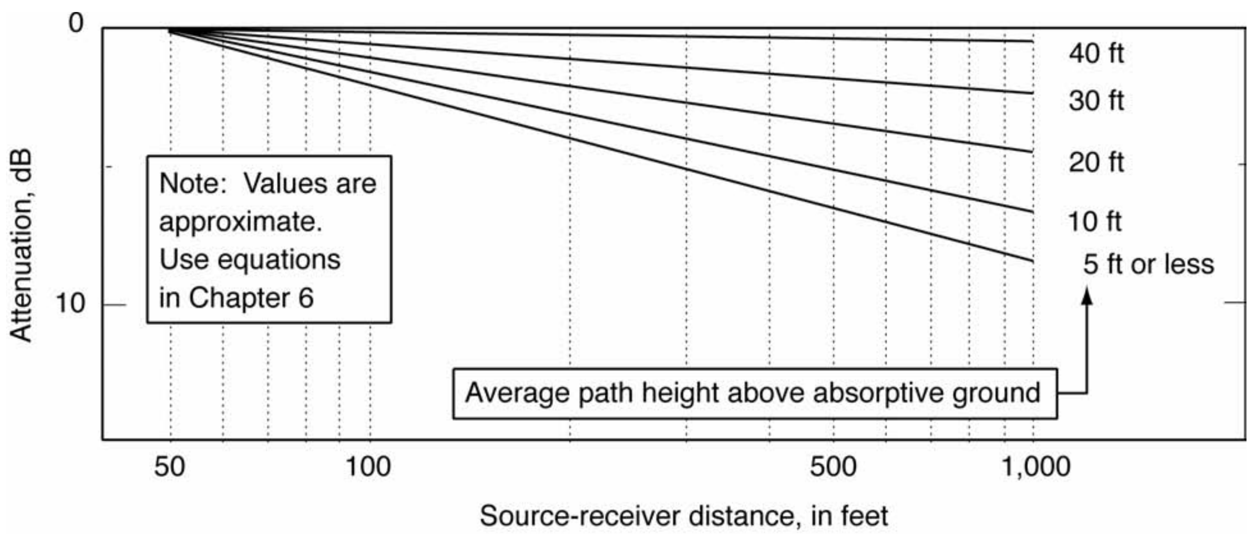


Figure 2-7. Attenuation due to Soft Ground

<u>Shielding</u>. 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 2-8, and this diffraction reduces the sound level at the receiver.

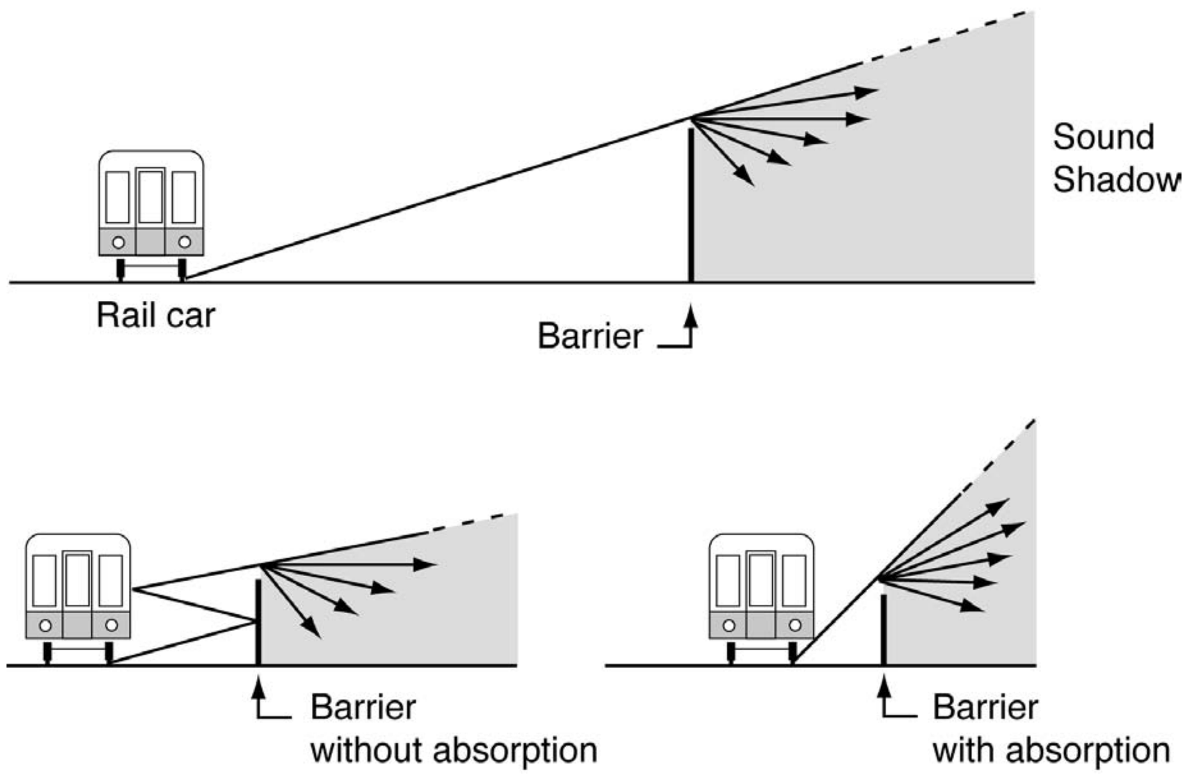


Figure 2-8. Noise Barrier Geometry

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.

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.

2.4 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)] 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.[(2)(3)(4)(5)] Conclusions from this seminal EPA work remain scientifically valid to this day.

Figure 2-9 contains a synthesis of actual case studies of community reaction to newly introduced sources of noise in a residential urban neighborhood.[(6)] 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 2.5. 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.

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 2-10.[(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, has not significantly changed the shape of the original Schultz curve.[(8)(9)]

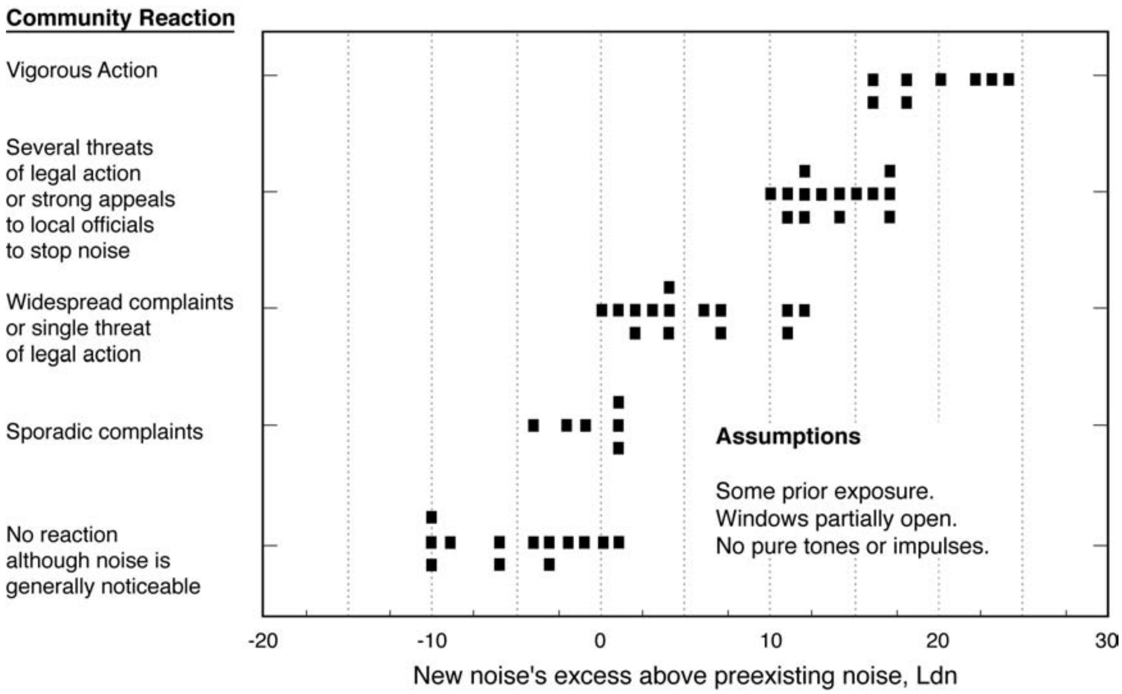


Figure 2-9. Community Reaction to New Noise, Relative to Existing Noise In a Residential Urban Environment

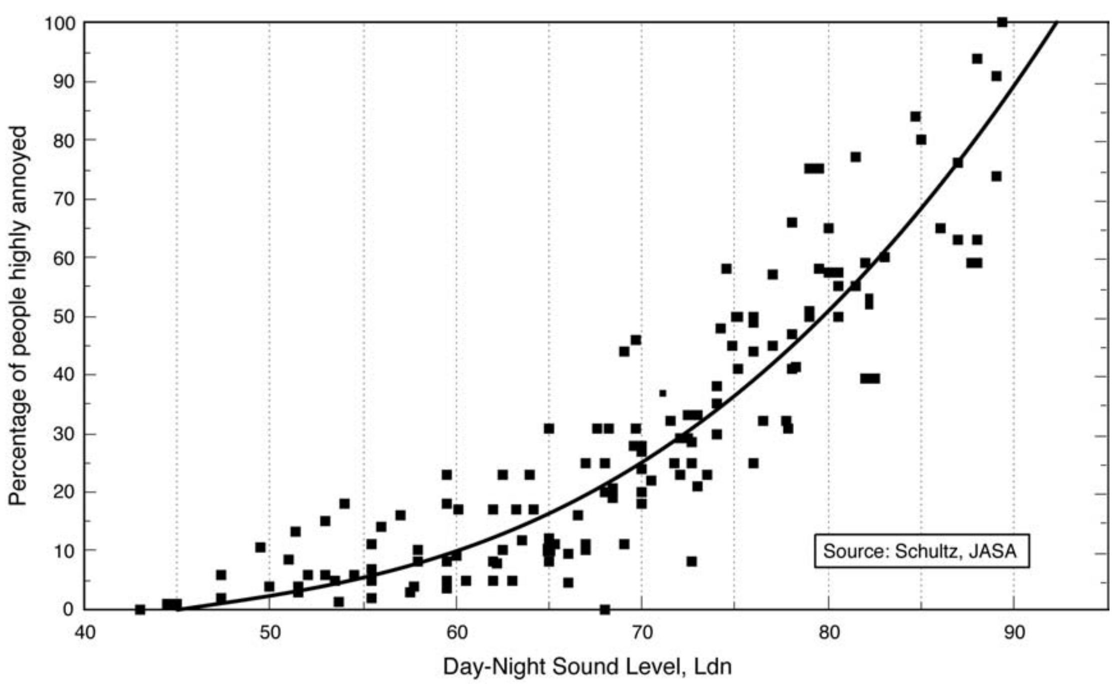


Figure 2-10. Community Annoyance Due to Noise

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 to which residents have mostly become accustomed. 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.

2.5 DESCRIPTORS FOR TRANSIT NOISE

This manual uses the following single-number descriptors for transit-noise measurements, computations, and assessment. The terminology is consistent with common usage in the United States. For comparison with national standard terminology, see Appendix A.

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

The *Maximum Sound 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 Average 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.

2.5.1 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 2-11 shows some typical A-weighted Sound Levels for both transit and non-transit sources.

As is apparent from Figure 2-11, 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 labeled "dBA" to denote the way A-weighted Sound Levels are typically written, for example, 80 dBA. The letter "A" indicates that the sound has been filtered to reduce the strength of very low and very high-frequency sounds, as described in Section 2.1. 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. Other frequency weighting such as B, C, and linear weights have been used to filter sound for specific applications.

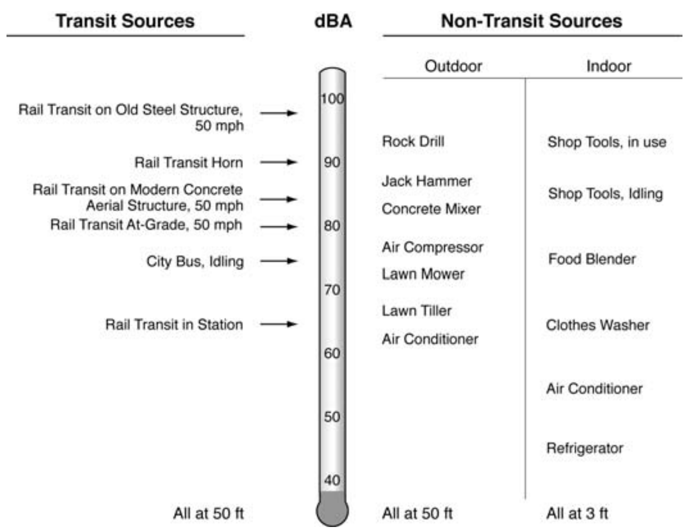


Figure 2-11. Typical A-weighted Sound Levels

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.

2.5.2 Maximum Sound 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 Sound 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 2-12, where time is plotted horizontally and A-weighted sound level is plotted vertically.

Because L_{max} is commonly used in vehicle-noise specifications and because it is commonly measured for individual vehicles, equations are included in Appendices E and F 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.

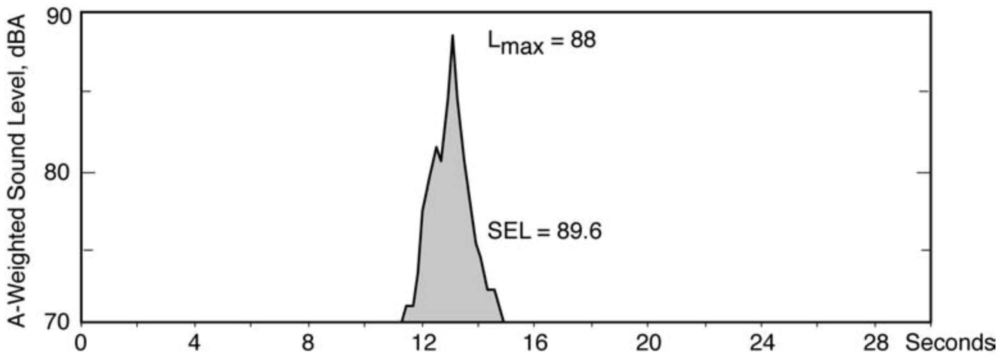


Figure 2-12. Typical Transit-Vehicle Passby

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

Shaded in Figure 2-12 is the noise "exposure" during a transit-vehicle passby. This exposure represents the total amount of sound energy that enters the receiver's ears (or the measurement microphone) during the vehicle passby. Figure 2-13 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 exposure is large due to *duration*.

The quantitative measure of the noise exposure 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:

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

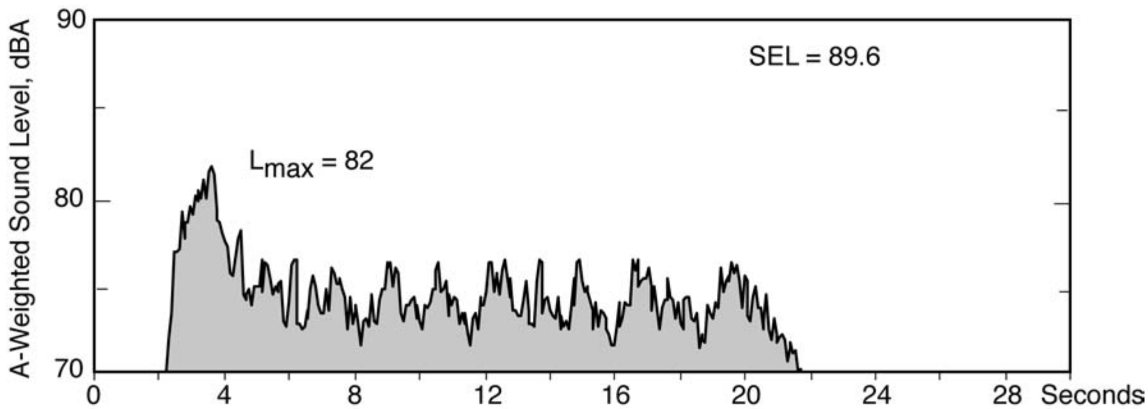


Figure 2-13. Typical Fixed-Facility Noise Event

Figure 2-14 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 is "energy" exposure. Only in this way do the shaded zones properly correspond to the noise exposures 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, therefore, allows 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.

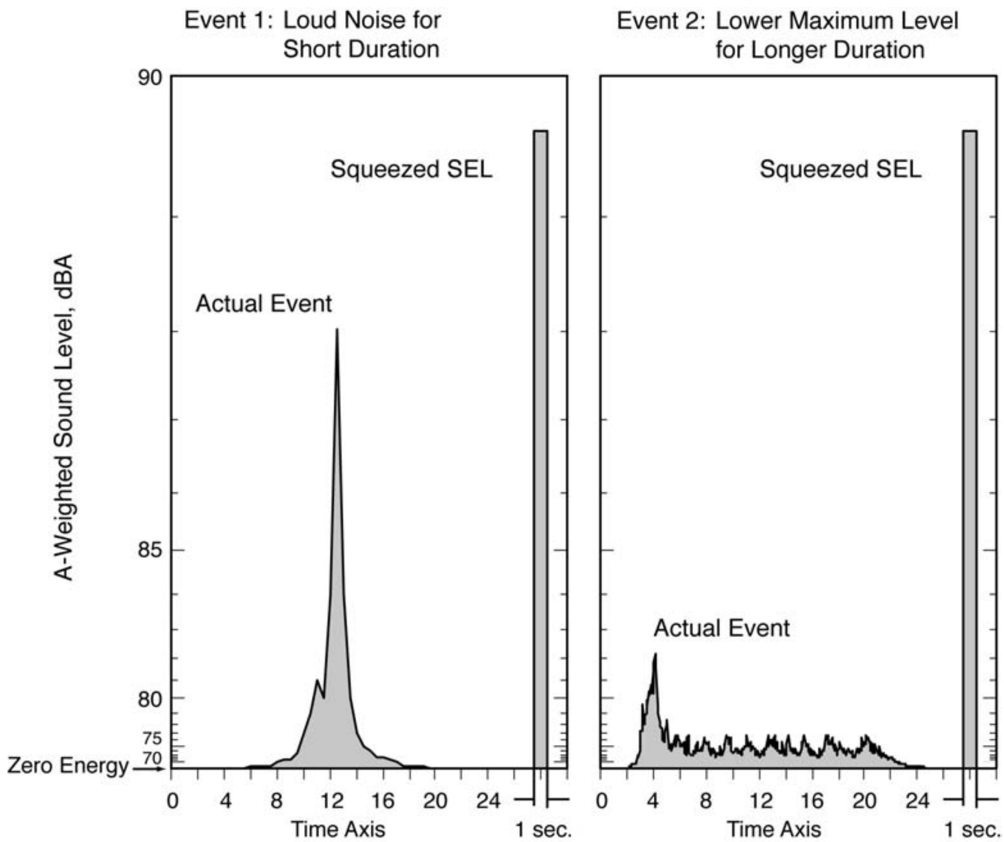


Figure 2-14. An "Energy" View of Noise Events

2.5.4 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 2-15 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 exposure 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 totaled here over a full hour; it accumulates from all noise events during that hour. Subtraction of 35.6 from this one-hour sound exposure converts it into a time average, as explained in Section 2.5.6. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total sound energy 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:

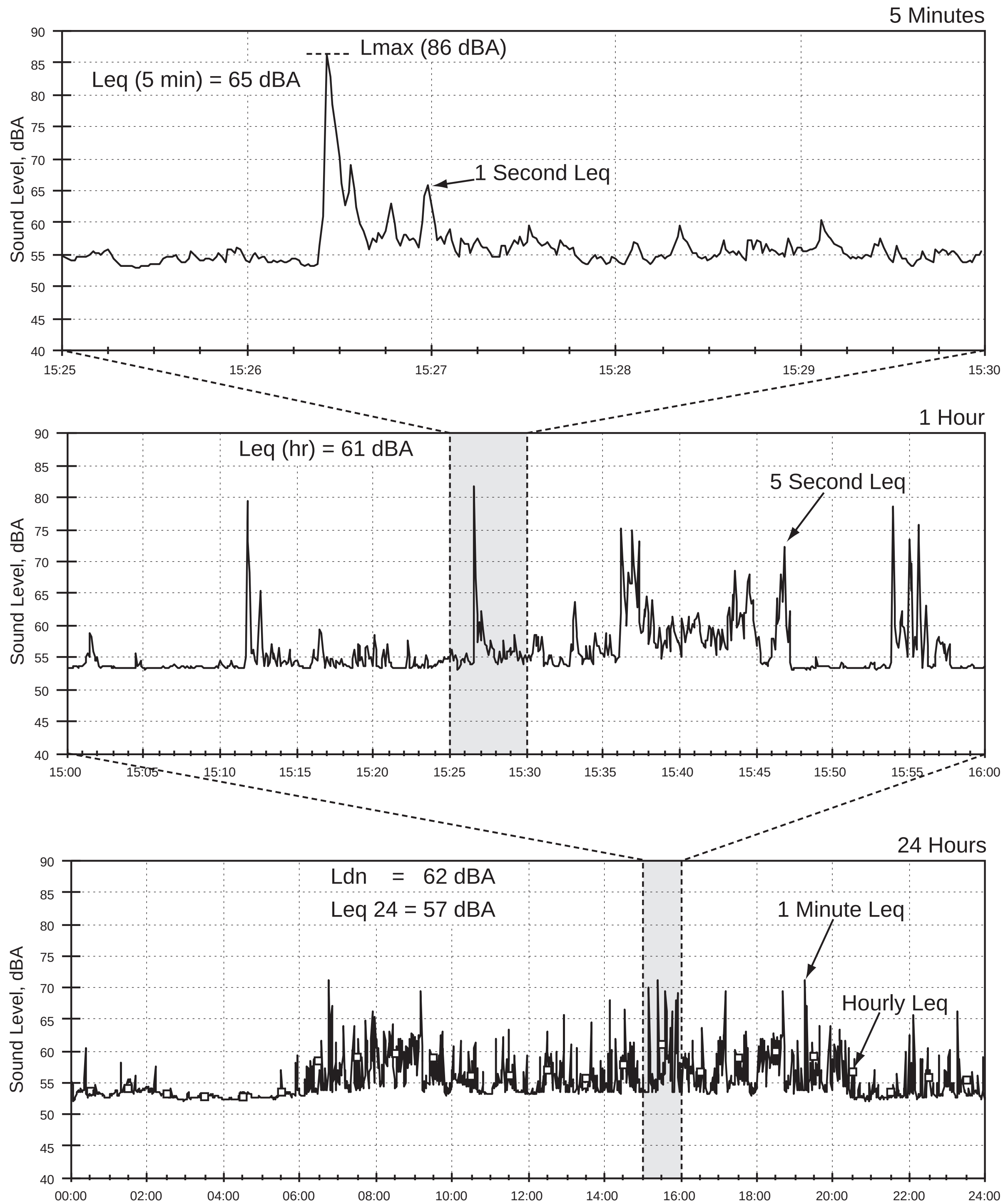
$$L_{eq}(hour) = 10 \log_{10} \begin{bmatrix} \text{Energy Sum of} \\ \text{all SELs} \end{bmatrix} - 35.6$$

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 2-15 shows the sound level fluctuations over a full 24-hour period. It is discussed in Section 2.5.5.

Figure 2-16 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 2.5.6 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 2-15. Example A-weighted Sound Level Time Histories

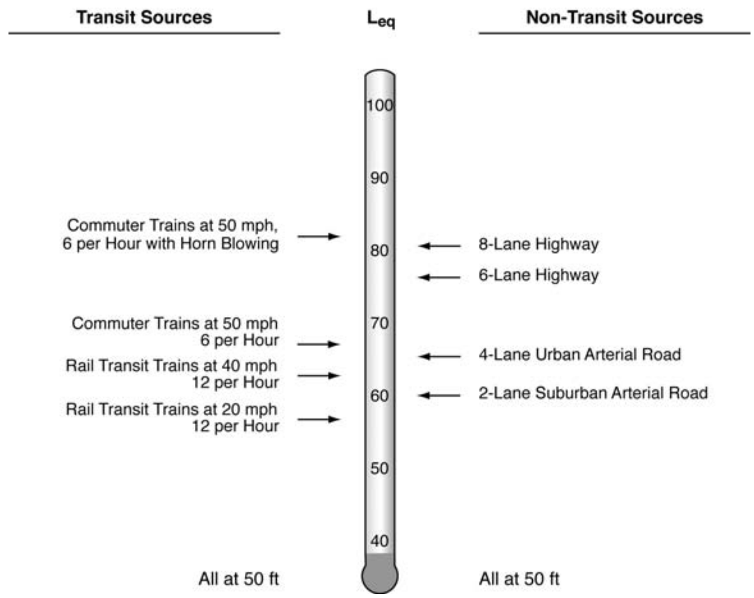


Figure 2-16. Typical Hourly L_{eq}'s

2.5.5 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 2-15. 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 totaling.

Sound energy is totaled 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 2.5.6. In brief, if the actual fluctuating noise were replaced by a constant noise equal to this average value, the same total sound energy 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 totaling, as in the previous equation. L_{dn} due to a series of transit-noise events can also be computed as:

$$L_{dn} = 10 \log_{10} \begin{bmatrix} \text{Energy sum of} \\ \text{all SELs} \end{bmatrix} - 49.4$$

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

Figure 2-17 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.

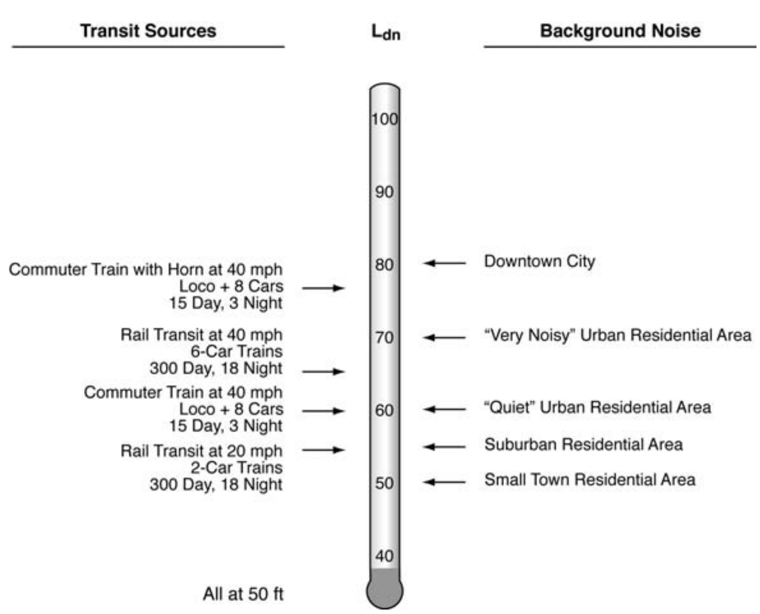


Figure 2-17. Typical L_{dn}'s

2.5.6 A Noise-Exposure Analogy for L_{eq} and L_{dn}

In Figure 2-15, the area under the curves represents noise exposure. An analogy between rainfall and noise is sometimes helpful to further explain these noise exposures.

The one-hour noise time history 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 accumulation. Also, note that heavier showers increase the amount more than do lighter ones, and longer showers increase the amount more than shorter ones. The same is true for noise: (1) every transit event increases the one-hour noise exposure; (2) loud events increase the noise exposure more than do quieter ones; and (3) events that stretch out longer in time increase the noise exposure more than shorter ones.

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 exposure that underlies L_{eq} and in the 24-hour noise exposure 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-weighted Sound Levels. Noise exposure includes all transit events, all noise levels that occur during their time periods -- without exception. Every added event, even the quiet ones, will increase the noise exposure, 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, similar to the effect of rainfall in watering a field or garden, scientific evidence strongly indicates that total noise exposure 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.

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 exposure, 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.

2.5.7 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 E and F 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.

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3. NOISE IMPACT CRITERIA

This chapter presents the criteria to be used in evaluating noise impact from mass transit projects. Different approaches are taken depending on the type of project and the agencies involved. In general terms, these criteria describe the noise environment considered acceptable for a given situation. Because some projects are strictly transit projects while other projects are basically highway projects that include a transit component, two different sets of criteria are required as follows:

- **Rail and Bus Facilities:** This category includes all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit), as well as fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, substations, etc. Also included are rail transit projects built within a highway or railroad corridor. Certain bus facilities are included in this category, such as bus rapid transit (BRT) on separate roadways and bus operations on local streets and highways where the project does not include roadway construction or modification that significantly changes roadway capacity. The distinguishing feature in all these cases is that the existing noise levels generated by roadway traffic and other sources will not change as a result of the project; therefore the project noise is exclusively due to the new transit sources. For projects like these, FTA is generally the lead agency and the methodology from this manual is the appropriate approach.

- **Highway/Transit Projects:** Projects in this category involve transit as part of new highway construction or modifications to existing highways to increase carrying capacity. For these multi-modal projects, the Federal Highway Administration (FHWA) may be a joint lead agency with FTA, and the state department of transportation (DOT) would probably also be participating in the environmental impact assessment. Projects would involve traffic lanes with preferential treatment for buses or high-occupancy vehicles (HOVs). The distinguishing feature here is that the *project* noise includes a combination of highway and transit sources. Examples are: new highway construction providing general-purpose lanes as well as dedicated bus/HOV lanes and lane additions or reconfigurations on existing highways or arterials to accommodate buses/HOVs. These multi-modal projects fall into two sub-categories and the appropriate method to use for noise prediction and impact assessment depends on whether the highway noise dominates throughout day and night or the transit noise dominates during off-peak and late night hours.

If sufficient evidence shows that highway noise dominates, the methods of FHWA, including the latest authorized version of the Traffic Noise Model (TNM), should be used. Otherwise both FHWA and FTA prediction and impact assessment procedures should be used to determine whether neither, one or each mode causes impact and where mitigation is best applied.

Factors to consider when deciding which sub-category is appropriate for a given project are as follows:

- **Volume of traffic:** Major freeways and interstate highways often carry significant volumes of traffic throughout the day and night, such that the highway noise dominates at all times. Transit noise in this case may be insignificant in comparison, and the FHWA prediction method and noise abatement criteria would be used.
- **Traffic patterns:** Some highways and arterials serve primarily as commuter routes such that nighttime traffic diminishes considerably, while transit systems continue to operate well into the late hours. Here the dominant noise source at times of maximum sensitivity may be transit. Consequently, both FHWA and FTA prediction methods would be used.
- **Type of traffic:** Some highways and arterials may serve commuters during the daytime hours, but provide access to business centers by trucks at night. In this case, the roadway noise would likely continue to dominate and the FHWA methods would be appropriate.
- **Alignment configuration:** Elevation of the transit mode in the median or beside a busy highway may result in transit noise contributing more noise to nearby neighborhoods than a highway that may be partially shielded by rows of buildings adjacent to the right-of-way. In this case, both the FHWA and FTA methods should be used.

The noise impact criteria for rail and bus facilities are presented in Section 3.1. These criteria were developed specifically for transit noise sources operating on fixed guideways or at fixed facilities in urban areas. The criterion for the onset of Moderate Impact varies according to the existing noise level and the predicted project noise level, and is determined by the threshold at which the percentage of people highly annoyed by the project noise starts to become measurable. The corresponding criterion for Severe Impact similarly varies according to the existing noise level as well as the project noise level, but is determined by a higher, more significant percentage of people highly annoyed by project noise. Guidelines for the application of the criteria are included in Section 3.2, and background materials on the development of the criteria are included in Appendix B.

3.1 NOISE IMPACT CRITERIA FOR TRANSIT PROJECTS

The noise impact criteria for mass transit projects involving rail or bus facilities are shown graphically in Figure 3-1 and are tabulated in Table 3-1. The equations used to define these criteria are included in Appendix B. The criteria apply to all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit) as well as fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, and substations. They may also be used for bus projects operating on local streets and separate roadways built exclusively for buses. In contrast, for busways and HOV lanes which are to be integrated in existing highways (e.g., the addition of new lanes or the redesignation of existing lanes on a highway), FHWA's noise abatement criteria are the appropriate noise criteria to use. Likewise, if the project is a new highway involving both general-purpose and dedicated bus/HOV lanes, the FHWA approach is followed. The FHWA criteria are briefly summarized in Section 3.3.

3.1.1 Basis of Noise Impact Criteria

The noise impact criteria in Figure 3-1 and Table 3-1 are based on comparison of the existing outdoor noise levels and the future outdoor noise levels from the proposed project. They incorporate both absolute criteria, which consider activity interference caused by the transit project alone, and relative criteria, which consider annoyance due to the change in the noise environment caused by the transit project.

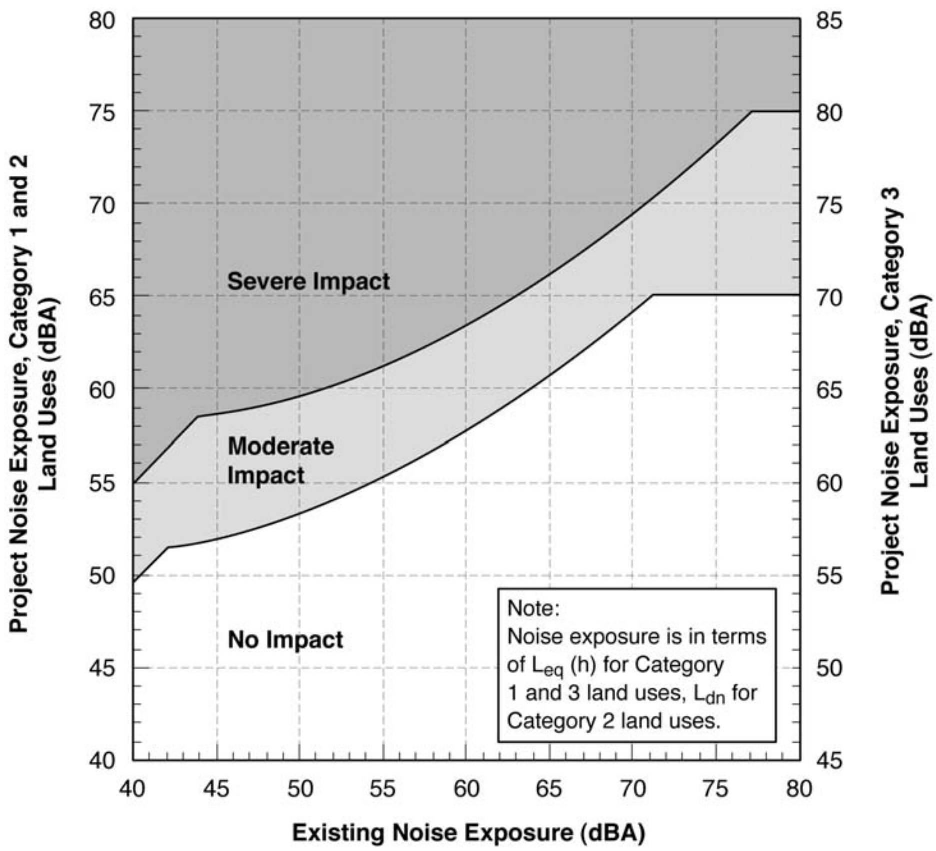

Figure 3-1. Noise Impact Criteria for Transit Projects

The noise criteria and descriptors depend on land use, as defined in Table 3-2. Further guidance on the definition of land use, the selection of the appropriate noise metric and the application of the criteria is given in Section 3.2 of this chapter, with more detailed guidelines given in Chapters 5 and 6.

Table 3-1. Noise Levels Defining Impact for Transit Projects

Existing Noise Exposure* $L_{eq}(h)$ or L_{dn} (dBA)	**Project Noise Impact Exposure,*** $L_{eq}(h)$ or L_{dn} (dBA)					
	Category 1 or 2 Sites			**Category 3 Sites**		
	No Impact	Moderate Impact	Severe Impact	No Impact	Moderate Impact	Severe Impact
<43	< Ambient+10	Ambient + 10 to 15	>Ambient+15	<Ambient+15	Ambient + 15 to 20	>Ambient+20
43	<52	52-58	>58	<57	57-63	>63
44	<52	52-58	>58	<57	57-63	>63
45	<52	52-58	>58	<57	57-63	>63
46	<53	53-59	>59	<58	58-64	>64
47	<53	53-59	>59	<58	58-64	>64
48	<53	53-59	>59	<58	58-64	>64
49	<54	54-59	>59	<59	59-64	>64
50	<54	54-59	>59	<59	59-64	>64
51	<54	54-60	>60	<59	59-65	>65
52	<55	55-60	>60	<60	60-65	>65
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54	<55	55-61	>61	<60	60-66	>66
55	<56	56-61	>61	<61	61-66	>66
56	<56	56-62	>62	<61	61-67	>67
57	<57	57-62	>62	<62	62-67	>67
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59	<58	58-63	>63	<63	63-68	>68
60	<58	58-63	>63	<63	63-68	>68
61	<59	59-64	>64	<64	64-69	>69
62	<59	59-64	>64	<64	64-69	>69
63	<60	60-65	>65	<65	65-70	>70
64	<61	61-65	>65	<66	66-70	>70
65	<61	61-66	>66	<66	66-71	>71
66	<62	62-67	>67	<67	67-72	>72
67	<63	63-67	>67	<68	68-72	>72
68	<63	63-68	>68	<68	68-73	>73
69	<64	64-69	>69	<69	69-74	>74
70	<65	65-69	>69	<70	70-74	>74
71	<66	66-70	>70	<71	71-75	>75
72	<66	66-71	>71	<71	71-76	>76
73	<66	66-71	>71	<71	71-76	>76
74	<66	66-72	>72	<71	71-77	>77
75	<66	66-73	>73	<71	71-78	>78
76	<66	66-74	>74	<71	71-79	>79
77	<66	66-74	>74	<71	71-79	>79
>77	<66	66-75	>75	<71	71-80	>80

* L_{dn} is used for land use where nighttime sensitivity is a factor; L_{eq} during the hour of maximum transit noise exposure is used for land use involving only daytime activities.

Table 3-2. Land Use Categories and Metrics for Transit Noise Impact Criteria

Land Use Category	Noise Metric (dBA)	Description of Land Use Category
1	Outdoor $L_{eq}(h)^*$	Tracts of land where quiet is an essential element in their intended purpose. This category includes lands set aside for serenity and quiet, and such land uses as outdoor amphitheaters and concert pavilions, as well as National Historic Landmarks with significant outdoor use. Also included are recording studios and concert halls.
2	Outdoor L_{dn}	Residences and buildings where people normally sleep. This category includes homes, hospitals and hotels where a nighttime sensitivity to noise is assumed to be of utmost importance.
3	Outdoor $L_{eq}(h)^*$	Institutional land uses with primarily daytime and evening use. This category includes schools, libraries, theaters, and churches where it is important to avoid interference with such activities as speech, meditation and concentration on reading material. Places for meditation or study associated with cemeteries, monuments, museums, campgrounds and recreational facilities can also be considered to be in this category. Certain historical sites and parks are also included.

* L_{eq} for the noisiest hour of transit-related activity during hours of noise sensitivity.

3.1.2 Defining the Levels of Impact

The noise impact criteria are defined by two curves which allow increasing project noise levels as existing noise increases up to a point, beyond which impact is determined based on project noise alone. Below the lower curve in Figure 3-1, a proposed project is considered to have no noise impact since, on the average, the introduction of the project will result in an insignificant increase in the number of people highly annoyed by the new noise. The curve defining the onset of noise impact stops increasing at 65 dB for Category 1 and 2 land use, a standard limit for an acceptable living environment defined by a number of Federal agencies. Project noise above the upper curve is considered to cause Severe Impact since a significant percentage of people would be highly annoyed by the new noise. This curve flattens out at 75 dB for Category 1 and 2 land use, a level associated with an unacceptable living environment. As indicated by the right-hand scale on Figure 3-1, the project noise criteria are 5 decibels higher for Category 3 land uses since these types of land use are considered to be slightly less sensitive to noise than the types of land use in categories 1 and 2.

Between the two curves the proposed project is judged to have Moderate Impact. The change in the cumulative noise level is noticeable to most people, but may not be sufficient to cause strong, adverse reactions from the community. In this transitional area, other project-specific factors must be considered to determine the magnitude of the impact and the need for mitigation, such as the existing level, predicted level of increase over existing noise levels and the types and numbers of noise-sensitive land uses affected.

Although the curves in Figure 3-1 are defined in terms of the project noise exposure and the existing noise exposure, it is important to emphasize that it is the increase in the cumulative noise – when project is added to existing – that is the basis for the criteria. The complex shapes of the curves are based on the considerations of cumulative noise increase described in Appendix B. To illustrate this point, Figure 3-2 shows the noise impact criteria for Category 1 and 2 land use in terms of the allowable increase in the cumulative noise exposure. The horizontal axis is the existing noise exposure and the vertical axis is the increase in cumulative noise level due to the transit project. The measure of noise exposure is L_{dn} for residential areas and L_{eq} for land uses that do not have nighttime noise sensitivity. Since L_{dn} and L_{eq} are measures of total acoustic energy, any new noise source in a community will cause an increase, even if the new source level is less than the existing level. Referring to Figure 3-2, it can be seen that the criterion for Moderate Impact allows a noise exposure increase of 10 dBA if the existing noise exposure is 42 dBA or less but only a 1 dBA increase when the existing noise exposure is 70 dBA

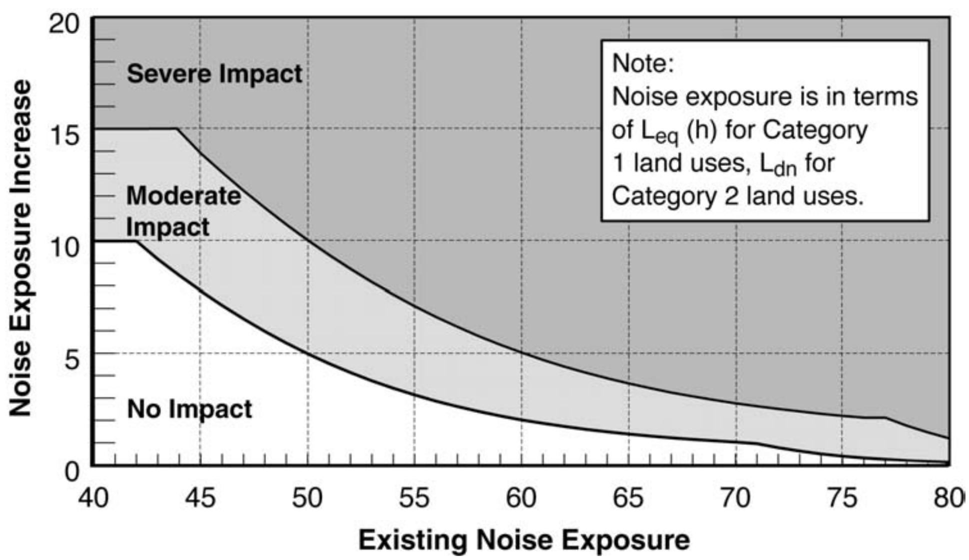


Figure 3-2. Increase in Cumulative Noise Levels Allowed by Criteria (Land Use Cat. 1 &2)

As the existing level of ambient noise increases, the allowable level of transit noise increases, but the total amount that community noise exposure is allowed to increase is reduced. This accounts for the unexpected result that a project noise exposure which is less than the existing noise exposure can still cause impact. This is clearer from the examples given in Table 3-3 which indicate the level of transit noise allowed for different existing levels of exposure.

Table 3-3. Noise Impact Criteria: Effect on Cumulative Noise Exposure			
L_{dn} or L_{eq} in dBA (rounded to nearest whole decibel)			
Existing Noise Exposure	**Allowable Project Noise Exposure**	**Allowable Combined Total Noise Exposure**	**Allowable Noise Exposure Increase**
45	51	52	7
50	53	55	5
55	55	58	3
60	57	62	2
65	60	66	1
70	64	71	1
75	65	75	0

Any increase greater than shown above in Table 3-3 will cause Moderate Impact. This table shows that as the existing noise exposure increases from 45 dBA to 75 dBA, the allowed transit noise exposure increases from 51 dBA to 65 dBA. However, the allowed increase in the cumulative noise level decreases from 7 dBA to 0 dBA (rounded to the nearest whole decibel). The justification for this is that people already exposed to high levels of noise should be expected to tolerate only a small increase in the amount of noise in their community. In contrast, if the existing noise levels are quite low, it is reasonable to allow a greater change in the community noise for the equivalent difference in annoyance. It should be noted that these criteria are based on general community reactions to noise at varying levels which have been documented in scientific literature and do not account for specific community attitudinal factors which may exist.

3.2 APPLICATION OF NOISE IMPACT CRITERIA

3.2.1 Noise-Sensitive Land Uses

As indicated in Section 3.1.1, the noise impact criteria and descriptors depend on land use, designated either Category 1, Category 2 or Category 3. Category 1 includes uses where quiet is an essential element in their intended purpose, such as indoor concert halls or outdoor concert pavilions or National Historic Landmarks where outdoor interpretation routinely takes place. Category 2 includes residences and buildings where people sleep, while Category 3 includes institutional land uses with primarily daytime and evening use such as schools, places of worship and libraries.

The criteria do not apply to most commercial or industrial uses because, in general, the activities within these buildings are compatible with higher noise levels. They do apply to business uses which depend on quiet as an important part of operations, such as sound and motion picture recording studios.

Historically significant sites are treated as noise-sensitive depending on the land use activities. Sites of national significance with considerable outdoor use required for site interpretation would be in Category 1. Historical sites that are currently used as residences will be in Category 2. Historic buildings with indoor use of an interpretive nature involving meditation and study fall into Category 3. These include museums, significant birthplaces and buildings in which significant historical events occurred.

Most busy downtown areas have buildings which are historically significant because they represent a particular architectural style or are prime examples of the work of an historically significant designer. If the buildings or structures are used for commercial or industrial purposes and are located in busy commercial areas, they are not considered noise-sensitive and the noise impact criteria do not apply. Similarly, historical transportation structures, such as terminals and railroad stations, are not considered noise-sensitive land uses themselves. These buildings or structures are, of course, afforded special protection under Section 4(f) of the DOT Act and Section 106 of the National Historic Preservation Act. However, based strictly on how they are used and the settings in which they are located, these types of historical buildings are not considered noise-sensitive sites.

Parks are a special case. Whether a park is noise-sensitive depends on how it is used. Most parks used primarily for active recreation would not be considered noise-sensitive. However, some parks---even some in dense urban areas-–are used for passive recreation like reading, conversation, meditation, etc. These places are valued as havens from the noise and rapid pace of everyday city life and they should be treated as noise-sensitive. The noise sensitivity of parks should be determined on a case-by-case basis after carefully considering how each facility is used. The state or local agency with jurisdiction over the park should be consulted on questions about how the park is used and how much use it gets.

3.2.2 Noise Metrics

The basis for the development of the noise impact criteria (see Appendix B) has been the relationship between the percentage of highly annoyed people and the noise levels of their residential environment. Consequently, the criteria are centered around residential land use with the use of L_{dn} as the noise descriptor sensitive to noise intrusion at night. The noise criteria use L_{dn} for other land uses where nighttime sensitivity is a factor. The criteria are also to be applied to non-residential land uses that are sensitive to noise during daytime hours. Because the L_{dn} and the maximum daytime hourly L_{eq} have similar values for a typical noise environment, the daytime or early evening L_{eq} can be used for evaluating noise impact at locations where nighttime sensitivity is not a factor. For land use involving only daytime activities (e.g. churches, schools, libraries, parks) the impact is evaluated in terms of L_{eq}(h), defined as the L_{eq} for the noisiest hour of transit-related activity during which human activities occur at the noise-sensitive location.

However, due to the types of land use included in Category 3, the criteria allow the project noise for Category 3 sites to be 5 decibels greater than for Category 1 and Category 2 sites. With the exception of recreational facilities, which are clearly less sensitive to noise than Category 1 and 2 sites, Category 3 sites include primarily indoor activities and thus the criteria account for the noise reduction provided by the building structure.

Although the maximum noise level (L_{max}) is not used in this manual as the basis for the noise impact criteria for transit projects, it is a useful metric for providing a fuller understanding of the noise impact from some transit operations. Specifically, rail transit characteristically produces high intermittent noise levels which may be objectionable depending on the distance from the alignment. Thus, it is recommended that L_{max} information be provided in environmental documents to supplement the noise impact assessment and to help satisfy the "full disclosure" requirements of NEPA. Procedures for computing the L_{max} for a single train passby are provided in Appendix F.

3.2.3 Considerations in Applying the Noise Impact Criteria

The procedure for assessing impact is to determine the existing noise exposure and the predicted project noise exposure at a given site, in terms of either L_{dn} or L_{eq}(h) as appropriate, and to plot these levels on Figure 3-1. The location of the plotted point in the three impact ranges is an indication of the magnitude of the impact. For simplicity, noise impact can also be determined by using Table 3-1, rounding all noise level values to the nearest whole decibel before using the table. This level of precision is sufficient for determining the degree of noise impact at specific locations and should be adequate for most applications. However, a more precise determination of noise impact may be appropriate in some situations, such as when estimating the distance from the project to which noise impact extends. In such cases, more precise noise limits can be determined using the criteria equations provided in Appendix B.

In certain cases, the cumulative form of the noise criteria shown in Figure 3-2 must be used. These cases involve projects where changes are proposed to an existing transit system, as opposed to a new project in an area previously without transit. Such changes might include operations of a new type of vehicle, modifications of track alignments within existing transit corridors, or changes in facilities that dominate existing noise levels. In these cases, the existing noise sources change as a result of the project, and so it is not possible to define project noise separately from existing noise. An example would be a commuter rail corridor where the existing noise along the alignment is dominated by diesel locomotive-hauled trains, and where the project involves electrification with the resulting replacement of some of the diesel-powered locomotives with electric trains operating at increased frequency of service and higher speeds on the same tracks. In this case, the existing noise can be determined and a new future noise can be calculated, but it is not possible to describe what constitutes the "project noise." For example, if the existing noise dominated by trains was measured to be an Ldn of 63 dBA at a particular location, and the new combination of diesel and electric trains is projected to be an Ldn of 65 dBA, the change in the noise exposure due to the project would be 2 dB. Referring to Figure 3-2, a 2 dB increase with an existing noise exposure of 63 dBA would be rated as a Moderate Impact. Normally the project noise is added to the existing noise to come up with a new cumulative noise, but in this case, the existing noise was dominated by a source that changed due to the project so it would be incorrect to add the project noise to the existing noise. Consequently, the existing noise determined by measurement is compared with a new calculated future noise, but a description of what constitutes the actual project is complex.

Another example would be a rail corridor where a track is added and grade crossings are closed, potentially resulting in a change in train location and horn operation. Here the "project noise" results from moving some trains closer to some receivers, away from others, and elimination of horns. In this case, the change in noise level is more readily determined than the noise from the actual project elements. In all cases, Figure 3-2 for changes in a transit system results in the same assessment of impact as Figure 3-1 for development of transit facilities in a new area.

For residential land use, the noise criteria are to be applied outside the *building locations* at noise-sensitive areas with frequent human use including outdoor patios, decks, pools, and play areas . If none, the criteria should be applied near building doors and windows. For parks and other significant outdoor use, apply criteria at the *property line*. However, for locations where land use activity is solely indoors, noise impact may be less significant if the outdoor-to-indoor reduction is greater than for typical buildings (about 25 dB with windows closed). Thus, if the project sponsor can demonstrate indoor activity only, mitigation may not be needed.

It is important to note that the criteria specify a comparison of future project noise with existing noise and *not* with projections of future "no-build" noise exposure (i.e. without the project). Furthermore, it should be emphasized that it is not necessary nor recommended that existing noise exposure be determined by measuring at every noise-sensitive location in the project area. Rather, the recommended approach is to characterize the noise environment for "clusters" of sites based on measurements or estimates at representative locations in the community. In view of the sensitivity of the noise criteria to the existing noise exposure, careful characterization of pre-project ambient noise is important. Guidelines for selecting representative receiver locations and determining ambient noise are provided in Appendix C and Appendix D, respectively.

3.2.4 Mitigation Policy Considerations

The following statutes and implementing regulations concerning environmental protection guide the Federal Transit Administration's decisions on the need for noise mitigation. While the environmental impact statement requirement in the National Environmental Policy Act (NEPA) is widely known, the statute also establishes a broad mandate for Federal agencies to incorporate environmental protection and enhancement measures into the programs and projects they help finance.(1) In conjunction with FHWA, FTA has issued a regulation implementing NEPA which sets out the agencies' general policy on environmental mitigation. It states that measures necessary to mitigate adverse impacts are to be incorporated into the project and, further, that such measures are eligible for Federal funding when FTA determines that ". . . the proposed mitigation represents a reasonable public expenditure after considering the impacts of the action and the benefits of the proposed mitigation measures."(2)

While NEPA establishes broad policy, a more explicit statutory mandate for mitigating adverse noise impacts is set forth in the Federal Transit Laws.(3) Before approving a construction grant, FTA must make a finding that ". . . (ii) the preservation and enhancement of the environment, and the interest of the community in which a project is located, were considered; and (iii) no adverse environmental effect is likely to result from the project, or no feasible and prudent alternative to the effect exists and all reasonable steps have been taken to minimize the effect." (49 U.S.C. 5324(b)(3)(A)).

3.2.5 Determining the Need for Noise Mitigation

Because intrusive noise is frequently among the most significant environmental concerns of planned mass transit projects, FTA, working with the project sponsor, makes every reasonable effort to reduce predicted noise to levels deemed acceptable for affected noise-sensitive land uses. The noise impact criteria in Chapter 3 provide the framework for identifying the magnitude of the impact. Then, the need for noise mitigation is determined based on the magnitude and consideration of factors specifically related to the proposed project and affected land uses.

Project-generated noise in the “No Impact” range is not likely to be found annoying. Noise projections in this range are considered acceptable by FTA and mitigation is not required. At the other extreme, noise projections in the “Severe” range represent the most compelling need for mitigation. However, before mitigation measures are considered, the project sponsor should first evaluate alternative locations/alignments to determine whether it is feasible to avoid Severe impacts altogether. In densely populated urban areas, this evaluation of alternative locations may reveal a trade-off of one group of impacted noise-sensitive sites for another – especially for surface rail alignments passing through built-up areas. However, this is not always the case; projects which are characterized more as point sources of noise than line sources often present a greater opportunity for selecting alternative sites. Note that this guidance manual and FTA's environmental impact regulation both attempt to encourage project sites which are compatible with surrounding development. The regulation designates certain projects as categorical exclusions when located in areas with compatible land use (e.g., bus terminals and maintenance facilities located in areas with mostly commercial or industrial use). In this manual, the list of noise-sensitive land uses in Chapter 3 does not include most commercial and industrial land uses, thus obviating the need to consider noise mitigation in areas with predominantly commercial or industrial use.

If it is not practical to avoid Severe impacts by changing the location of the project, mitigation measures must be considered. Impacts in this range have the greatest adverse impact on the community; thus there is a presumption by FTA that mitigation will be incorporated in the project unless there are truly extenuating circumstances which prevent it. The goal is to gain substantial noise reduction through the use of mitigation measures, not simply to reduce the predicted levels to just below the Severe Impact threshold. Since FTA has to determine whether the mitigation is feasible and prudent, the evaluation of specific measures should include the noise reduction potential, the cost, the effect on transit operations and maintenance, and any other relevant factors, for example, any new environmental impacts which may be caused by the measure. A thorough evaluation enables FTA to make the findings required by section 5324(b) of the Federal Transit Laws and possibly other statutes, such as Section 4(f) of the DOT Act or Section 106 of the National Historic Preservation Act.

Projected noise levels in the Moderate Impact range will also require consideration and adoption of mitigation measures when it is considered reasonable. The range of Moderate Impact delineates an area where project planners are alerted to the potential for adverse impacts and complaints from the community and must then carefully consider project specifics as well as details concerning the affected properties in determining the need for mitigation. While impacts in this range are not of the same magnitude as Severe impacts, there can be circumstances regarding the factors outlined below which make a compelling argument for mitigation.

The following considerations will help project planners and FTA staff in reaching these determinations:

- The number of noise-sensitive sites affected at this level. A row or cluster of residences adjacent to a rail transit line establishes a greater need for mitigation than one or several isolated residences in a mixed-use area.
- The increase over existing noise levels. Since the noise impact criteria are delineated as bands or ranges, project noise can vary 5-7 decibels within the band of Moderate Impact at any specific ambient noise level. If the project and ambient noise plot falls just below the Severe range (in Figure 3-1), the need for mitigation is strongest. Similarly, if the plot falls just above the No Impact threshold, there is less need.
- The noise sensitivity of the property. Table 3-2 gives a comprehensive list of noise-sensitive land uses; yet there can be differences in noise sensitivity depending on individual circumstances. For example, parks and recreational areas vary in their sensitivity depending on the type of use they experience (active vs. passive recreation) and the settings in which they are located.
- Effectiveness of the mitigation measure(s). What is the magnitude of the noise reduction that can be achieved? Are there conditions which limit effectiveness, for example, noise barrier effectiveness for a multi-story apartment building?
- Neighborhoods with ambient noise levels already heavily influenced by transportation noise, especially the same type of noise source as the project. Ambient levels above 65 dB (Ldn) are considered “normally unsatisfactory” for residential land use by the Department of Housing and Urban Development. Thus there is a stronger need for mitigation if a project is proposed in an area currently experiencing high noise levels from surface transportation. An example would be a project where additional commuter tracks are added to a very busy rail corridor. If this project were placed in a less noisy environment, the impact assessment might show a Severe Impact, but when the project is overlaid on an existing noisy environment, the result could be Moderate Impact or, possibly, No Impact. However, in this situation the new cumulative noise environment may be very objectionable because people will not be compartmentalizing the existing noise versus the new noise and reacting only to the new noise. In this circumstance impacts predicted in the Moderate range should be treated as if they were Severe.
- Community views. This manual provides the methodology to make an objective assessment of the need for noise mitigation. However, the views of the community cannot be overlooked. The NEPA compliance process provides the framework for hearing the community's concerns about a proposed project and then making a good-faith effort to address those concerns. Many projects can be expected to have projected noise levels within the Moderate Impact range and decisions regarding mitigation should be made only after considering input from the affected public, relevant government agencies and community organizations. There have been cases where the solution to the noise problem – a sound barrier – was rejected by community members because of perceived adverse visual effects.
- Special protection provided by law. Section 4(f) of the DOT Act and Section 106 of the National Historic Preservation Act come into play frequently during the environmental review of transit projects. Section 4(f) protects historic sites and publicly-owned parks, recreation areas and wildlife refuges. Section 106

protects historic and archeological resources. In general, noise in the Moderate Impact range would not substantially impair the use of a property afforded protection under Section 4(f). Thus it would not constitute a "constructive use" as this term is defined in Section 4(f) regulations. In the Section 106 process protecting historic and cultural properties, Moderate Impact may or may not be considered an "adverse effect" depending on the individual circumstances. Historic properties are only noise-sensitive based on how they are used. As previously noted, some historic properties are not noise-sensitive at all. It is possible, though, that a historic building housing sensitive uses like a library or museum could be adversely affected by noise in the Moderate range. The regulatory processes stemming from these statutes require coordination and consultation with agencies and organizations having jurisdiction over these resources. Their views on the project's impact on protected resources are given careful consideration by FTA and the project sponsor, and their recommendations may influence the decision to adopt noise reduction measures.

Cost is an important consideration in reaching decisions about noise mitigation measures. One guideline for gauging the reasonableness of the cost of mitigation is the state DOT's procedures on the subject. Each state has established its own cost threshold for determining whether installation of sound barriers for noise reduction is a reasonable expenditure. The states' cost thresholds range from $15,000 to $50,000 per benefited residence, with a cost-weighted average of $24,000 per residence. Several airport authorities have placed limits on the costs they will incur for sound insulation per residence for homes that are impacted according to Federal Aviation Administration criteria. These costs range from $20,000 to $35,000 per residence (2002 dollars). As a starting point, FTA considers the midpoints of these ranges--$25,000 to $30,000 per benefited residence--to be reasonable from the standpoint of cost. It should be noted, though, that higher costs may be justified depending on the specific set of circumstances applying to a project.

The decision to include noise mitigation in a project is made by FTA after public review of the environmental document. This decision is reached in consultation with the project sponsor. If mitigation measures are deemed necessary to satisfy the statutory requirements, they will be incorporated as an integral part of the project, and subsequent grant documents will reference these measures as contractual obligations on the part of the project sponsor. FTA is required by law to ensure that the project sponsor complies with all design and mitigation commitments contained in the environmental document (23 U.S.C. 139 (c) (4)). There are some differences as to how noise mitigation and vibration mitigation are handled in EISs. The different approaches are discussed in Chapter 13.

3.3 NOISE IMPACT CRITERIA FOR HIGHWAY/TRANSIT PROJECTS

Under specific circumstances, noise impact from a mass transit project should be determined using FHWA's assessment procedures and noise abatement criteria, instead of the FTA procedures and guidelines. General guidance is given at the beginning of this chapter. FHWA methods are required for highway/transit projects (or portions of projects) that meet the following conditions:

- The project is jointly funded with FHWA and the state DOT is assisting with the impact assessment.

- The mass transit portions of the project are directly adjacent to (or within) FHWA-funded portions of the project.
- The project is located where highway noise predominates throughout the day and night.

In contrast, FTA methods should be used for other portions of the project that do not meet these requirements—for example, portions where the transit right-of-way diverges from the highway, or associated bus terminals and other transit facilities off the highway right-of-way.

In some cases, both FHWA and FTA methods should be used, such as when both highway and transit cause significant noise, but at different times of day. An example would be a transit alignment that shares the right-of-way with an arterial road with heavy traffic. Traffic noise may dominate during the peak commuting hours but not during off-peak periods when transit continues to operate. In this case, both sets of criteria would be used to determine whether impact occurs from neither, one or each mode.

In following the FHWA procedures, only loudest-hour noise levels are computed and assessed. These noise levels may be computed either with (1) the hourly calculation method in Chapter 6 of this manual or (2) the FHWA Traffic Noise Model (TNM). Often this choice of computation methods will depend upon the assistance provided by the FHWA-funded staff on the project. Even if methods in Chapter 6 are used for computation, however, the resulting noise levels must be assessed with FHWA methods under these circumstances.

FHWA criteria appear in the Code of Federal Regulations,[4, 5] which is supplemented by a separate FHWA policy and guidance document.[6] All three documents are available at: www.fhwa.dot.gov/environment/noise. The following sections summarize these FHWA criteria and their use.

3.3.1 FHWA Impact Criteria

FHWA requires assessment at affected existing activities, developed lands, and undeveloped lands for which development is planned, designed and programmed. At these locations, traffic noise is computed for the project's design year, which is often 20 years from the onset of environmental studies. This computation uses the traffic for the hour with the worst impact "on a regular basis." In practice, traffic engineers often predict traffic volumes and speeds at several times during an average design-year day, and then noise computations decide the "worst" hour. Because assessment is for a single hour rather than for a 24-hour period, the noise metric is an hourly one, L_{eq}(h).

FHWA requires two assessments of noise impact: one related to land-use type and the other to existing noise level.

First, noise impact occurs when predicted traffic noise levels "approach or exceed" the applicable Noise Abatement Criteria (NAC) in Table 3-4. FHWA allows individual state highway agencies to define "approach or exceed." As a result, the actual impact criteria are all 1 to 3 decibels lower than the values in this table. Contact specific state highway agencies to learn their definition of "approach or exceed." In addition, FHWA requires that primary consideration be given to exterior areas (Activity Categories A, B and C). The table's interior NAC (Category E) is used only where either (1) there are no affected exterior activities or (2) exterior activities are not impacted because they are far from or are physically shielded from the roadway.

Table 3-4. FHWA Noise Abatement Criteria

Activity Category	Hourly A-weighted Sound Level (dBA)		Description of Activity Category
	$L_{eq}(h)$	$L_{10}(h)$	
A	57 Exterior	60 Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 Exterior	70 Exterior	Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 Exterior	75 Exterior	Developed lands, properties, or activities not included in Categories A or B above.
D	--	--	Undeveloped lands.
E	52 Interior	55 Interior	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

Note: Noise mitigation must be studied where predicted traffic noise levels approach or exceed the values in this table. Individual state highway agencies define "approach or exceed" within their states. As a result, the actual criteria that trigger mitigation studies are all 1 to 3 decibels lower than the values in this table. Contact specific state highway agencies to learn their definition of "approach or exceed."

Second, noise impact occurs when predicted traffic noise levels substantially exceed existing noise levels (future no-build noise levels are not used here). FHWA allows individual state highway agencies to define "substantially exceed." Contact specific state highway agencies to learn their definition of "substantially exceed" (a criterion of 10 decibels above existing levels is the most common).

3.3.2 Use of Impact Criteria

When impact occurs by either method of assessment, NAC or substantial increase, FHWA requires study of the following noise abatement measures: traffic management, alteration of horizontal and vertical alignments, noise barriers whether within or outside the right-of-way, acquisition of buffer zones, noise insulation of public-use or nonprofit institutional structures. Measures that are both feasible and reasonable must be incorporated into the project.

Feasibility. Feasibility deals with engineering considerations. To be feasible, an abatement measure must first meet all safety, maintenance and other accepted design requirements. After safety/maintenance issues are resolved, FHWA considers a noise-abatement measure to be feasible if that measure can technically achieve a noise reduction of 5 decibels or more, given its physical aspects and those of its surroundings. Such acoustical feasibility is objective, not subjective. It is a matter of acoustical computation, depending upon such factors as topography, location of other nearby sound sources, and location of driveways, ramps, and cross streets.

Reasonableness. In the context of FHWA regulations, reasonableness is a more subjective matter. Reasonableness implies that common sense and good judgment were applied in arriving at a decision concerning the abatement measure. FHWA requires that: (1) the views of the impacted residents be a major consideration, and (2) the overall noise abatement benefits outweigh the overall adverse social, economic, and environmental effects, as well as the abatement cost.

Reasonableness also depends upon community wishes, aesthetics, community desires for their surrounding view, projected noise-level increase above existing levels, projected noise-level increase above future no-build levels, amount of development that occurred before and after the initial construction of the highway, type of protected development, effectiveness of land-use controls by the local jurisdiction, construction effects of the abatement measure on the natural environment, and the potential ability of the abatement measure to reduce noise during project construction, as well. Many state highway agencies restrict or expand this list of factors.

Reasonableness also depends upon cost effectiveness. FHWA requires state highway agencies to develop quantitative cost-effectiveness guidelines, which generally consider abatement cost and the number of people protected by the abatement measure—and sometimes also the amount of noise reduction provided by the abatement measure.

REFERENCES

1. United States Congress, National Environmental Policy Act of 1969; P.L. 91-190, January 1, 1970.

2. U.S. Department of Transportation, Federal Transit Administration and Federal Highway Administration, "Environmental Impact and Related Procedures." Final Rule, 52 Federal Register 32646-32669; August 28, 1987 (23 Code of Federal Regulations 771.105(d)).

3. The Federal Transit Laws, 49 U.S.C. 5301 et seq.

4. Federal Highway Administration. *23 CFR Part 772: Procedures for Abatement of Highway Traffic Noise and Construction Noise -- Final rule*. Federal Register, Vol. 62, No. 154, 11 August 1997.

5. Federal Highway Administration. *23 CFR Part 772: Procedures for Abatement of Highway Traffic Noise and Construction Noise*. Federal Register, Vol. 67, No. 58, 26 March 2002 (provides further background).

6. Federal Highway Administration. *Highway Traffic Noise Analysis and Abatement Policy and Guidance.* Office of Environment and Planning, Noise and Air Quality Branch, Washington DC, June 1995 (71 pages).

4. NOISE SCREENING PROCEDURE

The noise screening procedure is designed to identify locations where a project may cause noise impact. If no noise-sensitive land uses are present within a defined area of project noise influence, then no further noise assessment is necessary. This approach allows the focusing of further noise analysis on locations where impacts are likely. The screening procedure takes account of the noise impact criteria, the type of project and noise-sensitive land uses. For screening purposes, all noise-sensitive land uses are considered to be in a single category.

4.1 SCREENING DISTANCES

The distances given in Table 4-1 delineate a project's noise study area. The areas defined by the screening distances are meant to be sufficiently large to encompass all potentially impacted locations. They were determined using relatively high-capacity scenarios for a given project type. Data used in the calculations are listed in Table 4-2 as assumptions based on operations of a given project type and using the lowest threshold of impact, 50 dB, from the criteria curves in Figure 3-1. These distances can be scaled up or down for different sized projects by use of the methodology in Chapter 5, General Noise Assessment. FTA provides an Excel spreadsheet program to assist in these adjustments. The Federal Railroad Administration horn noise model is used to develop the screening distance at commuter rail grade crossings where horns and warning bells are used.(1)

The noise screening procedure is applicable to all types of transit projects. The types of projects listed in Table 4-1 cover nearly all of the kinds of projects expected to undergo environmental assessment. Clarification can be obtained from FTA on any special cases that are not represented in the table.

4.2 STEPS IN SCREENING PROCEDURE

The screening method works as follows:

- Determine the type of project and locate on Table 4-1.

- Review assumptions in Table 4-2. Make adjustments in screening distances to suit the project through the use of the methodology in Chapter 5, or the FTA spreadsheet model. The appropriate screening distance is where the project noise reaches 50 dBA for the descriptor shown.

- Determine the appropriate column under Screening Distance in Table 4-1. If buildings occur in the sound paths, then use the distances under Intervening Buildings. Otherwise use the distances under "Unobstructed”.

- Note the distance in feet for that project in Table 4-1, or in the adjusted values obtained from Step 2. Apply this distance from the guideway centerline or nearest right-of-way line on both sides of a highway or access road. For small fixed facilities apply the distance from the center of the noise-generating activity. In the case of a fixed facility spread out over a large area, apply the distance from the outer boundary of the proposed project site.

- Within the distance noted above, locate any of the noise-sensitive land uses listed in Table 3-2.

- If it is determined that none of the listed land uses are within the distances noted in Table 4-1, then no further noise analysis is needed. On the other hand, if one or more of the noise-sensitive land uses are within the screening distances noted in Table 4-1, as adjusted, then further analysis is needed and the procedure described in Chapter 5 is followed.

<table>
<tr><th colspan="4">Table 4-1. Screening Distances for Noise Assessments</th></tr>
<tr><th colspan="2" rowspan="2">Type of Project</th><th colspan="2">Screening Distance* (ft)</th></tr>
<tr><th>Unobstructed</th><th>Intervening Buildings</th></tr>
<tr><td colspan="4">Fixed Guideway Systems:</td></tr>
<tr><td colspan="2">Commuter Rail Mainline</td><td>750</td><td>375</td></tr>
<tr><td rowspan="2">Commuter Rail Station</td><td>With Horn Blowing</td><td>1,600</td><td>1,200</td></tr>
<tr><td>Without Horn Blowing</td><td>250</td><td>200</td></tr>
<tr><td colspan="2">Commuter Rail-Highway Crossing with Horns and Bells</td><td>1,600</td><td>1,200</td></tr>
<tr><td colspan="2">Rail Rapid Transit</td><td>700</td><td>350</td></tr>
<tr><td colspan="2">Rail Rapid Transit Station</td><td>200</td><td>100</td></tr>
<tr><td colspan="2">Light Rail Transit</td><td>350</td><td>175</td></tr>
<tr><td colspan="2">Access Roads</td><td>100</td><td>50</td></tr>
<tr><td rowspan="3">Low- and Intermediate-Capacity Transit</td><td>Steel Wheel</td><td>125</td><td>50</td></tr>
<tr><td>Rubber Tire</td><td>90</td><td>40</td></tr>
<tr><td>Monorail</td><td>175</td><td>70</td></tr>
<tr><td colspan="2">Yards and Shops</td><td>1000</td><td>650</td></tr>
<tr><td colspan="2">Parking Facilities</td><td>125</td><td>75</td></tr>
<tr><td colspan="2">Access Roads</td><td>100</td><td>50</td></tr>
<tr><td colspan="2">Ancillary Facilities</td><td></td><td></td></tr>
<tr><td colspan="2">Ventilation Shafts</td><td>200</td><td>100</td></tr>
<tr><td colspan="2">Power Substations</td><td>250</td><td>125</td></tr>
<tr><td colspan="4">Bus Systems:</td></tr>
<tr><td colspan="2">Busway</td><td>500</td><td>250</td></tr>
<tr><td colspan="2">BRT on exclusive roadway</td><td>200</td><td>100</td></tr>
<tr><td rowspan="5">Bus Facilities</td><td>Access Roads</td><td>100</td><td>50</td></tr>
<tr><td>Transit Mall</td><td>225</td><td>150</td></tr>
<tr><td>Transit Center</td><td>225</td><td>150</td></tr>
<tr><td>Storage & Maintenance</td><td>350</td><td>225</td></tr>
<tr><td>Park & Ride Lots w/Buses</td><td>225</td><td>150</td></tr>
<tr><td colspan="2">Ferry Boat Terminals:</td><td>300</td><td>150</td></tr>
<tr><td colspan="4">*Measured from centerline of guideway/roadway for mobile sources; from center of noise-generating activity for stationary sources.</td></tr>
</table>

Table 4-2. Assumptions for Screening Distances for Noise Assessments				
Type of Project		**Operations**	**Speeds**	**Descriptor**
Fixed Guideway Systems:				
Commuter Rail Mainline		66 day /12 night; 1 loco, 6 cars	55 mph	Ldn
Commuter Rail Station	With Horn Blowing	22 day / 4 night	N/A	Ldn
	W/O Horn Blowing	22 day / 4 night	N/A	Ldn
Commuter Rail-Highway Crossing with Horns and Bells		22 day / 4 night	55 mph	Ldn
Rail Rapid Transit		220 day / 24 night; 6-car trains	50 mph	Ldn
Rail Rapid Transit Station		220 day / 24 night	20 mph	Ldn
Light Rail Transit		150 day / 18 night; 2 artic veh.	35 mph	Ldn
Access Roads to Stations		1000 cars, 12 buses	35 mph	PH Leq*
Low- and Intermediate-Capacity Transit	Steel Wheel	220 day / 24 night	30 mph	Ldn
	Rubber Tire	220 day / 24 night	30 mph	Ldn
	Monorail	220 day / 24 night	30 mph	Ldn
Yards and Shops		20 train movements	N/A	PH Leq
Parking Facilities		1000 cars	N/A	PH Leq
Access Roads to Parking		1000 cars	35 mph	PH Leq
Ancillary Facilities				
Ventilation Shafts		Rapid Transit in Subway	50 mph	Ldn
Power Substations		Sealed shed, air conditioned	N / A	Ldn
***Bus Systems*:**				
Busway		30 buses, 120 automobiles	50 mph	PH Leq
BRT on exclusive roadway		30 buses	35 mph	PH Leq
Bus Facilities	Access Roads	1000 cars	35 mph	PH Leq
	Transit Mall	20 buses	N/A	PH Leq
	Transit Center	20 buses	N/A	PH Leq
	Storage & Maintenance	30 buses	N/A	PH Leq
	Park & Ride Lots w/Buses	1000 cars, 12 buses	N/A	PH Leq
Ferry Boat Terminals:		8 boats with horns used in normal docking cycle	N/A	PH Leq

* PH Leq = hour of maximum transit activity

REFERENCES

1. U.S. Department of Transportation, Federal Railroad Administration. "Final Environmental Impact Statement: Interim Final Rule for the Use of Locomotive Horns at Highway-Rail Grade Crossings; Technical Supplement to DEIS and Chapter 3.4," Office of Railroad Development, Washington, D.C., December 5, 2003. Also see: http://www.fra.dot.gov/downloads/RRDev/hornmodel.xls.

5. GENERAL NOISE ASSESSMENT

This chapter contains procedures for the computation of both project and existing ambient noise levels for use in noise assessments required beyond the stage of the screening procedure of Chapter 4.

The **Screening Procedure** described in Chapter 4 is used to determine whether any noise-sensitive receivers are within a distance where impact is likely to occur. The distance given in the table defines the study area of any subsequent noise impact assessment. Where there is potential for noise impact, the procedures of Chapters 5 and 6 will be used to determine the extent and severity of impact. In some cases, a General Assessment may be all that is needed. On the other hand, if the proposed project is in close proximity to noise-sensitive land uses and it appears at the outset that the impact would be substantial, it is prudent to conduct a Detailed Analysis.

The **General Assessment** is used for a wide range of projects which show potential noise impact from the screening procedure. For a variety of smaller transit projects, a General Assessment may be all that is needed to evaluate noise impact and propose mitigation measures where necessary. It is also used to compare alternatives, such as locations of facilities or alignments, or even candidate transportation modes in a corridor. A General Assessment can provide the appropriate level of detail about noise impacts when an Alternatives Analysis/Draft EIS is being prepared to evaluate alternatives for a major capital investment. The procedure involves noise predictions commensurate with the level of design of the alternatives in the early stages of major investment planning. Estimates are made of project noise levels and of existing noise conditions to estimate the location of a noise impact contour which defines the outer limit of an impact corridor or area. An inventory of noise impacts within the area identifies locations where noise mitigation is likely and is used in comparing noise impact among alternatives. Noise mitigation policy considerations are discussed in Section 3.2.4 and the application of noise mitigation measures is described in Section 6.8.

Detailed Analysis is undertaken when the greatest accuracy is needed to assess impacts and the effectiveness of mitigation measures on a site-specific basis. In order to do this, the project must be defined to the extent that location, alignment, mode and operating characteristics are determined.

Detailed Analysis is often accomplished during the preliminary engineering phase. The results of the Detailed Analysis would be used in predicting the effectiveness of noise mitigation measures on particular noise-sensitive receivers. The procedures for performing a Detailed Analysis are described in Chapter 6.

This chapter describes the procedure for performing a General Noise Assessment. The General Assessment is based on noise source and land use information likely to be available at an early stage in the project development process. Sections of this chapter cover the key elements of the prediction procedure:

- Section 5.2 describes how to predict noise source levels with preliminary estimations of the effect of mitigation.
- Section 5.3 covers a simplified procedure for estimating noise propagation characteristics assuming flat terrain, with approximate shielding by rows of buildings or other barriers.
- Section 5.4 includes a simplified procedure for estimating existing noise.
- Section 5.5 shows how to estimate the noise impact contour that defines the approximate outer limit of noise impact.
- Section 5.6 describes how to conduct the noise impact inventory and how to present the information in an environmental document or a technical noise report.
- Four examples of General Assessments are given at the end of this chapter.

5.1 OVERVIEW

The steps in the General Noise Assessment are shown in Figure 5-1 and are described below. When several alternatives are evaluated in an environmental document, this approach can be applied to each alternative and the results compared.

Project Alternatives. Place the alternative under study into one of three categories: fixed-guideway transit, highway/transit, or stationary facility. Determine the Source Reference Level from the tables in Section 5.2. Each Source Reference Level pertains to a typical operation for one hour for a stationary source or one vehicle passby under reference operating conditions. Each utilizes the SEL noise descriptor, as discussed in Chapter 2.

Operational Characteristics. Convert the Source Reference Level to noise exposure in terms of L_{eq}(h) or L_{dn} under approximate project operating conditions, using the appropriate equations depending upon the type of source. The noise exposure is determined at the reference distance of 50 feet.

Propagation Characteristics. Draw noise exposure-vs.-distance curve for this source, using the graphic in Section 5.3. This curve will show the source's noise exposure as a function of distance, ignoring shielding. To account for shielding attenuation from rows of buildings, use a general rule for estimating the reduction in noise level and draw an adjusted exposure-vs-distance curve.

Study Area Characteristics. Estimate the existing noise exposure for areas surrounding the project from Table 5-7 in Section 5.4.

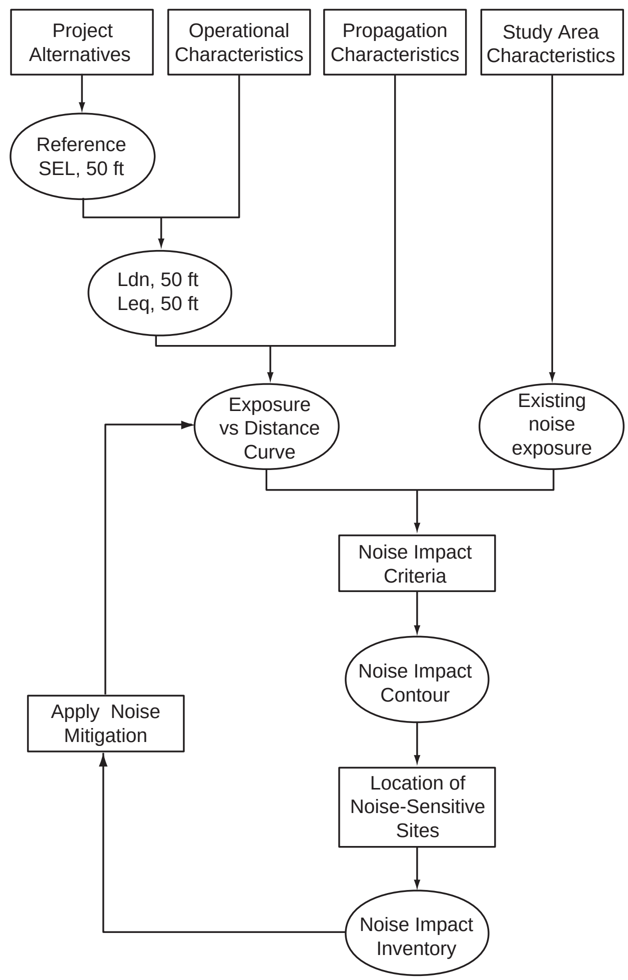


Figure 5-1. Procedure for General Noise Assessment

Noise Impact Contour Estimation. On a point-by-point basis, locate the project noise exposure and existing noise exposure combination that results in Moderate Impact according to the impact criteria from Chapter 3. Connect the points to obtain a contour line around the project which signifies the outer limits of Moderate Impact.

Alternatively, in the case where it is desired to make a comparison among different modal alternatives, specific decibel-level noise contours can be determined from the exposure-vs-distance curves (for example, 60dB, 65dB, 70dB contours).

Noise Impact Inventory. Tabulate noise-sensitive land uses within the specific contours using general assumptions for shielding attenuation from rows of buildings.

Noise Mitigation. Apply estimates of the noise reduction from mitigation in the community areas where potential impact has been identified and repeat the tabulation of noise impacts.

5.2 NOISE SOURCE LEVELS FOR GENERAL ASSESSMENT

The General Noise Assessment procedure begins by determining the project noise exposure at a reference distance for the various project alternatives. The reference noise exposure estimation procedures differ depending on the type of project (fixed-guideway, highway/transit, or stationary facility) as described in the following sections.

5.2.1 Fixed-Guideway Transit Sources

Fixed-guideway transit sources include commuter rail, rail rapid transit, light rail transit, automated guideway transit (AGT), monorail, and magnetically levitated vehicles (maglev). The noise characteristics of each depend on the system characteristics described in Chapter 2. For commuter railroads and light rail transit systems, the crossing of streets and highways at grade is likely, in which case the noise assessment of warning devices will have to be taken into account. At an early project stage, the information available includes:

- Candidate transit mode
- Guideway options
- Time of operation
- Operational headways
- Design speed
- Alternative alignments

This information is not sufficient to predict noise levels at all locations along the right-of-way, but by using conservative estimates (for example, maximum design speeds and operations at design capacities) it is sufficient to estimate worst-case noise impact contours.

Reference Levels in SEL. The procedure starts with predicting the source noise levels, expressed in terms of SEL at a reference distance and a reference speed. These are given in Table 5-1.

The reference SEL's are used in the equations of Table 5-2 to predict the noise exposure at 50 feet. Also shown in Table 5-2 are rough estimates of the noise reduction available from wayside noise barriers, the most common noise mitigation measure. See Chapter 6 for a complete description of the benefits resulting from noise mitigation. The approximate noise barrier lengths and locations developed in a General Assessment provide a preliminary basis for evaluating the costs and benefits of impact mitigation.

Table 5-1. Reference SEL's at 50 feet from Track and 50 mph

Source / Type		Reference Conditions	Reference SEL (SEL_{ref}), dBA
Commuter Rail, At-Grade	Locomotives	Diesel-electric, 3000 hp, throttle 5	92
		Electric	90
	Diesel Multiple Unit (DMU)	Diesel-powered, 1200 hp	85
	Horns	Within ¼ mile of grade crossing	110
	Cars	Ballast, welded rail	82
Rail Transit		At-grade, ballast, welded rail	82
Transit whistles / warning devices		Within 1/8 mile of grade crossing	93
AGT	Steel wheel	Aerial, concrete, welded rail	80
	Rubber Tire	Aerial, concrete guideway	78
Monorail		Aerial straddle beam	82
Maglev		Aerial, open guideway	72

Noise Exposure at 50 feet. After determining the reference levels for each of the noise sources, the next step is to determine the noise exposure at 50 feet expressed in terms of L_{eq}(h) and L_{dn}. The additional data needed include:

- Number of train passbys during the day (defined as 7am to 10 pm) and night (defined as 10 pm to 7 am).
- Maximum number of train passbys during hours that Category 1 or Category 3 land uses are normally in use. This is usually the peak hour train volume.
- Number of vehicles per train (if this number varies during the day, take the average).
- Speed (maximum expected).
- Guideway configuration.
- Noise barrier location (if noise mitigation is determined necessary at the end of the first pass on the General Assessment).
- Location of highway and street grade crossings, if any.

These data are used in the equations in Table 5-2 to obtain adjustment factors to calculate L_{dn} and L_{eq}(h) at 50 feet.

Table 5-2. Computation of Noise Exposure at 50 feet for Fixed-Guideway General Assessment	
LOCOMOTIVES[†] Hourly L_{eq} at 50 ft:	$L_{eqL}(h) = SEL_{ref} + 10\log(N_{locos}) + K\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ Where K = -10 for passenger diesel; = 0 for DMU; = +10 for electric
LOCOMOTIVE WARNING HORNS[†††] Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} + 10\log(V) - 35.6$
RAIL VEHICLES[††] Hourly L_{eq} at 50 ft:	$L_{eqC}(h) = SEL_{ref} + 10\log(N_{cars}) + 20\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ use the following adjustments as applicable: + 5 → JOINTED TRACK + 3 → EMBEDDED TRACK ON GRADE + 4 → AERIAL STRUCTURE WITH SLAB TRACK (except AGT & monorail) - 5 → if a NOISE BARRIER blocks the line of sight
TRANSIT WARNING HORNS[†††] Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} - 10\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$
COMBINED Hourly L_{eq} at 50 ft:	$L_{eq}(h) = 10\log\left[10^{\left(L_{eqL}/10\right)} + 10^{\left(L_{eqC}/10\right)}\right]$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\big\vert_{\ v = v_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\big\vert_{\ v = v_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left((L_{eq}(night)+10)/10\right)}\right] - 13.8$

N_{locos} = average number of locomotives per train

N_{cars} = average number of cars per train

S = train speed, in miles per hour

V = average hourly volume of train traffic, in trains per hour

V_d = average hourly daytime volume of train traffic, in trains per hour

$$= \frac{number\ of\ trains, 7am\ to\ 10\,pm}{15}$$

V_n = average hourly nighttime volumes of train traffic, in trains per hour

$$= \frac{number\ of\ trains, 10\,pm\ to\ 7am}{9}$$

† Assumes a passenger diesel locomotive power rating at approximately 3000 hp

†† Includes all commuter rail cars, transit cars, AGT and monorail

††† Based on FRA's horn noise model (www.fra.dot.gov/downloads/RRDev/hornmodel.xls)

5.2.2 Highway/Transit Sources

The highway/transit type sources include most transit modes that do not require a fixed-guideway. Examples are high-occupancy vehicles, such as buses, commuter vanpools and carpools. As noted in Chapter 3, some highway/transit projects are best analyzed with FHWA's noise prediction and impact assessment procedures. However, the procedures in this manual can be used for all types of projects involving highway vehicles. The noise characteristics of the vehicles depend on the system characteristics described in Chapter 2. Recent research has shown there is no statistically significant difference in the reference noise levels from various types of buses, so all buses are placed in a single category. At an early project development stage, the information available is as follows:

- Vehicle type
- Transitway design options
- Time of operation
- Typical headways
- Design speed
- Alternative alignments

This information is not sufficient to predict noise levels at all locations along the right-of-way, but is sufficient to estimate worst-case noise impact contours. The procedure is consistent with FHWA's highway noise prediction method (see Section 6.7.2 for an overview of the computation methods), with buses and vans corresponding to user-defined source emission levels and speed coefficients for buses and automobiles, respectively[1].

Reference Levels in SEL. Projections of noise from highway/transit sources begin by defining the source SEL at a reference distance of 50 feet and a reference speed. These are given in Table 5-3. The reference distance SEL's are used in the equations of Table 5-4 to predict the noise exposure at 50 feet. Also shown in Table 5-4 is a rough estimate of the minimum noise reduction available with wayside sound barriers. See Chapter 6 for descriptions of other mitigation measures and procedures for developing more accurate estimates of noise reduction from mitigation measures. The approximate noise barrier lengths and locations developed in a General Assessment allow preliminary estimates of the costs and benefits of impact mitigation.

Noise Exposure at 50 feet. After determining the reference levels for each of the noise sources, the next step is to determine the noise exposure at 50 feet. The additional data needed include:

- Number of vehicle passbys during the day (7am to 10 pm) and night (10 pm to 7 am).
- Number of vehicle passbys during hours that Category 1 or Category 3 land uses are normally in use.
- Speed (maximum expected).
- Transitway configuration (with or without noise barrier).

These data are used in the equations in Table 5-4 with the reference SEL's to calculate $L_{eq}(h)$ and L_{dn} at 50 feet.

Table 5-3. Source Reference Levels at 50 feet from Roadway, 50 mph

Source†	**Reference SEL (dBA)**
Automobiles and Vans	74
Buses (diesel-powered)	82
Buses (electric)	80
Buses (hybrid)	83**

† Assumes normal roadway surface conditions

** For hybrid buses, Reference SEL should be determined on a case-by-case basis.

Table 5-4. Computation of L_{eq} and L_{dn} at 50 feet for Highway/Transit General Assessment

Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(V) + C_s \log\left(\frac{S}{50}\right) - 35.6$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\vert v = v_d$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\vert v = v_n$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$
Speed Constant:	C_s = 15 Diesel Buses = 28 Electric Buses = 30, Automobile and van pools
Adjustment:	- 5 Noise Barrier

V	= hourly volume of vehicles of this type, in vehicles per hour.
V_d	= average hourly daytime volume of vehicles of this type, in vehicles per hour
	$= \frac{totalvehiclevolume, 7 am to 10 pm}{15}$
V_n	= average hourly nighttime volume of vehicles of this type, in vehicles per hour
	$= \frac{totalvehiclevolume, 10 pm to 7 am}{9}$
S	= average vehicle speed, in miles per hour

5.2.3 Stationary Sources

This section covers the general approach to assessment of noise from fixed transit system facilities. New transit facilities undergo a site review for best location which includes consideration of the noise sensitivity of surrounding land uses. Although many facilities, such as bus maintenance garages, are usually located in industrial and commercial areas, some facilities such as bus terminals, ferry terminals, train stations and park-and-ride lots may be placed near residential neighborhoods where noise impact may occur. Access roads to some of these facilities may also pass through noise-sensitive areas. In a General Assessment, only the salient features of each fixed facility are considered in the noise analysis.

Reference Levels in SEL. The source reference levels given in Table 5-5 are determined based on measurements for the peak hour of operation of a typical stationary source of the type and size noted. A large facility, such as a rail yard, is spread out over considerable area with various noise levels depending on the layout of the facility. Specifying the reference SEL at a distance of 50 feet from the property line would be misleading in this case. Consequently, the reference distance is described as "the equivalent distance of 50 feet," which is determined by estimating the noise levels at a greater distance and projecting back to 50 feet, assuming the noise sources are concentrated at the center of the site. If the location of noise sources is known, then the distance should be taken from the point of the noisiest activity on the site (e.g. the dock in the case of ferry boat operations). The reference SEL's are used in the equations of Table 5-6 to predict noise exposure at an equivalent distance of 50 feet from the center of the site. Noise from access roads is treated according to the procedures described in Section 5.2.2.

Table 5-6 also includes an estimate of the minimum noise reduction available with wayside noise barriers. Only approximate locations and lengths for barrier or other noise mitigation measures are developed during a General Assessment to provide a preliminary indication of the costs and benefits of mitigation.

Noise Exposure at Equivalent Distance of 50 feet. After determining the reference SEL's for each of the noise sources, the next step is to determine the noise exposure expressed in terms of L_{eq} and L_{dn} at an equivalent distance of 50 feet. The additional data needed include:

- Number of layover tracks and hours of use.
- Number of buses, if different from assumed reference conditions (if this number varies during the day, take the average).
- Number of ferry boat landings, if different from assumed reference conditions (if this number varies during the day, take the average).
- Actual capacity of parking garage or lot.

These data are used in the equations in Table 5-6 with the reference SEL's to calculate $L_{eq}(h)$ and L_{dn} at an equivalent distance of 50 feet.

Table 5-5. Source Reference Levels at 50 feet from Center of Site, Stationary Sources		
Source	**Reference SEL (dBA)**	**Reference Conditions**
Rail System:		
Yards and Shops	118	20 train movements in peak activity hour
Layover Tracks (commuter rail)	109	One train with diesel locomotive idling for one hour
Crossovers	100	One train
Crossing signals	109	3600 seconds duration
Bus System:		
Storage Yard	111	100 buses accessing facility in peak activity hour
Operating Facility	114	100 buses accessing facility, 30 buses serviced and cleaned in peak activity hour
Transit Center	101	20 buses in peak activity hour
Ferry Terminal:		
Ferry Boat (no fog horn sounded)	97	4 ferry boats landings in one hour
Ferry Boat (fog horn sounded)	100	
Parking Garage	92	1000 cars in peak activity hour
Park & Ride Lot	101	12 buses, 1000 cars in peak activity hour

Table 5-6. Computation of L_{eq} and L_{dn} at 50 feet for Stationary Source General Assessment

Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + C_N - 35.6$	
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = 10\log\left[\left(\frac{1}{15}\right)\sum_{7am-10pm} 10^{L_{eq(h)}/10}\right]$	
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = 10\log\left[\left(\frac{1}{9}\right)\sum_{10pm-7am} 10^{L_{eq}(h)/10}\right]$	
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$	
Volume Adjustment:	$C_N = 10\log\left(\frac{N_T}{20}\right),$	Rail Yards and Shops
	$= 10\log(N_T),$	Layover Tracks
	$= 10\log(N_T),$	Crossovers
	$= 10\log\left(\frac{N_B}{100}\right),$	Bus Storage Yard
	$= 10\log\left(\frac{N_B}{200} + \frac{N_S}{60}\right),$	Bus Operating Facility
	$= 10\log\left(\frac{N_B}{20}\right),$	Bus Transit Center
	$= 10\log\left(\frac{N_F}{4}\right),$	Ferry Terminal
	$= 10\log\left(\frac{N_A}{1000}\right),$	Parking Garage
	$= 10\log\left(\frac{N_A}{2000} + \frac{N_B}{24}\right),$	Park & Ride Lot
Duration Adjustment:	$= 10\log(E/3600),$	Crossing Signals
Other Adjustment:	-5	Noise Barrier at Property Line

N_T = Number of trains per hour
N_B = Number of buses per hour
N_F = Number of ferry boat landings per hour
N_S = Number of buses serviced and cleaned per hour
N_A = Number of automobiles per hour

E = average hourly duration of one event in seconds

Note: If any of these numbers is zero, then omit that term

5.3 COMPUTATION OF NOISE EXPOSURE-VS.-DISTANCE CURVES

The previous section results in estimates of noise exposure at 50 feet for each type of project. The following procedure is used to estimate the project noise exposure at other distances, resulting in a noise exposure-vs.-distance curve sufficient for use in a General Assessment. The procedure is as follows:

1. Determine the L_{dn} or L_{eq} at 50 feet for one of the three project types in Section 5.2.

2. Select the appropriate distance correction curve from Figure 5-2.

3. Apply the Distance Corrections ($C_{distance}$) to the noise exposure at 50 feet using:

$$L_{dn}(orL_{eq})\Big|_{atnewdistance} = L_{dn}(orL_{eq})\Big|_{at50feet} - C_{distance}$$

4. Plot the noise exposure curve as a function of distance. This curve will be used to determine the noise impact contour for the first row of unobstructed buildings. This plot can be used to display noise from both unmitigated and mitigated conditions in order to assess the benefits from mitigation measures.

5. For second row receivers and beyond, it is necessary to account for shielding attenuation from rows of intervening buildings. Without accounting for shielding, impact may be substantially over-estimated. Use the following general rules of thumb to determine the effect of shielding from intervening rows of buildings:

   - Assign -4.5 dB of shielding attenuation for the *first* row of intervening buildings only.
   - Assign -1.5 dB of shielding attenuation for each subsequent row, up to a maximum total attenuation of 10 dB.

   Figure 5-2 can then be used to develop a curve of noise exposure vs. distance when there is shielding. The curve of noise exposure as a function of this distance will be used to determine the location of the noise impact contours.

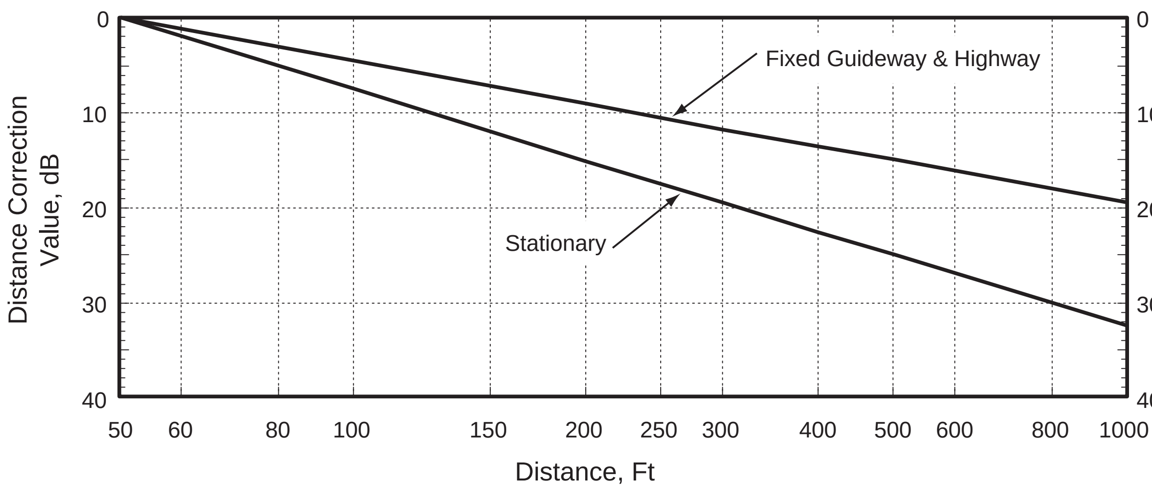


Figure 5-2. Curves for Estimating Exposure vs. Distance in General Noise Assessment

5.4 ESTIMATING EXISTING NOISE EXPOSURE

The existing noise in the vicinity of the project is required to determine the noise impact according to the criteria described in Chapter 3. Recall that impact is assessed based on a combination of the existing ambient noise exposure and the additional noise exposure that will be caused by the project. In the Detailed Analysis, the existing noise exposure is based on noise measurements at representative locations in the community. It is generally a good idea to base all estimates of existing noise on measurements, especially at locations known to be noise-sensitive. However, measurements are not always available at the General Assessment stage. This section describes how to estimate the existing noise in the project study area from general data available early in project planning. The procedure uses Table 5-7, where a neighborhood's existing noise exposure is based on proximity to nearby major roadways or railroads or on population density. For areas near major airports, published aircraft noise contours can also be used to estimate the existing noise exposure. The process is as follows:

1. Mapping: Obtain scaled mapping and aerial photographs showing the project location and alternatives. A scale of 1" = 200' or 400' is convenient for the accuracy needed in the noise assessment. The size of the base map should be sufficient to show distances of at least 1000' from the center of the alignment or property center, depending on whether the project is a guideway/roadway or a stationary facility.

2. Identify Sensitive Receivers: Review the maps, together with the most current land use information, to determine the proximity of noise-sensitive land uses to the project and to the nearest major roadways and railroad lines. When necessary, windshield surveys or more detailed land use maps may be used to confirm the location of sensitive receivers. For land uses more than

1000 feet from major roadways or railroad mainlines (see definitions in Table 5-7), obtain an estimate of the population density in the immediate area, expressed in people per square mile.

3. Use Table 5-7 to Estimate Existing Noise Exposure: Existing noise exposure is estimated by first looking at a site's proximity to major roads and railroad lines. If these noise sources are far enough away that ambient noise is dominated by local streets and community activities, then the estimate is made based on population density. The decision of which to use is made by comparing the noise levels from each of the three categories, roadways, railroads and population density, and selecting the highest level. In case of a lightly used railroad, one train per day or less, select the population density category.

Major roadways are separated into two categories: "Interstates," or roadways with four or more lanes that allow trucks; and "Others," parkways without trucks and city streets with the equivalent of 75 or more heavy trucks per hour or 300 or more medium trucks per hour. The estimated roadway noise levels are based on data for light to moderate traffic on typical highways and parkways using FHWA highway noise prediction procedures. Where a range of distances is given, the predictions are made at the outer limit, thereby underestimating the traffic noise at the inner distance. For highway noise, distances are measured from the centerline of the near lane for roadways with two lanes, while for roadways with more than two lanes the distance is measured from the geometric mean of the roadway. This distance is computed as follows:

$$D_{GM} = \sqrt{(D_{NL})(D_{FL})}$$

where D_{GM} is the distance to the geometric mean, D_{NL} and D_{FL} are distances to the nearest lane and farthest lane centerlines, respectively.

For railroads, the estimated noise levels are based on an average train traffic volume of 5-10 trains per day at 30-40 mph for main line railroad corridors, and the noise levels are provided in terms of L_{dn} only. Distances are referenced to the track centerline, or in the case of multiple tracks, to the centerline of the rail corridor. Because of the intermittent nature of train operations, train noise will affect the L_{eq} only during certain hours of the day, and these hours may vary from day to day. Therefore, to avoid underestimating noise impact when using the one-hour L_{eq} descriptor, it is recommended that the L_{eq} at sites near rail lines be estimated based on nearby roadways or population density unless very specific train information is available.

In areas away from major roadways, noise from local streets or in neighborhoods is estimated using a relationship determined during a research program by the U.S. EPA.[(2)] EPA determined that ambient noise can be related to population density in locations away from transportation corridors, such as airports, major roads and railroad tracks, according to the following relation:

$$L_{dn} = 22 + 10\log(p) \qquad \text{(in dBA)}$$

where p = population density in people per square mile.

Table 5-7. Estimating Existing Noise Exposure for General Assessment

Distance from Major Noise Source[1] (feet)			Population Density (people per sq mile)	Noise Exposure Estimates			
Interstate Highways[2]	Other Roadways[3]	Railroad Lines[4]		L_{eq} Day	L_{eq} Evening	L_{eq} Night	L_{dn}
10 - 50				75	70	65	75
50 - 100				70	65	60	70
100 - 200				65	60	55	65
200 - 400				60	55	50	60
400 - 800				55	50	45	55
800 and up				50	45	40	50
	10 - 50			70	65	60	70
	50 - 100			65	60	55	65
	100 - 200			60	55	50	60
	200 - 400			55	50	45	55
	400 and up			50	45	40	50
		10 - 30		--	--	--	75
		30 - 60		--	--	--	70
		60 - 120		--	--	--	65
		120 - 240		--	--	--	60
		240 - 500		--	--	--	55
		500 - 800		--	--	--	50
		800 and up		--	--	--	45
			1 - 100	35	30	25	35
			100 - 300	40	35	30	40
			300 - 1000	45	40	35	45
			1000 - 3000	50	45	40	50
			3000 - 10000	55	50	45	55
			10000 - 30000	60	55	50	60
			30000 and up	65	60	55	65

NOTES:

[1] Distances do not include shielding from intervening rows of buildings. General rule for estimating shielding attenuation in populated areas: Assume 1 row of buildings every 100 ft; -4.5 dB for the first row, -1.5 dB for every subsequent row up to a maximum of -10 dB attenuation.

[2] Roadways with 4 or more lanes that permit trucks, with traffic at 60 mph.

[3] Parkways with traffic at 55 mph, but without trucks, and city streets with the equivalent of 75 or more heavy trucks per hour and 300 or more medium trucks per hour at 30 mph.

[4] Main line railroad corridors typically carrying 5-10 trains per day at speeds of 30-40 mph.

In areas near major airports, published noise contours can be used to estimate the existing noise exposure. The L_{dn} from such contours should be applied if greater than the estimates of existing noise from other sources at a given location.

5.5 DETERMINING NOISE IMPACT CONTOURS

It is often desirable to draw noise impact contours on the land use map mentioned in the previous section to aid the impact inventory. Once the contours are on the map, the potential noise impacts can be estimated by counting the buildings inside the contours.

The first step is to identify the noise-sensitive neighborhoods and buildings and estimate existing noise exposure following the procedures described in Section 5.4. The estimate of existing noise exposure is used along with the noise impact criteria in Figure 3-1 to determine how much additional noise exposure would need to be created by the project before there would be Moderate Impact or Severe Impact.

The next step is to determine the distances from the project boundary to the two impact levels using the noise exposure-vs.-distance curves from Section 5.3. Plot points on the map corresponding to those distances in the neighborhood under study. Continue this process for all areas surrounding the project. The plotted points are connected by lines to represent the noise impact contours.

Alternatively, if it is desired to plot specific decibel-level noise contours, for example, 65 dBA, the distances can also be determined directly from the approach described in Section 5.3. Again, the points associated with a given decibel level are plotted on the map and connected by lines to represent that contour.

Locations of points will change with respect to the project boundary as the existing ambient exposure changes, as project source levels change, and as shielding effects change. In general, the points should be placed close enough to allow a smooth curve to be drawn. For a General Assessment, the contours may be drawn through buildings and salient terrain features as if they were not present. This practice is acceptable considering the level of detail associated with a project in its early stages of development. Examples 5-1 and 5-4 describe the development of noise contours, with illustrations in Figures 5-3 and 5-4.

5.6 INVENTORY NOISE IMPACT

The final step in the General Assessment is to develop an inventory of noise-impacted land uses. Using the land-use information and noise impact contours from Sections 5.4 and 5.5, it should be possible to locate which buildings are within the impact contours. In some cases it may be necessary to supplement the land-use information or determine the number of dwelling units within a multi-family building with a visual survey. If the objective is to compare and contrast major alignment or modal alternatives on the basis of noise impact, as in an Alternatives Analysis/Draft EIS, it may not be necessary to identify every different type of noise-sensitive land use. The inventory might be limited to only a few types, for example, residential and public institutional uses.

The steps for developing the inventory are:

1. Construct tables for all the noise-sensitive land uses identified in the three land-use categories from Section 5.4.

2. Tabulate buildings and sites that lie between the impact contours and the project boundary. For residential buildings, an estimate of the number of dwelling units is satisfactory. This is done for each alternative being considered.

3. Prepare summary tables showing the number of buildings (and estimated dwelling units, if available) within each impact zone for each alternative. Various alternatives can be compared in this way, including those with and without noise mitigation measures.

4. Determine the need for mitigation based on the policy considerations discussed in Section 3.2.4 and the application guidelines provided in Section 6.8.

Example 5-1. General Noise Assessment for a Commuter Rail System in an Existing Abandoned Railroad Right of Way

The following example illustrates the General Noise Assessment procedure for a new fixed-guideway project. The hypothetical project is a commuter rail system to be built within the abandoned right-of-way of a railroad. The example covers a segment of the corridor that passes through a densely developed area with population density of 25,000 people per square mile in mixed single-family and multi-family residential land use as shown in Figure 5-3. The example is presented in two parts: first, a segment where the rail line is grade-separated and a horn is not sounded; and second, an at-grade street-rail crossing where the horn is sounded.

Assumptions for Example

The assumptions for the project are as follows:

- **Project Corridor:** Existing population density is 25,000 people per square mile.

- **Commuter Rail System:** Commuter train with one locomotive and a three car consist on a double-track at-grade system with welded rail. Trains operate with 20-minute headways during peak hours, and 1-hour headways during off-peak. Speeds are approximately 40 mph along the corridor.

- **Operating Schedule:**

	Period	Headway (minutes)		Trains per hour		
		Inbound	Outbound	Inbound	Outbound	Total
Daytime	7am - 8am	20	20	3	3	6
	8am – 4pm	60	60	1	1	2
	4pm - 6pm	20	20	3	3	6
	6pm - 10pm	60	60	1	1	2
Nighttime	10pm – 11pm	60	60	1	1	2
	11pm – 5am	--	--	--	--	--
	5am - 6am	60	60	1	1	2
	6am - 7am	20	20	1	1	2

Procedure

The Screening Procedure calls for additional analysis for noise-sensitive land use within 375 feet of a commuter rail mainline. Figure 5-3 shows that the closest residences are about 100 ft from the Commuter Rail corridor centerline, thereby requiring further noise analysis. The procedure is summarized as follows:

Part 1. Grade-Separated Street Crossing

Determination of Noise Exposure at 50 feet

1. Determine average hourly daytime and nighttime volumes of train traffic.

   Daytime (7am - 10pm):
   V_d = 42 trains/15 hours = 2.8 trains/hour

   Nighttime (10pm - 7am):
   V_n = 6 trains/9 hours = 0.7 trains/hour

2. Calculate L_{eq}(day), and L_{eq}(night) 50 ft.

   From Table 5-1 and 5-2 these levels are determined as follows:

$$
\begin{aligned}
L_{eqL}(day) &= SEL_{ref} + 10\log(N_{locos}) - 10\log(S/50) + 10\log(V_d) - 35.6 \\
&= 92 + 10 \log (1) - 10 \log (40/50) + 10 \log (2.8) - 35.6 \\
&= 61.8 \text{ dB}
\end{aligned}
$$

$$
\begin{aligned}
L_{eqC}(day) &= SEL_{ref} + 10 \log (N_{cars}) + 20 \log (S/50) + 10 \log (V_n) - 35.6 \\
&= 82 + 10 \log (3) + 20 \log (40/50) + 10 \log (2.8) - 35.6 \\
&= 53.7 \text{ dB}
\end{aligned}
$$

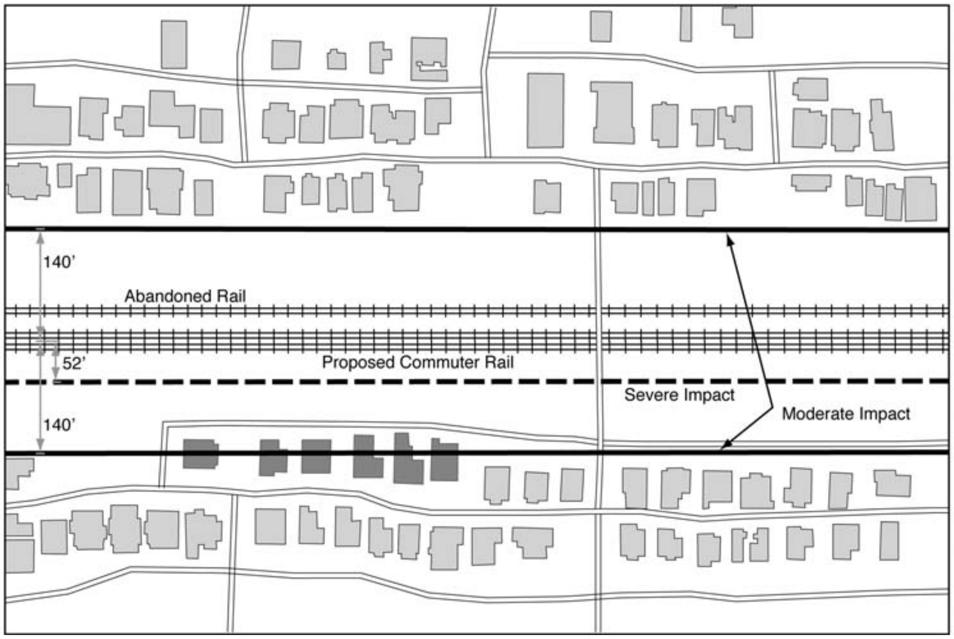


Figure 5-3. Noise Impacts of Commuter Rail

Calculate the total daytime L_{eq} for the locomotive and rail cars.

$$L_{eqT}(day) = 10*\log(10^{(LeqL/10)} + 10^{(LeqC/10)})$$
$$= 10*\log(10^{(62.2/10)} + 10^{(54.1/10)})$$
$$= 62.4 \text{ dB}$$

Calculate the nighttime L_{eq} for the locomotive and rail cars.

$$L_{eqL}(night) = SEL_{ref} + 10\log(N_{locos}) - 10\log(S/50) + 10\log(V_n) - 35.6$$
$$= 92 + 10 \log (1) - 10 \log (40/50) + 10 \log (0.7) - 35.6$$
$$= 55.8 \text{ dB}$$

$$L_{eqC}(night) = SEL_{ref} + 10 \log (N_{cars}) + 20 \log (S/50) + 10 \log (V_n) - 35.6$$
$$= 82 + 10 \log (3) + 20 \log (40/50) + 10 \log (0.7) - 35.6$$
$$= 47.7 \text{ dB}$$

Calculate the total nighttime L_{eq} for the locomotive and rail cars.

$$L_{eqT}(night) = 10*\log(10^{(LeqL/10)} + 10^{(LeqC/10)})$$
$$= 10*\log(10^{(55.6/10)} + 10^{(47.5/10)})$$
$$= 56.4 \text{ dB}$$

3. Calculate project L_{dn} at 50 ft.

From Table 5-2 this level is determined as follows:

$$L_{dn} = 10\log\left[(15)10^{Leq(day)/10} + (9)10^{(Leq(night)+10)/10}\right] - 13.8$$

which gives:

$$L_{dn} = 78.2 - 13.8$$

or

$$L_{dn} = 64.4 \text{ dB}$$

Estimate Existing Noise Exposure

4. Estimate existing noise at noise-sensitive sites. Since the existing alignment is on an abandoned railroad, the dominant existing noise source can be described by a "generalized" noise level to characterize a large area. An estimate of the existing noise environment is obtained from Table 5-7 with population density of 25,000 people per square mile, giving an Ldn = 60 dBA.

   From Figure 5-3, unobstructed residences range from 100 to 200 ft from the rail line. Based on Table 5-7 the L_{dn} is 60 dB for the area.

Noise Impact Contours

5. The following table is constructed using the impact criteria curves.
   Note: The project criteria for L_{eq} is not shown since L_{eq} only applies to the non-residential receptors.

Existing Noise, L_{dn} or L_{eq}(day)	Onset of Moderate Impact	Onset of Severe Impact
	L_{dn}	L_{dn}
60 dB	58 dB	64 dB

6. Distance to impact contours are determined using the curve in Figure 5-2 for "Fixed-Guideway" and the project impact thresholds obtained above. The results are summarized as follows for the residences:

Existing Noise, L_{dn} or L_{eq}(h)	Distance to Noise Impact Threshold, feet	
	Moderate Impact	Severe Impact
60 dB	140	52

7. Draw contours for each affected land use, based on the above table and its distance from the rail line. Note that the impact distances listed are in terms of distance to the *centerline of the Commuter Rail corridor*.

8. Within the contours defining "Moderate Impact" are six residential buildings (shaded in Figure 5-3).

Noise Mitigation

9. The procedure is repeated assuming a noise barrier to be placed at the railroad right-of-way line. The barrier serves to reduce project noise from the Commuter Rail by at least 5 dB. This, however, does not affect the project criteria to be used in determining impact. That is, the same existing noise levels (as the case without a barrier) are used to determine these thresholds.

   The net effect of the noise barrier is to decrease the Moderate Impact distance from 140 to 60 ft. Hence, the noise barrier eliminates all residential noise impact for this segment of the project area.

Part 2. Crossing At-Grade with Horn Blowing

Now consider the case of an active street crossing of the commuter railroad tracks. The General Assessment method includes source reference levels for horns on moving trains and warning bells (crossing signals) at the street crossing. According to Table 5-1, the horn noise applies to track segments within ¼ mile of the grade crossing. Using the train volumes from Part 1 and the information in Tables 5-1 and 5-2, the day- and nighttime Leqs from sounding the horns are determined at 50 feet as follows:

$$
\begin{aligned}
L_{eqL}(day)_{horns} &= SEL_{ref} + 10\log(V_d) - 35.6 \\
&= 113 + + 10\log(3.1) - 35.6 \\
&= 82.3 \text{ dB}
\end{aligned}
$$

$$
\begin{aligned}
L_{eqC}(night)_{horns} &= SEL_{ref} + 10\log(V_n) - 35.6 \\
&= 113 + 10\log(0.7) - 35.6 \\
&= 75.9 \text{ dB}
\end{aligned}
$$

The L_{dn} at 50 ft. from train horns is the next calculation:

From Table 5-2 this level is determined as follows:

$$L_{dn} = 10\log\left[(15)10^{Leq(day)/10} + (9)10^{(Leq(night)+10)/10}\right] - 13.8$$

which gives:

$$L_{dn} = 84 \text{ dB}$$

At-grade street crossings will have warning bells, typically sounding for 20 seconds for every train pass-by. The total day- and nighttime durations are as follows:

E_d = average daytime hourly duration
= 20 seconds x 3.1 trains/hour = 62 seconds/hour

E_n = average nighttime hourly duration
= 20 seconds x 0.7 trains/hour = 14 seconds/hour.

From Table 5-6 for stationary sources:

$L_{eqL}(day)_{cs}$ = SEL_{ref} + $10\log(E_d/3600) - 35.6$
= 109 + + 10 log (62/3600) - 35.6
= 55.8 dB

$L_{eqC}(night)_{cs}$ = $SEL_{ref} + 10\log(E_n/3600) - 35.6$
= 109 + 10 log (14/3600) - 35.6
= 49.3 dB

Applying the L_{dn} equation from Table 5-6, $L_{dn, cs}$ = 57.5 dB.

Compared to horn blowing, the crossing signal noise is negligible.

Noise impact distances are found in the same way as in Part 1, with a new noise level, L_{dn} = 84 dB.

Again, the existing noise level is used to determine the onset of Moderate and Severe Impacts:

Existing Noise, L_{dn} or L_{eq}(day)	Onset of Moderate Impact	Onset of Severe Impact
	L_{dn}	L_{dn}
60 dB	58 dB	64 dB

Distance to impact contours is determined using the curve in Figure 5-2 for "Fixed-Guideway" and the project impact thresholds obtained above. The results are summarized as follows for the residences:

Existing Noise, L_{dn} or L_{eq}(h)	Distance to Noise Impact Threshold, feet	
	Moderate Impact	Severe Impact
60 dB	1000	500

Contours are drawn as in Part 1, extending to the distances above for ¼ mile on either side of the grade crossing.

End of Example 5-1

Example 5-2. Example of Highway/Transit Corridor Projects

This example illustrates two cases of highway/transit projects, one where the highway noise dominates and the FHWA procedures should be used and another where the FTA methodology is appropriate.

Case 1: Highway dominates

A new LRT system is planned for the median of a major freeway that carries heavy traffic both day and night. The noise levels at the first row of houses along the freeway were measured during peak hour, mid-day and late evening with hourly Leq readings of 65 dBA, 63 dBA and 60 dBA, respectively. The LRT tracks will be 125 feet from the first row of houses. The LRT operations during peak hour will be 4-car trains at 45 mph, with 5-minute headways in both directions. Late evening service decreases to 2-car trains and 20 minute headways. Referring to Table 5-2, “Rail Vehicles,” the applicable terms for determining the peak hour Leq in this case are: SEL_{REF} = 82 dBA; N = 4 cars per train; S = 45 mph; and V = 24 trains per hour. Inserting these parameters into the equation in Table 5-2, the LRT peak-hour noise level is determined to be 65 dBA at 50 feet, and from Figure 5-2, the level at 125 feet is 60 dBA. The corresponding calculation for late evening hourly Leq results in 51 dBA.

FTA is providing a share of the funding for the LRT project, but the State DOT and the FHWA are co-lead agencies because the median requires considerable preparation for the tracks, including replacing bridge piers of street crossings and moving some highway lanes. In this case, the freeway dominates the noise environment in the area both day and night, by 5 dB during peak hour and 9 dB at night. According to Chapter 3, the FHWA procedures are to be used when sufficient evidence shows that highway noise dominates. Consequently TNM is used to calculate the future noise levels at the first row of houses, with a result of peak-hour Leq of 66 dBA. The State has a policy of implementing noise abatement measures if the FHWA Noise Abatement Criteria (NAC) are approached and the increase over existing noise levels is 5 dB or more at residential land use.

Combining the freeway noise and LRT noise during the peak traffic hour by decibel addition results in a combined noise level of 67 dBA.

In this case, no mitigation is proposed because although the combined level reaches the FHWA NAC of 67 dBA for residential land use, the increase in noise over existing conditions is only 2 dB, thereby failing this State’s policy requirement of at least a 5 dB increase over existing levels to justify noise mitigation measures.

Case 2: LRT dominates at night

A new LRT is planned for the median of a major arterial highway used by commuters primarily during rush hours. Traffic volume on the arterial drops considerably during off-peak and nighttime hours. Currently the arterial has signalized intersections, but in the future the cross streets will be grade-separated, but commercial businesses and residential developments will continue to be accessible with “right-turn-off / right-turn-on”. The existing noise at the nearest homes adjacent to the arterial has been measured, resulting in a peak-hour Leq of 63 dBA and an Ldn of 60 dBA.

The future traffic noise after improvements to the arterial is projected to be 65 dBA for the two-hour morning peak period and the same for the two-hour evening peak period, falling to hourly Leq’s of 60 dBA during the remaining daytime hours and 50 dBA after 10 p.m. Accordingly, Ldn is calculated to be 61 dBA from the arterial at the homes.

The LRT is proposed to be on elevated structure in the median of the arterial, located 125 feet from the nearest homes in the development. The proposed operations at this location are:

- Peak hours (7:00 a.m. to 9:00 a.m. and 5:00 p.m. to 7:00 p.m.): 4-car trains, with 5 minute headways, at 50 mph.
- Off-peak hours (9:00 a.m. to 5:00 p.m. and 7:00 p.m. to 10:00 p.m.): 3-car trains, with 10 minute headways, at 50 mph.
- Night hours (10:00 p.m. to 1:00 a.m.): 2-car trains, with 15 minute headways, at 40 mph.

This train schedule results in an average hourly volume of 15.2 trains per hour, with an average of 3.42 cars per train in both directions during the daytime, and 2-car trains with an average hourly volume of 2.67 trains per hour during the nighttime. According to the equations in Table 5-2 and the propagation curve in Figure 5-2, the Ldn = 63 dBA at these homes. The combined arterial and LRT noise is projected to be Ldn = 64.7 dBA by decibel addition.

FTA procedures are appropriate in this case, since the LRT continues to operate into the nighttime hours and actually dominates the noise environment because the arterial noise diminishes in those hours. Here is a case where the cumulative noise impact curve (Figure 3-2) is applicable because the project included changes to the arterial as well as addition of a new transportation source. With an existing Ldn of 60 dB and a future Ldn of 64.7 dBA, Figure 3-2 indicates the increase of 4.7 dB would cause Moderate Impact.

End of Example 5-2

Example 5-3. General Noise Assessment for a BRT System in an Existing Railroad Right of Way

This example for an uncomplicated Bus Rapid Transit (BRT) project is meant to illustrate the approach for a highway/transit type project using the FTA procedures.

A new BRT corridor is planned in an existing abandoned railroad right-of-way. For this project source,

SEL_{ref} = 82 for buses
S = 25 mph
V_d = (344 buses)/(15 hours) = 22.9 buses per hour
V_n = (116 buses)/(9 hours) = 12.9 buses per hour

In addition, from Table 5-4,

C_s = 15 for buses

Using the equations in Table 5-4 the resulting L_{eq}'s at 50 feet are:

L_{eq}(day) = 55.5
L_{eq}(night) = 53

This total day and night traffic results in:

L_{dn} = 60 at 50 ft

The surrounding area is residential with 2,500 people per square mile starting approximately 100 feet away from the proposed alignment. Using Table 5-7 the existing noise in the area is 50 dBA.

From Figure 3-1 the impacts thresholds are:

Background Level	Moderate Impact	Severe Impact
50	54	59

Therefore, from Figure 5-2:

Project Level	Onset of Moderate Impact	Onset of Severe Impact
60	125 feet	60 feet

This results in impacts to the residences. A barrier is proposed for mitigation, resulting in a predicted new level of 55 and:

Mitigated Project Level	Onset of Moderate Impact	Onset of Severe Impact
55	60 feet	N/A

The onset of Severe Impact is listed as N/A because the Severe Impact criterion is not exceeded by the project. Mitigation is accomplished by a barrier because the Moderate Impact contour has been moved in to a distance of 60 feet, whereas the residential area lies beyond 100 feet.

End of Example 5-3

Example 5-4. General Noise Assessment for a Transit Center

The following example illustrates the procedure for performing a General Noise Assessment for a stationary source. The example represents a typical FTA-assisted project in an urban area, the siting of a busy transit center in a mixed commercial and residential area, as shown in Figure 5-4.

Assumptions for Example

The assumptions for the Transit Center and its environs are as follows:

- **Main Street Traffic:** Peak hour traffic of 1200 autos, 20 heavy trucks, 300 medium trucks.

- **Population Density:** 12 houses per block; single family homes; 3 people per family.

  Block area = 78,750 square feet.
  Population density = 9,750 people/square mile.

- **Bus Traffic:**

Period	Hours	Buses per Hour
Peak, Morning	7am - 9am	30
Peak, Afternoon	4pm - 6pm	30
Mid-day	9am - 4pm	15
Evening	6pm - 10pm	12
Early Morning (Night)	6am - 7am	15
Late Night	10pm - 1am	4

Procedure

Before beginning the General Assessment, note that the Screening Procedure calls for additional analysis if any residential or other noise-sensitive land use is within 150 feet of a Transit Center when there are intervening buildings. According to Figure 5-4 the nearest residence is about 140 feet from the center of the proposed Transit Center, thereby calling for further analysis. The General Assessment proceeds as follows:

Determination of Noise Exposure at 50 feet

1. Determine the average number of buses per hour during day and night.

   Day (7am - 10pm):
   N_B *(avg day)* = 273 buses/15 hours = 18.2 buses/hour average

   Night (10pm - 7am):
   N_B *(avg night)* = 27 buses/9 hours = 3 buses/hour average

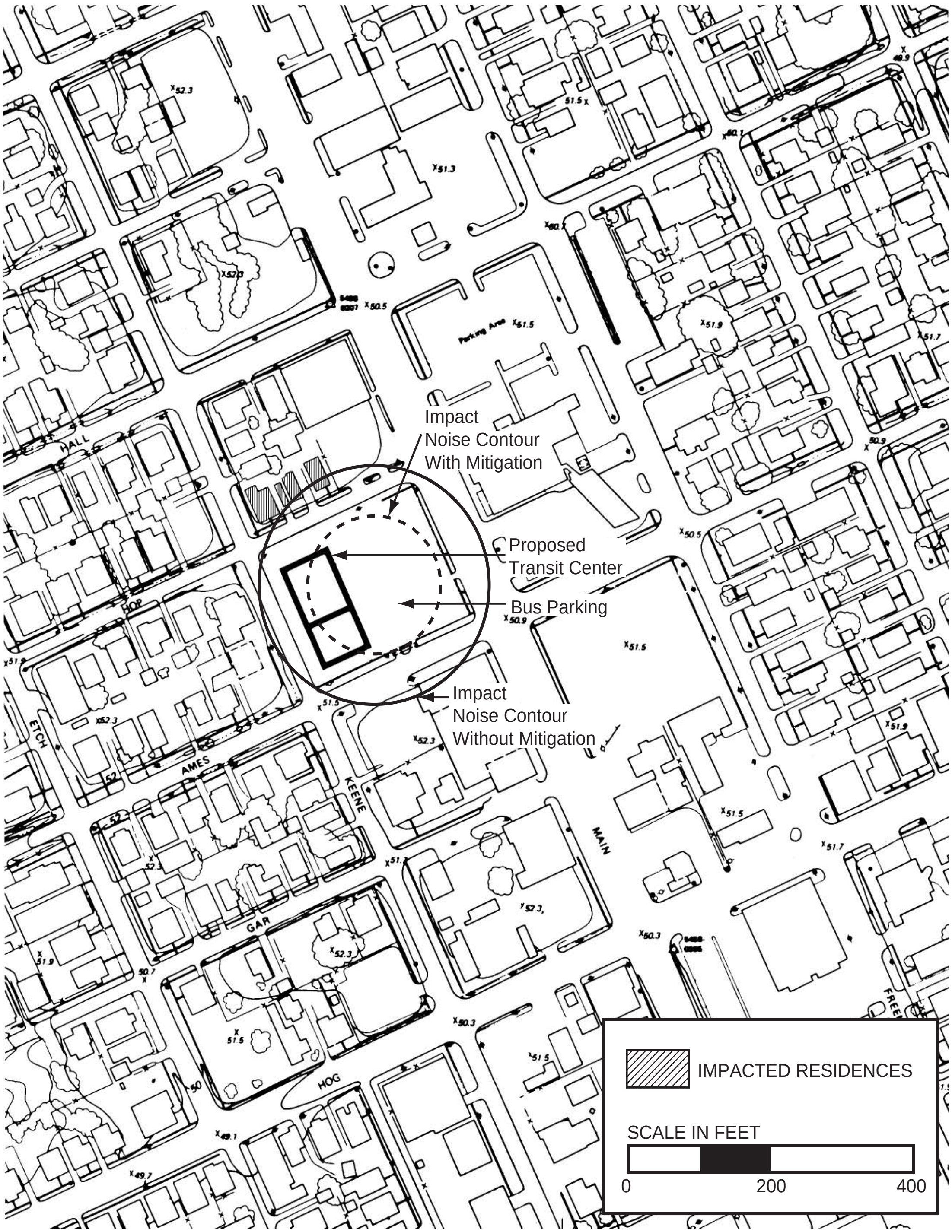


Figure 5-4. Example of Project for General Assessment: Siting of Transit Center in Mixed Commercial/Residential Area

2. Calculate $L_{eq}(day)$ and $L_{eq}(night)$ at 50 feet, assuming no noise barrier.

From Table 5-5 and Table 5-6 the levels are determined as follows:

$$L_{eq}(day) = SEL_{ref} + C_N - 35.6$$
$$= 101 + 10 \log (18.2/20) - 35.6$$
$$= 65 \text{ dB}$$

$$L_{eq}(night) = SEL_{ref} + C_N - 35.6$$
$$= 101 + 10 \log (3/20) - 35.6$$
$$= 57 \text{ dB}$$

3. Calculate L_{dn} at 50 ft for the project.

From Table 5-6 the level at 50 feet is determined as follows:

$$L_{dn} = 10 \log\left[(15)10^{Leq(day)/10} + (9)10^{(Leq(night)+10)/10}\right] - 13.8$$

which gives:

$$L_{dn} = 79.7 - 13.8$$
or $$L_{dn} = 66 \text{ dB}$$

Estimate Existing Noise Exposure

4. Estimate existing noise at noise-sensitive sites from the dominant noise source, either major roadways or local streets (population density).

<u>Roadway Noise Estimate:</u> The traffic on Main Street qualifies this street for the "Other Major Roadway" category in Table 5-7. According to the map, the nearest residence is 275 feet from the edge of Main Street. The table shows existing L_{dn} = 55 dB at this distance for representative busy city street traffic.

<u>Population Density Noise Estimate:</u> As a check on which ambient noise category to use, noise from local streets is estimated from the population density of 9,750 people/square mile. Table 5-7 indicates the L_{dn} should be approximately 55 dB.

The existing noise level associated with the residential neighborhood is therefore taken to be L_{dn} = 55 dB. In case the two estimates are different, use the lower L_{dn} value.

Noise Impact Contours

5. <u>Distance to Impact Contours:</u> For an existing noise exposure of 55 dB, the noise impact criteria indicate that the onset of Moderate Impact will occur at a project noise level of 56 dB, and onset of Severe Impact will occur at 62 dB. The next step is to determine the distances from the center of the property at which these levels are reached. This is accomplished by use of Figure 5-2, the exposure-vs-distance curve. With the project noise level at 50 feet given as 66 dB and the two

impact levels at 56 dB and 62 dB, the differences are 10 dB and 4 dB, respectively. Using the curve in Figure 5-2 labeled "Stationary" source, the distance to where the project level drops 10 dB is approximately 160 feet, and 4 dB attenuation occurs at about 80 feet. Consequently, the Moderate Impact contour occurs about 140 feet from the center of the property and the Severe Impact contour occurs at 80 feet.

6. <u>Draw Contours:</u> Lines are drawn at 80 feet and 140 feet from the center of the property of the proposed Transit Center. These lines represent the noise impact contours. (Note in Figure 5-4 the Severe Impact contour is left out for clarity: it is just within the dashed line representing the Moderate Impact contour after mitigation.)

7. <u>Assessment:</u> Within, or touching, the contour defining "Moderate Impact" are three residential buildings (shaded in Figure 5-4). No residences are within the "Severe Impact contour."

Noise Mitigation

8. <u>Noise Barrier:</u> The process is repeated with a hypothetical noise barrier at the property line on the residential side of the Transit Center. This would consist of a wall approximately 15 feet high partially enclosing the transit center, sufficient to screen the residences but not the commercial block facing Main Street. According to Table 5-6, the approximate noise barrier effect is -5 dB. Repeating the procedure above, the effect of the noise barrier is to shrink the Moderate Impact contour to 90 feet and the Severe Impact contour to 45 feet, which in this example eliminates all adverse effect on the residences.

End of Example 5-4

REFERENCES

1. U.S. Department of Transportation, Federal Highway Administration, *FHWA Traffic Noise Model User's Guide*, Report FHWA-PD-96-009, Washington, DC, January 1998. In addition, *FHWA Traffic Noise Model User's Guide (Version 2.5 Addendum)*, April 2004.

2. U.S. Environmental Protection Agency, "Population Distribution of the United States as a Function of Outdoor Noise Level," Report 550/9-74-009, June 1974.

6. DETAILED NOISE ANALYSIS

This chapter describes the detailed computation of both project and existing noise levels for a comprehensive assessment of project noise impact. The main purpose of this chapter is to provide a procedure that allows prediction of impact and assessment of the effectiveness of mitigation with greater precision than can be achieved with the General Assessment. In some cases, decisions on appropriate mitigation measures can be made based on the results of the General Assessment. When a more detailed evaluation of mitigation measures is needed, the procedures in this chapter should be followed.

It is important to recognize that use of the Detailed Analysis methods will not provide more accurate results than the General Assessment unless more detailed and specific input data are used. In the case of a transit center, for example, the General Assessment provides a source level at a reference distance from the center of the site based on the number of buses at the facility during each hour. Thus, the only information needed for a General Assessment of the transit center is the site location and hourly bus volumes. However, a Detailed Analysis would require specific information on the locations, reference levels, traffic volumes and duration of operations for individual sources that contribute to the total noise output of the transit center. Such information would include a detailed design plan for the facility, the locations of idling buses and the idling durations, as well as the bus and automobile traffic patterns and volumes. A Detailed Analysis cannot be done until such information is available.

Detailed Noise Analysis is appropriate in two main circumstances: first, for a major fixed-guideway project after the preferred mode and alignment have been selected; and second, for any other transit project where potentially severe impacts are identified at an early stage. For fixed-guideway projects, once the preferred mode and alignment are established, the project sponsor begins preliminary engineering and works to complete the environmental impact assessment, usually with a Final EIS. Information required for the Detailed Noise Analysis is generally available at the preliminary engineering stage; such information includes hourly operational schedules during day and night, speed profiles, plan and profiles of guideways, locations of access roads, and landform topography including terrain and building features.

Even for relatively minor transit projects, noise impacts are likely to occur whenever the project is in close proximity to noise-sensitive sites, particularly residences. Some examples are: (1) a terminal or station sited adjacent to a residential neighborhood; (2) a maintenance facility located near a school; (3) a storage yard adjacent to residences; and (4) an electric substation located adjacent to a hospital. As with the larger fixed-guideway projects mentioned above, a Detailed Noise Analysis for these projects will require information normally developed at the preliminary design stage.

The procedures of this chapter include everything needed for a fully detailed transit noise analysis. They are aimed at major transit projects that have enough lead time for thorough environmental analysis. They need not be followed to the letter; they can be tempered by competent engineering judgment and adapted somewhat to specific project constraints.

This chapter employs equations as the primary mode of computation, rather than graphs or tables of numbers, in order to facilitate the use of spreadsheets and/or programmable calculators. Moreover, these equations and their supporting text have been streamlined to provide as concise a view of the Detailed Noise Analysis as possible. As a result, basic noise concepts are not repeated in this chapter.

The steps in the procedure appear in Figure 6-1 and are described below. They parallel the steps for the General Noise Assessment, though they are more refined in the prediction of project noise and subsequent evaluation of mitigation measures.

1. Receivers of Interest. Select receivers of interest, guided by Section 6.1. The number of receivers will depend upon the land use in the vicinity of the proposed project and the extent of the study area defined by the Screening Procedure. If a General Assessment has been done, this will give a good indication of the extent of potential impacts.

2. Project Noise. Determine whether the project is primarily a fixed-guideway transit, highway/transit, or stationary facility. Note that a major fixed-guideway system will have stationary facilities associated with it, and that a stationary facility may have highway/transit elements associated with it. Identify the project noise sources that are in the vicinity of receivers of interest. For these sources, determine the source reference noise in terms of SEL from the tables in Section 6.2. Each reference SEL pertains to reference operating conditions for stationary sources or to one vehicle passby under reference operating conditions for fixed-guideway and highway/transit sources. These reference levels should incorporate source-noise mitigation only if such mitigation will be incorporated into the system specifications. For example, if the specifications include vehicle noise limits which may not be exceeded, these limits should be used to determine the reference level, and this level should be used in the analysis rather than the standard, tabulated reference level. Convert each source SEL to noise exposure (L_{dn} or L_{eq} (h)) at 50 feet, for the appropriate project operating parameters, using additional equations in Section 6.2.

3. Propagation and Summation of Project Noise at Receivers of Interest. Draw a noise exposure-vs.-distance curve for each relevant source, using the equations in Section 6.3. This curve will show source noise as a function of distance, accounting for shielding along the path, as well as any

propagation-path mitigation that will be included in the project. From these curves, determine the total project noise exposure at all receivers of interest by combining the levels from all relevant sources (Section 6.4).

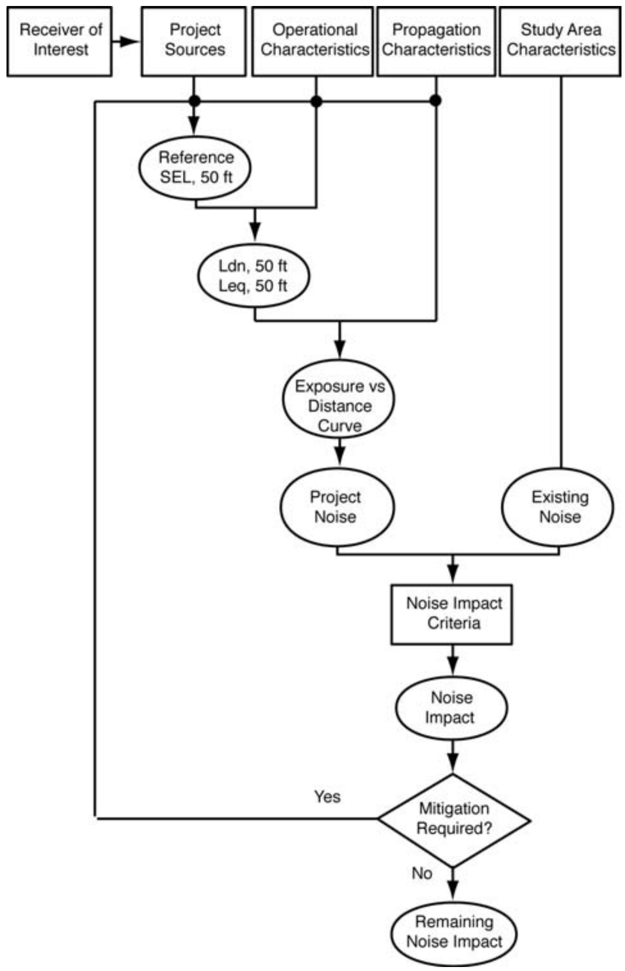


Figure 6-1. Procedure for Detailed Analysis

4. Existing Noise in the Study Area. Estimate the existing noise exposure at each receiver of interest, using the methods in Section 6.6.

5. Noise Impact Assessment. Assess noise impact at each receiver of interest using the procedures in Section 6.7 which incorporate the noise impact criteria of Chapter 3.

6. Mitigation of Noise Impact. Where the assessment shows either Severe Impact or Moderate Impact, evaluate alternative mitigation measures referring to Section 6.8. Then loop back to modify

the project-noise computations, thereby accounting for the adopted mitigation, and reassess the remaining noise impact.

6.1 RECEIVERS OF INTEREST

The steps in identifying the receivers of interest, both the number of receivers needed and their locations, are shown in Figure 6-2. Later sections discuss the measurement/computation of ambient noise, the computation of project noise, and the resulting assessment of noise impact that is done for each receiver. The basic steps, which are discussed in the following subsections, are:

1. Identify all noise-sensitive land uses.
2. Find individual receivers of interest. Examples are isolated residences and institutional resources such as schools.
3. Cluster residential neighborhoods and other relatively large noise-sensitive areas.

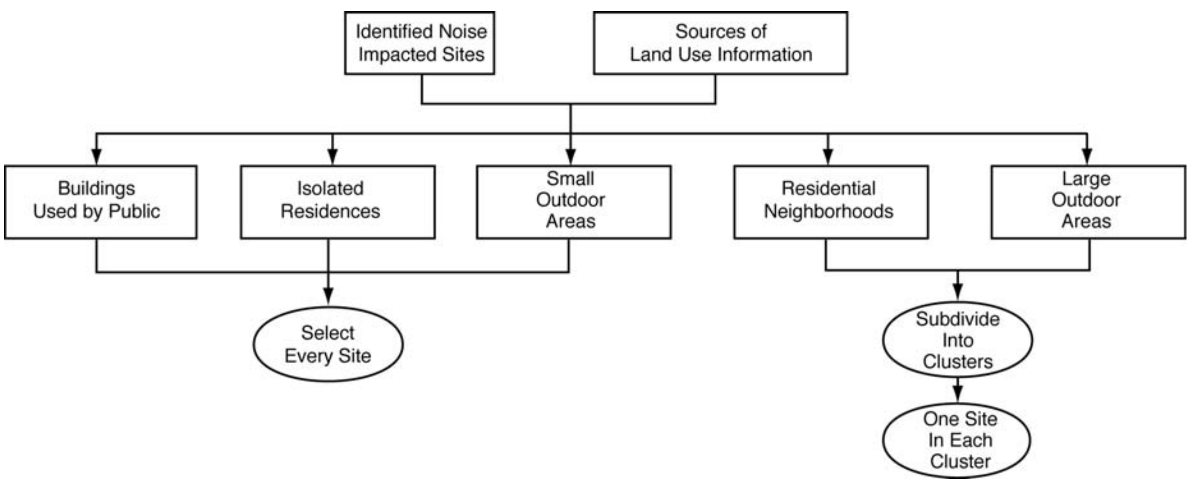


Figure 6-2. Guide to Selecting Receivers of Interest

6.1.1 Identifying Noise-Sensitive Land Uses

A Detailed Noise Analysis should usually be performed on all noise-sensitive land uses where impact is identified by the General Noise Assessment. If a General Noise Assessment has not been done, but there appears to be potential for noise impacts, all noise-sensitive sites within the area defined by the noise screening procedure should be included. In areas where ambient noise is low, the assessment will include land uses that are farther from the proposed project than for areas with higher ambient levels.

Some of the land-use materials and methods that can be helpful in locating noise-sensitive land uses in the vicinity of the proposed project include:

- **Land-use maps**, prepared by regional or local planning agencies or by the project staff. Area-wide maps often do not have sufficient detail to be of much use. However, they can provide broad guidance and may suggest residential pockets hidden within otherwise commercial zones. Of more use are project-specific maps which provide building-by-building detail on the land nearest the proposed project.
- **USGS maps,** prepared by the United States Geological Survey generally at 2000-foot scale. These maps contain details of house placement, except in highly urbanized areas, and generally show the location of all schools and places of worship, plus many other public-use buildings. In addition, the topographic contours on these maps may be useful later during noise computation.
- **Road and town maps**. These can supplement the USGS maps, are generally more up-to-date, and may be of larger scale.
- **Aerial photographs,** especially those of 400-foot scale or better. When current, aerial photos are valuable in locating all potential noise-sensitive land uses close to the proposed project. In addition, they can be useful in determining the distances between receivers and the project.
- **Windshield survey** of the corridor. Definitive identification of noise-sensitive sites is accomplished by a windshield survey in which the corridor is driven and land uses are annotated on base maps. The windshield survey, supplemented by footwork where needed, is especially useful in identifying newly-constructed sites and in confirming land uses very close to the proposed project.
- **Geographic Information Systems (GIS).** Mapping needed for identifying noise-sensitive land uses is often available in electronic GIS format. GIS data may include land parcels, building structures, aerial photography and project-specific information. These data may be obtained during the project study or from local or regional agencies that store and maintain GIS data. Using electronic GIS data has advantages over paper mapping in being able to automate the process of identifying noise-sensitive land use and accurately being able to determine their distances to the project alignment.

Table 6-1 contains the types of land use of most interest in the impact assessment, separated into three types of land use. If noise impact was identified at other types of buildings/areas with noise-sensitive use by the General Noise Assessment, these should be selected also.

6.1.2 Selecting Individual Receivers of Interest

Select as an individual receiver of interest: (1) every major noise-sensitive building used by the public; (2) every isolated residence; and (3) every relatively small outdoor noise-sensitive area. Use judgment here to avoid analyzing noise where such analysis is obviously not needed. For example, many roadside motels are not particularly sensitive to noise from outdoors. On the other hand, be careful to include buildings used by the public or outdoor areas which are considered to be particularly noise-sensitive by the community. Isolated residences that are particularly close to the project should certainly be included, while those at some distance may often be omitted or "clustered" together with other land uses, as described in the next section. Use judgment also concerning relatively small outdoor noise-sensitive areas. For example, playgrounds can often be omitted unless they directly abut the proposed project, since noise sensitivity in playgrounds is generally low.

Table 6-1. Land Uses of Interest		
Land Uses	**Specific Use**	**Selecting Receivers**
Outdoor noise-sensitive areas	Certain parks Historic sites used for interpretation Amphitheaters Passive recreation areas Cemeteries Other outdoor noise-sensitive areas	For relatively small noise-sensitive areas: same as indoor noise-sensitive sites. For relatively large areas: same as for residential areas.
Residences	Single family residences Multi-family residences (apartment buildings, duplexes, etc.)	Select each isolated residence as a receiver of interest. For residential areas, cluster by proximity to project sources, proximity to ambient-noise sources, and location along project line. Choose one receiver of interest in each cluster.
Indoor noise-sensitive sites	Places of worship Schools Hospitals/nursing homes Libraries Public meeting halls Concert halls/auditoriums/theaters Recording/broadcast studios Museums and certain historic buildings Hotels and motels Other public buildings with noise-sensitive indoor use	Select noise-sensitive buildings as separate receivers of interest.

6.1.3 Clustering Residential Neighborhoods and Outdoor Noise-Sensitive Areas

Residential neighborhoods and relatively large outdoor noise-sensitive areas can often be clustered, simplifying the analysis that is required without compromising the accuracy of the analysis. The goal is to subdivide all such neighborhoods/areas into clusters of approximately uniform noise, each containing a collection of noise-sensitive sites. Attempt to obtain uniformity of both project noise and ambient noise, guided by these considerations:

1. In general, project noise drops off with distance from the project. For this reason, project noise uniformity requires nearly equal distances between the project noise source and all points within the cluster. Such clusters will usually be shaped as long narrow strips parallel to the transit corridor and/or circling project point sources such as a maintenance facility. Suggested are clusters within which the project noise will vary over a range of 5 decibels or less. Be guided here by the fact that project noise will drop off approximately 3 decibels per doubling of distance for line sources and 6 decibels per doubling of distance for point sources over open terrain. Drop-off with distance will be faster in areas containing obstacles to sound propagation, such as rows of buildings.

2. Ambient noise usually drops off from non-project sources in the same manner as does noise from project sources. For this reason, clustering for uniform ambient noise will usually result in long narrow strips parallel to major roadways or circling major point sources of ambient noise, such as a manufacturing facility. Suggested are clusters within which the ambient noise will vary over a range

of 5 decibels or less, though this may be hard to judge without measurements. In areas without predominant sources of noise, like highways, ambient noise varies with population density, which is generally uniform along the corridor. In situations where ambient noise tends to be uniform, the clusters can encompass relatively large areas.

After defining the cluster, select one receiver as representative in each cluster. Generally choose the receiver closest to the project and at an intermediate distance from the predominant sources of existing noise. Detailed procedures for clustering appear in Appendix C along with an example of clustering for a segment of rail line. This method will generally result in an adequate selection of receivers along the corridor or surrounding the site.

6.2 PROJECT NOISE

Once receivers have been selected, projections of noise from the project must be developed for each receiver. This section describes the first step, calculating the noise exposure at an equivalent distance of 50 feet from each project noise source. As shown in Figure 6-3, the basic procedures for the computation are: (1) Separate nearby sources into these source-type categories: fixed-guideway sources, highway/transit sources, and stationary sources; (2) Determine the reference SEL for each source; and (3) Use the projected source operating parameters to convert each reference SEL to noise exposure (either L_{dn} or $L_{eq}(h)$) at 50 feet.

Table 6-2 lists many of the noise sources that are involved in transit projects. The right-hand column of the table indicates whether or not each source is a major contributor to overall noise impact. Note that some noise sources, such as track maintenance equipment, create high noise levels but are not indicated as "major." Although such sources are loud, they rarely stay in a neighborhood for more than a day or two; therefore, the overall noise exposure is relatively minor. Computations are required for all major noise sources in this table. The computations for the three basic groups – fixed-guideway sources, highway/transit sources, and stationary sources – appear in separate sections below.

6.2.1 Fixed-Guideway Sources

This section describes the computation of project noise at 50 feet from fixed-guideway sources of transit noise, identified in the second column of Table 6-2.

<u>Step 1: Source SELs at 50 feet</u>

For each major fixed-guideway noise source, first determine the reference SEL at 50 feet, either by measurement or by table look-up. Table 6-3 provides guidance on which method is preferred for each source type. A "NO" implies that the source levels are based on a solid and consistent data base; a "YES" means that a solid data base is not available. In general, measurements are preferred for source types that vary significantly from project to project, including any emerging technology sources. Table look-up is adequate for source types that do not vary significantly from project to project. In general, table look-up is adequate for fewer source types during Detailed Noise Analysis than during General Noise Assessment where less precision is acceptable.

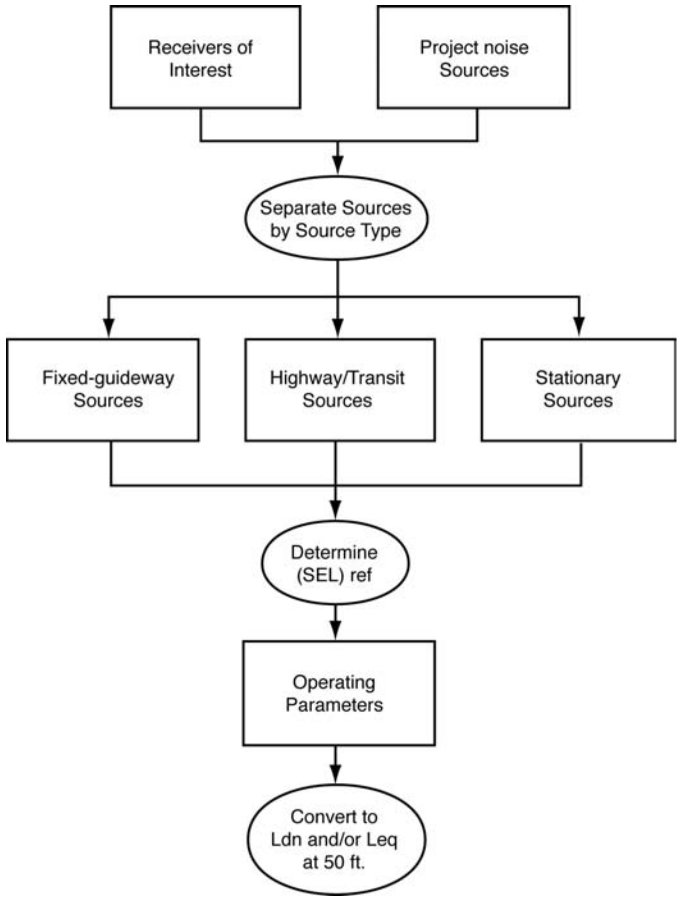


Figure 6-3. Flow Diagram for Determining Project Noise at 50 ft

For sources where measurements are indicated in Table 6-3, Appendix E discusses measurement procedures and conversion of these measurements to the reference conditions of Table 6-3. These procedures have been placed in an appendix because of their relative complexity. For projects where source-noise specifications have been defined (e.g., noise limits are usually included in the specifications for purchase of new transit vehicles), these specifications may be used instead of measurements, after conversion to reference conditions with the equations of Appendix E. This would only be appropriate where there is a firm commitment to adopt the noise specifications in the vehicle procurement documents during final design and adhere to the specifications throughout the procurement, delivery and testing of the vehicles.

For sources where table look-up is indicated in Table 6-3, the table provides appropriate Source Reference SELs. Approximate L_{max} values also appear in the table for general user information and for comparison with factors such as the noise limits that are included in transit vehicle specifications. As discussed in Chapter 2, L_{max} is not used directly in the evaluation of noise impact.

Table 6-2. Sources of Transit Noise

Project Type	Source Type	Actual Source	Major?
Commuter Rail Light Rail Rail Rapid Transit	Fixed-Guideway	Locomotive and rail car passbys	YES
		Horns and whistles	YES
		Crossing signals	YES
		Crossovers/switches	YES
		Squeal on tight curves	YES
		Track-maintenance equipment	NO
	Stationary	Substations	YES
		Chiller plants	NO
Busways Bus Transit Malls	Highway/Transit	Bus passbys	YES
		Buses parking	NO
	Stationary	Buses idling	YES
Automated Guideway Transit Monorail	Fixed-Guideway	Vehicle passbys	YES
	Miscellaneous	Line equipment	NO
Terminals Stations Transit Centers	Fixed-Guideway	Locomotive and rail car passbys	YES
		Crossovers/switches	YES
		Squeal on tight curves	YES
	Highway/Transit	Bus passbys	YES
		Buses parking	NO
		Automobile passbys	NO
	Stationary	Locomotives idling	YES
		Buses idling	YES
		Ferry boats landing, idling and departing at dock	YES
		HVAC equipment	NO
		Cooling towers	NO
		P/A systems	NO
Park-and-Ride Lots	Highway/Transit	Bus passbys	YES
		Buses idling	YES
		Automobile passbys	NO
	Stationary	P/A systems	NO
Traffic Diversion Projects	Highway/Transit	Highway vehicle passbys	YES
Storage Facilities Maintenance Facilities	Fixed-Guideway	Locomotive and rail car passbys	YES
		Locomotives idling	YES
		Squeal on tight curves	YES
		Horns, warning signals, coupling/ uncoupling, auxiliary equipment, crossovers/ switches, brake squeal and air release	YES
	Highway/Transit	Bus passbys	YES
	Stationary	Buses idling	YES
		Yard/shop activities	NO
		Car washes	NO
		HVAC Equipment	NO
		P/A Systems	NO

<table>
<tr><th colspan="4">Table 6-3. Source Reference SELs at 50 Feet:
Fixed-Guideway Sources @ 50 mph</th></tr>
<tr><th>Source</th><th>Reference SEL (dBA)</th><th>Approximate L_{max} (dBA)</th><th>Prefer Measurements?</th></tr>
<tr><td>Rail Cars</td><td>82</td><td>80</td><td>NO</td></tr>
<tr><td>Locomotives – Diesel</td><td>92</td><td>88</td><td>NO</td></tr>
<tr><td>Locomotives – Electric</td><td>90</td><td>86</td><td>NO</td></tr>
<tr><td>Diesel Multiple Unit (DMU)</td><td>85</td><td>81</td><td>YES</td></tr>
<tr><td>AGT - Steel Wheel</td><td>80</td><td>78</td><td>YES</td></tr>
<tr><td>AGT - Rubber Tire</td><td>78</td><td>75</td><td>YES</td></tr>
<tr><td>Monorail</td><td>82</td><td>80</td><td>YES</td></tr>
<tr><td>Maglev</td><td>72</td><td>70</td><td>YES</td></tr>
<tr><td>Transit Car Horns (Emergency)</td><td>93</td><td>90</td><td>NO</td></tr>
<tr><td>Transit Car Whistles</td><td>81</td><td>78</td><td>NO</td></tr>
<tr><td colspan="4">Locomotive Horns</td></tr>
<tr><td>At Grade Crossing</td><td>113</td><td>110</td><td rowspan="3">NO</td></tr>
<tr><td>From Crossing to 1/8 mile</td><td>$113-3*(D_p/660)$</td><td>110</td></tr>
<tr><td>From 1/8 mile to ¼ mile</td><td>110</td><td>110</td></tr>
<tr><td colspan="4">D_p = distance from grade crossing parallel to tracks</td></tr>
</table>

Step 2: Conversion to Noise Exposure at 50 feet

Step 1 results in reference SELs at 50 feet. Step 2 is to convert from these reference SELs to noise exposure based on operating conditions and parameters such as train consists, speed, and number of trains per hour. The steps are:

1. Identify operating conditions. Trains with different consists require separate conversion since they will produce different noise exposure. The same is true for trains at different speeds, or under different operating conditions. As guidance here, the following percentage changes in operating conditions will produce an approximate 2-decibel change in noise exposure:

    - 40 percent change in number of locomotives or cars per train
    - 40 percent change in number of trains per hour
    - 40 percent change in number of trains per day, or per night (for computation of L_{dn})
    - 15 percent change in train speed
    - Change of one notch in diesel locomotive throttle setting (e.g. from notch 5 to notch 6)

    In general, where operating conditions change by these amounts, separate calculations should be made. Without separate conversions, the risk is that the results may not be accurate enough.

2. Establish relevant time periods. For each of these source types/conditions, decide what are the relevant time periods for all receivers that may be affected by this source. For residential receivers, the two time periods of interest for computation of L_{dn} are: daytime (7 am to 10 pm) and nighttime

(10 pm to 7 am). If the source will affect non-residential receivers, choose the loudest project hour during noise-sensitive activity. Several different hours may be of interest for non-residential receivers depending on the hours the facility is used.

3. Collect input data.
   - Source reference SELs for locomotives, rail cars, and warning horns.
   - N_{cars}, the number of rail cars in the train.
   - N_{locos}, the number of locomotives in the train, if any.
   - *S*, the train speed, in miles per hour.
   - *T*, the average throttle setting of the train's locomotive(s), if it is diesel-electric.[1] If this input is not available, assume a throttle setting of 8.
   - For residential receivers of interest:

     V_d, the average hourly train volume during daytime hours (equals the total number of train passbys between 7 am and 10 pm, divided by 15), and

     V_n, the average hourly train volume during nighttime hours (equals the total number of train passbys between 10 pm and 7 am, divided by 9).
   - For non-residential receivers: *V*, the hourly train volume for each hour of interest.
   - Track type (continuously welded or jointed) and profile (at-grade or elevated).

4. Calculate L_{eq} at 50 ft for each hour of interest.
   - Compute $L_{eqL}(h)$ for the locomotive(s) using the first equation in Table 6-4.
   - Compute $L_{eqC}(h)$ for the rail car(s) using the second equation in Table 6-4. Use the adjustments indicated in the table, as needed.
   - Compute $L_{eqH}(h)$ for the train horn using the third equation in Table 6-4.
   - Compute the total $L_{eq}(h)$ using the fourth equation in Table 6-4. Two totals may be necessary: one with the warning horn and one without it. These will pertain to different neighborhoods along the corridor, depending upon whether the horn is sounded in that neighborhood or not.

5. Compute L_{dn} at 50 ft. If the project noise will affect any residential receivers, compute the total train L_{dn} from the fifth equation in Table 6-4. Again two totals may be necessary: one with the warning horn and one without it, as explained above.

---

1 Otherwise, this term is not applicable and should be omitted from the equation in Table 6-4.

Table 6-4. Computation of L_{eq} and L_{dn} at 50 feet: Fixed-Guideway Sources	
LOCOMOTIVES† Hourly L_{eq} at 50 ft:	$L_{eqL}(h) = SEL_{ref} + 10\log(N_{locos}) + C_T + K\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ $where C_T = \begin{cases} 0 & for T < 6 \\ 2(T-5) & for T \geq 6 \end{cases}$ $and\ K = -10\ for\ passenger\ diesel; = 0\ for\ DMU; = +10\ for\ electric$
AIL VEHICLES†† Hourly L_{eq} at 50 ft:	$L_{eqC}(h) = SEL_{ref} + 10\log(N_{cars}) + 20\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$ use the following adjustments as applicable: + 5 → JOINTED TRACK + 3 → EMBEDDED TRACK ON GRADE + 4 → AERIAL STRUCTURE WITH SLAB TRACK
LOCOMOTIVE WARNING HORNS††† Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} + 10\log(V) - 35.6$
TRANSIT WARNING HORNS††† Hourly L_{eq} at 50 ft:	$L_{eqH}(h) = SEL_{ref} - 10\log\left(\frac{S}{50}\right) + 10\log(V) - 35.6$
COMBINED Hourly L_{eq} at 50 ft:	$L_{eq}(h) = 10\log\left[10^{\left(L_{eqL}/10\right)} + 10^{\left(L_{eqC}/10\right)} + 10^{\left(L_{eqH}/10\right)}\right]$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\big\vert_{v=v_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\big\vert_{v=v_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\cdot 10^{\left(L_{eq}(day)/10\right)} + (9)\cdot 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$

N_{locos}	= average number of locomotives per train
N_{cars}	= average number of cars per train
T	= average throttle setting of diesel-powered locomotives and DMU's
S	= train speed, in miles per hour
V	= average hourly volume of train traffic, in trains per hour
V_d	= average hourly daytime volume of traffic, in trains per hour $= \frac{number\ of\ trains, 7am\ to\ 10pm}{15}$
V_n	= average hourly nighttime volume of train traffic, in trains per hour $= \frac{number\ of\ trains, 10pm\ to 7am}{9}$

† Assumes a passenger diesel locomotive power rating of approximately 3000 hp

†† Includes all commuter rail cars, transit cars, AGT and monorail

††† Based on FRA's horn noise model (www.fra.dot.gov/downloads/RRDev/hornmodel.xls)

Example 6-1. Computation of L_{eq} and L_{dn} at 50 feet for Fixed-Guideway Source

A commuter train with 1 diesel locomotive and 6 cars will pass close to a residential area at a grade crossing. For this project source,

SEL_{ref}	=	92 for locomotives,
	=	82 for rail cars,
	=	113 for locomotive warning horns at grade crossing

In addition,

N_{cars}	=	6
N_{locos}	=	1
S	=	43 mph
T	=	8
V_d	=	(40 trains)/(15 hours)= 2.667 trains per hour, and
V_n	=	(2 trains)/(9 hours) = 0.222 trains per hour.

The track is also jointed in this vicinity. Using Table 6-4, the resulting daytime L_{eq}'s at 50 feet are as follows:

L_{eqL}(day)	=	67.3 for locomotives,
L_{eqC}(day)	=	62.1 for cars, and
L_{eqH}(day)	=	81.7 for horns.
Total L_{eq}(day)	=	81.9 in neighborhoods where the horn is sounded, and
	=	69.3 in neighborhoods where it is not.

Using Table 6-4, the resulting nighttime L_{eq}'s at 50 feet are as follows:

L_{eqL}(night)	=	56.5 for locomotives,
L_{eqC}(night)	=	51.3 for cars, and
L_{eqH}(night)	=	70.9 for horns,
Total L_{eq}(night)	=	71.1 with horns, and
	=	57.6 without horns.

Finally, this total day and night traffic results in:

L_{dn}	=	81.6 at 50 ft in neighborhoods where horns are sounded, and
	=	68.7 at 50 ft in neighborhoods where they are not.

(Note: Computation results should always be rounded to the nearest decibel at the end of the computation. In all examples of this chapter, however, the first decimal place is retained in case readers wish to precisely match their own computations against the example computations.)

End of Example 6-1

6.2.2 Highway/Transit Sources

This section describes the computation of project noise at 50 feet for highway/transit sources, identified in the second column of Table 6-2. This method is based on the original FHWA highway noise prediction model, with updated noise emission levels.(1) This model can be used because the vehicle equations are applicable to speeds typical of freely-flowing traffic on city streets and access roads. In Chapter 3 there is a discussion of specific types of projects and conditions for which the FHWA procedures should be used, including TNM, the currently approved highway noise prediction model.

Step 1: Source SELs at 50 feet

Determine the source reference SEL at 50 feet for each "major" highway/transit source near a receiver of interest. As indicated in the fourth column of Table 6-5, it is usually adequate to use the standard Reference SELs of Table 6-5 for highway/transit sources. If measurements are chosen, however, Appendix E discusses the measurement procedures, plus procedures for the conversion of these measurements to reference conditions of Table 6-5. These measurement/conversion procedures have been placed in an appendix because of their relative complexity.

Table 6-5. Source Reference SELs at 50 Feet: Highway/Transit Sources @ 50 mph.

Source	Reference SEL (dBA)	Approximate L_{max} (dBA)	Prefer Measurements?
Automobiles	74	70	No
Buses (diesel)	82	79	No
Buses (electric trolleybus)	80	77	No
Buses (hybrid)[i]	83	80	Yes

[i]Hybrid bus with full-time diesel engine and electric drive motors.

Step 2: Conversion to Noise Exposure

Convert the source reference SELs at 50 feet to actual operating conditions such as actual vehicle speed and number of vehicles per hour. Next convert to noise exposure using the following steps:

1. Identify actual source operating conditions. Noise emission from most transit buses does not depend significantly upon whether the buses are accelerating or cruising. On the other hand, accelerating suburban buses are significantly louder than are cruising suburban buses. For this reason, suburban buses require separate conversion along roadway stretches where they are accelerating. Separate conversion is also needed for all highway/transit vehicles at different speeds, since speed affects noise emissions. As guidance here, the following percentage changes in operating conditions will produce an approximate 2-decibel change in noise exposure:

    - 40 percent change in number of vehicles per hour
    - 40 percent change in number of vehicles per day, or per night (for computation of L_{dn})
    - 15 percent change in vehicle speed.

    In general, where operating conditions change by these amounts, separate conversions should be made.

2. Establish relevant time periods. For each of these source types/conditions, decide what are the relevant time periods for all receivers that may be affected by this source. If the source will affect residential receivers, two time periods are of interest to compute L_{dn}: daytime (7 am to 10 pm) and nighttime (10 pm to 7 am). In addition, if the source will affect non-residential receivers, choose the loudest facility hour during noise-sensitive activity. Several different hours may be of interest for non-residential receivers, depending on the hours the facility is used.

3. Collect input data. Gather the following information:
   - Source reference SELs for the vehicle types of concern.
   - *S,* the average running speed in miles per hour.
   - For residential receivers of interest:

     V_d, the average hourly vehicle volume during daytime hours (equals the total number of vehicle passbys between 7 am and 10 pm, divided by 15), and

     V_n, the average hourly vehicle volume during nighttime hours (equals the total number of vehicle passbys between 10 pm and 7 am the next day, divided by 9).
   - For non-residential receivers of interest: *V*, the hourly vehicle volume for each hour of interest, in vehicles per hour.

4. Calculate L_{eq} at 50 ft for each hour of interest. Compute $L_{eq}(h)$ for the vehicle type using the first equation in Table 6-6.

5. Compute L_{dn} at 50 ft. If this vehicle type will affect any residential receivers, compute the total L_{dn} for the vehicle type using the fourth equation in Table 6-6.

Table 6-6. Computation of L_{eq} and L_{dn} at 50 feet: Highway/Transit Sources

Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(V) + C_{emissions} - 10\log\left(\frac{S}{50}\right) - 35.6$
Daytime L_{eq} at 50 ft:	$L_{eq}(day) = L_{eq}(h)\big\|_{v=v_d}$
Nighttime L_{eq} at 50 ft:	$L_{eq}(night) = L_{eq}(h)\big\|_{v=v_n}$
L_{dn} at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$
Noise Emissions	$C_{emissions}$ $= 25\times\log\left(\frac{S}{50}\right)$ → buses $= 1.6$ → accelerating 3-axle commuter buses $= 40\times\log\left(\frac{S}{50}\right)$ → automobiles
Other adjustments	-3 → automobiles, open-graded asphalt +3 → automobiles, grooved pavement

V = hourly volume of vehicles of this type, in vehicles per hour

V_d = average hourly daytime volume of vehicles of this type, in vehicles per hour

$$= \frac{totalvehiclevolume, 7amto10pm}{15}$$

V_n = average hourly nighttime volume of vehicles of this type, in vehicles per hour

$$= \frac{totalvehiclevolume, 10pmto7am}{9}$$

S = average vehicle speed in miles per hour (distance divided by time, excluding stop time at red lights)

Note: Idling buses appear under Stationary Sources.

Example 6-2. Computation of L_{eq} and L_{dn} at 50 feet for Highway/Transit Source

A bus route with city buses will pass close to a school that is in session from 8 am to 4 pm on weekdays. Within this time period, the hour of greatest activity for this bus route is 8 am to 9 am. For this project source,

SEL_{ref} = 82 dB
S = 40 mph, and
V = 30 buses per hour

Using Table 6-6, the resulting hourly L_{eq} at 50 ft = 59.7 dB.
(Note: Computation results should always be rounded to the nearest decibel at the end of the computation.)

Continuing the example, this same bus also passes close to a residential area. For this project source, SEL_{ref} is the same as above, as is S. In addition,

V_d = (200 buses)/(15 hours) = 13.33 buses per hour, and
V_n = (20 buses)/(9 hours) = 2.22 buses per hour.

Using Table 6-6, the resulting L_{eq}'s at 50 ft are as follows:

L_{eq}(day) = 56.2 dB and
L_{eq}(night) = 48.4 dB.

Finally, the total day and night traffic results in L_{dn} at 50 ft = 57.2 dB.

End of Example 6-2

6.2.3 Stationary Sources

This section describes the computation of project noise at 50 feet for stationary sources of transit noise, identified in the second column of Table 6-2.

Step 1: Source SELs at 50 feet

Determine the reference SEL at 50 feet for each major source, either by measurement or by table look-up. Table 6-7 provides guidance on which method is preferred for each source type. In general, measurements are preferred for source types that vary significantly from project to project. For example, curve squeal is highly variable depending on weather conditions, curve radius, and train speed. In general, a standard steel wheel on steel rail system will tend to initiate curve squeal at curves with radii less than 100 time the truck wheelbase. Table look-up is adequate for source types that do not vary significantly from project to project (crossing signals, for example). Ferry boat landings are included in the stationary source category because the noise from the landing remains in one area even though the boats move in and out.

Table 6-7. Source Reference SELs at 50 Feet: Stationary Sources

Source	Reference SEL (dBA)	Approximate L_{max} (dBA)	Prefer Measurements?
Auxiliary Equipment	101	65	YES
Locomotive Idling	109	73	NO
Rail Transit Idling	106	70	NO
Buses Idling	111	75	NO
Ferry Boat Landing, Idling and Departing	91	78	NO
Ferry Boat Fog Horn	90	84	NO
Track Crossover	100	90	NO
Track Curve Squeal	136	100	YES
Car Washes	111	75	YES
Crossing Signals	109	73	NO
Substations	99	63	NO

For sources where measurements are indicated in Table 6-7, Appendix E discusses the measurement procedures, plus procedures for the conversion of these measurements to the reference conditions of Table 6-7.

For most sources where table look-up is indicated in Table 6-7, the table provides appropriate reference SELs for one typical noise event at 50 feet and of 1-hour duration (3600 seconds). For ferry boats and fog horns, the reference SELs are for one typical noise event at 50 feet. Approximate L_{max} values are also given in the table for general user information.

Layover facilities and transit centers can be the sources of low-frequency noise from idling diesel engines. Sounds with considerable low-frequency components can cause greater annoyance than would be expected based on their A-weighted levels. Low-frequency sounds often cause windows and walls to vibrate resulting in secondary effects in buildings such as rattling of dishes in cupboards and wall-mounted pictures. The SEL's in Table 6-7 are adjusted to include a factor to take increased annoyance into account. However, for a detailed analysis at locations where such idling takes place for an extended period, the method described in ANSI Standard S12.9-Part 4, Annex D, should be used.[2]

Step 2: Conversion to Noise Exposure at 50 feet

Step 1 results in reference SELs at 50 feet. Step 2 is to convert from these reference SELs to actual operating conditions, such as actual event durations and numbers of events, and calculate noise exposure at 50 ft. The steps are:

1. Identify actual source durations and numbers of events. The following percentage changes in durations/numbers will produce an approximate 2-decibel change in noise exposure:

    - 40 percent change in event duration (e.g. from 30 to 42 minutes)
    - 40 percent change in number of events per hour (e.g. from 10 to 14 events per hour).

    In general, where durations/numbers change by these amounts, separate conversions should be made.

2. Establish relevant time periods. For each source, determine the relevant time periods for all receivers that may be affected by the source. For residential receivers, the two time periods of interest to compute L_{dn} are: daytime (7 am to 10 pm) and nighttime (10 pm to 7 am). If the source will affect non-residential receivers, choose the loudest facility hour during noise-sensitive activity.

3. Collect input data. Gather the following input information:
    - Source reference SELs for each relevant source.
    - E, the average duration of one event, in seconds.
    - For residential receivers of interest:

        N_d, the average number of events per hour that occur during the daytime (equals the total number of events between 7 am and 10 pm, divided by 15), and

        N_n, the average number of events per hour that occur during the nighttime (equals the total number of events between 10 pm and 7 am, divided by 9).

    - For non-residential receivers of interest: N, the number of events that occur during each hour of interest, in events per hour.

4. Compute L_{eq} at 50 ft. For each hour of interest, compute the L_{eq} for the source using the first equation in Table 6-8.

5. Compute L_{dn} at 50 ft. If this source will affect any residential receivers of interest, compute the total L_{dn} for the source using the fourth equation in Table 6-8.

Table 6-8. Computation of L_{eq} and L_{dn} at 50 feet: Stationary Sources	
Hourly L_{eq} at 50 ft:	$L_{eq}(h) = SEL_{ref} + 10\log(N) + 10\log\left(\frac{E}{3600}\right) - 35.6$
Daytime Leq at 50 ft:	$L_{eq}(day) = L_{eq}(h)\Big\vert_{N=N_d}$
Nighttime Leq at 50 ft:	$L_{eq}(night) = L_{eq}(h)\Big\vert_{N=N_n}$
Ldn at 50 ft:	$L_{dn} = 10\log\left[(15)\times 10^{\left(L_{eq}(day)/10\right)} + (9)\times 10^{\left(L_{eq}(night)+10/10\right)}\right] - 13.8$

E† = duration of one event, in seconds
N = number of events of this type that occur during one hour
N_d = hourly average number of events of this type that occur during daytime (7am to 10pm)
$= \frac{number that occur between 7 am and 10 pm}{15}$
N_n = hourly average number of events of this type that occur during nighttime (10pm to 7am)
$= \frac{number that occur between 10 pm and 7 am}{9}$
† Omit the term containing E for ferry boat and fog horn and crossover noise sources

Example 6-3. Computation of L_{eq} and L_{dn} at 50 feet for Stationary Source

A signal crossing lies close to a school that is in session from 8 am to 4 pm on weekdays. Within this time period, the hour of greatest activity for the signal crossing is 8am to 9am. For this project source,

SEL_{ref}	=	109 dB
E	=	25 seconds (counting both cycles of the signal), and
N	=	22

Using Table 6-8 the resulting L_{eq}(h) = 65.2 from 8 to 9 am. (Computation results should always be rounded to the nearest decibel at the end of the computation.)

This same signal crossing lies close to a residential area. For this project source, SEL_{ref} is the same as above, as is E. In addition,

N_d	=	(200)/(15 hours) = 13.3 events per hour, and
N_n	=	(12)/(9 hours) = 1.33 events per hour.

Using Table 6-8, the resulting daytime and nighttime L_{eq}'s are:

L_{eq}(day)	=	63.0 and
L_{eq}(night)	=	53.0.

Finally, using the fourth equation in Table 6-8, the resulting L_{dn} at 50 feet = 63.0 dB.

End of Example 6-3

6.3 PROPAGATION CHARACTERISTICS

Once estimates of noise exposure at 50 feet from each source are available, then propagation characteristics must be taken into account to compute the noise exposure at receivers of interest. The steps, shown in Figure 6-4, for this are: 1) determine the propagation characteristics between each source and the receiver of interest; then, 2) draw a noise exposure-vs.-distance curve outward from each relevant source as a function of distance; and 3) add a final adjustment using the appropriate shielding term based on intervening barriers between source and receiver.

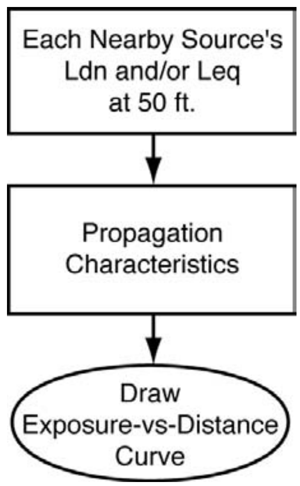


Figure 6-4. Flow Diagram for Determining Project Noise at Receiver Location

6.3.1 Noise Exposure vs. Distance

The following steps result in a noise exposure-vs.-distance curve for each project source:

1. Draw several approximate topographic sections, each perpendicular to the path of moving sources or outward from point sources, similar to those shown in Figure 6-5. Draw separate sections, if necessary, to account for significant changes in topography. Use judgment here to prevent an extreme number of different topographic sections. Often, several typical sections will suffice throughout the transit corridor.

2. For each topographic section, use the relationship illustrated in Figure 6-5 to determine the effective path height, H_{eff}, and from it the Ground Factor, G. Larger Ground Factors mean larger amounts of ground attenuation with increasing distance from the source. As shown in the figure, the effective path height depends upon source heights, which are standardized at the bottom of the figure, and upon receiver heights, which can often be taken as 5 feet for both outdoor receivers and first-floor receivers. With these standard heights, only one H_{eff} (and therefore one Ground Factor)

results from each cross section. For acoustically "hard" (i.e. non-absorptive) ground conditions, G should be taken to be zero.

3. Then for each L_{dn} and each L_{eq} at 50 feet developed earlier in the analysis, plot a noise exposure-vs.-distance curve with L_{dn} or L_{eq} represented on the vertical axis and distance on the horizontal axis using one of the following equations:

L_{dn} or L_{eq}

$$= (L_{dn} or L_{eq})\Big|_{at\,50\,ft} - 20\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{50}\right)$$

for stationary sources

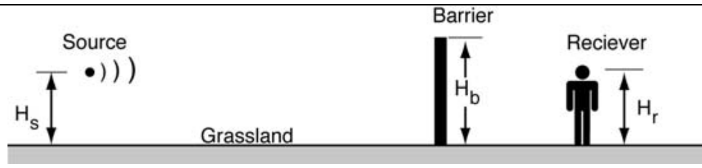
$$= (L_{dn} or L_{eq})\Big|_{at\,50\,ft} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right)$$

for fixed-guideway rail car passbys

$$= (L_{dn} or L_{eq})\Big|_{at\,50\,ft} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right)$$

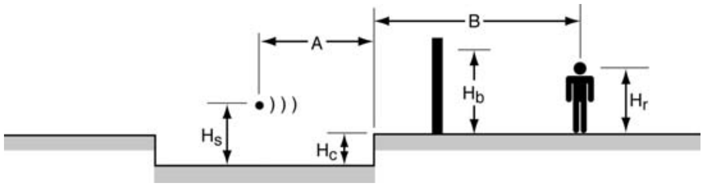
For fixed-guideway locomotive and rubber-tired vehicle passbys, highway vehicle passbys and horns

<u>IN GENERAL</u>: H_{eff} = sum of average path heights on either side of barrier



$$H_{eff} = \frac{H_s + 2H_b + H_r}{2} \quad (1)$$

<u>Example 1: Source in shallow cut</u>

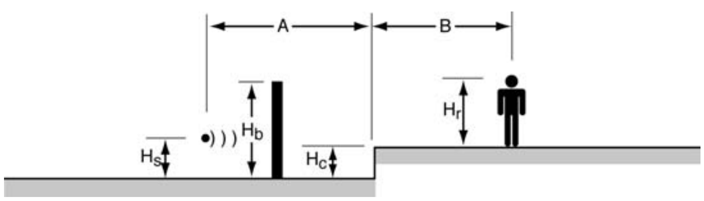


$For B \le A/2$,

$$H_{eff} = \frac{H_S + 2H_b + H_c + H_r}{2}$$

* Otherwise use Equation (1)

<u>Example 2: Receiver elevated</u>



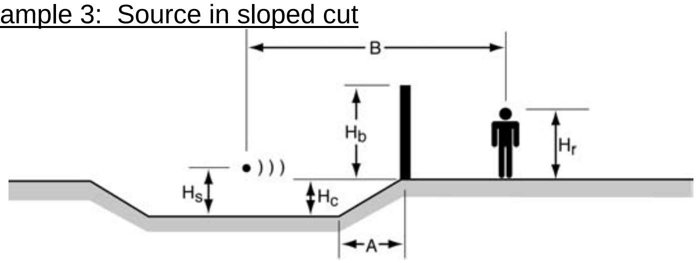
$For H_b \ge H_c$,

$$H_{eff} = \frac{H_s + 2H_b - H_c + H_r}{2}$$

$For H_b \le H_c$,

$$H_{eff} = \frac{H_s + H_c + H_r}{2}$$

<u>Example 3: Source in sloped cut</u>



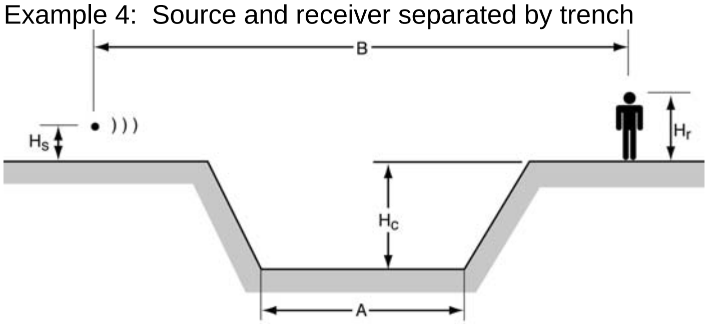
$For A \le B/2$,

use equation (1)

$For A \ge B/2$,

$$H_{eff} = \frac{H_s + 2H_b + H_c + H_r}{2}$$

Example 4: Source and receiver separated by trench



$For A \ge B/2$,

$$H_{eff} = \frac{H_s + 2H_c + H_r}{2}$$

$For A \le B/2$,

$$H_{eff} = \frac{H_s + H_r}{2}$$

<u>Source Heights:</u>

H_s = 8 ft, trains **with** diesel-electric locomotives

2 ft, trains **without** diesel-electric locomotives

0 ft, automobiles

3 ft, 2-axle city buses

8 ft, 3-axle commuter buses

Note: Equations for H_{eff} remain valid even when H_b = 0.

<u>Ground Factor</u>

For soft ground:

$$G = \begin{cases} 0.66 & H_{eff} \le 5 \\ 0.75\left(1 - \frac{H_{eff}}{42}\right) & 5 \le H_{eff} \le 42 \\ 0 & H_{eff} \ge 42 \end{cases}$$

For hard ground:

G=0

Figure 6-5. Computation of Ground Factor G for Ground Attenuation

Example 6-4. Computing Exposure-vs.-Distance Curve for Fixed-Guideway Source

A commuter train will produce the following levels without horn blowing at 50 feet:

L_{eq}(8-9am)	=	72 decibels
L_{dn}	=	68 decibels.

For sound propagation over grassland with a flat cross-sectional geometry without a noise barrier, and H_R = 5 feet:

H_{eff}	=	6.5 feet

and from Figure 6-5 the resulting Ground Factor is:

G	=	0.63

Hence the relevant equations from above become:

L_{eq}(8-9am)	=	72 _ 10 log(D/50) _ 6.3 log(D/42)
L_{dn}	=	68 _ 10 log(D/50) _ 6.3 log(D/42)

Plots of these two equations appear in Figure 6-6. From these curves, the noise levels due to this train operation can be determined for a receiver of interest at any distance. The only factor not accounted for is the effect of shielding between source and receiver, which is the subject of the next section.

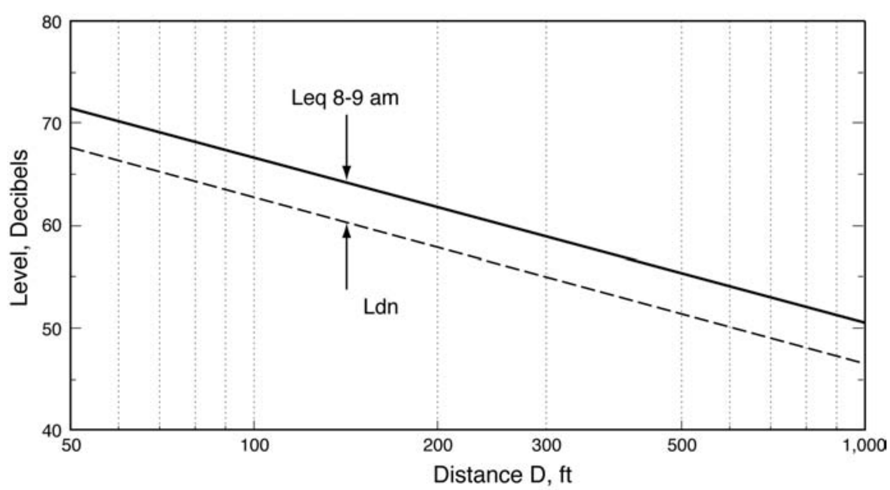


Figure 6-6. Example Exposure-vs.-Distance Curves

End of Example 6-4

6.3.2 Shielding at each Receiver

The resulting L_{eq}'s and L_{dn}'s from the previous section do not include shielding between source and receiver. Such shielding can be due to intervening noise barriers, terrain features, rows of buildings, and dense tree zones. The individual attenuations are computed using the equations from Table 6-9 for barriers and terrain, or from Table 6-10 for rows of buildings and dense tree zones.

The results are attenuation values which are applied to the previously determined project noise at receiver locations (Figure 6-4).

Table 6-9. Computation of Shielding: Barriers and Terrain

Condition	Equation†
For ***non-absorptive*** transit barriers within 5 feet of the track:	$A_{barrier} = \min\{12 \, or \, [5.3 \times \log(P) + 6.7]\}$
For ***absorptive*** transit barriers within 5 feet of the track:	$A_{barrier} = \min\{15 \, or \, [5.3 \times \log(P) + 9.7]\}$
For all other barriers, and for protrusion of terrain above the line of sight:	$A_{barrier} = \min\left\{15 \, or \left[20 \times \log\left(\frac{2.51\sqrt{P}}{\tanh[4.46\sqrt{P}]}\right) + 5\right]\right\}$
Barrier Insertion Loss	$IL_{barrier} = \max\left\{0 \, or \left[A_{barrier} - 10(G_{NB} - G_B)\log\left(\frac{D}{50}\right)\right]\right\}$

D = closest distance between the receiver and the source, in feet
P = path length difference, in feet (see figure below)
G_{NB} = Ground factor G computed *without barrier* (see Figure 6-5)
G_B = Ground factor G computed *with barrier* (see Figure 6-5)

† The term "tanh(variable)" stands for hyperbolic tangent, available on many scientific calculators. If "tanh" is not available, then compute E = exp(variable), and set tanh(variable) = (E - 1/E) / (E + 1/E), where exp(variable) is the "exponential" function, also written as e^x on calculator keypads.

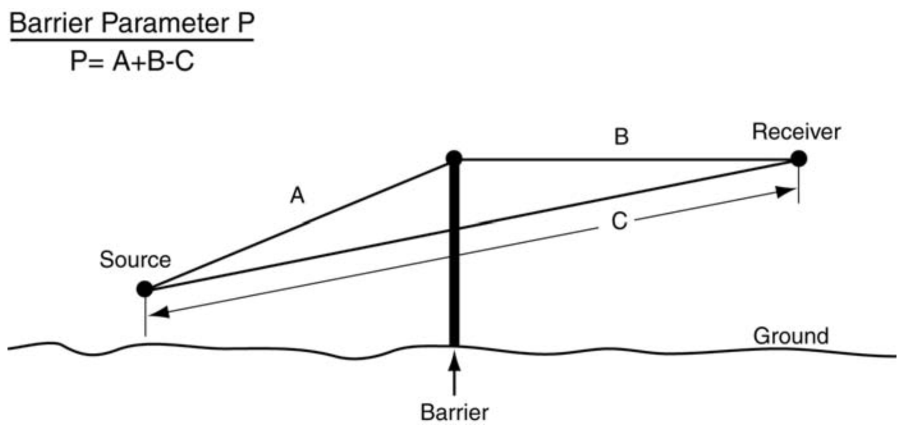


Figure 6-7. Sketch Showing Noise Barrier Parameter "P"

Table 6-10. Computation of Shielding: Rows of Buildings and Dense Tree Zones	
Condition	**Equation**
If gaps in the row of buildings constitute less than 35 percent of the length of the row:	$A_{buildings} = \min\{10 or [1.5(R-1)+5]\}$
If gaps in the row of buildings constitute between 35 and 65 percent of the length of the row:	$= \min\{10 or [1.5(R-1)+3]\}$
If gaps in the row of buildings constitute more than 65 percent of the length of the row:	= 0
Where at least 100 feet of trees intervene between source and receiver, *and* if no clear line-of-sight exists between source and receiver, *and* if the trees extend 15 feet or more above the line-of-sight:	$A_{trees} = \min\left\{10 or \frac{W}{20}\right\}$
If above conditions do not occur:	= 0
R = number of rows of houses that intervene between source and receiver W = width of the tree zone along the line-of-site between source and receiver, in feet	
NET ATTENUATION	$A_{shielding} = \max\{IL_{barrier} or A_{buildings} or A_{trees}\}$

Example 6-5. Computation of Shielding

Intervening between the rail corridor and a receiver of interest is the following shielding:

(1) a 15-foot high noise barrier, 40 feet from the closest track and 130 feet from the 5-foot-high receiver, and
(2) a dense tree zone 100 feet thick. The source height H_S = 8 feet, per Figure 6-5.

For the barrier: A = 40.61 feet, B = 130.38 feet, C = 170.03 feet, and therefore P = 0.96 feet, according to Table 6-9.

From Figure 6-5,

H_{eff} (no barrier) = 6.5 feet and
H_{eff} (with barrier) = 21.5 feet,

which results in

G_{NB} = 0.63, and
G_B = 0.37.

From Table 6-9, the resulting barrier attenuation is

$$
\begin{aligned}
A_{barrier} &= \min\{15 \textit{ or } 20x\log[2.45/\tanh(4.37)]+5\} \\
&= \min\{15 \textit{ or } 12.8\} \\
&= 12.8 \text{ dB}
\end{aligned}
$$

and the resulting barrier Insertion Loss is

$$
\begin{aligned}
IL_{barrier} &= 12.8 - 10(0.63-0.37)x\log(170/50) \\
&= 12.8 - 1.4 \\
&= 11.4 \text{ decibels.}
\end{aligned}
$$

For the tree zone: The attenuation is estimated to be 5 decibels using Table 6-10. The total shielding is the maximum of the barrier and tree zone shielding, i.e. 11.4 decibels. (Computation results should always be rounded to the nearest decibel at the end of the calculation.)

End of Example 6-5

6.3.3 Combined Propagation Characteristics

The result of combining shielding with geometrical spreading and ground effects involves subtracting the attenuation values obtained from Tables 6-9 and 6-10 from the noise exposure values obtained in Section 6.3.1 at the receiver location.

	$= (L_{dn} or L_{eq})\Big\|_{at\,50\,ft} - 20\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{50}\right) - A_{shielding}$	$\rightarrow$ for stationary sources
L_{dn} or L_{eq}	$= (L_{dn} or L_{eq})\Big\|_{at\,50\,ft} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{42}\right) - A_{shielding}$	$\rightarrow$ for fixed-guideway rail car passbys
	$= (L_{dn} or L_{eq})\Big\|_{at\,50\,ft} - 10\log\left(\frac{D}{50}\right) - 10G\log\left(\frac{D}{29}\right) - A_{shielding}$	$\rightarrow$ for fixed-guideway locomotive and rubber-tired vehicle passbys, highway vehicle passbys and horns

6.4 COMBINED NOISE EXPOSURE FROM ALL SOURCES

Once propagation adjustments have been made for the noise exposure from each source separately, then the sources must be combined to predict the total project noise at the receivers. Table 6-11 contains the equations for combining sources. Total noise exposure is used in Section 6.7 to assess the transit noise at each receiver of interest.

Table 6-11. Computing Total Noise Exposure

Total L_{eq} from All Sources Combined, for the hour of interest:	$L_{eq}(total) = 10\log\left(\sum_{allsources} 10^{L_{eq}/10}\right)$
Total L_{dn} from All sources Combined:	$L_{dn}(total) = 10\log\left(\sum_{allsources} 10^{L_{dn}/10}\right)$

Example 6-6. Computation of Total Exposure from Combined Sources

A commuter train operation produces the following levels at a certain receiver of interest:

L_{eq}(8-9am) = 72 decibels, and
L_{dn} = 68 decibels.

At this same receiver, a light rail system produces the following levels:

L_{eq}(8-9am) = 69 decibels, and
L_{dn} = 70 decibels.

No other project sources affect this receiver. Using Table 6-11, the receiver's total noise exposures are therefore:

L_{eq}(8-9am, total) = 73.8 decibels, and
L_{dn}(total) = 72.1 decibels.

(Computation results should always be rounded to the nearest decibel at the end of the calculation.)

End of Example 6-6

6.5 MAXIMUM NOISE LEVEL FOR FIXED-GUIDEWAY SOURCES

The assessment of noise impact in this manual utilizes either the L_{dn} or the L_{eq} descriptor. As such, in determining impact it is not necessary to determine and tabulate the maximum levels (L_{max}). However, it is often desirable to include computations of L_{max} in environmental documents, particularly for rail projects, because the noise from an individual train passby is quite distinguishable from the existing background noise. The L_{max} is also the descriptor used in vehicle specifications. Because L_{max} represents the sound level heard during a transportation vehicle passby, people can relate this metric with other noise experienced in the environment. Particularly with rail transit projects, it is representative of what people hear at any particular instant and can be measured with a sound level meter. A comparison of L_{max} with other sources can be made by referring to Figure 2-11. Thus, although L_{max} is not used in this manual as a basis for assessing noise impact, it can provide people with a more complete description of the noise effects of a proposed project and should be reported in environmental documents. Equations for computing L_{max} from SEL are given in Appendix F.

6.6 STUDY AREA CHARACTERISTICS

This section contains procedures to estimate existing noise exposure at each receiver of interest identified previously for use in assessing noise impact. Figure 6-8 shows the flow diagram for estimating ambient noise. First decide whether to measure noise exposure, to compute it from partial measurements, or to estimate it from the table provided in this chapter. Different methods may be used at different receivers along the project. Finally, make the measurements, computations or estimates of the ambient noise at each receiver of interest.

6.6.1 Deciding Whether to Measure, Compute, or Estimate

In general, it is better to measure existing noise than to compute or estimate it. Measurements are more precise than computations and estimates and therefore lead to more precise conclusions concerning noise impact. However, measurements are expensive, are often thwarted by weather, and take significant time in the field. So the choice between measurements and computations/estimates is a choice between the precision of measurements and the convenience of computations/estimates. A mixture of these is generally selected, relying on measurements where the greatest precision is needed.

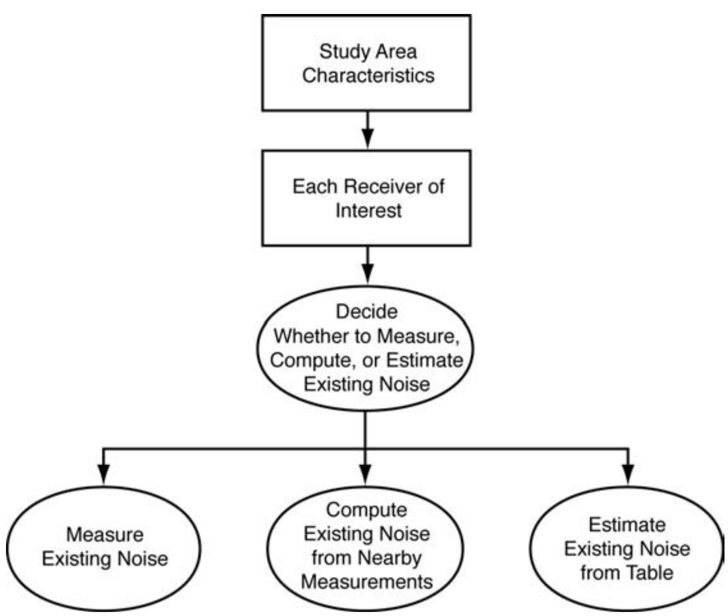


Figure 6-8. Flow Diagram for Determining Existing Noise

A penalty comes along with the convenience of computations and especially of tabular estimates. Because computations/estimates are less precise than measurements, the procedures for them (in Appendix D) are purposely conservative and consequently are inappropriate for the accuracy needed in a Detailed Noise Analysis. When more precise impact projections are desired, measurements must be chosen instead.

The combination of measurements, computations, and estimates depends partly upon the type of land use. For non-residential land uses with daytime use only, it is usually adequate to measure only one hour's ambient L_{eq}, preferably during the hour when project activity is likely to cause the greatest impact. This is relatively easy to measure. On the other hand, in residential areas that are not near major roadways, a full day's ambient L_{dn} is usually required. The following sections describe the approaches to be taken in each case and how to combine the results to characterize the existing ambient conditions.

6.6.2 Noise Exposure Measurements

Full one-hour measurements are the most precise way to determine ambient noise exposure for non-residential receivers. For residential receivers, full 24-hour measurements are most precise. Such full-duration measurements are preferred over other options, where time and study funds allow. The following procedures apply to full-duration measurements:

- For non-residential land uses, measure a full hour's L_{eq} at the receiver of interest, on at least two non-successive weekdays (generally between noon Monday and noon Friday). Select the hour of the day when the maximum project activity is expected to occur.
- For residential land uses, measure a full 24-hours' L_{dn} at the receiver of interest, for a single weekday (generally between noon Monday and noon Friday).
- Use judgment in positioning the measurement microphone. Location of the microphone at the receiver depends upon the proposed location of the transit noise source. If, for example, a new rail line will be in front of the house, do not locate the microphone in the back yard. Figure 6-9 illustrates recommended measurement positions for various locations of the project, with respect to the house and the existing source of ambient noise.
- Undertake all measurements in accordance with good engineering practice following guidelines given in ASTM and ANSI standards.[3,4]

6.6.3 Noise Exposure Computations from Partial Measurements

Often measurements can be made at some of the receivers of interest and then these measurements can be used to estimate noise exposure at nearby receivers. In other situations, several hourly L_{eq}'s can be measured at a receiver and then the L_{dn} computed from these. Both of these options require experience and knowledge of acoustics to select representative measurement sites.

Measurements at one receiver can be used to represent the noise environment at other sites, but only when proximity to major noise sources is similar among the sites. For example, a residential neighborhood with otherwise similar homes may have greatly varying noise environments: one part of the neighborhood may be located where the ambient noise is clearly due to highway traffic; a second part, toward the interior of the neighborhood, may have highway noise as a factor but also a significant contribution from other community noise; and a third part located deep into the residential area will have local street traffic and other community activities dominate the ambient noise. In this example, three or more measurement sites would be required to represent the varying ambient noise conditions in a single neighborhood.

Typical situations where representative measurement sites can be used to estimate noise levels at other sites occur when both share the following characteristics:

- proximity to the same major transportation noise sources, such as highways, rail lines and aircraft flight patterns;

- proximity to the same major stationary noise sources, such as power plants, industrial facilities, rail yards and airports;
- similar type and density of housing, such as single-family homes on quarter-acre lots and multi-family housing in apartment complexes.

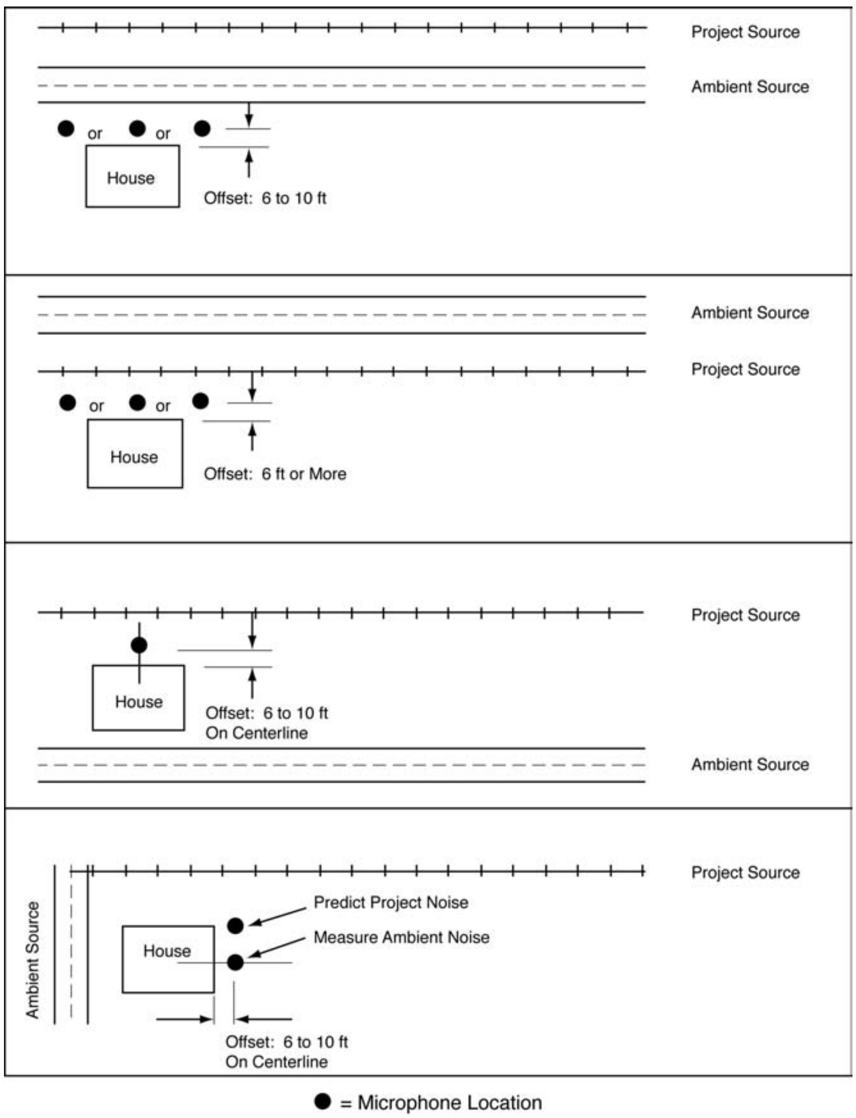


Figure 6-9. Recommended Microphone Locations for Existing Noise Measurements

Acoustical professionals are often adept at such computations from partial data and are encouraged here to use their experience and judgment in fully utilizing the measurements in their computations. Required here is an attempt to somewhat underestimate ambient noise in the process, to account for reduced precision compared to full noise measurements.

On the other hand, people lacking the background in acoustics are encouraged to use the procedures in Appendix D to accomplish this same aim. These procedures are an attempt to systematize such computations from partial measurements. The methods in Appendix D are designed with a safety factor to underestimate ambient noise to account for reduced precision compared to full noise measurements.

6.6.4 Estimating Existing Noise Exposure

The least precise way to determine noise exposure is to estimate it from a table. This method can be used for the General Noise Assessment, but it is not recommended for a Detailed Noise Analysis. However, it can be used in the absence of better data for locations where roadways or railroads are the predominant ambient noise source. Table 5-7 presents these ambient levels. In general, the tabulated values of noise exposure are underestimates. As explained above, underestimates here are intended to compensate for the reduced precision of the estimated ambient levels compared to the options that incorporate full or partial measurements.

Notwithstanding the guidance above, there is one situation where it may be more accurate to estimate rather than measure the existing noise exposure, namely in areas near major airports where aircraft noise is dominant. Because airport noise is highly variable based on weather conditions and corresponding runway usage, it is preferable in such cases to base the existing noise exposure on published aircraft noise contours in terms of Annual Average L_{dn}.

6.7 NOISE IMPACT ASSESSMENT

This section contains procedures for the assessment of project noise impact, utilizing the ambient noise and project noise results from the previous analysis. Two assessment methods are included:

- Rail and Bus Facilities: This category includes all rail projects (e.g., rail rapid transit, light rail transit, commuter rail, and automated guideway transit), as well as fixed facilities such as storage and maintenance yards, passenger stations and terminals, parking facilities, substations, etc. Also included are rail transit projects built within a highway or railroad corridor. Certain bus facilities are included in this category, such as bus rapid transit (BRT) on separate roadways and bus operations on local streets and highways where the project does not include roadway construction or modification that significantly changes roadway capacity. The distinguishing feature in all these cases is that the existing noise levels generated by roadway traffic and other sources will not change as a result of the project; therefore the project noise is exclusively due to the new transit sources. For projects like these, FTA is generally the lead agency and the methodology from this manual is the appropriate approach.
- Highway/Transit Projects: Projects in this category involve transit as part of new highway construction or modifications to existing highways to increase carrying capacity. For these multi-

modal projects, the Federal Highway Administration (FHWA) may be a joint lead agency with FTA, and the State department of transportation (DOT) would probably also be participating in the environmental impact assessment. Projects would involve traffic lanes with preferential treatment for buses or high-occupancy vehicles (HOVs). The distinguishing feature here is that the *project* noise includes a combination of highway and transit sources. Examples are: new highway construction providing general-purpose lanes as well as dedicated bus/HOV lanes and lane additions or reconfigurations on existing highways or arterials to accommodate buses/HOVs. These multi-modal projects fall into two sub-categories and the appropriate method to use for noise prediction and impact assessment depends on whether the highway noise dominates throughout day and night or the transit noise dominates during off-peak and late night hours. If sufficient evidence shows that highway noise dominates, the methods of FHWA, including the latest authorized version of the Traffic Noise Model (TNM), should be used. Otherwise both FHWA and FTA prediction procedures should be used along with both sets of impact assessment criteria since the transit mode's greatest impact will likely not occur during the worst traffic hours.

The factors to consider when deciding which sub-category is appropriate for a given project are given in the beginning of Chapter 3.

6.7.1 Assessment for Rail and Bus Facilities

For these types of projects, noise impact is assessed at each receiver of interest using the criteria for transit projects described in Chapter 3. The assessment procedure is as follows:

1. Tabulate existing ambient noise exposure (rounded to the nearest whole decibel) at all receivers of interest from earlier in the analysis. In cases where large residential buildings are exposed to noise on one side only, the receivers on that side are included in the analysis.

2. Tabulate project noise exposure at these receivers from the analytical procedures described in this chapter.

3. Determine the level of noise impact (No Impact, Moderate Impact or Severe Impact) following the procedures in Chapter 3.

4. Document the results in noise-assessment inventory tables. These tables should include the following types of information:

   - Receiver identification and location
   - Land-use description
   - Number of noise-sensitive sites represented (number of dwelling units in residences or acres of outdoor noise-sensitive land)
   - Closest distance to the project

- Existing noise exposure
- Project noise exposure
- Level of noise impact (No Impact, Moderate Impact, or Severe Impact)

These tables should provide a sum of the total number of receivers, especially numbers of dwelling units, predicted to experience Moderate Impact or Severe Impact.

5. Illustrate the areas of Moderate Impact and Severe Impact on maps or aerial photographs. Two methods of impact display are labeling and contouring. In a Detailed Analysis, the most accurate indication of impact is a label attached to each impacted building or cluster identified in the inventory table. A less precise illustration of impacted areas is a plot of project noise contours on the maps or aerial photographs, along with shaded impact areas. This is done by delineating two impact lines: one between the areas of No Impact and Moderate Impact and the second between Moderate Impact and Severe Impact. Such impact contours would be similar to those estimated in the General Assessment of Chapter 5, but with greater precision. As a cautionary note, it is difficult to position noise contours in urban areas due to shielding, terrain features and other propagation anomalies. If noise contours are used, they should be considered illustrative rather than definitive. If desired to conform with the practices of another agency, the contouring may perhaps include several contour lines of constant project noise, such as L_{dn} 65, L_{dn} 70 and L_{dn} 75.

6. Discussion of the magnitude of the impacts is an essential part of the assessment. The magnitude of noise impact is defined by the two threshold curves delineating onset of Moderate Impact and Severe Impact. Interpretation of the two impact regimes is discussed in Chapter 3.

6.7.2 Assessment for Highway/Transit Projects

For most highway/transit projects where highway noise dominates, the FHWA Noise Abatement Criteria should be used, with the exceptions noted in Chapter 3.(5) In general the appropriate calculation method is the current version of FHWA's Traffic Noise Model (TNM). The TNM was first released by FHWA in April 1998 for use on Federal-aid highway projects.(6) TNM is a state of the art computer program used for predicting noise impacts in the vicinity of highways. TNM Version 2.5 was released in April 2004, which includes updates to the User's Guide and Technical Manual.(7)

The program allows for a detailed assessment at each receiver of interest by separately calculating the noise contribution of each roadway segment. For each roadway segment, the noise from each vehicle type is computed from reference energy-mean emission levels, adjusted for:

- Vehicle volume,
- Vehicle speed,
- Grade,
- Roadway segment length, and

- Source-to-receiver distance.

Further adjustments needed to accurately model the sound propagation from source to receiver include:

- Shielding provided by rows of buildings,
- Effects of different ground types,
- Source and receiver elevations, and
- Effect of any intervening noise barriers.

The program sums the noise contributions of each vehicle type for a given roadway segment at the receiver. TNM then repeats this process for all roadway segments, summing their contributions to generate the predicted noise level at each receiver.

6.8 MITIGATION OF NOISE IMPACT

6.8.1 Noise Mitigation Measures

Where the noise impact assessment shows either Severe Impact or Moderate Impact, this section provides guidance on considering and implementing noise reduction measures. In general, mitigation options are chosen from those below, and then portions of the project noise are recomputed and reassessed to account for this mitigation. This allows an accurate prediction of the level of noise reduction. It is important to emphasize that the source levels used in this manual are typical of systems designed according to current engineering practice, but they do not include special noise control features that could be incorporated in the specifications at extra cost. This approach provides a reasonable analysis of conditions without mitigation measures. If special features that result in noise reductions are included in any of the predictions, then the Federal environmental document must include a commitment by the project sponsor to adopt such treatments before the project is approved for construction. Since cost considerations often play into decisions before committing to mitigation, this manual provides general cost information based on data presented in a Transit Cooperative Research Program (TCRP) report.[8] A detailed discussion of mitigation costs is presented in Chapter 5 of the TCRP report, especially the tables included in Chapter 5.

Mitigation of noise impact from transit projects may involve treatments at the three fundamental components of the noise problem: (1) at the noise source, (2) along the source-to-receiver propagation path or (3) at the receiver. Generally, the transit property has authority to treat the source and some elements of the propagation path, but may have little or no authority to modify anything at the receiver.

A list of practical noise mitigation measures that should be considered by project sponsors is summarized in Table 6-12 and discussion of the measures follows. This table is organized according to whether the treatment applies to the source, path or receiver, and includes estimates of the acoustical effectiveness of each treatment.

6.8.2 Source Treatments

<u>Vehicle Noise Specifications (Rail and Bus)</u>

Among the most effective noise mitigation treatments is noise control at the outset, during the specification and design of the transit vehicle. Such source treatments apply to all transit modes. By developing and enforcing stringent but achievable noise specifications, the transit property takes a major step in controlling noise everywhere on the system. It is important to ensure that the noise levels quoted in the specifications are achievable with the application of best available technology during the development of the vehicle and reasonable in light of the noise reduction benefits and costs.

Effective enforcement includes significant penalties for non-compliance with the specifications. The noise mitigation achieved by source treatment depends on the quality of installation and maintenance. In the past, transit vehicles have been delivered that did not meet a noise specification, causing complaints from the public and requiring additional noise mitigation measures applied to the wayside.

Table 6-12. Transit Noise Mitigation Measures

Application	Mitigation Measure		Effectiveness
SOURCE	Stringent Vehicle & Equipment Noise Specifications		Varied
	Operational Restrictions		Varied
	Resilient or Damped Wheels*	For Rolling Noise on Tangent Track:	2 dB
		For Wheel Squeal on Curved Track:	10-20 dB
	Vehicle Skirts*		6-10 dB
	Undercar Absorption*		5 dB
	Spin-slide control (prevents flats)*		**
	Wheel Truing (eliminates wheel flats)*		**
	Rail Grinding (eliminates corrugations)*		**
	Turn Radii greater than 1000 ft*		(Avoids Squeal)
	Rail Lubrication on Sharp Curves*		(Reduces Squeal)
	Movable-Point Frogs (reduce rail gaps at crossovers)*		(Reduces Impact Noise)
	Engine Compartment Treatments (Buses)		6-10 dB
PATH	Sound Barriers close to Vehicles		6-15 dB
	Sound Barriers at ROW Line		3-10 dB
	Alteration of Horiz. & Vert. Alignments		Varied
	Acquisition of Buffer Zones		Varied
	Ballast on At-Grade Guideway*		3 dB
	Ballast on Aerial Guideway*		5 dB
	Resilient Track Support on Aerial Guideway		Varied
RECEIVER	Acquisition of Property Rights for Construction of Sound Barriers		5-10 dB
	Building Noise Insulation		5-20 dB

* Applies to rail projects only

** These mitigation measures work to maintain a rail system in its as-new condition. Without incorporating them into the system, noise levels could increase up to 10 dB.

Stationary Source Noise Specifications

Stringent but achievable noise specifications also represent an effective approach for mitigating noise impact from stationary sources associated with a transit system. Such equipment includes fixed plant equipment (for example, transformers and mechanical equipment) as well as grade-crossing signals. For example, noise impact from grade-crossing signals can be mitigated by specifying equipment that sets the level of the warning signal lower where ambient noise is lower, that minimizes the signal duration, and that minimizes signal noise in the direction of noise-sensitive receivers.

Wheel Treatments (Rail)

A major source of noise from steel-wheel/steel-rail systems is the wheel/rail interaction which has three components: roar, impact and squeal. Roar is the rolling noise caused by small-scale roughness on the wheel tread and rail running surface. Impacts are caused by discontinuities in the running surface of the rail or by a flat spot on the wheels. Squeal occurs when a steel-wheel tread or its flange rubs across the rail, setting up resonant vibrations in the wheel which cause it to radiate a screeching sound. Various wheel designs and other mitigation measures exist to reduce the noise from each of these three mechanisms.

- **Resilient wheels** serve to reduce rolling noise, but only slightly. A typical reduction is 2 decibels on tangent track. This treatment is more effective in eliminating wheel squeal on tight turns; reductions of 10 to 20 decibels for high-frequency squeal noise are typical. The costs for resilient wheels are approximately $3000 per wheel, in comparison to about $700 for standard steel wheels.

- **Damped wheels,** like resilient wheels, serve to reduce rolling noise, but only slightly. A typical reduction is 2 decibels on tangent track. This treatment involves attaching vibration absorbers to standard steel wheels. Damping is effective in eliminating wheel squeal on tight turns; reductions of 5 to 15 decibels for high-frequency squeal noise are typical. The costs for damped wheels add approximately $500 to $1000 to the normal $700 for each steel wheel.

- **Spin-slide control systems,** similar to anti-locking brake systems (ABS) on automobiles, reduce the incidence of wheel flats, a major contributor of impact noise. Trains with smooth wheel treads can be up to 20 decibels quieter than those with wheel flats. To be effective, the anti-locking feature should be in operation during all braking phases, including emergency braking. Wheel flats are more likely to occur during emergency braking than during dynamic braking. The cost of slip-slide control may be incorporated in the new vehicle costs, but may be between $5,000 and $10,000 per vehicle.

- **Maintenance** of wheels by truing eliminates wheel flats from the treads and restores the wheel profile. As discussed above, wheel flats are a major source of impact noise. A good maintenance program includes the installation of equipment to detect and correct wheel flats on a continuing basis. Costs vary according to transit property practices, but the TCRP report identifies a cost for truing wheels at $60 per wheelset.

Vehicle Treatments (Rail and Bus)

Vehicle noise mitigation measures are applied to the various mechanical systems associated with propulsion, ventilation and passenger comfort.

- **Propulsion systems** of transit vehicles include diesel engines, electric motors and diesel-electric combinations. Noise from the propulsion system depends on the type of unit and how much noise mitigation is built into the design. Mufflers on diesel engines are generally required to meet noise specifications; however, mufflers are generally practical only on buses, not on locomotives. Control of noise from engine casings may require shielding the engine by body panels without louvers, dictating other means of cooling and ventilation.
- **Ventilation** requirements for vehicle systems are related to the noise generated by a vehicle. Fan noise often remains a major noise source after other mitigation measures have been instituted because of the need to have direct access to cooling air. This applies to heat exchangers for electric traction motors, diesel engines and air-conditioning systems. Fan-quieting can be accomplished by installation of one of several new designs of quiet, efficient fans. Forced-air cooling on electric traction motors can be quieter than self-cooled motors at operating speeds. Placement of fans on the vehicle can make a significant difference in the noise radiated to the wayside or to patrons on the station platforms.
- The **vehicle body** design can provide shielding and absorption of the noise generated by the vehicle components. Acoustical absorption under the car has been demonstrated to provide up to 5 decibels of mitigation for wheel/rail noise and propulsion-system noise on rapid transit trains. Similarly, vehicle skirts over the wheels can provide more than 5 decibels of mitigation. By carrying their own noise barriers, vehicles with these features can provide cost-effective noise reduction.

Use of Locomotive Horns at Grade Crossings

In cases where commuter rail operations share tracks or rights-of-way with freight or intercity passenger trains that are part of the "general railroad system," the safety rules of the Federal Railroad Administration (FRA) apply. In particular, the rule for the use of locomotive horns at highway-rail grade crossings is in effect.[9] This rule requires generally that horns be sounded at public road crossings, although some exceptions are allowed in carefully defined circumstances. One exception enables the establishment of a "quiet zone" in which certain supplemental safety measures (SSM's) are used in place of the locomotive horn to provide an equivalent level of safety at grade crossings. By adopting an approved SSM at each public grade crossing, a quiet zone of at least a half-mile long can be established. These measures are in addition to the standard safety devices required at most public grade crossings (e.g., stop signs, reflectorized crossbucks, flashing lights with gates that do not completely block travel over the tracks). Below are four SSM's which have been predetermined by the FRA to fully compensate for the lack of a locomotive horn:

- Temporary closure of a public highway-rail grade crossing. This measure requires closure of the grade crossing one period for each 24 hours, and must be closed the same time each day.

- Four-quadrant gate system. This measure involves the installation of at least one gate for each direction of traffic to fully block vehicles from entering the crossing.
- Gates with medians or channelization devices. This measure keeps traffic in the proper travel lanes as it approaches the crossing. This denies the driver the option of circumventing the gates by traveling in the opposing lane.
- One-way street with gates. This measure consists of one-way streets with gates installed so that all approaching travel lanes are completely blocked.

In addition to the pre-approved SSM's, the FRA rule also identifies a range of other measures that may be used in establishing a quiet zone. These could be modified SSM's or non-engineering types of measures, such as increased monitoring by law enforcement for grade crossing violations or instituting public education and awareness programs that emphasize the risks associated with grade crossings and applicable requirements. These alternative safety measures (ASMs) require approval by FRA based on a demonstration that public safety would not be compromised by eliminating the horn.

Locomotive horns are quite loud, and horn noise is often the major contributor in projections of adverse noise impact in the community from proposed commuter rail projects. Since sound barriers are not feasible at highway-rail grade crossings, the establishment of quiet zones may be an attractive option. The lead agency in designating a quiet zone is the local public authority responsible for traffic control and law enforcement on the roads crossing the tracks. In order to satisfy the FRA regulatory requirements, the public transit agency must work closely with this agency while also coordinating with any freight or passenger railroad operator sharing the right-of-way. Depending on the circumstances, establishment of a quiet zone would probably not be completed in the time frame of the environmental review process. However, as with other types of mitigation, the final environmental document should discuss the main considerations in adopting the quiet zone, for example, engineering feasibility, receptiveness of the local public authority, consultation with the railroad, preliminary cost estimates, etc., and show evidence of the planning and interagency coordination that has occurred to date. If a quiet zone will be relied on as a mitigation measure, the final environmental document should provide reasonable assurance that any remaining issues can and will be resolved.

The cost of establishing a quiet zone varies considerably, depending on the number of intersections that must be treated and the specific SSM's, ASM's, or combination of measures that are used. The FRA gives a cost estimate of $15,000 per crossing for installing two 100-foot-long non-traversable medians that prevent motorists from driving around closed gates. A typical installation of a four-quadrant gate system is in the range of $175,000-$300,000 per crossing. Who pays for the installation of modifications can become a major consideration in a decision to pursue a quiet zone designation, especially in cases where noise from preexisting railroad operations has been a sore point in the community. In cases where a quiet zone would mitigate a Severe Impact situation brought about by the proposed transit project, the costs would be borne by the local transit agency and FTA in the same proportion as the overall cost-sharing for the project.

Guideway Support (Bus and Rail)

The smoothness of the running surface is critical in the mitigation of noise from a moving vehicle. Smooth roadways for buses and smooth rail running surfaces for rail systems are required. In either case, roughness of the street, roadway and rail surfaces can be eliminated by resurfacing roads or grinding rails, thereby reducing noise levels by up to 10 decibels. Bridge expansion joints are also a source of noise for rubber-tire vehicles. This source of noise can be reduced by placing expansion joints on an angle or by specifying the serrated type rather than joints with right-angle edges.

In the case of steel-wheel/steel-rail systems with non-steerable trucks and sharp turns, squeal can be mitigated by installation of rail lubricators. Squeal in such systems can usually be eliminated altogether by designing all turn radii to be greater than 1000 feet, or 100 times the truck wheelbase, whichever is less.

Operational Restrictions (Rail and Bus)

Two changes in operations that can mitigate noise are the lowering of speed and the reduction of nighttime (10 pm to 7 am) operations. Because noise from most transit vehicles depends on speed, a reduction of speed results in lower noise levels. The effect can be considerable. For example, the speed dependency of steel-wheel/steel-rail systems for L_{eq} and L_{dn} (see Table 6-4) results in a 6 dB reduction for a halving of the speed. Complete elimination of nighttime operations has a strong effect on reducing the L_{dn}, because nighttime noise is increased by 10 decibels when calculating L_{dn}. Restrictions on operations are usually not feasible because of service demands, and FTA does not pursue restrictions on operations as a noise reduction measure. However, if early morning idling can be curtailed to the minimum necessary, this can have a measurable effect on L_{dn}.

Other operational restrictions that can reduce noise impact for light rail and commuter rail systems include minimizing or eliminating horn blowing and other types of warning signals at grade crossings. While these mitigation options are limited by safety considerations, they can be effective in the right circumstances and they are discussed elsewhere in this section (e.g., wayside horns).

6.8.3 Path Treatments

Sound Barriers

Sound barriers are effective in mitigating noise when they break the line-of-sight between source and receiver. The mechanism of sound shielding is described in Chapter 2. The necessary height of a barrier depends on such factors as the source height and the distance from the source to the barrier. For example, if a barrier is located very close to a rapid transit train, it need only be 3 to 4 feet above the top of rail to be effective. Barriers close to vehicles can provide noise reductions of 6 to 10 decibels. For barriers further away, such as on the right-of-way line or for trains on the far track, the height must be increased to provide equivalent effectiveness. Otherwise, the effectiveness can drop to 5 decibels or less, even if the barrier breaks the line-of-sight. Where the barrier is very close to the transit vehicle or where the vehicles travel between sets of parallel barriers, barrier effectiveness can be increased by as much as 5 decibels by applying sound-absorbing material to the inner surface of the barrier.

Similarly, the length of the barrier wall is important to its effectiveness. The barrier must be long enough to screen out a moving train along most of its visible path. This is necessary so that train noise from beyond the ends of the barrier will not severely compromise noise-barrier performance at sensitive locations.

Noise barriers can be made of any outdoor weather-resistant solid material that meets a minimum sound transmission loss requirement. The sound requirements are not particularly strict; they can be met by many commonly available materials, such as 16-gauge steel, 1-inch thick plywood, and any reasonable thickness of concrete. The normal minimum requirement is a surface density of 4 pounds per square foot. To hold up under wind loads, structural requirements are more stringent. Achieving the maximum possible noise reduction requires careful sealing of gaps between barrier panels and between the barrier and the ground or elevated guideway deck.

Costs for noise barriers, based on highway installations, range from $25 to $35 per square foot of installed noise barrier at-grade, not counting design and inspection costs(10). Installation on aerial structure may be a factor of two greater, especially if the structure has to be strengthened to accommodate the added weight and wind load.

Location of a transit alignment in cut, as part of grade separation, can accomplish the same result as installation of a noise barrier at-grade or on aerial structure. The walls of the cut serve the same function as barrier walls in breaking the line-of-sight between source and receiver.

Wayside Horns

The sounding of a locomotive horn as the train approaches an at-grade intersection produces a very wide noise "footprint" in the community. Using wayside horns at the intersection instead of the locomotive horn has been shown to substantially reduce the noise footprint without compromising safety at the grade crossing. A wayside horn does not need to be as loud as a locomotive horn, but the real advantage is the focusing of the warning sound only on the area where it is needed. These are pole-mounted horns used in conjunction with flashing lights and gates at the intersection, with a separate horn oriented toward each direction of oncoming vehicle traffic. Field tests have shown that noise levels in nearby residential and business areas can be reduced significantly with wayside horns, depending on the location with respect to the grade crossing.

A plan to use wayside horns in place of the locomotive horn at public grade crossings must be coordinated with several public and private entities, notably the local agency having responsibility for traffic control and law enforcement on the road crossings, the state agency responsible for railroad safety, any railroads that share the right-of-way, and FRA. Public notification must also be given.

Preliminary cost information from testing programs indicates a wayside horn system at a railroad/ highway grade crossing costs approximately $50,000.

Noise Buffers

Because noise levels attenuate with distance, one noise mitigation measure is to increase the distance between noise sources and the closest sensitive receivers. This can be accomplished by locating alignments away from sensitive sites. Acquisition of land or purchasing easements for noise buffer zones is an option that may be considered if impacts due to the project are severe enough.

Ground Absorption

Propagation of noise over ground is affected by whether the ground surface is absorptive or reflective. Noise from vehicles on the surface is strongly affected by the character of the ground in the immediate vicinity of the vehicle. Roads and streets for buses are hard and reflective, but the ground at the side of a road has a significant effect on the propagation of noise to greater distance. This effect is described in Chapter 2 and taken into account in the computations of this chapter. Guideways for rail systems can be either reflective or absorptive, depending on whether they are concrete or ballast. Ballast on a guideway can reduce train noise 3 decibels at-grade and up to 5 decibels on aerial structure.

6.8.4 Receiver Treatments

Sound Barriers

In certain cases it may be possible to acquire limited property rights for the construction of sound barriers at the receiver. As discussed above, barriers need to break the line-of-sight between the noise source and the receiver to be effective and are most effective when they are closest to either the source or the receiver. Computational procedures for estimating barrier effectiveness are given earlier in this chapter.

Building Insulation

In cases where sound barriers are not feasible, such as multi-story buildings, buildings very close to the rights-of-way, or grade crossings, the only practical noise mitigation measure may be to provide sound insulation for the buildings. Effective treatments include caulking and sealing gaps in the building façade, and installation of new doors and windows that are specially designed to meet acoustical transmission-loss requirements. Exterior doors facing the noise source should be replaced with well-gasketed, solid-core wood doors and well-gasketed storm doors. Acoustical windows are usually made of multiple layers of glass with air spaces between to provide noise reduction. Acoustical performance ratings are published in terms of “Sound Transmission Class” (STC) for these special windows. A minimum STC rating of 39 should be used on any window exposed to the noise source. These treatments are beneficial for heat insulation as well as for sound insulation. As an added consideration for costs, however, acoustical windows are usually non-operable so that central ventilation or air conditioning is needed.

Additional building sound insulation, if needed, can be provided by sealing vents and ventilation openings and relocating them to a side of the building away from the noise source. In cases where low frequency noise from diesel locomotives is the problem, it may be necessary to increase the mass of the building façade of wood frame houses by adding a layer of sheathing to the exterior walls.

Criteria for Interior Noise Levels. Depending on the quality of the original building façade, especially windows and doors, sound insulation treatments can improve the noise reductions from transit noise by 5 to 20 dBA. In order to be considered cost-effective, a treatment should provide a minimum of 5 dBA reduction in the interior of the building and provide an interior noise level of 65 dBA or less from transit sources. In homes where noise impact from train horns is identified, the sound insulation should provide sufficient noise reduction such that horn noise inside the building is 70 dBA or less.

Examples of residential sound insulation for rail or highway projects are limited. However, much practical experience with sound insulation of buildings has been gained through grants for noise mitigation to local airport authorities by the Federal Aviation Administration (FAA). Based on FAA experience, a typical single-family home can be fitted for sound insulation for costs ranging from $25,000 to $50,000.

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7. BASIC GROUND-BORNE VIBRATION CONCEPTS

Ground-borne vibration can be a serious concern for nearby neighbors of a transit system route or maintenance facility, causing buildings to shake and rumbling sounds to be heard. In contrast to airborne noise, ground-borne vibration is not a common environmental problem. It is unusual for vibration from sources such as buses and trucks to be perceptible, even in locations close to major roads. Some common sources of ground-borne vibration are trains, buses on rough roads, and construction activities such as blasting, pile-driving and operating heavy earth-moving equipment.

The effects of ground-borne vibration include feelable movement of the building floors, rattling of windows, shaking of items on shelves or hanging on walls, and rumbling sounds. In extreme cases, the vibration can cause damage to buildings. Building damage is not a factor for normal transportation projects, with the occasional exception of blasting and pile-driving during construction. Annoyance from vibration often occurs when the vibration exceeds the threshold of perception by only a small margin. A vibration level that causes annoyance will be well below the damage threshold for normal buildings.

The basic concepts of ground-borne vibration are illustrated for a rail system in Figure 7-1. The train wheels rolling on the rails create vibration energy that is transmitted through the track support system into the transit structure. The amount of energy that is transmitted into the transit structure is strongly dependent on factors such as how smooth the wheels and rails are and the resonance frequencies of the vehicle suspension system and the track support system. These systems, like all mechanical systems, have resonances which result in increased vibration response at certain frequencies, called natural frequencies.

The vibration of the transit structure excites the adjacent ground, creating vibration waves that propagate through the various soil and rock strata to the foundations of nearby buildings. The vibration propagates from the foundation throughout the remainder of the building structure. The maximum vibration amplitudes of the floors and walls of a building often will be at the resonance frequencies of various components of the building.

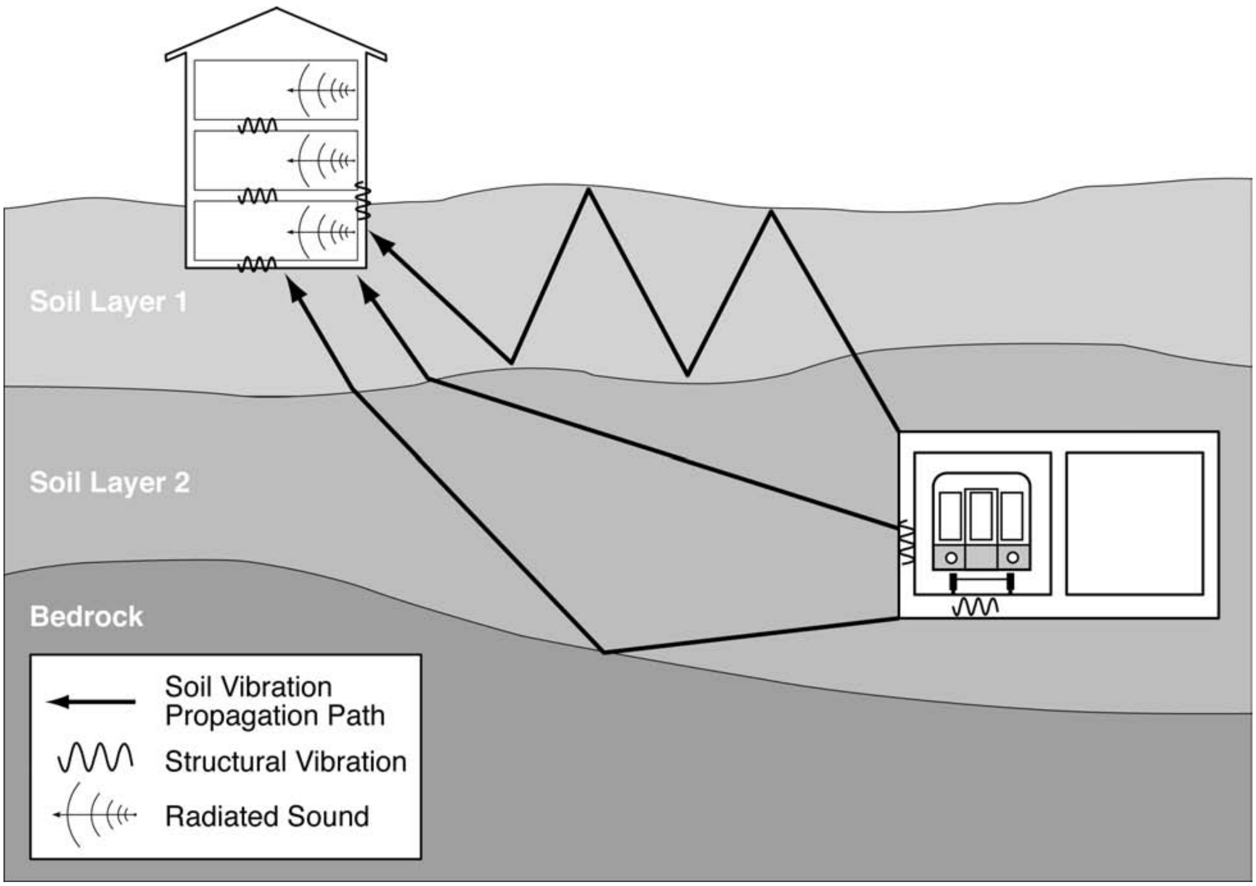

Figure 7-1. Propagation of Ground-Borne Vibration into Buildings

The vibration of floors and walls may cause perceptible vibration, rattling of items such as windows or dishes on shelves, or a rumble noise. The rumble is the noise radiated from the motion of the room surfaces. In essence, the room surfaces act like a giant loudspeaker causing what is called ground-borne noise.

Ground-borne vibration is almost never annoying to people who are outdoors. Although the motion of the ground may be perceived, without the effects associated with the shaking of a building, the motion does not provoke the same adverse human reaction. In addition, the rumble noise that usually accompanies the building vibration is perceptible only inside buildings.

7.1 DESCRIPTORS OF GROUND-BORNE VIBRATION AND NOISE

7.1.1 Vibratory Motion

Vibration is an oscillatory motion which can be described in terms of the displacement, velocity, or acceleration. Because the motion is oscillatory, there is no net movement of the vibration element and the average of any of the motion descriptors is zero. Displacement is the easiest descriptor to understand. For a vibrating floor, the displacement is simply the distance that a point on the floor moves away from its static position. The velocity represents the instantaneous speed of the floor movement and acceleration is the rate of change of the speed.

Although displacement is easier to understand than velocity or acceleration, it is rarely used for describing ground-borne vibration. Most transducers used for measuring ground-borne vibration use either velocity or acceleration. Furthermore, the response of humans, buildings, and equipment to vibration is more accurately described using velocity or acceleration.

7.1.2 Amplitude Descriptors

Vibration consists of rapidly fluctuating motions with an average motion of zero. Several descriptors can be used to quantify vibration amplitude, three of which are shown in Figure 7-2. The raw signal is the lighter-weight curve in the top graph. This curve shows the instantaneous vibration velocity which fluctuates positive and negative about the zero point. The peak particle velocity (PPV) is defined as the maximum instantaneous positive or negative peak of the vibration signal. PPV is often used in monitoring of blasting vibration since it is related to the stresses that are experienced by buildings.

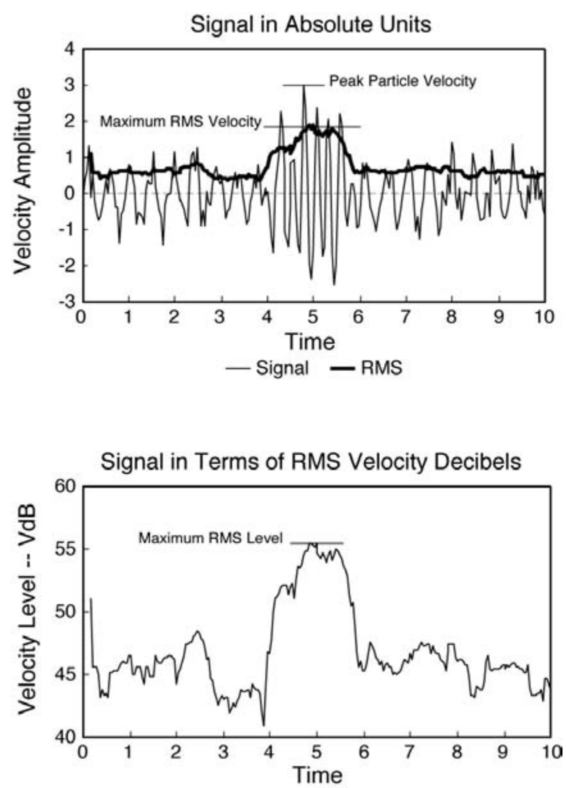

Figure 7-2. Different Methods of Describing a Vibration Signal

Although peak particle velocity is appropriate for evaluating the potential of building damage, it is not suitable for evaluating human response. It takes some time for the human body to respond to vibration signals. In a sense, the human body responds to an average vibration amplitude. Because the net average of a vibration signal is zero, the root mean square (rms) amplitude is used to describe the "smoothed" vibration amplitude. The root mean square of a signal is the square root of the average of the squared amplitude of the signal. The average is typically calculated over a one-second period. The rms amplitude is shown superimposed on the vibration signal in Figure 7-2. The rms amplitude is always less than the PPV* and is always positive.

The PPV and rms velocity are normally described in inches per second in the USA and meters per second in the rest of the world. Although it is not universally accepted, decibel notation is in common use for vibration.

Decibel notation acts to compress the range of numbers required to describe vibration. The bottom graph in Figure 7-2 shows the rms curve of the top graph expressed in decibels. Vibration velocity level in decibels is defined as:

$$L_v = 20 \times \log_{10}\left(\frac{v}{v_{ref}}\right)$$

where "L_v" is the velocity level in decibels, "v" is the rms velocity amplitude, and "v_{ref}" is the reference velocity amplitude. A reference must always be specified whenever a quantity is expressed in terms of decibels. The accepted reference quantities for vibration velocity are 1×10^{-6} inches/second in the USA and either 1×10^{-8} meters/second or 5×10^{-8} meters/second in the rest of the world. Because of the variations in the reference quantities, it is important to be clear about what reference quantity is being used whenever velocity levels are specified. ***All** vibration levels in this manual are referenced to 1×10^{-6} in./sec.* Although not a universally accepted notation, the abbreviation "VdB" is used in this document for vibration decibels to reduce the potential for confusion with sound decibels.

7.1.3 Ground-Borne Noise

As discussed above, the rumbling sound caused by the vibration of room surfaces is called ground-borne noise. The annoyance potential of ground-borne noise is usually characterized with the A-weighted sound level. Although the A-weighted level is almost the only metric used to characterize community noise, there are potential problems when characterizing low-frequency noise using A-weighting. This is because of the non-linearity of human hearing which causes sounds dominated by low-frequency components to seem louder than broadband sounds that have the same A-weighted level. The result is that ground-borne noise with a level of 40 dBA sounds louder than 40 dBA broadband noise. This is accounted for by setting the limits for ground-borne noise lower than would be the case for broadband noise.

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*The ratio of PPV to maximum rms amplitude is defined as the **crest factor** for the signal. The crest factor is always greater than 1.71, although a crest factor of 8 or more is not unusual for impulsive signals. For ground-borne vibration from trains, the crest factor is usually 4 to 5.

7.2 HUMAN PERCEPTION OF GROUND-BORNE VIBRATION AND NOISE

This section gives some general background on human response to different levels of building vibration, laying the groundwork for the criteria for ground-borne vibration and noise that are presented in Chapter 8.

7.2.1 Typical Levels of Ground-Borne Vibration and Noise

In contrast to airborne noise, ground-borne vibration is not a phenomenon that most people experience every day. The background vibration velocity level in residential areas is usually 50 VdB or lower, well below the threshold of perception for humans which is around 65 VdB. Most perceptible indoor vibration is caused by sources within buildings such as operation of mechanical equipment, movement of people or slamming of doors. Typical outdoor sources of perceptible ground-borne vibration are construction equipment, steel-wheeled trains, and traffic on rough roads. If the roadway is smooth, the vibration from traffic is rarely perceptible.

Figure 7-3 illustrates common vibration sources and the human and structural response to ground-borne vibration. The range of interest is from approximately 50 VdB to 100 VdB. Background vibration is usually well below the threshold of human perception and is of concern only when the vibration affects very sensitive manufacturing or research equipment. Electron microscopes and high-resolution lithography equipment are typical of equipment that is highly sensitive to vibration.

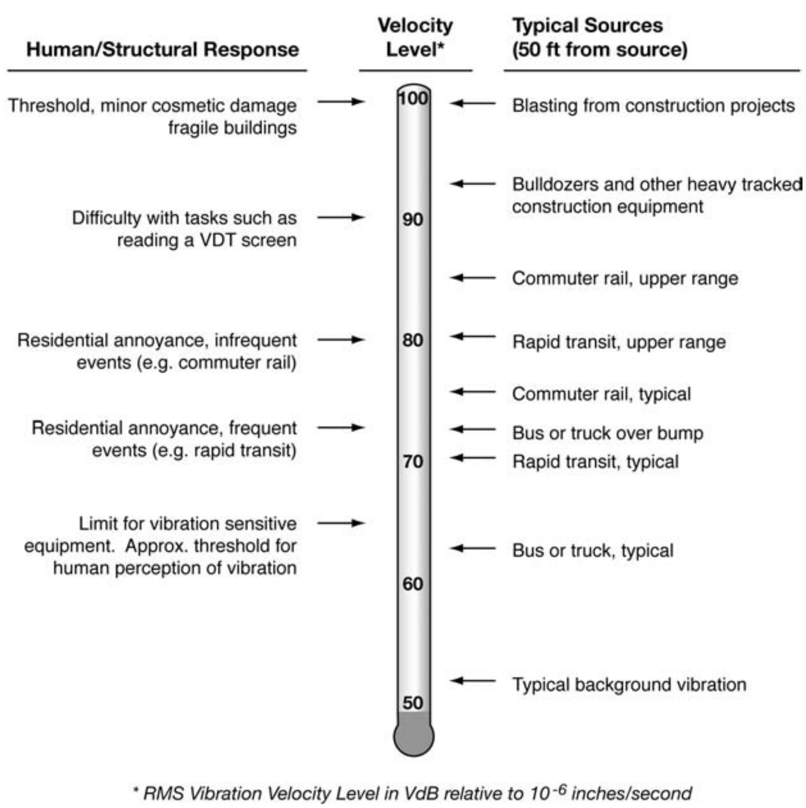

Figure 7-3. Typical Levels of Ground-Borne Vibration

Although the perceptibility threshold is about 65 VdB, human response to vibration is not usually significant unless the vibration exceeds 70 VdB. Rapid transit or light rail systems typically generate vibration levels of 70 VdB or more near their tracks. On the other hand, buses and trucks rarely create vibration that exceeds 70 VdB unless there are bumps in the road. Because of the heavy locomotives on diesel commuter rail systems, the vibration levels average about 5 to 10 decibels higher than rail transit vehicles. If there is unusually rough road or track, wheel flats, geologic conditions that promote efficient propagation of vibration, or vehicles with very stiff suspension systems, the vibration levels from any source can be 10 decibels higher than typical. Hence, at 50 feet, the upper range for rapid transit vibration is around 80 VdB and the high range for commuter rail vibration is 85 VdB. If the vibration level in a residence reaches 85 VdB, most people will be strongly annoyed by the vibration.

The relationship between ground-borne vibration and ground-borne noise depends on the frequency content of the vibration and the acoustical absorption of the receiving room. The more acoustical absorption in the room, the lower will be the noise level. For a room with average acoustical absorption, the unweighted sound pressure level is approximately equal to the average vibration velocity level of the room surfaces.[*] Hence, the A-weighted level of ground-borne noise can be estimated by applying A-weighting to the vibration velocity spectrum. Since the A-weighting at 31.5 Hz is -39.4 dB, if the vibration spectrum peaks at 30 Hz, the A-weighted sound level will be approximately 40 decibels lower than the velocity level. Correspondingly, if the vibration spectrum peaks at 60 Hz, the A-weighted sound level will be about 25 decibels lower than the velocity level.

7.2.2 Quantifying Human Response to Ground-Borne Vibration and Noise

One of the major problems in developing suitable criteria for ground-borne vibration is that there has been relatively little research into human response to vibration, in particular, human annoyance with building vibration. The American National Standards Institute (ANSI) developed criteria for evaluation of human exposure to vibration in buildings in 1983[(1)] and the International Organization for Standardization (ISO) adopted similar criteria in 1989[(2)] and revised them in 2003 [(3)]. The 2003 version of ISO 2361-2 acknowledges that "human response to vibration in buildings is very complex." It further indicates that the degree of annoyance can not always be explained by the magnitude of the vibration alone. In some cases the complaints are associated with measured vibration that is lower than the perception threshold. Other phenomena such as ground-borne noise, rattling, visual effects such as movement of hanging objects, and time of day (e.g., late at night) all play some role in the response of individuals. To understand and evaluate human response, which is often measured by complaints, all of these related effects need to be considered. The available data documenting real world experience with these phenomena is still relatively sparse. Experience with U.S. rapid transit projects represents a good foundation for developing suitable limits for residential exposure to ground-borne vibration and noise from transit operations.

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[*]The sound level approximately equals the average vibration velocity level *only* when the velocity level is referenced to 1 micro-inch/second. When velocity level is expressed using the international standard of 1×10^{-8} m/sec, the sound level is approximately 8 decibels lower than the average velocity level.

Figure 7-4 illustrates the relationship between the vibration velocity level measured in 22 homes and the general response of the occupants to the vibration. The data shown were assembled from measurements performed for several transit systems along with subjective ratings by the researchers and residents. These data were previously published in the "State-of-the-Art Review of Ground-borne Noise and Vibration."[4] Both the occupants and the people who performed the measurements agreed that floor vibration in the "Distinctly Perceptible" category was unacceptable for a residence. The data in Figure 7-4 indicate that residential vibration exceeding 75 VdB is unacceptable for a repetitive vibration source such as rapid transit trains that pass every 5 to 15 minutes. Also shown in Figure 7-4 is a curve showing the percent of people annoyed by vibration from high-speed trains in Japan.[5] The scale for the percent annoyed is on the right-hand axis of the graph. The results of the Japanese study confirm the conclusion that at a vibration velocity level of 75 to 80 VdB, many people will find the vibration annoying.

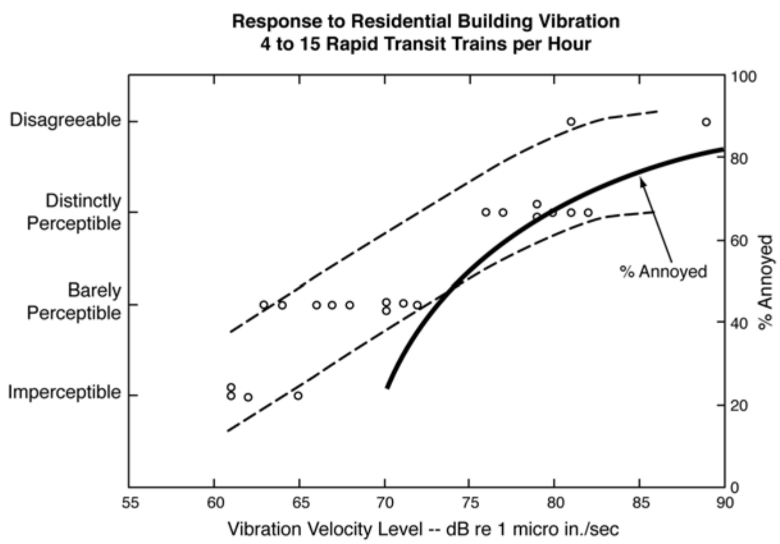

Figure 7-4. Response to Transit-induced Residential Vibration

Table 7-1 describes the human response to different levels of ground-borne noise and vibration. The first column is the vibration velocity level, and the next two columns are for the corresponding noise level assuming that the vibration spectrum peaks at 30 Hz or 60 Hz. As discussed above, the A-weighted noise level will be approximately 40 dB less than the vibration velocity level if the spectrum peak is around 30 Hz, and 25 dB lower if the spectrum peak is around 60 Hz. Table 7-1 illustrates that achieving either the acceptable vibration or acceptable noise levels does not guarantee that the other will be acceptable. For example, the noise caused by vibrating structural components may be very annoying even though the vibration cannot be felt. Alternatively, a low-frequency vibration could be annoying while the ground-borne noise level it generates is acceptable.

Table 7-1. Human Response to Different Levels of Ground-Borne Noise and Vibration

Vib. Velocity Level	Noise Level		Human Response
	Low Freq1	Mid Freq2	
65 VdB	25 dBA	40 dBA	Approximate threshold of perception for many humans. Low-frequency sound usually inaudible, mid-frequency sound excessive for quiet sleeping areas.
75 VdB	35 dBA	50 dBA	Approximate dividing line between barely perceptible and distinctly perceptible. Many people find transit vibration at this level annoying. Low-frequency noise acceptable for sleeping areas, mid-frequency noise annoying in most quiet occupied areas.
85 VdB	45 dBA	60 dBA	Vibration acceptable only if there are an infrequent number of events per day. Low-frequency noise annoying for sleeping areas, mid-frequency noise annoying even for infrequent events with institutional land uses such as schools and churches.

Notes:
1. Approximate noise level when vibration spectrum peak is near 30 Hz.
2. Approximate noise level when vibration spectrum peak is near 60 Hz.

7.3 GROUND-BORNE VIBRATION FOR DIFFERENT TRANSIT MODES

This section provides a brief discussion of typical problems with ground-borne vibration and noise for different modes of transit.

- **Steel-Wheel Urban Rail Transit:** This category includes both heavy rail transit and light rail transit. Heavy rail is generally defined as electrified rapid transit trains with dedicated guideway, and light rail as electrified transit trains that do not require dedicated guideway. The ground-borne vibration characteristics of heavy and light rail vehicles are very similar since they have similar suspension systems and axle loads. Most of the studies of ground-borne vibration in this country have focused on urban rail transit. Problems with ground-borne vibration and noise are common when there is less than 50 feet between a subway structure and building foundations. Whether the problem will be perceptible vibration or audible noise is strongly dependent on local geology and the structural details of the building. Complaints about ground-borne vibration from surface track are more common than complaints about ground-borne noise. A significant percentage of complaints about both ground-borne vibration and noise can be attributed to the proximity of special trackwork, rough or corrugated track, or wheel flats.

- **Commuter and Intercity Passenger Trains:** This category includes passenger trains powered by either diesel or electric locomotives. In terms of vibration effects at a single location, the major difference between commuter and intercity passenger trains is that the latter are on a less frequent schedule. Both often share track with freight trains, which have quite different vibration characteristics as discussed below. The locomotives usually create the highest vibration levels. There is the potential of vibration-related problems anytime that new commuter or intercity rail passenger service is introduced in an urban or suburban area.

- **High-Speed Passenger Trains:** High-speed passenger trains have the potential of creating high levels of ground-borne vibration. Ground-borne vibration should be anticipated as one of the major environmental impacts of any high-speed train located in an urban or suburban area. The Amtrak trains on the Northeast Corridor between Boston and Washington, D.C., which attain moderate to high speeds in some sections with improved track, fit into this category.

- **Freight Trains:** Local and long-distance freight trains are similar in that they both are diesel-powered and have the same types of cars. They differ in their overall length, number and size of locomotives, and number of heavily loaded cars. Locomotives and rail cars with wheel flats are the sources of the highest vibration levels. Because locomotive suspensions are similar, the maximum vibration levels of local and long-distance freights are similar. It is not uncommon for freight trains to be the source of intrusive ground-borne vibration. Most railroad tracks used for freight lines were in existence for many years before the affected residential areas were developed. Vibration from freight trains can be a consideration for FTA-assisted projects when a new transit line will share an existing freight train right-of-way. Relocating the freight tracks within the right-of-way to make room for the transit tracks must be considered a direct impact of the transit system which must be evaluated as part of the proposed project. However, vibration mitigation is very difficult to implement on tracks where trains with heavy axle loads will be operating.

- **Automated Guideway Transit Systems (AGT):** This transit mode encompasses a wide range of transportation vehicles providing local circulation in downtown areas, airports and theme parks. In general, ground-borne vibration can be expected to be generated by steel-wheel/steel-rail systems even when limited in size. Because AGT systems normally operate at low speeds, have lightweight vehicles, and rarely operate in vibration-sensitive areas, ground-borne vibration problems are very rare.

- **Bus Projects:** Because the rubber tires and suspension systems of buses provide vibration isolation, it is unusual for buses to cause ground-borne noise or vibration problems. When buses cause effects such as rattling of windows, the source is almost always airborne noise. Most problems with bus-related vibration can be directly related to a pothole, bump, expansion joint, or other discontinuity in the road surface. Smoothing the bump or filling the pothole will usually solve the problem. Problems are likely when buses will be operating inside buildings. Intrusive building vibration can be caused by sudden loading of a building slab by a heavy moving vehicle or by vehicles running over lane divider bumps. A bus transfer station with commercial office space in the same building may have annoying vibration within the office space caused by bus operations.

7.4 FACTORS THAT INFLUENCE GROUND-BORNE VIBRATION AND NOISE

One of the major problems in developing accurate estimates of ground-borne vibration is the large number of factors that can influence the levels at the receiver position. This section gives a general appreciation of which factors have significant effects on the levels of ground-borne vibration. Table 7-2 is a summary of some of the many factors that are known to have, or are suspected of having, a significant influence on the levels of ground-borne vibration and noise. As indicated, the physical parameters of the transit facility, the geology, and the receiving building all influence the vibration levels. The important physical parameters can be divided into the following four categories:

- **Operational and Vehicle Factors:** This category includes all of the parameters that relate to the vehicle and operation of the trains. Factors such as high speed, stiff primary suspensions on the vehicle, and flat or worn wheels will increase the possibility of problems from ground-borne vibration.

- **Guideway:** The type and condition of the rails, the type of guideway, the rail support system, and the mass and stiffness of the guideway structure will all have an influence on the level of ground-borne vibration. Jointed rail, worn rail, and wheel impacts at special trackwork can all cause substantial increases in ground-borne vibration. A rail system guideway will be either subway, at-grade, or elevated. It is rare for ground-borne vibration to be a problem with elevated railways except when guideway supports are located within 50 feet of buildings. For guideways at-grade, directly radiated noise is usually the dominant problem, although vibration can be a problem. For subways, ground-borne vibration is often one of the most important environmental problems. For rubber-tired systems, the smoothness of the roadway/guideway is the critical factor; if the surface is smooth, vibration problems are unlikely.

- **Geology:** Soil and subsurface conditions are known to have a strong influence on the levels of ground-borne vibration. Among the most important factors are the stiffness and internal damping of the soil and the depth to bedrock. Experience with ground-borne vibration is that vibration propagation is more efficient in stiff clay soils, and shallow rock seems to concentrate the vibration energy close to the surface and can result in ground-borne vibration problems at large distances from the track. Factors such as layering of the soil and depth to water table can have significant effects on the propagation of ground-borne vibration.

- **Receiving Building:** The receiving building is a key component in the evaluation of ground-borne vibration since ground-borne vibration problems occur almost exclusively inside buildings. The train vibration may be perceptible to people who are outdoors, but it is very rare for outdoor vibration to cause complaints. The vibration levels inside a building are dependent on the vibration energy that reaches the building foundation, the coupling of the building foundation to the soil, and the propagation of the vibration through the building. The general guideline is that the heavier a building is, the lower the response will be to the incident vibration energy.

Table 7-2. Factors that Influence Levels of Ground-Borne Vibration and Noise	
Factors Related to Vibration Source	
Factors	**Influence**
Vehicle Suspension	If the suspension is stiff in the vertical direction, the effective vibration forces will be higher. On transit cars, only the primary suspension affects the vibration levels, the secondary suspension that supports the car body has no apparent effect.
Wheel Type and Condition	Use of pneumatic tires is one of the best methods of controlling ground-borne vibration. Normal resilient wheels on rail transit systems are usually too stiff to provide significant vibration reduction. Wheel flats and general wheel roughness are the major cause of vibration from steel wheel/steel rail systems.
Track/Roadway Surface	Rough track or rough roads are often the cause of vibration problems. Maintaining a smooth surface will reduce vibration levels.
Track Support System	On rail systems, the track support system is one of the major components in determining the levels of ground-borne vibration. The highest vibration levels are created by track that is rigidly attached to a concrete trackbed (e.g. track on wood half-ties embedded in the concrete). The vibration levels are much lower when special vibration control track systems such as resilient fasteners, ballast mats and floating slabs are used.
Speed	As intuitively expected, higher speeds result in higher vibration levels. Doubling speed usually results in a vibration level increase of 4 to 6 decibels.
Transit Structure	The general rule-of-thumb is that the heavier the transit structure, the lower the vibration levels. The vibration levels from a lightweight bored tunnel will usually be higher than from a poured concrete box subway.
Depth of Vibration Source	There are significant differences in the vibration characteristics when the source is underground compared to surface level.
Factors Related to Vibration Path	
Factor	**Influence**
Soil Type	Vibration levels are generally higher in stiff clay-type soils than in loose sandy soils.
Rock Layers	Vibration levels are usually high near at-grade track when the depth to bedrock is 30 feet or less. Subways founded in rock will result in lower vibration amplitudes close to the subway. Because of efficient propagation, the vibration level does not attenuate as rapidly in rock as it does in soil.
Soil Layering	Soil layering will have a substantial, but unpredictable, effect on the vibration levels since each stratum can have significantly different dynamic characteristics.
Depth to Water Table	The presence of the water table may have a significant effect on ground-borne vibration, but a definite relationship has not been established.
Factors Related to Vibration Receiver	
Factor	**Influence**
Foundation Type	The general rule-of-thumb is that the heavier the building foundation, the greater the coupling loss as the vibration propagates from the ground into the building.
Building Construction	Since ground-borne vibration and noise are almost always evaluated in terms of indoor receivers, the propagation of the vibration through the building must be considered. Each building has different characteristics relative to structureborne vibration, although the general rule-of-thumb is the more massive the building, the lower the levels of ground-borne vibration.
Acoustical Absorption	The amount of acoustical absorption in the receiver room affects the levels of ground-borne noise.

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8. VIBRATION IMPACT CRITERIA

Because of the relatively rare occurrence of annoyance due to ground-borne vibration and noise, there has been only limited sponsored research of human response to building vibration and structure-borne noise. However, with the construction of new rail rapid transit systems in the past 30 years, considerable experience has been gained as to how people react to various levels of building vibration. This experience, combined with the available national and international standards,[1,2,3] represents a good foundation for predicting annoyance from ground-borne noise and vibration in residential areas as well as interference with vibration-sensitive activities.

The criteria for environmental impact from ground-borne vibration and noise are based on the maximum root-mean-square (rms) vibration levels for repeated events of the same source. The criteria presented in Table 8-1 account for variation in project types as well as the frequency of events, which differ widely among transit projects. Most experience is with the community response to ground-borne vibration from rail rapid transit systems with typical headways in the range of 3 to 10 minutes and each vibration event lasting less than 10 seconds. It is intuitive that when there will be many fewer events each day, as is typical for commuter rail projects, it should take higher vibration levels to evoke the same community response. This is accounted for in the criteria by distinguishing between projects with varying numbers of events, where *Frequent Events* are defined as more than 70 events per day, *Occasional Events* range between 30 and 70 events per day, and *Infrequent Events* are fewer than 30 events per day. Most commuter rail branch lines will fall into the infrequent events category, although the trunk lines of some commuter rail lines serving major cities are in the occasional events category.

The criteria are primarily based on experience with passenger train operations with only limited experience from freight train operations. The difference is that passenger train operations, whether rapid transit, commuter rail, or intercity passenger railroad, create vibration events that last less than about 10 seconds. A typical line-haul freight train is about 5000 feet long. At a speed of 30 mph, it will take a 5000-foot freight train approximately two minutes to pass. Even though the criteria are primarily based on experience with shorter vibration events and this manual is oriented to transit projects, there will be situations where potential impacts from freight train ground-borne vibration will need to be evaluated. The prime example is when freight train tracks must be relocated to provide space for a transit project within a railroad right-of-way. Some guidelines for applying these criteria to freight train operations are given later in this chapter.

8.1 VIBRATION IMPACT CRITERIA FOR GENERAL ASSESSMENT

8.1.1 Sensitive-Use Categories

The criteria for acceptable ground-borne vibration are expressed in terms of rms velocity levels in decibels and the criteria for acceptable ground-borne noise are expressed in terms of A-weighted sound levels. The limits are specified for the three land-use categories defined below:

- **Vibration Category 1 - High Sensitivity:** Included in Category 1 are buildings where vibration would interfere with operations within the building, including levels that may be well below those associated with human annoyance. Concert halls and other special-use facilities are covered separately in Table 8-2. Typical land uses covered by Category 1 are: vibration-sensitive research and manufacturing, hospitals with vibration-sensitive equipment, and university research operations. The degree of sensitivity to vibration will depend on the specific equipment that will be affected by the vibration. Equipment such as electron microscopes and high resolution lithographic equipment can be very sensitive to vibration, and even normal optical microscopes will sometimes be difficult to use when vibration is well below the human annoyance level. Manufacturing of computer chips is an example of a vibration-sensitive process.

  The vibration limits for Vibration Category 1 are based on acceptable vibration for moderately vibration-sensitive equipment such as optical microscopes and electron microscopes with vibration isolation systems. Defining limits for equipment that is even more sensitive requires a detailed review of the specific equipment involved. This type of review is usually performed during the Detailed Analysis associated with the final design phase and not as part of the environmental impact assessment. Mitigation of transit vibration that affects sensitive equipment typically involves modification of the equipment mounting system or relocation of the equipment rather than applying vibration control measures to the transit project.

  Note that this category does not include most computer installations or telephone switching equipment. Although the owners of this type of equipment often are very concerned about the potential of ground-borne vibration interrupting smooth operation of their equipment, it is rare for computer or other electronic equipment to be particularly sensitive to vibration. Most such equipment is designed to operate in typical building environments where the equipment may experience occasional shock from bumping and continuous background vibration caused by other equipment.

- **Vibration Category 2 - Residential:** This category covers all residential land uses and any buildings where people sleep, such as hotels and hospitals. No differentiation is made between different types of residential areas. This is primarily because ground-borne vibration and noise are experienced indoors and building occupants have practically no means to reduce their exposure. Even in a noisy urban area, the bedrooms often will be quiet in buildings that have effective noise insulation and tightly closed windows. Moreover, street traffic often abates at night when transit continues to operate. Hence, an occupant of a bedroom in a noisy urban area is likely to be just as exposed to ground-borne noise and vibration as someone in a quiet suburban area. The criteria apply to the transit-generated ground-borne vibration and noise whether the source is subway or surface running trains.

- **Vibration Category 3 - Institutional:** Vibration Category 3 includes schools, churches, other institutions, and quiet offices that do not have vibration-sensitive equipment, but still have the potential for activity interference. Although it is generally appropriate to include office buildings in this category, it is not appropriate to include all buildings that have any office space. For example, most industrial buildings have office space, but it is not intended that buildings primarily for industrial use be included in this category.

Table 8-1. Ground-Borne Vibration (GBV) and Ground-Borne Noise (GBN) Impact Criteria for General Assessment

Land Use Category	GBV Impact Levels (VdB re 1 micro-inch /sec)			GBN Impact Levels (dB re 20 micro Pascals)		
	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]	Frequent Events[1]	Occasional Events[2]	Infrequent Events[3]
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB[4]	65 VdB[4]	65 VdB[4]	N/A[4]	N/A[4]	N/A[4]
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

Notes:

1. "Frequent Events" is defined as more than 70 vibration events of the same source per day. Most rapid transit projects fall into this category.
2. "Occasional Events" is defined as between 30 and 70 vibration events of the same source per day. Most commuter trunk lines have this many operations.
3. "Infrequent Events" is defined as fewer than 30 vibration events of the same kind per day. This category includes most commuter rail branch lines.
4. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC systems and stiffened floors.
5. Vibration-sensitive equipment is generally not sensitive to ground-borne noise.

There are some buildings, such as concert halls, TV and recording studios, and theaters, that can be very sensitive to vibration and noise but do not fit into any of the three categories. Because of the sensitivity of these buildings, they usually warrant special attention during the environmental assessment of a transit project. Table 8-2 gives criteria for acceptable levels of ground-borne vibration and noise for various types of special buildings.

Table 8-2. Ground-Borne Vibration and Noise Impact Criteria for Special Buildings

Type of Building or Room	Ground-Borne Vibration Impact Levels (VdB re 1 micro-inch/sec)		Ground-Borne Noise Impact Levels (dB re 20 micro-Pascals)	
	Frequent [1] Events	Occasional or Infrequent[2] Events	Frequent[1] Events	Occasional or Infrequent[2] Events
Concert Halls	65 VdB	65 VdB	25 dBA	25 dBA
TV Studios	65 VdB	65 VdB	25 dBA	25 dBA
Recording Studios	65 VdB	65 VdB	25 dBA	25 dBA
Auditoriums	72 VdB	80 VdB	30 dBA	38 dBA
Theaters	72 VdB	80 VdB	35 dBA	43 dBA

Notes:
1."Frequent Events" is defined as more than 70 vibration events per day. Most rapid transit projects fall into this category.
2."Occasional or Infrequent Events" is defined as fewer than 70 vibration events per day. This category includes most commuter rail systems.
3.If the building will rarely be occupied when the trains are operating, there is no need to consider impact. As an example, consider locating a commuter rail line next to a concert hall. If no commuter trains will operate after 7 pm, it should be rare that the trains interfere with the use of the hall.

The criteria in Tables 8-1 and 8-2 are related to ground-borne vibration causing human annoyance or interfering with use of vibration-sensitive equipment. It is extremely rare for vibration from train operations to cause any sort of building damage, even minor cosmetic damage. However, there is sometimes concern about damage to fragile historic buildings located near the right-of-way. Even in these cases, damage is unlikely except when the track will be very close to the structure. Damage thresholds that apply to these structures are discussed in Section 12.2.2.

8.1.2 Existing Vibration Conditions

One factor not incorporated in the criteria is how to account for existing vibration. In most cases, the existing environment does not include a significant number of perceptible ground-borne vibration or noise events. The most common example of needing to account for the pre-existing vibration is when the project will be located in an existing rail corridor. When the project will cause vibration more than 5 VdB greater than the existing source, the existing source can be ignored and the standard vibration criteria applied to the project. Following are methods of handling representative scenarios:

1. *Infrequently-used rail corridor (fewer than 5 trains per day):* Use the general vibration criteria, Tables 8-1 and 8-2.

2. *Moderately-used rail corridor (5 to 12 trains per day):* If the existing train vibration exceeds the impact criteria given in Tables 8-1 and 8-2, there will be no impact from the project vibration if the levels estimated using the procedures outlined in either Chapter 10 or 11 are at least 5VdB less than the existing train vibration. Otherwise, vibration criteria in Tables 8-1 and 8-2 apply to the project. The existing train vibration can be either measured or estimated using the General Assessment procedures in Chapter 10. It is usually preferable to measure vibration from existing train traffic.

3. *Heavily-used rail corridor (more than 12 trains per day):* If the existing train vibration exceeds the impact criteria given in Tables 8-1 and 8-2, the project will cause additional impact if the project significantly increases the number of vibration events. Approximately doubling the number of events is required for a significant increase.

   If there is not a significant increase in vibration events, there will be additional impact only if the project vibration, estimated using the procedures of Chapters 10 or 11, will be 3 VdB or more higher than the existing vibration. An example of a case with no additional impact would be an automated people mover system planned for a corridor with an existing rapid transit service with 220 trains per day. On the other hand, there could be impact if it is a new commuter rail line planned to share a corridor with the rapid transit system. In this latter case, the project vibrations are likely to be higher than the existing vibrations by 3 VdB or more.

4. *Moving existing tracks:* Another scenario where existing vibration can be significant is when a new transit project will use an existing railroad right-of-way and result in shifting the location of existing railroad tracks. The track relocation and reconstruction can result in lower vibration levels, in which case this aspect of the project represents a benefit, not an adverse impact. If the track relocation will cause higher vibration levels at sensitive receptors, then the projected vibration levels must be compared to the appropriate impact criterion to determine if there will be new impacts. If impact is judged to have existed prior to moving the tracks, new impact will be assessed only if the relocation results in more than a 3 VdB increase in vibration level.

8.1.3 Application to Freight Trains

The impact thresholds given in Tables 8-1 and 8-2 are based on experience with vibration from rail transit systems. They have been used to assess vibration from freight trains since no specific impact criteria exist for freight railroads. However, the significantly greater length, weight and axle loads of freight trains make it problematic to use these impact criteria for freight rail. Nevertheless, in shared right-of-way situations where the proposed transit alignment causes the freight tracks to be moved closer to sensitive sites, these impact criteria will have to be used. In assessing the freight train vibration, a dual approach is recommended with separate consideration of the locomotive and rail car vibration. Because the locomotive vibration only lasts for a very short time, the few-event criterion is appropriate for fewer than 30 events per day. However, for a typical line-haul freight train where the rail car vibration lasts for several minutes, the many-event limits should be applied to the rail car vibration. Some judgment must be exercised to make sure that the approach is reasonable. For example, some spur rail lines carry very little rail traffic (sometimes only one train per week) or have short trains, in which case the criteria may be disregarded altogether.

Finally, it should be pointed out that the vibration control measures developed for rail transit systems are not effective for freight trains. Consequently, any decision to relocate freight tracks closer to sensitive sites should be made with the understanding that the increased vibration impact due to freight rail will be very difficult, if not impossible, to mitigate.

8.2 VIBRATION IMPACT CRITERIA FOR DETAILED ANALYSIS

8.2.1 Ground-Borne Vibration

Specification of mitigation measures requires more detailed information and more refined impact criteria than what were used in the General Assessment. A frequency distribution, or spectrum, of the vibration energy determines whether the vibrations are likely to generate a significant response in a receiving building or structure. The Detailed Analysis method in this manual provides an estimate of building response in terms of a one-third octave band frequency spectrum. This section provides criteria for assessing the potential for interference or annoyance from building response and for determining the performance of vibration reduction methods.

International standards have been developed for the effects of vibration on people in buildings with ratings related to annoyance and interference with activities based on frequency distribution of acceptable vibrations.(2) These criteria have been supplemented by industry standards for vibration-sensitive equipment.(3) Both sets of criteria are expressed in terms of one-third octave band velocity spectra, with transient events like train passbys described in terms of the maximum rms vibration velocity level with a one-second averaging time. The measurement point is specified as the floor of the receiving building at the location of the prescribed activity.

The vibration impact criteria are shown in Figure 8-1 where the international standard curves and the industry standards are plotted on the same figure. Interpretations of the various levels are presented in Table 8-3. Detailed Analysis results in one-third octave band spectra levels that are plotted over the curves shown in Figure 8-1. Band levels that exceed a particular criterion curve indicate the need for mitigation and the frequency range within which the treatment needs to be effective.

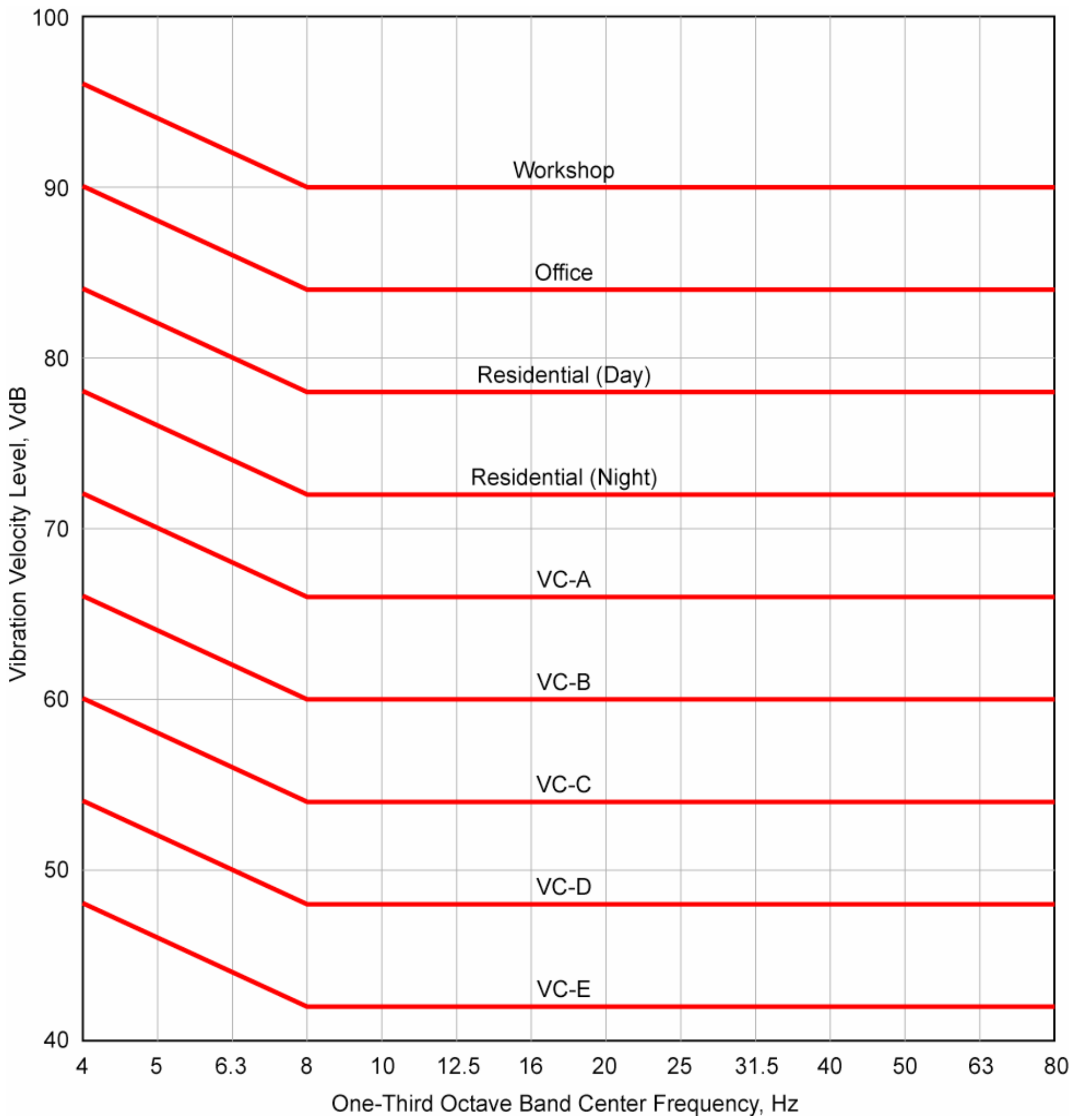

Figure 8-1. Criteria for Detailed Vibration Analysis

Table 8-3. Interpretation of Vibration Criteria for Detailed Analysis		
Criterion Curve[1] (See Figure 8-1)	**Max L_v (VdB)[2]**	**Description of Use**
Workshop	90	Distinctly feelable vibration. Appropriate to workshops and non-sensitive areas.
Office	84	Feelable vibration. Appropriate to offices and non-sensitive areas.
Residential Day	78	Barely feelable vibration. Adequate for computer equipment and low-power optical microscopes (up to 20X).
Residential Night, Operating Rooms	72	Vibration not feelable, but ground-borne noise may be audible inside quiet rooms. Suitable for medium-power optical microscopes (100X) and other equipment of low sensitivity.
VC-A	66	Adequate for medium- to high-power optical microscopes (400X), microbalances, optical balances, and similar specialized equipment.
VC-B	60	Adequate for high-power optical microscopes (1000X), inspection and lithography equipment to 3 micron line widths.
VC-C	54	Appropriate for most lithography and inspection equipment to 1 micron detail size.
VC-D	48	Suitable in most instances for the most demanding equipment, including electron microscopes operating to the limits of their capability.
VC-E	42	The most demanding criterion for extremely vibration-sensitive equipment.

[1]Descriptors on curves are those provided by References 2 and 3.
[2]As measured in 1/3-octave bands of frequency over the frequency range 8 to 80 Hz.

These criteria use a frequency spectrum because vibration-related problems generally occur due to resonances of the structural components of a building or vibration-sensitive equipment. Resonant response is frequency-dependent. A Detailed Analysis can provide an assessment that identifies potential problems resulting from resonances.

The detailed vibration criteria are based on generic cases when people are standing or equipment is mounted on the floor in a conventional manner. Consequently, the criteria are less stringent at very low frequencies below 8 Hz. Where special vibration isolation has been provided in the form of pneumatic isolators, the resonant frequency of the isolation system is very low. Consequently, in this special case, the curves may be extended flat at lower frequencies.

8.2.2 Ground-Borne Noise

Ground-borne noise impacts are assessed based on criteria for human annoyance and activity interference. The results of the Detailed Analysis provide vibration spectra inside a building. These vibration spectra can be converted to sound pressure level spectra in the occupied spaces using the method described in Section 11.2.2. For residential buildings, the criteria for acceptability are given in terms of the A-weighted sound pressure level in Table 8-1. For special buildings listed in Table 8-2, a single-valued level may not be sufficient to assess activity interference at the Detailed Analysis stage. Each special building may have a unique specification for acceptable noise levels. For example, a recording studio may have stringent requirements for allowable noise in each frequency band. Therefore, the ground-borne noise criteria for each sensitive building in this category will have to be determined on a case-by-case basis.

REFERENCES

1. Acoustical Society of America, "American National Standard: Guide to Evaluation of Human Exposure to Vibration in Buildings," ANSI S3.29-1983 (ASA 48-1983).

2. International Organization for Standardization, "Evaluation of Human Exposure to Whole-Body Vibration, Part 2: Continuous and Shock-Induced Vibrations in Buildings (1-80Hz)," ISO-2361-2, 1989.

3. Institute of Environmental Sciences and Technology, “Considerations in Clean Room Design,” RR-CC012.1, 1993.

9. VIBRATION SCREENING PROCEDURE

The vibration screening procedure is designed to identify projects that have little possibility of creating significant adverse impact. If the screening procedure does not identify any potential problem areas, it is usually safe to eliminate further consideration of vibration impact from the environmental analysis.

9.1 STEPS IN SCREENING PROCEDURE

The steps in the vibration screening procedure are summarized in Figure 9-1 in a flow chart format. Following is a summary of the steps:

Initial Decision: If the project includes any type of steel-wheeled/steel-rail vehicle, there is potential for vibration impact. Proceed directly to the evaluation of screening distances. Transit projects that do not involve vehicles, such as a station rehabilitation, do not have potential for vibration impact unless the track system will be modified (e.g., tracks moved or switches modified). Rail systems include urban rapid transit, light rail transit, commuter rail, and steel-wheel intermediate capacity transit systems. For projects that involve rubber-tire vehicles, vibration impact is unlikely except in unusual situations. Three specific factors shown in Figure 9-1 should be checked to determine if there is potential vibration impact from bus projects or any other projects that involve rubber-tire vehicles:

1. Will there be expansion joints, speed bumps, or other design features that result in unevenness in the road surface near vibration-sensitive buildings? Such irregularities can result in perceptible ground-borne vibration at distances up to 75 feet away.
2. Will buses, trucks or other heavy vehicles be operating close to a sensitive building? Research using electron microscopes and manufacturing of computer chips are examples of vibration-sensitive activities.

3. Does the project include operation of vehicles inside or directly underneath buildings that are vibration-sensitive? Special considerations are often required for shared-use facilities such as a bus station located inside an office building complex.

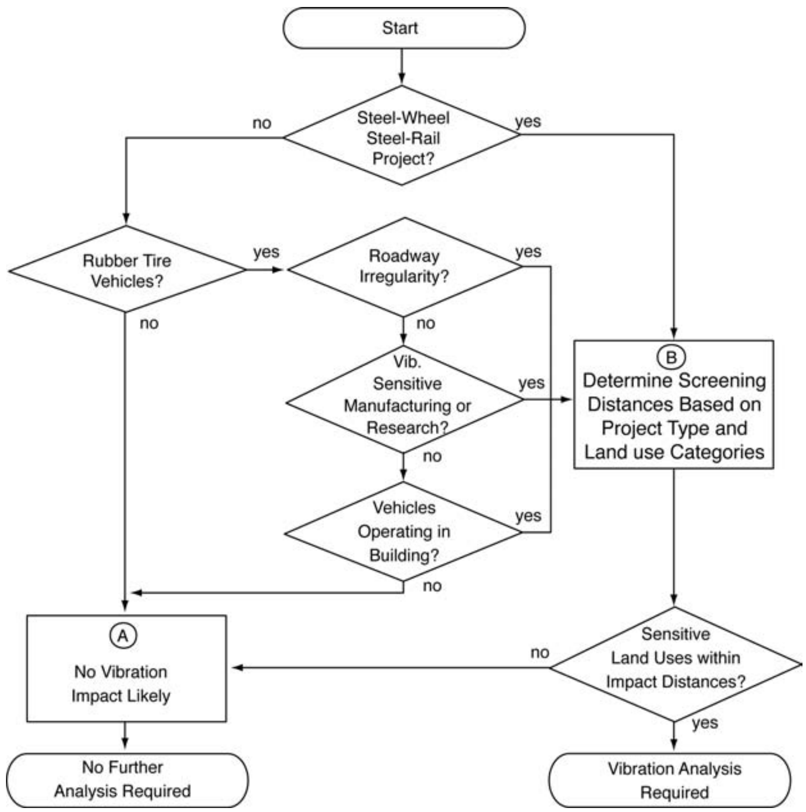

Figure 9-1. Flow Chart of Vibration Screening Process

No Impact (Box A): The decisions in step 1 lead to either box A, "No vibration impact likely," or box B. Reaching box A indicates that further analysis is not required. The majority of smaller FTA-assisted projects, such as bus terminals and park-and-ride lots, will be eliminated from further consideration of ground-borne vibration impact in the first step.

Screening Distances (Box B): If the result of the first step is that there is potential for vibration impact, determine if any vibration-sensitive land uses are within the screening zones. Vibration-sensitive land uses are identified in Chapter 8. Tables 9-1 and 9-2 are used to determine the applicable vibration screening distances for the project.

Impact: If there are any vibration-sensitive land uses within the screening distances, there is the potential for vibration impact. The result of the screening procedure is that a General Vibration Assessment should be done as part of the environmental analysis.

9.2 SCREENING DISTANCES

9.2.1 Project Categories

The vibration screening procedure is applicable to all types of FTA-assisted projects. The project categories for the vibration screening procedure are summarized in Table 9-1 for four types of rail transit. The fifth category includes all bus projects. Any project that does not include some type of vehicle is not likely to cause vibration impact.

With respect to Project Type 5, the rubber-tire vehicle category, most complaints about vibration caused by buses and trucks are related to rattling of windows or items hung on the walls. These vibrations are usually the result of airborne noise and not ground-borne vibration. In the case where ground-borne vibration is the source of the problem, the vibration can usually be related to potholes, some sort of bump in the road, or other irregularities.

Table 9-1. Project Types for Vibration Screening Procedure

Project Type	Description
1. Conventional Commuter Railroad	Both the locomotives and the passenger vehicles create significant vibration. The highest vibration levels are usually created by the locomotives. Electric commuter rail vehicles create levels of ground-borne vibration that are comparable to electric rapid transit vehicles.
2. Rail Rapid Transit	Ground-borne vibration impact from rapid transit trains is one of the major environmental issues for new systems. For operation in subway, the ground-borne vibration is usually a significant environmental impact. It is less common for at-grade and elevated rapid transit lines to create intrusive ground-borne vibration.
3. Light Rail Transit	The ground-borne vibration characteristics of light rail systems are very similar to those of rapid transit systems. Because the speeds of light rail systems are usually lower, the typical vibration levels usually are lower. Steel-wheel/steel-rail Automated Guideway Transit (AGT) will fall into either this category or the Intermediate Capacity Transit category depending on the level of service and train speeds.
4. Intermediate Capacity Transit	Because of the low operating speeds of most ICT systems, significant vibration problems are not common. However, steel-wheel ICT systems that operate close to vibration-sensitive buildings have the potential of causing intrusive vibration. With a stiff suspension system, an ICT system could create intrusive vibration.
5. Bus and Rubber-Tire Transit Projects	This category encompasses most projects that do not include steel-wheel trains of some type. Examples are diesel buses, electric trolley buses, and rubber-tired people movers. Most projects that do not include steel-wheel trains do not cause significant vibration impact.

9.2.2 Distances

The screening distances are given in Table 9-2. These distances are based on the criteria presented in Chapter 8, with a 5-decibel factor of safety included. The distances have been determined using vibration prediction procedures that are summarized in Chapter 10 assuming "normal" vibration propagation. As discussed in Chapter 10, efficient vibration propagation can result in substantially higher vibration levels.

Because of the 5-decibel safety factor, even with efficient propagation, the screening distances will identify most of the potentially impacted areas. By not specifically accounting for the possibility of efficient vibration propagation, there is some possibility that some potential impact areas will not be identified in the screening process. When there is evidence of efficient propagation, such as previous complaints about existing transit facilities or a history of problems with construction vibration, the distances in Table 9-2 should be increased by a factor of 1.5.

Table 9-2. Screening Distances for Vibration Assessment

Type of Project	**Critical Distance for Land Use Categories* Distance from Right-of-Way or Property Line**		
	Cat. 1	**Cat. 2**	**Cat. 3**
Conventional Commuter Railroad	600	200	120
Rail Rapid Transit	600	200	120
Light Rail Transit	450	150	100
Intermediate Capacity Transit	200	100	50
Bus Projects (if not previously screened out)	100	50	--

* The land-use categories are defined in Chapter 8. Some vibration-sensitive land uses are not included in these categories. Examples are: concert halls and TV studios which, for the screening procedure, should be evaluated as Category 1; and theaters and auditoriums which should be evaluated as Category 2.

10. GENERAL VIBRATION ASSESSMENT

This chapter outlines procedures that can be used to develop generalized predictions of ground-borne vibration and noise. This manual includes three different levels of detail for projecting ground-borne vibration:

- **Screening:** The screening procedure is discussed in Chapter 9. A standard table of impact distances is used to determine if ground-borne vibration from the project may affect sensitive land uses. More detailed analysis is required if any sensitive land uses are within the screening distances. The screening procedure does not require any specific knowledge about the vibration characteristics of the system or the geology of the area. If different propagation conditions are known to be present, a simple adjustment is provided.

- **General Assessment:** The general level of assessment, as described in this chapter, is an extension of the screening procedure. It uses generalized data to develop a curve of vibration level as a function of distance from the track. The vibration levels at specific buildings are estimated by reading values from the curve and applying adjustments to account for factors such as track support system, vehicle speed, type of building, and track and wheel condition. The general level deals only with the overall vibration velocity level and the A-weighted sound level. It does not consider the frequency spectrum of the vibration or noise.

- **Detailed Analysis:** Discussed in Chapter 11, the Detailed Analysis involves applying all of the available tools for accurately projecting the vibration impact at specific sites. The procedure outlined in this manual includes a test of the vehicle (or similar vehicle) to define the forces generated by the vibration source and tests at the site in question to define how the local geology affects vibration propagation. It is considerably more complex to develop detailed projections of ground-borne vibration than it is to develop detailed projections of airborne noise. Accurate projections of ground-borne vibration require professionals with experience in performing and interpreting vibration propagation tests. As such, detailed vibration predictions are usually performed during the final design phase of a project when there is sufficient reason to suspect adverse vibration impact from the project. The procedure for Detailed Vibration Analysis presented in Chapter 11 is based on measurements to characterize vibration propagation at specific sites.

There is not always a clear distinction between general and detailed predictions. For example, it is often appropriate to use several representative measurements of vibration propagation along the planned alignment in developing generalized propagation curves. Other times, generalized prediction curves may be sufficient for the majority of the alignment, but with Detailed Analysis applied to particularly sensitive buildings such as a concert hall. The methods for analyzing transit vibration in this manual are consistent with those described in recognized handbooks and international standards.[1, 2]

The purpose of the General Assessment is to provide a relatively simple method of developing estimates of the overall levels of ground-borne vibration and noise that can be compared to the acceptability criteria given in Chapter 8. For many projects, particularly when comparing alternatives, this level of detail will be sufficient for the environmental impact assessment. Where there are potential problems, the Detailed Analysis is then undertaken during final design of the selected alternative to accurately define the level of impact and design mitigation measures. A Detailed Analysis usually will be required when designing special track-support systems such as floating slabs or ballast mats. Detailed Analysis is not usually required if, as is often the case, the mitigation measure consists of relocating a crossover or turnout. Usually, the General Assessment is adequate to determine whether a crossover needs to be relocated.

The basic approach for the General Assessment is to define a curve, or set of curves, that predicts the overall ground-surface vibration as a function of distance from the source, then apply adjustments to these curves to account for factors such as vehicle speed, building type, and receiver location within the building. Section 10.1 includes curves of vibration level as a function of distance from the source for the common types of vibration sources such as rapid transit trains and buses. When the vehicle type is not covered by the curves included in this section, it will be necessary to define an appropriate curve either by extrapolating from existing information or performing measurements at an existing facility.

10.1 SELECTION OF BASE CURVE FOR GROUND SURFACE VIBRATION LEVEL

The base curves for three standard transportation systems are defined in Figure 10-1. This figure shows typical ground-surface vibration levels assuming equipment in good condition and speeds of 50 mph for the rail systems and 30 mph for buses. The levels must be adjusted to account for factors such as different speeds and different geologic conditions than assumed. The adjustment factors are discussed in Section 10.2.

The curves in Figure 10-1 are based on measurements of ground-borne vibration at representative North American transit systems. The top curve applies to trains that are powered by diesel or electric locomotives. It includes intercity passenger trains and commuter rail trains. The curve for rapid transit rail cars covers both heavy and light-rail vehicles on at-grade and subway track. It is somewhat surprising that subway and at-grade track can be represented by the same curve since ground-borne vibration created by a train operating in a subway has very different characteristics than vibration from at-grade track. However, in spite of these differences, the overall vibration velocity levels are comparable. Subways tend to have more vibration problems than at-grade track. This is probably due to two factors: (1) subways are usually located in more densely developed areas, and (2) the airborne noise is usually a more serious problem for at-grade systems than the ground-borne vibration. Another difference between subway and at-grade track is that the ground-borne vibration from subways tends to be higher frequency than the vibration from at-grade track, which makes the ground-borne noise more noticeable.

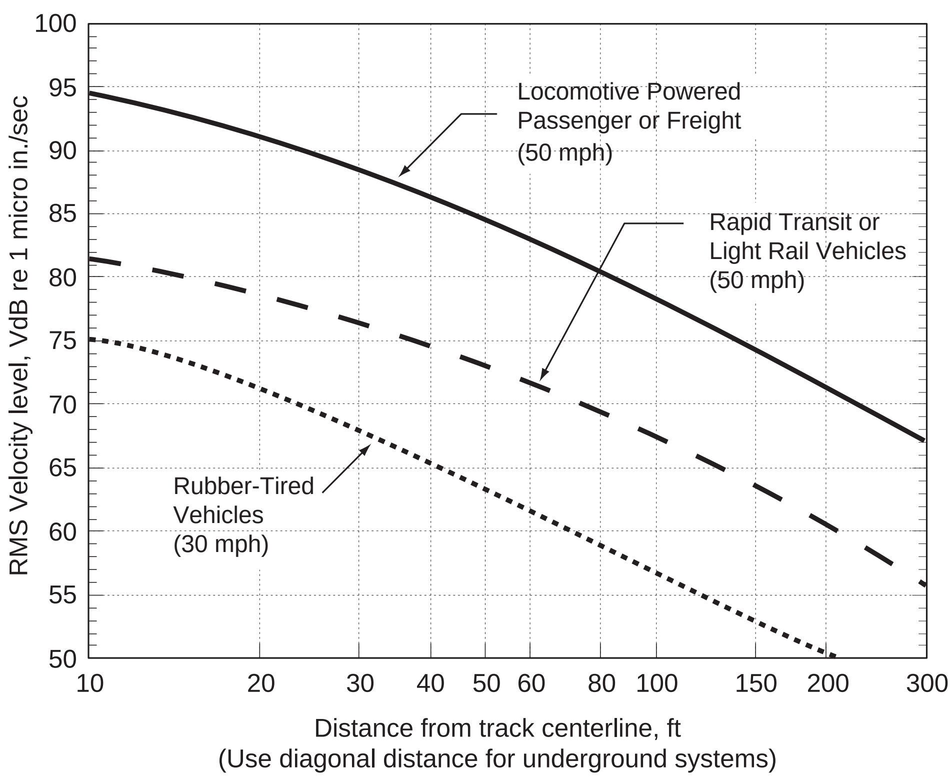

Figure 10-1. Generalized Ground Surface Vibration Curves

The curves in Figure 10-1 were developed from many measurements of ground-borne vibration. Experience with ground-borne vibration data is that, for any specific type of transit mode, a significant variation in vibration levels under apparently similar conditions is not uncommon. The curves in Figure

10-1 represent the upper range of the measurement data from well-maintained systems. Although actual levels fluctuate widely, it is rare that ground-borne vibration will exceed the curves in Figure 10-1 by more than one or two decibels unless there are extenuating circumstances, such as wheel- or running-surface defects.

One approach to dealing with the normal fluctuation is to show projections as a range. For example, the projected level from Figure 10-1 for an LRT system with train speeds of 50 mph is about 72 VdB at a distance of 60 feet from the track centerline, just at the threshold for acceptable ground-borne vibration for residential land uses. To help illustrate the normal fluctuation, the projected level of ground-borne vibration might be given as 67 to 72 VdB. This approach is not recommended since it tends to confuse the interpretation of whether or not the projected vibration levels exceed the impact threshold. However, because actual levels of ground-borne vibration will sometimes differ substantially from the projections, some care must be taken when interpreting projections. Some guidelines are given below:

1. Projected vibration is below the impact threshold. Vibration impact is unlikely in this case.
2. Projected ground-borne vibration is 0 to 5 decibels greater than the impact threshold. In this range there is still a significant chance that actual ground-borne vibration levels will be below the impact threshold. In this case, the impact would be reported in the environmental document as exceeding the applicable threshold and a commitment would be made to conduct more detailed studies to refine the vibration impact analysis during final design and determine appropriate mitigation, if necessary. A site-specific Detailed Analysis may show that vibration control measures are not needed.
3. Projected ground-borne vibration is 5 decibels or more greater than the impact threshold. Vibration impact is probable and Detailed Analysis will be needed during final design to help determine appropriate vibration control measures.

The two most important factors that must be accounted for in a General Assessment are the type of vibration source (the mode of transit) and the vibration propagation characteristics. It is well known that there are situations where ground-borne vibration propagates much more efficiently than normal. The result is unacceptable vibration levels at distances two to three times the normal distance. Unfortunately, the geologic conditions that promote efficient propagation have not been well documented and are not fully understood. Shallow bedrock or stiff clay soil often are involved. One possibility is that shallow bedrock acts to keep the vibration energy near the surface. Much of the energy that would normally radiate down is directed back towards the surface by the rock layer with the result that the ground surface vibration is higher than normal.

The selection of a base curve depends on the mode of rail transit under consideration. Appropriate correction factors are then added to account for any unusual propagation characteristics. For less common modes such as magnetically-levitated vehicles (maglev), monorail, or automated guideway transit (AGT), it is necessary to either make a judgment about which curve and adjustment factors best fit the mode or to develop new estimates of vibration level as a function of distance from the track. For example, the vibration from a rubber-tire monorail that will be operating on aerial guideway can be approximated using the bus/rubber tire systems with the appropriate adjustment for the aerial structure. Another example is a magnetic levitation system. Most of the data available on the noise and vibration characteristics of maglev vehicles comes from high-speed systems intended for inter-city service. Even though there is no direct contact between the vehicle and the guideway, the dynamic loads on the guideway can generate ground-borne vibration. Measurements on a German high-speed maglev resulted in ground-borne vibrations at 75 mph comparable to the base curve for rubber-tired vehicles at 30 mph.[3] Considerations for selecting a base curve are discussed below:

- **Intercity Passenger Trains:** Although intercity passenger trains can be an important source of environmental vibration, it is rare that they are significant for FTA-funded projects unless a new transit mode will use an existing rail alignment. When a new transit line will use an existing rail alignment, the changes in the intercity passenger traffic can result in either positive or negative impacts. Unless there are specific data available on the ground-borne vibration created by the train operations, the upper curve in Figure 10-1 should be used for intercity passenger trains.
- **Locomotive-Powered Commuter Rail:** The locomotive curve from Figure 10-1 should be used for any commuter rail system powered by either diesel or electric locomotives. The locomotives often create vibration levels that are 3 to 8 decibels higher than those created by the passenger cars. Self-powered electric commuter rail trains can be considered to be similar to rapid transit vehicles. Although they are relatively rare in the U.S., self-powered diesel multiple units (DMU's) create vibration levels somewhere between rapid transit vehicles and locomotive-powered passenger trains. When the axle loads and suspension parameters of a particular DMU are comparable to typical rapid transit vehicles, the rapid transit curve in Figure 10-1 can be used for that mode.
- **Subway Heavy Rail:** Complaints about ground-borne vibration are more common near subways than near at-grade track. This is not because subways create higher vibration levels than at-grade systems - rather it is because subways are usually located in high-density areas in close proximity to building foundations. When applied to subways, the rapid transit curve in Figure 10-1 assumes a relatively lightweight bored concrete tunnel in soil. The vibration levels will be lower for heavier subway structures such as cut-and-cover box structures and stations.
- **At-Grade Heavy Rail or LRT:** The available data show that heavy rail and light rail transit vehicles create similar levels of ground-borne vibration. This is not surprising since the vehicles have similar suspension systems and axle loads. Light-rail systems tend to have fewer problems with ground-borne vibration because of the lower operating speeds. Similar to the subway case, an adjustment factor must be used if the transit vehicle has a primary suspension that is stiff in the vertical direction.
- **Intermediate Capacity Transit:** The vibration levels created by an intermediate capacity transit system or an AGT system will depend on whether the vehicles have steel wheels or rubber wheels. If they have steel wheels, the transit car curve in Figure 10-1 should be used with appropriate adjustments for operating speed. The bus/rubber tire curve should be used for rubber-tired ICT systems.

- **Bus/Rubber Tire:** Rubber-tire vehicles rarely create ground-borne vibration problems unless there is a discontinuity or bump in the road that causes the vibration. The curve in Figure 10-1 shows the vibration level for a typical bus operating on smooth roadway.

10.2 ADJUSTMENTS

Once the base curve has been selected, the adjustments in Table 10-1 can be used to develop vibration projections for specific receiver positions inside buildings. All of the adjustments are given as single numbers to be added to, or subtracted from, the base level. The adjustment parameters are speed, wheel and rail type and condition, type of track support system, type of building foundation, and number of floors above the basement level. It should be recognized that many of these adjustments are strongly dependent on the frequency spectrum of the vibration source and the frequency dependence of the vibration propagation. The single number values are suitable for generalized evaluation of the vibration impact and vibration mitigation measures since they are based on typical vibration spectra. However, the single number adjustments are not adequate for detailed evaluations of impact of sensitive buildings or for detailed specification of mitigation measures. Detailed Analysis requires consideration of the relative importance of different frequency components.

Table 10-1. Adjustment Factors for Generalized Predictions of Ground-Borne Vibration and Noise

Factors Affecting Vibration Source				
Source Factor	**Adjustment to Propagation Curve**			**Comment**
		Reference Speed		
Speed	Vehicle Speed	50 mph	30 mph	Vibration level is approximately proportional to 20*log(speed/speed$_{ref}$). Sometimes the variation with speed has been observed to be as low as 10 to 15 log(speed/speed$_{ref}$).
	60 mph	+1.6 dB	+6.0 dB	
	50 mph	0.0 dB	+4.4 dB	
	40 mph	-1.9 dB	+2.5 dB	
	30 mph	-4.4 dB	0.0 dB	
	20 mph	-8.0 dB	-3.5 dB	
Vehicle Parameters (not additive, apply greatest value only)				
Vehicle with stiff primary suspension	+8 dB			Transit vehicles with stiff primary suspensions have been shown to create high vibration levels. Include this adjustment when the primary suspension has a vertical resonance frequency greater than 15 Hz.
Resilient Wheels	0 dB			Resilient wheels do not generally affect ground-borne vibration except at frequencies greater than about 80 Hz.
Worn Wheels or Wheels with Flats	+10 dB			Wheel flats or wheels that are unevenly worn can cause high vibration levels. This can be prevented with wheel truing and slip-slide detectors to prevent the wheels from sliding on the track.
Track Conditions (not additive, apply greatest value only)				
Worn or Corrugated Track	+10 dB			If both the wheels and the track are worn, only one adjustment should be used. Corrugated track is a common problem. Mill scale on new rail can cause higher vibration levels until the rail has been in use for some time.
Special Trackwork	+10 dB			Wheel impacts at special trackwork will significantly increase vibration levels. The increase will be less at greater distances from the track.
Jointed Track or Uneven Road Surfaces	+5 dB			Jointed track can cause higher vibration levels than welded track. Rough roads or expansion joints are sources of increased vibration for rubber-tire transit.
Track Treatments (not additive, apply greatest value only)				
Floating Slab Trackbed	-15 dB			The reduction achieved with a floating slab trackbed is strongly dependent on the frequency characteristics of the vibration.
Ballast Mats	-10 dB			Actual reduction is strongly dependent on frequency of vibration.
High-Resilience Fasteners	-5 dB			Slab track with track fasteners that are very compliant in the vertical direction can reduce vibration at frequencies greater than 40 Hz.

Table 10-1. Adjustment Factors for Generalized Predictions of Ground-Borne Vibration and Noise (Continued)

Factors Affecting Vibration Path		
Path Factor	**Adjustment to Propagation Curve**	**Comment**
Resiliently Supported Ties	-10 dB	Resiliently supported tie systems have been found to provide very effective control of low-frequency vibration.
Track Configuration (not additive, apply greatest value only)		
Type of Transit Structure	Relative to at-grade tie & ballast: Elevated structure -10 dB Open cut 0 dB	The general rule is the heavier the structure, the lower the vibration levels. Putting the track in cut may reduce the vibration levels slightly. Rock-based subways generate higher-frequency vibration.
	Relative to bored subway tunnel in soil: Station -5 dB Cut and cover -3 dB Rock-based - 15 dB	
Ground-borne Propagation Effects		
Geologic conditions that promote efficient vibration propagation	Efficient propagation in soil +10 dB	Refer to the text for guidance on identifying areas where efficient propagation is possible.
	Propagation in rock layer **Dist.** / **Adjust.** 50 ft +2 dB 100 ft +4 dB 150 ft +6 dB 200 ft +9 dB	The positive adjustment accounts for the lower attenuation of vibration in rock compared to soil. It is generally more difficult to excite vibrations in rock than in soil at the source.
Coupling to building foundation	Wood Frame Houses -5 dB 1-2 Story Masonry -7 dB 3-4 Story Masonry -10 dB Large Masonry on Piles -10 dB Large Masonry on Spread Footings -13 dB Foundation in Rock 0 dB	The general rule is the heavier the building construction, the greater the coupling loss.
Factors Affecting Vibration Receiver		
Receiver Factor	**Adjustment to Propagation Curve**	**Comment**
Floor-to-floor attenuation	1 to 5 floors above grade: -2 dB/floor 5 to 10 floors above grade: -1 dB/floor	This factor accounts for dispersion and attenuation of the vibration energy as it propagates through a building.
Amplification due to resonances of floors, walls, and ceilings	+6 dB	The actual amplification will vary greatly depending on the type of construction. The amplification is lower near the wall/floor and wall/ceiling intersections.
Conversion to Ground-borne Noise		
Noise Level in dBA	Peak frequency of ground vibration: Low frequency (<30 Hz): -50 dB Typical (peak 30 to 60 Hz): -35 dB High frequency (>60 Hz): -20 dB	Use these adjustments to estimate the A-weighted sound level given the average vibration velocity level of the room surfaces. See text for guidelines for selecting low, typical or high frequency characteristics. Use the high-frequency adjustment for subway tunnels in rock or if the dominant frequencies of the vibration spectrum are known to be 60 Hz or greater.

Without careful consideration of the shape of the actual vibration spectra, an inappropriate vibration control measure may be selected that could actually cause an increase in the vibration levels.

The following guidelines are used to select the appropriate adjustment factors. Note that the adjustments for wheel and rail condition are not cumulative. The general rule-of-thumb to use when more than one adjustment may apply is to apply only the largest adjustment. For example: the adjustment for jointed track is 5 decibels and the adjustment for wheel flats is 10 decibels. In an area where there is jointed track and many vehicles have wheel flats, the projected vibration levels should be increased by 10 decibels, not 15 decibels.

- **Train Speed:** The levels of ground-borne vibration and noise vary approximately as 20 times the logarithm of speed. This means that doubling train speed will increase the vibration levels approximately 6 decibels and halving train speed will reduce the levels by 6 decibels. Table 10-1 tabulates the adjustments for reference vehicle speeds of 30 mph for rubber-tired vehicles and 50 mph for steel-wheel vehicles. The following relationship should be used to calculate the adjustments for other speeds.

$$adjustment(dB) = 20 \times \log\left(\frac{speed}{speed_{ref}}\right)$$

- **Vehicle:** The most important factors for the vehicles are the suspension system, wheel condition, and wheel type. Most new heavy rail and light rail vehicles have relatively soft primary suspensions. However, experience in Atlanta, New York, and other cities has demonstrated that a stiff primary suspension (vertical resonance frequency greater than 15 Hz) can result in higher than normal levels of ground-borne vibration. Vehicles for which the primary suspension consists of a rubber or neoprene "donut" around the axle bearing usually have a very stiff primary suspension with a vertical resonance frequency greater than 40 Hz.

  Deteriorated wheel condition is another factor that will increase vibration levels. It can be assumed that a new system will have vehicles with wheels in good condition. However, when older vehicles will be used on new track, it may be appropriate to include an adjustment for wheel condition. The reference curves account for wheels without defects, but wheels with flats or corrugations can cause vibration levels that are 10 VdB higher than normal. Resilient wheels will reduce vibration levels at frequencies greater than the effective resonance frequency of the wheel. Because this resonance frequency is relatively high, often greater than 80 Hz, resilient wheels usually have only a marginal effect on ground-borne vibration.

  It is important to use only one of the adjustments in this category, the greatest one that applies.

- **Track System and Support:** This category includes the type of rail (welded, jointed or special trackwork), the track support system, and the condition of the rail. The base curves all assume good-condition welded rail. Jointed rail causes higher vibration levels than welded rail; the amount higher depends on the condition of the joints. The wheel impacts at special trackwork, such as frogs at crossovers, create much higher vibration forces than normal. Because of the higher vibration levels at special trackwork, crossovers often end up being the principal areas of vibration impact on new systems. Modifying the track support system is one method of mitigating the vibration impact. Special track support systems such as ballast mats, high-resilience track fasteners, resiliently supported ties, and floating slabs have all been shown to be effective in reducing vibration levels.

  The condition of the running surface of the rails can strongly affect vibration levels. Factors such as corrugations, general wear, or mill scale on new track can cause vibration levels that are 5 to 15 decibels higher than normal. Mill scale will usually wear off after some time in service; however, the track must be ground to remove corrugations or to reduce the roughness from wear.

  Again, apply only one of the adjustments.

  Roadway surfaces in the case of rubber-tired systems are assumed to be smooth. Rough washboard surfaces, bumps or uneven expansion joints are the types of running surface defects that cause increased vibration levels over the smooth road condition.

- **Transit Structure:** The weight and size of a transit structure affects the vibration radiated by that structure. The general rule-of-thumb is that vibration levels will be lower for heavier transit structures. Hence, the vibration levels from a cut-and-cover concrete double-box subway can be assumed to be lower than the vibration from a lightweight concrete-lined bored tunnel. The vibration from elevated structures is lower than from at-grade track because of the mass and damping of the structure and the extra distance that the vibration must travel before it reaches the receiver. Elevated structures in automated guideway transit applications sometimes are designed to bear on building elements. These are a special case and may require detailed design considerations.

- **Propagation Characteristics:** In the General Assessment it is necessary to make a selection among the general propagation characteristics. For a subway, the selection is a fairly straightforward choice of whether or not the subway will be founded in bedrock. Bedrock is considered to be hard rock. It is usually appropriate to consider soft siltstone and sandstone to be more similar to soil than hard rock. As seen in Table 10-1, whether the subway is founded in soil or rock can be a 15 VdB difference in the vibration levels.

  When considering at-grade vibration sources, the selection is between "normal" vibration propagation and "efficient" vibration propagation. Efficient vibration propagation results in approximately 10 decibels higher vibration levels. This more than doubles the potential impact zone for ground-borne vibration. One of the problems with identifying the cause of efficient propagation is the difficulty in determining whether higher than normal vibration levels are due to geologic conditions or due to special source conditions (e.g. rail corrugations or wheel flats).

  Although it is known that geologic conditions have a significant effect on the vibration levels, it is rarely possible to develop more than a broad-brush understanding of the vibration propagation characteristics for a General Assessment. The conservative approach would be to use the 10-decibel adjustment for efficient propagation to evaluate all potential vibration impact. The problem with this approach is that it tends to greatly overstate the potential for vibration impact. Hence, it is best to review available geological data and any complaint history from existing transit lines and major construction sites near the transit corridor to identify areas where efficient propagation is possible. If there is any reason to suspect efficient propagation conditions, then a Detailed Analysis during final design would include vibration propagation tests at the areas identified as potentially efficient propagation sites.

Some geologic conditions are repeatedly associated with efficient propagation. Shallow bedrock, less than 30 feet below the surface, is likely to have efficient propagation. Other factors that can be important are soil type and stiffness. In particular, stiff clayey soils have sometimes been associated with efficient vibration propagation. Investigation of soil boring records can be used to estimate depth to bedrock and the presence of problem soil conditions.

A factor that can be particularly complex to address is the effect of vibration propagation through rock. There are three factors from Table 10-1 that need to be included when a subway structure will be founded in rock. First is the -15 decibel adjustment in the "Type of Transit Structure" category. Second is the adjustment based on the propagation distance in the "Geologic Conditions" category. This positive adjustment is applied to the distances shown in Figure 10-1; the adjustment increases with distance because vibration attenuates more slowly in rock than in the soil used as a basis for the reference curve. The third factor is in the "Coupling to Building" category. When a building foundation is directly on the rock layer, there is no "coupling loss" due to the weight and stiffness of the building. Use the standard coupling factors if there is at least a 10-foot layer of soil between the building foundation and the rock layer.

- **Type of Building and Receiver Location in Building:** Since annoyance from ground-borne vibration and noise is an indoor phenomenon, the effects of the building structure on the vibration must be considered. Wood frame buildings, such as the typical residential structure, are more easily excited by ground vibration than heavier buildings. In contrast, large masonry buildings with spread footings have a low response to ground vibration.

  Vibration generally reduces in level as it propagates through a building. As indicated in Table 10-1, a 1- to 2-decibel attenuation per floor is usually assumed. Counteracting this, resonances of the building structure, particularly the floors, will cause some amplification of the vibration. Consequently, for a wood-frame structure, the building-related adjustments nearly cancel out. The adjustments for the first floor assuming a basement are: -5 decibels for the coupling loss; -2 decibels for the propagation from the basement to the first floor; and +6 decibels for the floor amplification. The total adjustment in this case is -1 decibel.

- **Vibration to Ground-Borne Noise Adjustment**: It is possible to estimate the levels of radiated noise given the average vibration amplitude of the room surfaces (floors, walls and ceiling), and the total acoustical absorption in the room. The unweighted sound pressure level is approximately equal to the vibration velocity level when the velocity level is referenced to 1×10^{-6} inches/second.

However, to estimate the A-weighted sound level from the velocity level, it is necessary to have some information about the frequency spectrum. The A-weighting adjustment drops rapidly at low frequencies, reflecting the relative insensitivity of human hearing to low frequencies. For example, A-weighting is -16 dB at 125 Hz, -26 dB at 60 Hz and -40 dB at 30 Hz. Table 10-1 provides adjustments for vibration depending on whether it has low-frequency, typical or high-frequency characteristics. Some general guidelines for classifying the frequency characteristics are:

- Low Frequency: Low-frequency vibration characteristics can be assumed for subways surrounded by cohesiveless sandy soil or whenever a vibration isolation track support system will be used. Low-frequency characteristics can be assumed for most surface track.
- Typical: The typical vibration characteristic is the default assumption for subways. It should be assumed for subways until there is information indicating that one of the other assumptions is appropriate. It should be used for surface track when the soil is very stiff with a high clay content.
- High Frequency: High-frequency characteristics should be assumed for subways whenever the transit structure is founded in rock or when there is very stiff clayey soil.

10.3 INVENTORY OF VIBRATION-IMPACTED LOCATIONS

This chapter includes generalized curves for surface vibration for different transit modes along with adjustments to apply for specific operating conditions and buildings. The projected levels are then compared with the criteria in Chapter 8 to determine whether vibration impact is likely. The results of the General Assessment are expressed in terms of an inventory of all sensitive land uses where either ground-borne vibration or ground-borne noise from the project may exceed the impact thresholds. The General Assessment may include a discussion of mitigation measures which would likely be needed to reduce vibration to acceptable levels.

The purpose of the procedure is to develop a reasonably complete inventory of the buildings that may experience ground-borne vibration or noise that exceed the impact criteria. At this point, it is preferable to make a conservative assessment of the impact. That is, it is better to include some buildings where ground-borne vibration may be below the impact threshold than to exclude buildings where it may exceed the impact threshold. The inventory should be organized according to the categories described in Chapter 8. For each building where the projected ground-borne vibration or noise exceeds the applicable impact threshold, one or more of the vibration control options from Section 11.5 should be considered for applicability. See Section 11.4 for a more complete description of how the General Vibration Assessment fits into the overall procedure.

REFERENCES

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2. International Organization for Standardization, “Mechanical vibration – Ground-borne noise and vibration arising from rail systems,” ISO/FDIS 14837-1:2005.

3. U.S. Department of Transportation, Volpe National Transportation Systems Center, “Vibration Characteristics of the Transrapid TR08 Maglev System,” Report No. DOT-VNTSC-FRA-02-06, March 2002.

11. DETAILED VIBRATION ANALYSIS

The goal of the Detailed Analysis is to use all available tools to develop accurate projections of potential ground-borne vibration impact and, when necessary, to design mitigation measures. This is appropriate when the General Assessment has indicated impact and the project has entered the final design and engineering phase. It may also be appropriate to perform a Detailed Analysis at the outset when there are particularly sensitive land uses within the screening distances. Detailed Analysis will require developing estimates of the frequency components of the vibration signal, usually in terms of 1/3-octave-band spectra. Analytical techniques for solving vibration problems are complex and the technology continually advances. Consequently, the approach presented in this chapter focuses on the key steps usually taken by a professional in the field.

Three examples of cases where a Detailed Vibration Analysis might be required are:

Example 1: A particularly sensitive building such as a major concert hall is within the impact zone. A Detailed Analysis would ensure that effective vibration mitigation is feasible and economically reasonable.

Example 2: The General Assessment indicates that a proposed commuter rail project has the potential to create vibration impact for a large number of residential buildings adjacent to the alignment. The projections for many of the buildings exceed the impact threshold by less than 5 decibels, which means that more accurate projections may show that vibration levels will be below the impact criterion. Detailed Analysis will refine the impact assessment and help determine whether mitigation is needed.

Example 3: A transit alignment will be close to university research buildings where vibration-sensitive optical instrumentation is used. Vibration from the trains could make it impossible to continue using the building for this type of research. A Detailed Analysis would determine if it is possible to control the vibration from the trains such that sensitive instrumentation will not be affected.

A Detailed Vibration Analysis consists of three parts:

1. **Survey Existing Vibration.** Although knowledge of the existing levels of ground-borne vibration is not usually required for the assessment of vibration impact, there are times when a survey of the existing vibration is valuable. Examples include documenting existing background vibration at sensitive buildings, measuring the vibration levels created by sources such as existing rail lines, and, in some cases, characterizing the general background vibration in the project corridor. Characterizing the existing vibration is discussed in Section 11.1.

2. **Predict Future Vibration and Vibration Impact.** All of the available tools should be applied in a Detailed Analysis to develop the best possible estimates of the potential for vibration impact. Section 11.2 discusses an approach to projecting ground-borne vibration that involves performing tests to characterize vibration propagation at sites where significant impact is probable. Section 11.3 describes the vibration propagation test procedure and Section 11.4 discusses the assessment of vibration impact.

3. **Develop Mitigation Measures.** Controlling the impact from ground-borne vibration requires developing cost-effective measures to reduce the vibration levels. The Detailed Analysis helps to select practical vibration control measures that will be effective at the dominant vibration frequencies and compatible with the given transit structure and track support system. Vibration mitigation measures are discussed in Section 11.5.

The discussion in this chapter generally assumes that detailed vibration analysis applies to a steel-wheel/ rail system. The procedures could be adapted to bus systems. However, this is rarely necessary because vibration problems are very infrequent with rubber-tired transit.

11.1 CHARACTERIZING EXISTING VIBRATION CONDITIONS

Environmental vibration is rarely of sufficient magnitude to be perceptible or cause audible ground-borne noise unless there is a specific vibration source close by, such as a rail line. In most cases, feelable vibration inside a building is caused by equipment or activities within the building itself, such as heating and ventilation systems, footsteps or doors closing. Because the existing environmental vibration is usually below human perception, a limited vibration survey is sufficient even for a Detailed Analysis. This contrasts with analysis of noise impact where documenting the existing ambient noise level is required to assess the impact.

Examples of situations where measurements of the ambient vibration are valuable include:

- **Determining existing vibration at sensitive buildings:** Serious vibration impact may occur when there are vibration-sensitive manufacturing, research, or laboratory activities within the screening distances. Careful documentation of the pre-existing vibration provides valuable information on the real sensitivity of the activity to external vibration and gives a reference condition under which vibration is not a problem.

- **Using existing vibration sources to characterize propagation:** Existing vibration sources such as freight trains, industrial processes, quarrying operations, or normal traffic sometimes can be used to characterize vibration propagation. Carefully designed and performed measurements may eliminate the need for more complex propagation tests.
- **Documenting existing levels of general background:** Some measurements of the existing levels of background vibration can be useful simply to document that, as expected, the vibration is below the normal threshold of human perception. Existing vibration in urban and suburban areas is usually due to traffic. If a measurement site has existing vibration approaching the range of human perception (e.g., the maximum vibration velocity levels are greater than about 65 VdB), then this site should be carefully evaluated for the possibility of efficient vibration propagation. Areas with efficient vibration propagation could have vibration problems when the project is built.
- **Documenting vibration from existing rail lines:** Measurements to document the levels of vibration created by existing rail lines can be important in evaluating the impact of the new vibration source and determining vibration propagation characteristics in the area. As discussed in Chapter 8, if vibration from an existing rail line will be higher than that from the proposed transit trains, there may not be impact even though the normal impact criterion would be exceeded.

Although ground-borne vibration is almost exclusively a problem inside buildings, measurements of existing ambient vibration generally should be performed outdoors. Two important reasons for this are: (1) equipment inside the building may cause more vibration than exterior sources, and (2) the building structure and the resonances of the building can have strong, but difficult to predict, effects on the vibration. However, there are some cases where measurements of indoor vibration are important. Documenting the vibration levels inside a vibration-sensitive building can be particularly important since equipment and activities inside the building sometimes cause vibration greater than that due to external sources such as street traffic or aircraft overflights. Floor vibration measurements are taken near the center of a floor span where the vibration amplitudes are the highest.

The goal of most ambient vibration tests is to characterize the root mean square (rms) vertical vibration velocity level at the ground surface. In almost all cases it is sufficient to measure only vertical vibration and ignore the transverse components of the vibration. Although transverse components can transmit significant vibration energy into a building, the vertical component usually has greater amplitudes than transverse vibration. Moreover, vertical vibration is usually transmitted more efficiently into building foundations than transverse vibration.

The manner in which a transducer is mounted can affect the measured levels of ground-borne vibration. However, at the frequencies usually of concern for ground-borne vibration (less than about 200 Hz), straightforward methods of mounting transducers on the ground surface or on pavement are adequate for vertical vibration measurements. Quick-drying epoxy or beeswax is often used to mount transducers to smooth paved surfaces or to metal stakes driven into the ground. Rough concrete or rock surfaces require special mountings. One approach is to use a liberal base of epoxy to attach small aluminum blocks to the surface and then mount the transducers on the aluminum blocks.

Selecting sites for an ambient vibration survey requires good common sense. Sites selected to characterize a transit corridor should be distributed along the entire project and should be representative of the types of vibration environments found in the corridor. This would commonly include:

- measurements in quiet residential areas removed from major traffic arterials to characterize low-ambient vibrations;
- measurements along major traffic arterials and highways or freeways to characterize high-vibration areas;
- measurements in any area with vibration-sensitive activities; and
- measurements at any significant existing source of vibration such as railroad lines.

The transducers should be located near the building setback line for background vibration measurements. Ambient measurements along railroad lines ideally will include: multiple sites; several distances from the rail line at each site; and 4 to 10 train passbys for each test. Because of the irregular schedule for freight trains and the low number of operations each day, it is often impractical to perform tests at more than two or three sites along the rail line or to measure more than two or three passbys at each site. Rail type and condition strongly affect the vibration levels. Consequently, it is important to inspect the track at each measurement site to locate any switches, bad rail joints, corrugations, or other factors that could be responsible for higher than normal vibration levels.

The appropriate methods of characterizing ambient vibration are dependent on the type of information required for the analysis. Following are some examples:

- **Ambient Vibration:** Ambient vibration is usually characterized with a continuous 10- to 30-minute measurement of vibration. The L_{eq} of the vibration velocity level over the measurement period gives an indication of the average vibration energy. L_{eq} is equivalent to a long averaging time rms level. Specific events can be characterized by the maximum rms level (L_{max}) of the event or by performing a statistical analysis of rms levels over the measurement period. An rms averaging time of 1 second should be used for statistical analysis of the vibration level.
- **Specific Events:** Specific events such as train passbys should be characterized by the rms level during the time that the train passes by. If the locomotives have vibration levels more than 5 dB higher than the passenger or freight cars, a separate rms level for the locomotives should be obtained. The locomotives can usually be characterized by the L_{max} during the train passby. The rms averaging time or time constant should be 1 second when determining L_{max}. Sometimes it is adequate to use L_{max} to characterize the train passby, which is simpler to obtain than the rms averaged over the entire train passby.
- **Spectral Analysis:** When the vibration data will be used to characterize vibration propagation or for other special analysis, a spectral analysis of the vibration is required. An example would be if

vibration transmission of the ground is suspected of having particular frequency characteristics. For many analyses, 1/3-octave band charts are best for describing vibration behavior. Narrowband spectra also can be valuable, particularly for identifying pure tones and designing specific mitigation measures.

Note that it is preferable that ambient vibration be characterized in terms of the root mean square (rms) velocity level, not the peak particle velocity (ppv) as is commonly used to monitor construction vibration. As discussed in Chapter 7, rms velocity is considered more appropriate than ppv for describing human response to building vibration.

11.2 VIBRATION PREDICTION PROCEDURE

Predicting ground-borne vibration associated with a transportation project continues to be a developing field. Because ground-borne vibration is a complex phenomenon that is difficult to model and predict accurately, most projection procedures that have been used for transit projects rely on empirical data. The procedure described in this section is based on site-specific tests of vibration propagation. Developed under an FTA-funded research contract,(1) this procedure is recommended for detailed evaluations of ground-borne vibration. There have been other approaches to a prediction procedure including some that use pure numerical methods. For example, approaches using finite elements are being used to estimate ground-borne vibration from subway tunnels, but most numerical approaches are still in the early stages of development.

11.2.1 Overview of Prediction Procedure

The prediction method described in this section was developed to allow the use of data collected in one location to accurately predict vibration levels in another site where the geologic conditions may be completely different. The procedure is based on using a special measured function, called *transfer mobility*. Transfer mobility measured at an existing transit system is used to normalize ground-borne vibration data and remove the effects of geology. The normalized vibration is referred to as the force density. The force density can be combined with transfer mobility measurements at sensitive sites along a new project to develop projections of future ground-borne vibration.

Transfer mobility represents the relationship between a vibration source that excites the ground and the resulting vibration of the ground surface. It is a function of both frequency and distance from the source. The transfer mobility between two points completely defines the composite vibration propagation characteristics between the two points. In most practical cases, receivers are close enough to the train tracks that the vibration cannot be considered to be originating from a single point. The vibration source must be modeled as a line-source. Consequently, the point transfer mobility must be modified to account for a line-source. In the following text, TM_{point} is used to indicate the measured point-source transfer mobility and TM_{line} is used for the line-source transfer mobility derived from TM_{point}.

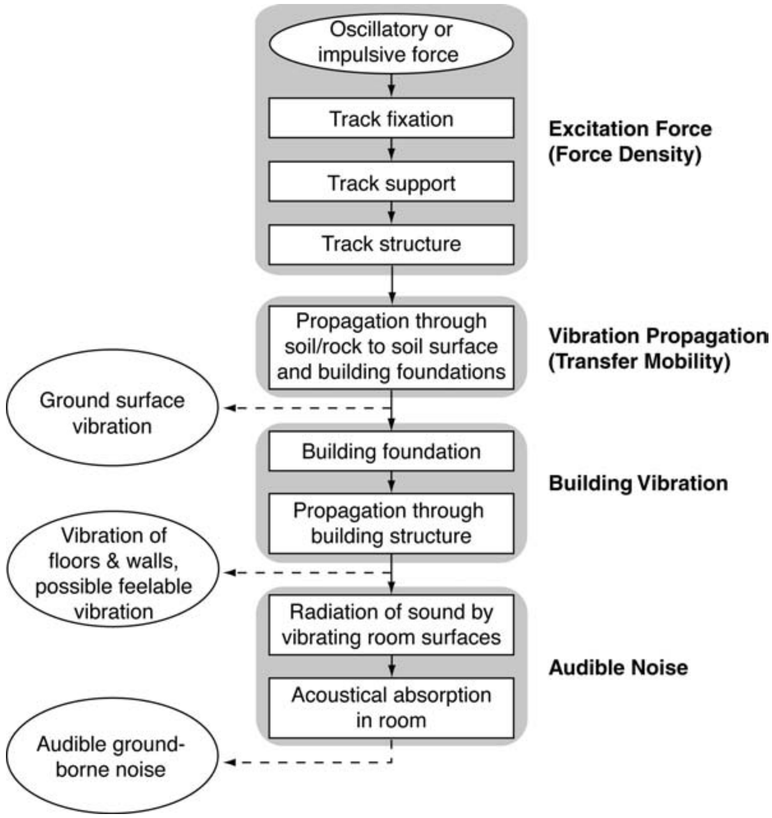

Figure 11-1. Block Diagram of Ground-Borne Vibration and Noise Model

The prediction procedure considers ground-borne vibration to be divided into several basic components as shown schematically in Figure 11-1. The components are:

1. **Excitation Force.** The vibration energy is created by oscillatory and impulsive forces. Steel wheels rolling on smooth steel rails create random oscillatory forces. When a wheel encounters a discontinuity such as a rail joint, an impulsive force is created. The force excites the transit structure, such as the subway tunnel, or the ballast for at-grade track. In the prediction method, the combination of the actual force generated at the wheel/rail interface and the vibration of the transit structure are usually combined into an equivalent force density level. The force density level describes the force that excites the soil/rock surrounding the transit structure.

2. **Vibration Propagation.** The vibration of the transit structure causes vibration waves in the soil that propagate away from the transit structure. The vibration energy can propagate through the soil or rock in a variety of wave forms. All ground vibration includes shear and compression waves. In addition, Rayleigh waves, which propagate along the ground surface, can be a major carrier of vibration energy. The mathematical modeling of vibration is complicated when, as is usually the case, there are soil strata with different elastic properties. As indicated in Figure 11-1, the

propagation through the soil/rock is modeled using the transfer mobility, which is usually determined experimentally.

The combination of the force density level and the transfer mobility is used to predict the ground-surface vibration. Here is the essential difference between the General and Detailed approaches: the projection process is simplified in a General Assessment by going directly to generalized estimates of the ground-surface vibration.

3. **Building Vibration.** When the ground vibration excites a building foundation, it sets the building into vibration motion and starts vibration waves propagating throughout the building structure. The interaction between the ground and the foundation causes some reduction in vibration levels. The amount of reduction is dependent on the mass and stiffness of the foundation. The more massive the foundation, the lower the response to ground vibration. As the vibration waves propagate through the building, they can create feelable vibration and can cause annoying rattling of windows and decorative items either hanging or on shelves.

4. **Audible Noise.** In addition to feelable vibration, the vibration of room surfaces radiates low-frequency sound that may be audible. As indicated in Figure 11-1, the sound level is affected by the amount of acoustical absorption in the receiver room.

A fundamental assumption of the prediction approach outlined here is that the force density, transfer mobility, and the building coupling to the ground are all independent factors. The following equations are the basis for the prediction procedure where all of the quantities are one-third octave band spectral levels in decibels with consistent reference values:

$$L_v = L_F + TM_{line} + C_{build}$$

$$L_A = L_v + K_{rad} + K_{A\text{-}wt}$$

where:

L_v = rms vibration velocity level,

L_A = A-weighted sound level,

L_F = force density for a line vibration source such as a train,

TM_{line} = line-source transfer mobility from the tracks to the sensitive site,

C_{build} = adjustments to account for ground–building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings,

K_{rad} = adjustment to account for conversion from vibration to sound pressure level including accounting for the amount of acoustical absorption inside the room (A value of zero can be used for K_{rad} for typical residential rooms when the decibel reference value for L_v is 1 micro in./sec.[1]),

$K_{A\text{-}wt}$ = A-weighting adjustment at the 1/3-octave band center frequency.

All of the quantities given above are functions of frequency. The standard approach to dealing with the frequency dependence is to develop projections on a 1/3-octave band basis using the average values for each 1/3-octave band. The end results of the analysis are the 1/3-octave band spectra of the ground-borne vibration and the ground-borne noise. The spectra are then applied to the vibration criteria for Detailed Analysis. The A-weighted ground-borne noise level can be calculated from the vibration spectrum. This more detailed approach is in contrast to the General Assessment where the overall vibration velocity level and A-weighted sound level are predicted without any consideration of the particular frequency characteristics of the propagation path.

11.2.2 Major Steps in Detailed Analysis

The major steps in performing a Detailed Analysis are intended to obtain quantities for the equations given above. These are:

1. Develop estimates of the force density. The estimate of force density can be based on previous measurements or a special test program can be designed to measure the force density at an existing facility. If no suitable measurements are available, testing should be done at a transit facility with equipment similar to the planned vehicles. Adjustments for factors such as train speed, track support system, and vehicle suspension may be needed to match the force density to the conditions at a specific site. Some appropriate adjustments can be found in the report "State-of- the-Art Review: Prediction and Control of Ground-Borne Noise and Vibration from Rail Transit Trains."[2]

2. Measure the point-source transfer mobility at representative sites. The transfer mobility is a function of both frequency and distance from the source. Point-source transfer mobility is used for sources with short lengths, such as single vehicles or columns supporting elevated structures.

3. Use numerical integration to estimate a line-source transfer mobility from the point-source transfer mobilities. Line-source transfer mobility is applicable to long sources like trains.

4. Combine force density and line-source transfer mobility to project ground-surface vibration.

5. Add adjustment factors to estimate the building response to the ground-surface vibration and to estimate the A-weighted sound level inside buildings.

The two key elements of the transfer mobility procedure are a measured force function that represents the vibration energy put into the ground and a measured transfer mobility that characterizes the propagation of the vibration from the source to the receiver. The unit of force density is force divided by square root of train length, represented here in decibels relative to 1 $lb/(ft)^{1/2}$. The force density represents an incoherent line of vibration force equal to the length of transit trains. The process of estimating force density from train vibration and transfer mobility tests is discussed in Section 11.3. Figure 11-2 shows some trackbed force densities that have been developed from measurements of vibration from heavy and light rail transit vehicles. This figure provides a comparison of the vibration forces from heavy commuter trains and light rail transit vehicles with different types of primary suspensions illustrating the range of vibration forces commonly experienced in a transit system. A force density of a vehicle includes the characteristics of its track support system at the measurement site. Adjustments must be made to the force density to account for differences between the facility where the force density was measured and the new system being analyzed.

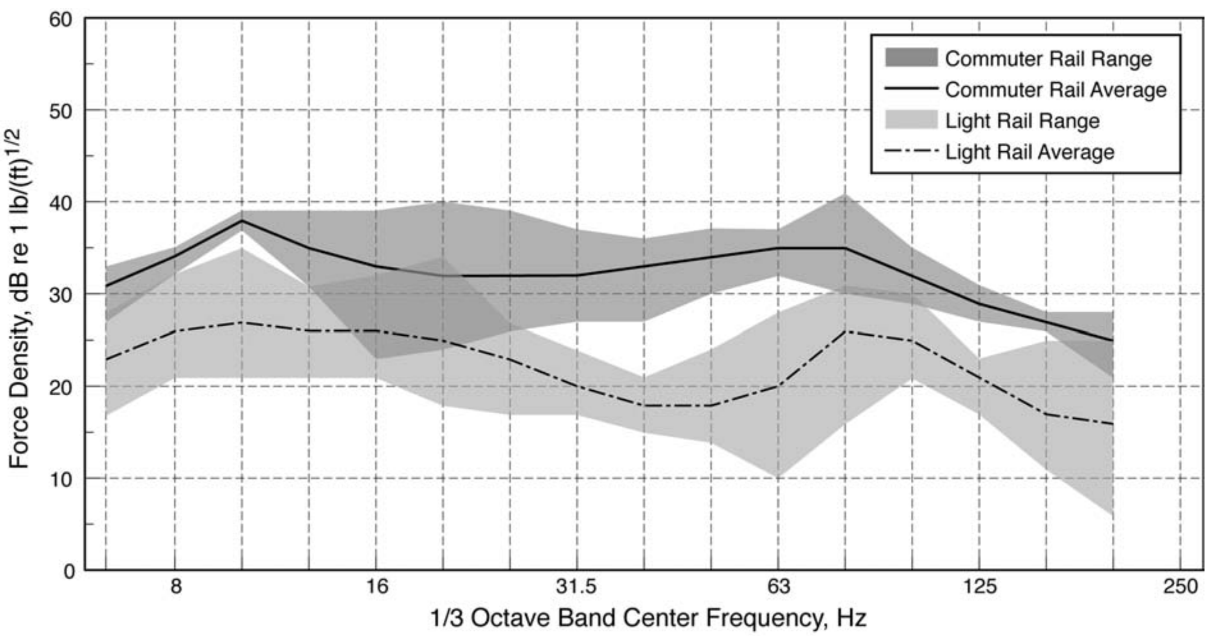

Figure 11-2. Typical Force Densities for Rail Transit Vehicles, 40 mph

The key elements of the vibration prediction procedure are implementation of field tests to measure the transfer mobility and the subsequent use of transfer mobility to characterize vibration propagation. The process of measuring transfer mobility involves impacting the ground and measuring the resulting vibration pulse at various distances from the impact. Standard signal-processing techniques are used to determine the transfer function, or frequency response function, between the exciting force and the resultant ground-surface vibration. Numerical regression methods are used to combine a number of two-point transfer functions into a smooth point-source transfer mobility that represents the average vibration propagation characteristics of a site as a function of both distance from the source and frequency. The transfer mobility is usually expressed in terms of a group of 1/3-octave band transfer mobilities. This processing is performed after transferring the data to a computer. Figure 11-3 shows the point-source transfer mobilities from a series of tests at the Transportation Technology Center in Pueblo, Colorado.(3,4,5,6)

Once the point-source transfer mobility has been defined, the line-source transfer mobility can be calculated using numerical integration techniques. This process has been described in a Transportation Research Board paper. (1) Figure 11-4 shows the line-source transfer mobilities that were derived from the point-source transfer mobilities shown in Figure 11-3. The line-source transfer mobilities are used to normalize measured vibration velocity levels from train passbys and to obtain force density.

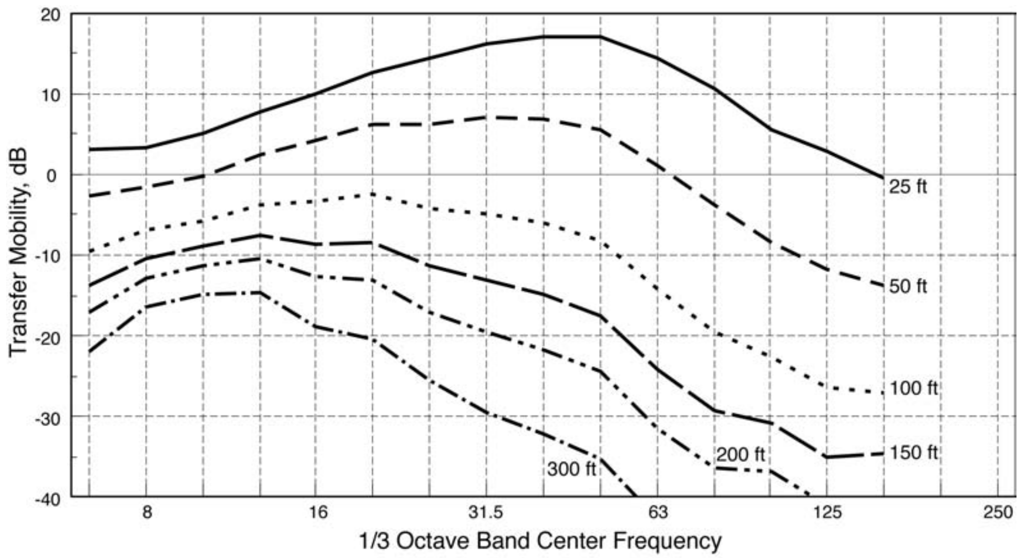

Figure 11-3. Example of Point-Source Transfer Mobility

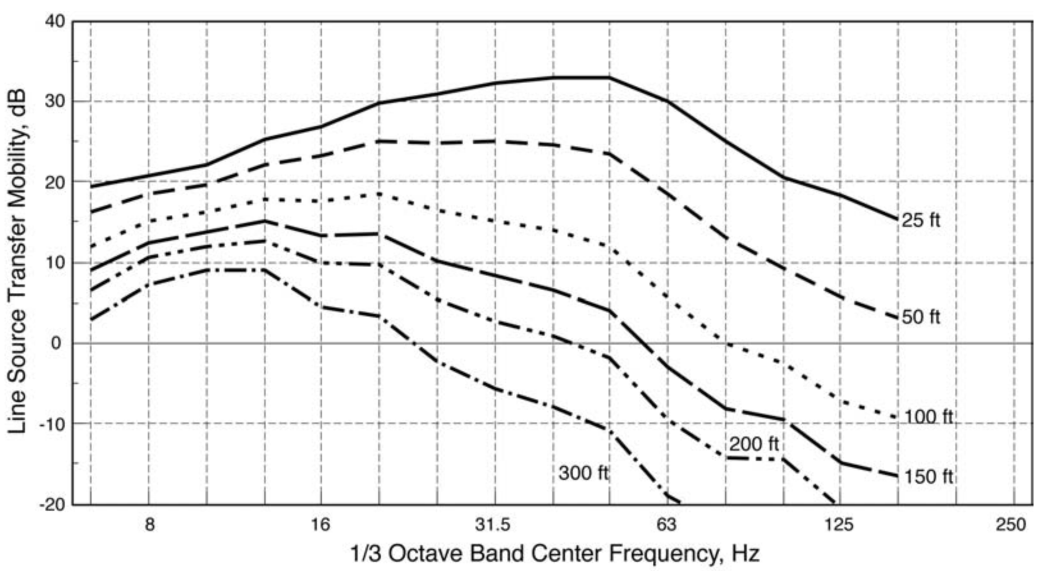

Figure 11-4. Example of Line-Source Transfer Mobility

The propagation of vibration from the building foundation to the receiver room is a very complex problem dependent on the specific design of the building. Detailed evaluation of the vibration propagation would require extensive use of numerical procedures such as the finite element method. Such a detailed evaluation is generally not practical for individual buildings considered in this manual. The propagation of vibration through a building and the radiation of sound by vibrating building surfaces is consequently estimated using simple empirical or theoretical models. The recommended procedures are outlined in the *Handbook of Urban Rail Noise and Vibration Control*.[7] The approach consists of adding the following adjustments to the 1/3-octave band spectrum of the projected ground-surface vibration:

1. **Building response or coupling loss.** This represents the change in the incident ground-surface vibration due to the presence of the building foundation. The adjustments in the *Handbook*, are shown in Figure 11-5. Note that the correction is zero when estimating basement floor vibration or vibration of at-grade slabs. Measured values may be used in place of these generic adjustments.

2. **Transmission through the building.** The vibration amplitude typically decreases as the vibration energy propagates from the foundation through the remainder of the building. The normal assumption is that vibration attenuates by 1 to 2 dB for each floor.

3. **Floor resonances.** Vibration amplitudes will be amplified because of resonances of the floor/ceiling systems. For a typical wood-frame residential structure, the fundamental resonance is usually in the 15- to 20-Hz range. Reinforced-concrete slab floors in modern buildings will have fundamental resonance frequencies in the 20- to 30- Hz range. An amplification resulting in a gain of approximately 6 dB should be used in the frequency range of the fundamental resonance.

   The projected floor vibration is used to estimate the levels of ground-borne noise. The primary factors affecting noise level are the average vibration level of the room surfaces and the amount of acoustical absorption within the room. As discussed above, the radiation adjustment is zero for typical rooms, which gives:

$$L_A \approx L_v + K_{A-wt}$$

   where L_A is the A-weighted sound level in a 1/3-octave band, L_v is the vibration velocity level in that band, and $K_{A\text{-}wt}$ is the A-weighting adjustment at the center frequency of the 1/3-octave band. The A-weighted levels in the 1/3-octave bands are then combined to give the overall A-weighted sound level.

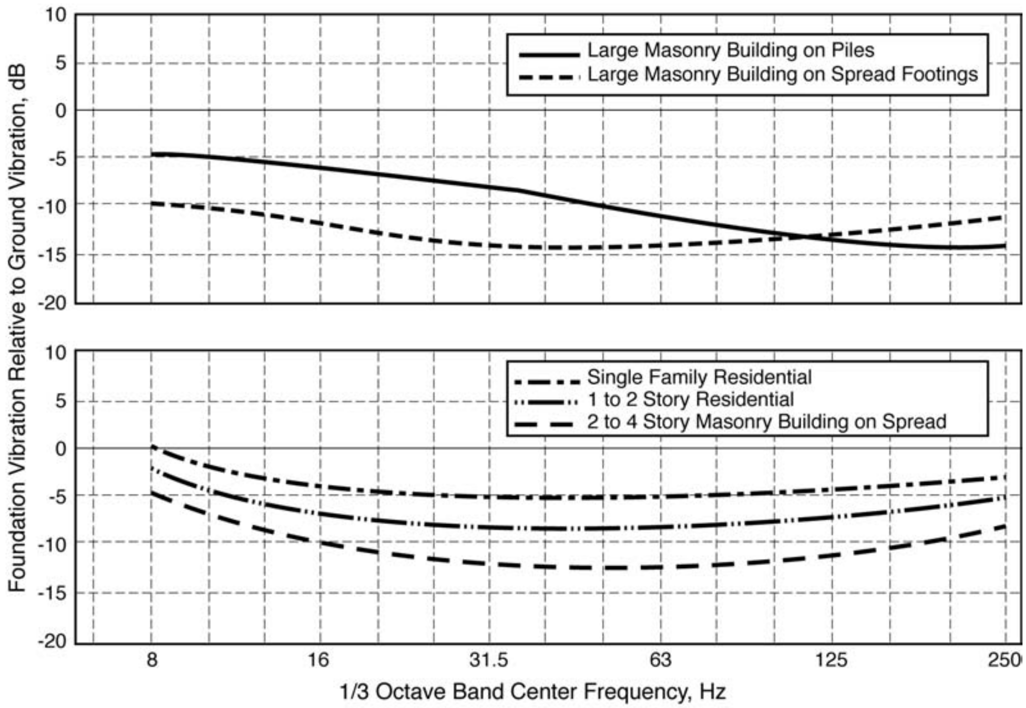

Figure 11-5. Foundation Response for Various Types of Buildings

11.3 MEASURING TRANSFER MOBILITY AND FORCE DENSITY

The test procedure to measure transfer mobility basically consists of dropping a heavy weight on the ground and measuring the force into the ground and the response at several distances from the impact. The goal of the test is to create vibration pulses that travel from the source to the receiver using the same path that will be taken by the transit system vibration. The transfer mobility expresses the relationship between the input force and the ground-surface vibration.

Figure 11-6 illustrates the field procedure for at-grade and subway testing of transfer mobility. A weight is dropped from a distance of 3 to 4 feet onto a force transducer. The responses of the force and vibration transducers are recorded on a multichannel tape recorder for later analysis in the laboratory. An alternative approach is to set up the analysis equipment in the field and capture the signals directly. This complicates the field testing but eliminates the laboratory analysis of tape-recorded data.

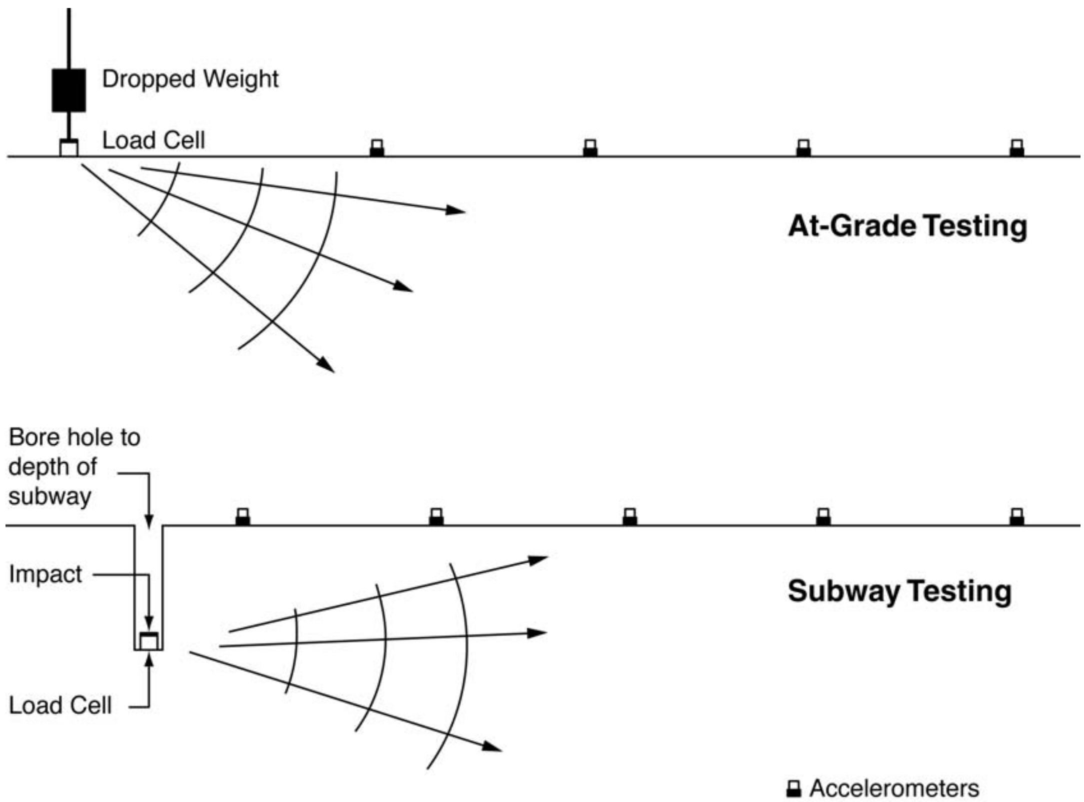

Figure 11-6. Test Configuration for Measuring Transfer Mobility

When the procedure is applied to subways, the force must be located at the approximate depth of the subway. This is done by drilling a bore hole and locating the force transducer at the bottom of the hole. The tests are usually performed at the same time that the bore holes are drilled. This allows using the soil-sampling equipment on the drill rig for the transfer mobility testing. The force transducer is attached to the bottom of the drill string and lowered to the bottom of the hole. A standard soil sampling hammer, which is usually a 140-pound weight dropped 18 inches onto a collar attached to the drill string, is used to excite the ground. The force transducer must be capable of operating under water if the water table is near the surface or a slurry drilling process is used.

11.3.1 Instrumentation

Performing a transfer mobility test requires specialized equipment. Most of the equipment is readily available from commercial sources. A load cell can be used as the force transducer. The force transducer should be capable of impact loads of 5,000 to 10,000 pounds. For borehole testing, the load cell must be hermetically sealed and capable of being used at the bottom of a 30- to 100-foot-deep hole partially filled with water. Typical instrumentation for the field-testing and laboratory analysis of transfer mobility is shown in Figure 11-7. Either accelerometers or geophones can be used as the vibration transducers. The

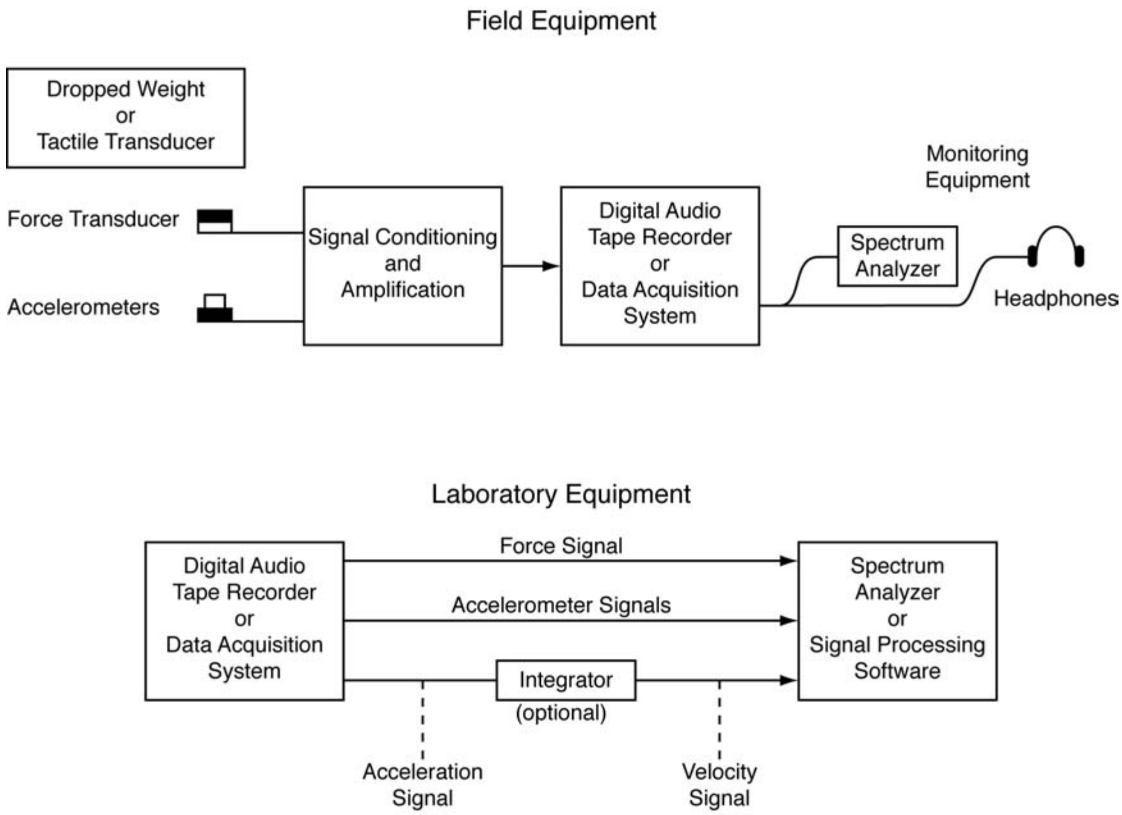

Figure 11-7. Equipment Required for Field Testing and Laboratory Analysis

requirement is that the transducers with the associated amplifiers be capable of accurately measuring levels of 0.0001 in./sec at 40 Hz and have a flat frequency response from 6 Hz to 400 Hz. Data must be acquired (either with digital audio tape or an alternative digital acquisition system) with a flat frequency response over the range of 6 to 400 Hz.

A narrowband spectrum analyzer or signal-processing software can be used to calculate the transfer function and coherence between the force and vibration data. The analyzer must be capable of capturing impulses from at least two channels to calculate the frequency spectrum of the transfer function between the force and vibration channels. All transfer functions should include the average of at least 20 impulses. The averaging of the impulses will provide significant signal enhancement, which is usually required to accurately characterize the transfer function. Signal enhancement is particularly important when the vibration transducer is more than 100 feet from the impact.

Transfer mobility may also be measured using other methods. One such method involves producing maximum-length sequence (MLS) force impulses with a tactile transducer. Signal-processing software is then used to calculate the transfer function from the MLS forces and measured vibrations. The MLS measurement method uses a pseudo-random binary sequence as the signal and has the advantage of increasing the signal-to-noise ratio of the measurement.

The laboratory equipment in Figure 11-7 shows using either a spectrum analyzer or signal-processing software to calculate the transfer function. Specialized multi-channel spectrum analyzers have built-in capabilities for computing transfer functions. The use of a spectrum analyzer has the advantage of being computationally efficient. On the other hand, signal-processing software can offer more flexibility in analyzing data signals and allows the use of different digital signal processing methods such as the MLS. Typical measurement programs involve acquisition of data in the field and later processing of the information in a laboratory. However, recent advances in instrumentation and signal-processing software allow data to be collected and analyzed while in the field.

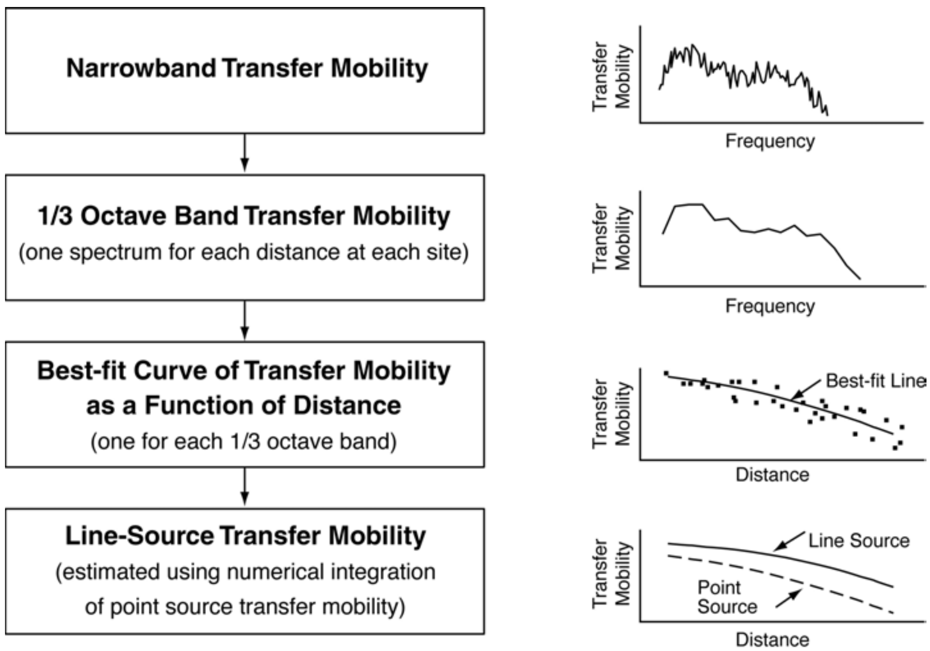

Figure 11-8. Analysis of Transfer Mobility

11.3.2 Analysis of Transfer Mobility Data

Two different approaches have been used to develop estimates of line-source transfer mobility. The first consists of using lines of transducers and the second consists of a line of impact positions. The steps to develop line-source transfer mobility curves from tests using one or more lines of transducers are shown in Figure 11-8. The procedure starts with the narrowband transfer function between source and receiver at each measurement position. There should be a minimum of four distances in any test line. Because of the possibility of local variations in propagation characteristics, if at all possible, two or more lines should be used to characterize a site. A total of 10 to 20 transducer positions are often used to characterize a site.

The first step in the analysis procedure is to calculate the equivalent 1/3-octave band transfer functions. This reduces each spectrum to 15 numbers. As shown in Figure 11-8, the 1/3-octave band spectrum is much smoother than the narrowband spectrum. The next step is to calculate a best-fit curve of transfer mobility as a function of distance for each 1/3-octave band. When analyzing a specific site, the best-fit curve will be based on 10 to 20 points. Up to several hundred points could be used to determine average best-fit curves for a number of sites.

The 1/3-octave band best-fit curves can be directly applied to point vibration sources. Buses can usually be considered to be point-sources, as can columns supporting elevated structures. However, for a line vibration source such as a train, numerical integration must be used to calculate an equivalent line-source transfer mobility. The numerical integration procedures are detailed in Reference 1.

The second procedure for estimating line-source transfer mobility, shown schematically in Figure 11-9, is best for detailed assessment of specific vibration paths or specific buildings. The vibration transducers are located at specific points of interest and a line of impacts is used. For example, a 165-foot train might be represented by a line of 11 impact positions along the track centerline at 15-foot intervals. It is possible to sum the point-source results using Simpson's rule for numerical integration to directly calculate line-source transfer mobility. This is a considerably more direct approach than is possible with lines of vibration transducers.

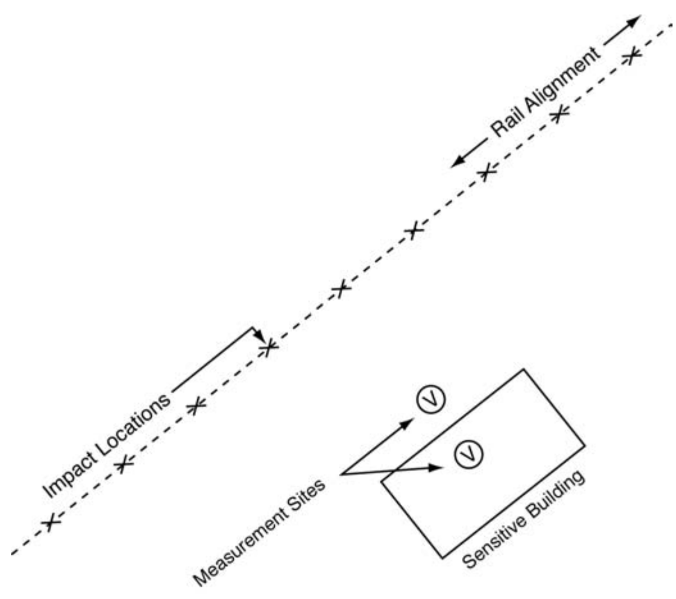

Figure 11-9. Schematic of Transfer Mobility Measurements Using a Line of Impacts

11.3.3 Deriving Force Density

Force Density is not a quantity that can be measured directly; it must be inferred from measurements of transfer mobility and train vibration at the same site. For deriving force density, the best results are achieved by deriving line-source transfer mobility from a line of impacts. The force density for each 1/3-octave band is then simply:

$$L_F = L_v - TM_{line}$$

where L_F is the force density, L_v is measured train ground-borne vibration, and TM_{line} is the line-source transfer mobility. The standard approach is to use the average force density from measurements at three or more positions.

11.4 ASSESSMENT OF VIBRATION IMPACT

The goals of the vibration assessment are to inventory all sensitive land uses that may be adversely impacted by the ground-borne vibration and noise from the proposed project and to determine the mitigation measures that will be required to eliminate or minimize the impact. This requires projecting the levels of ground-borne vibration and noise, comparing the projections with the impact criteria, and developing a list of suitable mitigation measures. Note that the General Assessment is incorporated as an intermediate step in the impact assessment because of its relative simplicity and potential to narrow the areas where Detailed Analysis needs to be done.

The assessment of vibration impact should proceed according to the following steps:

1. Screen the entire proposed transit alignment to identify areas where there is the potential of impact from ground-borne vibration. The vibration screening procedure is described in Chapter 9. If no sensitive land uses are within the screening distances, it is not necessary to perform any further assessment of ground-borne vibration.

2. Define the curves of ground-surface vibration level as a function of distance that can be used with the General Assessment. Usually this will mean selecting the appropriate curve from Chapter 10 for the proposed transit mode. For less common transit modes, it may be necessary to make measurements at an existing facility.

3. Use the General Assessment procedure to estimate vibration levels for specific buildings or groups of buildings. The projected levels are compared with the impact criteria for General Vibration Assessment (Tables 8-1 and 8-2) to determine whether vibration impact is likely. The goal of this step is to develop a reasonably accurate catalog of the buildings that will experience ground-borne vibration or noise levels that exceed the criteria. Applying the impact criteria for the General Assessment will result in a conservative assessment of the impact. That is, it is possible that some buildings that are identified as impacted may not be impacted under a more detailed analysis. However, at this stage it is better to include some buildings that may not be impacted than to

exclude some buildings that are likely to be impacted. In locations where the General Assessment indicates impact, the more refined techniques of Detailed Analysis would be employed.

4. In some cases it will be necessary to perform a vibration survey to characterize existing ambient vibration. As discussed in Section 11.1, although knowledge of the existing ambient vibration is not generally required to evaluate vibration impact, there are times when a survey of existing conditions is valuable. One common example is when a rail transit project will be located in an existing railroad right-of-way shared by freight trains. Chapter 8 includes some guidelines on how to account for existing vibration that is higher than the impact limit for the project vibration.

5. For areas where the General Assessment impact criteria are exceeded, review potential mitigation measures and assemble a list of feasible approaches to vibration control. To be feasible, the measure, or combination of measures, must be capable of providing a significant reduction of the vibration levels, at least 5 dB, while being reasonable from the standpoint of the added cost. The impact assessment and review of mitigation measures are preliminary at this point because vibration control is frequency-dependent, and specific recommendations of vibration control measures can be made only after evaluating the frequency characteristics of the vibration.

6. Use the Detailed Vibration Analysis to refine the impact assessment and to develop detailed vibration mitigation measures where needed. It is usually necessary to project vibration spectra at buildings which will be affected at levels higher than the impact thresholds (refer to Section 8.2). This type of assessment is normally performed as part of final design rather than during the environmental impact assessment stage. Because a Detailed Analysis is more accurate than a General Assessment, there will be times that the Detailed Analysis will show that the ground-borne vibration and noise levels will be below the applicable criteria and that mitigation is not required. If the projected levels are still above the limits, the spectra provided by the Detailed Analysis will be needed to evaluate vibration control approaches.

11.5 VIBRATION MITIGATION

The purpose of vibration mitigation is to minimize the adverse effects that the project ground-borne vibration will have on sensitive land uses. Because ground-borne vibration is not as common a problem as environmental noise, the mitigation approaches have not been as well defined. In some cases it has been necessary to develop innovative approaches to control the impact. Among the successful examples are the floating-slab systems that were developed for the San Francisco and Toronto rapid transit systems. However, the vibration control measures developed for rail transit systems are not effective for freight trains. The heavy axle loads associated with freight rail are outside the range of applicable design parameters for vibration reduction on lighter rail transit systems. Consequently the discussion in this section pertains to rail transit systems, not freight railroads. Any plan to relocate existing railroad tracks closer to vibration-sensitive sites in order to accommodate a new rail transit line in the right-of-way must be carefully considered since the increased vibration impact from freight trains will have to be borne by the community.

Although the focus is on rail systems in this section, there are very infrequent problems caused by buses and in these instances, the solution is rather straightforward. When buses do cause annoying ground-borne vibration, it is usually clear that the source of the problem is roadway roughness or unevenness caused by bumps, pot holes, expansion joints, or driveway transitions. Smoothing the roadway surface will usually solve the problem. In cases where a rubber-tired system runs inside a building, such as an airport people mover, vibration control may involve additional measures besides ensuring a smooth guideway. Loading and unloading of guideway support beams may generate dynamic forces that transmit into the building structure. Special guideway support systems may be required, similar to the discussion below regarding floating slabs.

The importance of adequate wheel and rail maintenance in controlling levels of ground-borne vibration cannot be overemphasized. Problems with rough wheels or rails can increase vibration levels by as much as 20 dB in extreme cases, negating the effects of even the most effective vibration control measures. It is rare that practical vibration control measures will provide more than 15 to 20 dB attenuation. When there are ground-borne vibration problems with existing transit equipment, the best vibration control measure often is to implement new or improved maintenance procedures. Grinding rough or corrugated rail and wheel truing to eliminate wheel flats and restore the wheel contour may provide more vibration reduction than would be obtainable from completely replacing the existing track system with floating slabs.

Given that the track and vehicles are in good condition, the options for further reductions in the vibration levels fit into one of seven categories: (1) maintenance procedures, (2) location and design of special trackwork, (3) vehicle modifications, (4) changes in the track support system, (5) building modifications, (6) adjustments to the vibration transmission path, and (7) operational changes.

Vibration reduction measures incur additional costs to a system. Some of the same treatments for noise mitigation can be considered for vibration mitigation. Costs for noise control measures are documented in a report from the Transit Cooperative Research Program (TCRP).[8] Where applicable to vibration reduction, costs for noise abatement methods from that report are given in the following discussion.

- **Maintenance:** As discussed above, effective maintenance programs are essential for controlling ground-borne vibration. When the wheel and rail surfaces are allowed to degrade the vibration levels can increase by as much as 20 dB compared to a new or well-maintained system. Some maintenance procedures that are particularly effective at avoiding increases in ground-borne vibration are:

    - Rail grinding on a regular basis. Rail grinding is particularly important for rail that develops corrugations. The TCRP report notes that periodic rail grinding actually results in a net savings per year on wheel and rail wear. Most transit systems contract out rail grinding, although some of the larger systems make the investment of approximately $1 million for the equipment and do their own grinding. Contractors typically charge a fixed amount per day for the equipment on site, plus an amount per pass-mile (one pass of the grinding machine for one mile). Typical fixed amounts would be $15,000 per day and $1000 per pass-mile.

- Wheel truing to re-contour the wheel, provide a smooth running surface, and remove wheel flats. The most dramatic vibration reduction results from removing wheel flats. However, significant improvements also can be observed simply from smoothing the running surface. A wheel truing machine costs approximately $1 million. The TCRP report figures a system with 700 vehicles would incur a yearly cost of $300,000 to $400,000 for a wheel truing program.
- Implement vehicle reconditioning programs, particularly when components such as suspension system, brakes, wheels, and slip-slide detectors will be involved. A slip-slide control system costs approximately $5,000 to $10,000 per vehicle, with a maintenance cost of $200 per year.
- Install wheel-flat detector systems to identify vehicles which are most in need of wheel truing. These systems are becoming more common on railroads and intercity passenger systems, but are relatively rare on transit systems. Therefore the costs are yet to be determined.

- **Planning and Design of Special Trackwork:** A large percentage of vibration impact from a new transit facility is often caused by wheel impacts at the special trackwork for turnouts and crossovers. When feasible, the most effective vibration control measure is to relocate the special trackwork to a less vibration-sensitive area. Sometimes this requires adjusting the location by several hundred feet and will not have a significant adverse impact on the operation plan for the system. Careful review of crossover and turnout locations during the preliminary engineering stage is an important step to minimizing potential for vibration impact. Another approach is to use special devices at turnouts and crossovers, special "frogs," that incorporate mechanisms to close the gaps between running rails. Frogs with spring-loaded mechanisms and frogs with movable points can significantly reduce vibration levels near crossovers. According to the TCRP report, a spring frog costs about $12,000, twice the cost of a standard frog. A movable point frog involves elaborate signal and control circuitry resulting in higher costs, approximately $200,000.

- **Vehicle Specifications:** The ideal rail vehicle, with respect to minimizing ground-borne vibration, should have a low unsprung weight, a soft primary suspension, a minimum of metal-to-metal contact between moving parts of the truck, and smooth wheels that are perfectly round. A limit for the vertical resonance frequency of the primary suspension should be included in the specifications for any new vehicle. A vertical resonance frequency of 12 Hz or less is sufficient to control the levels of ground-borne vibration. Some have recommended that transit vehicle specifications require that the vertical resonance frequency be less than 8 Hz.

- **Special Track Support Systems:** When the vibration assessment indicates that vibration levels will be excessive, it is usually the track support system that is changed to reduce the vibration levels. Floating slabs, resiliently supported ties, high-resilience fasteners, and ballast mats have all been used in subways to reduce the levels of ground-borne vibration. To be effective, all of these measures must be optimized for the frequency spectrum of the vibration. Most of these relatively standard procedures have been successfully used on several subway projects. Applications on at-grade and elevated track are less common. This is because vibration problems are less common for at-grade and elevated track; cost of the vibration control measures is a higher percentage of the construction costs of at-grade and elevated track; and exposure to the elements can require significant design modifications.

Each of the major vibration control measures for track support is discussed below. Costs for these treatments are not covered by the TCRP report, but are given as estimates based on transit agency experience.

- Resilient Fasteners: Resilient fasteners are used to fasten the rail to concrete track slabs. Standard resilient fasteners are very stiff in the vertical direction, usually in the range of 200,000 lb/in., although they do provide vibration reduction compared to some of the rigid fastening systems used on older systems (e.g., wood half-ties embedded in concrete). Special fasteners with vertical stiffness in the range of 30,000 lb/in. will reduce vibration by as much as 5 to 10 dB at frequencies above 30 to 40 Hz. Premium fasteners cost approximately $300 per track-foot, about 6 times the cost of standard fasteners.

- Ballast Mats: A ballast mat consists of a rubber or other type of elastomer pad that is placed under the ballast. The mat generally must be placed on a concrete pad to be effective. They will not be as effective if placed directly on the soil or the sub-ballast. Consequently, most ballast mat applications are in subway or elevated structures. Ballast mats can provide 10 to 15 dB attenuation at frequencies above 25 to 30 Hz. Ballast mats are often a good retrofit measure for existing tie-and-ballast track where there are vibration problems. Installed ballast mats cost approximately $180 per track-foot.

- Resiliently Supported Ties: The resiliently supported tie system consists of concrete ties supported by rubber pads. The rails are fastened directly to the concrete ties using standard rail clips. Existing measurement data indicate that resiliently supported ties may be very effective in reducing low-frequency vibration in the 15 to 40 Hz range. This makes them particularly appropriate for transit systems with vibration problems in the 20 to 30 Hz range. A resiliently supported tie system costs approximately $400 per track-foot. Although most commonly used in slab track or subway tunnel applications, another version of a resiliently supported tie system involves attaching thick rubber pads directly to the underside of ties in ballast. This treatment costs approximately the same as a ballast mat, or $180 per track foot.

- Floating Slabs: Floating slabs can be very effective at controlling ground-borne vibration and noise. They basically consist of a concrete slab supported on resilient elements, usually rubber or a similar elastomer. A variant that was first used in Toronto and is generally referred to as the double tie system, consists of 5-foot-long slabs with 4 or more rubber pads under each slab. Floating slabs are effective at frequencies greater than their single-degree-of-freedom vertical resonance frequency. The floating slabs used in

Washington DC, Atlanta, and Boston were all designed to have a vertical resonance in the 14 to 17 Hz range. A special floating slab in San Francisco's BART system uses a very heavy design with a resonance frequency in the 5 to 10 Hz frequency range. The primary disadvantage of floating slabs is that they tend to be the most expensive of the vibration control treatments. A typical double-tie floating slab system costs approximately $600 per track foot.

- o Other Marginal Treatments: Changing any feature of the track support system can change the levels of ground-borne vibration. Approaches such as using heavier rail, thicker ballast, or heavier ties can be expected to reduce the vibration levels. There also is some indication that vibration levels are lower with wood ties compared to concrete ties. However, there is little confirmation that any of these approaches will make a significant change in the vibration levels. This is unfortunate since modifications to the ballast, rails, or ties are virtually the only options for normal at-grade, tie-and-ballast track without resorting to a different type of track support system or widening the right-of-way to provide a buffer zone.

- **Building Modifications:** In some circumstances, it is practical to modify the impacted building to reduce the vibration levels. Vibration isolation of buildings basically consists of supporting the building foundation on elastomer pads similar to bridge bearing pads. Vibration isolation of buildings is seldom an option for existing buildings; normal applications are possible only for new construction. This approach is particularly important for shared-use facilities such as office space above a transit station or terminal. When vibration-sensitive equipment such as electron microscopes will be affected by transit vibration, specific modifications to the building structure may be the most cost-effective method of controlling the impact. For example, the floor upon which the vibration-sensitive equipment is located could be stiffened and isolated from the remainder of the building to reduce the vibration. Alternatively, the equipment could be isolated from the building at far less cost.

- **Trenches:** Use of trenches to control ground-borne vibration is analogous to controlling airborne noise with sound barriers. Although this approach has not received much attention in the U.S., there are cases where a trench can be a practical method for controlling transit vibration from at-grade track. A rule-of-thumb given by Richert and Hall(9) is that if the trench is located close to the source, the trench bottom must be at least 0.6 times the Rayleigh wavelength below the vibration source. For most soils, Rayleigh waves travel at around 600 ft/sec which means that the wavelength at 30 Hz is 20 ft. This means that the trench must be approximately 15 ft deep to be effective at 30 Hz.

  A trench can be effective as a vibration barrier if it is either open or solid. The Toronto Transit Commission tested a trench filled with styrofoam to keep it open and reported successful performance over a period of at least one year. Solid barriers can be constructed with sheet piling or concrete poured into a trench.

- **Operational Changes:** The most obvious operational change is to reduce the vehicle speed. Reducing the train speed by a factor of two will reduce vibration levels approximately 6 dB. Other operational changes that can be effective in special cases are:

    - Use the equipment that generates the lowest vibration levels during the nighttime hours when people are most sensitive to vibration and noise.
    - Adjust nighttime schedules to minimize movements in the most sensitive hours.

  While there are tangible benefits from speed reductions and limits on operations during the most sensitive time periods, these types of measures are usually not practical from the standpoint of service requirements. Furthermore, vibration reduction achieved through operating restrictions requires continuous monitoring and will be negated if vehicle operators do not adhere to established policies. As with the options for noise control, FTA does not recommend limits on operations as a way to reduce vibration impacts.

- **Buffer Zones:** Expanding the rail right-of-way sometimes will be the most economical method of reducing the vibration impact. A similar approach is to negotiate a vibration easement from the affected property owners, for example, a row of single-family homes adjacent to a proposed commuter rail line. However, there may be legal limitations on the ability of funding agencies to acquire land strictly for the purpose of mitigating vibration (or noise) impact.

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12. NOISE AND VIBRATION DURING CONSTRUCTION

Construction often generates community noise/vibration complaints, even when it takes place over a limited time frame. In recent years, public concerns about construction noise and vibration have increased significantly, due partly to lengthy periods of heavy construction on some “mega-projects” and also to the increasing prevalence of nighttime construction that is undertaken to avoid disrupting workday road and rail traffic. Noise and vibration complaints typically arise from interference with people's activities, especially when the adjacent community has no clear understanding of the extent or duration of the construction. Misunderstandings can arise when the contractor is considered to be insensitive by the community, even though the contractor believes the work is being performed in compliance with local ordinances. This situation underscores the need for early identification and assessment of potential problem areas.

An assessment of noise and vibration impact during construction can be made by following procedures outlined in this chapter. The type of assessment – qualitative or quantitative – and the level of analysis will be determined based on the scale of the project and surrounding land use. In cases where a full quantitative assessment is not warranted, a qualitative assessment of the construction noise and vibration environment can lead to greater understanding and tolerance in the community. For major projects with extended periods of construction at specific locations, a quantitative assessment can aid contractors in making bids by allowing changes in construction approach and including mitigation costs before the construction plans are finalized.

12.1 CONSTRUCTION NOISE ASSESSMENT

Noise impacts from construction may vary greatly depending on the duration and complexity of the project. The level of detail of a construction noise assessment depends on the scale and the type of project and the stage of environmental review. Many small projects need no construction noise assessment at all.

Examples include installation of safety features like grade-crossing signals, track improvements within the right-of-way, and erecting small buildings and facilities which are similar in scale to the surrounding development. For projects like these, it would suffice to describe the length of time of construction, the loudest equipment to be used, expected truck access routes, and avoidance of nighttime activity.

Other projects involving a limited period of construction time – less than a month in a noise-sensitive area – may warrant a qualitative treatment because of nearby noise-sensitive land uses. In these cases, the assessment may simply be a qualitative description of the equipment to be used, the duration of construction, and any mitigation requirements placed on particularly noisy operations. Where the length of construction in noise-sensitive areas is expected to last for more than several months or particularly noisy equipment will be involved, then construction noise impacts may be determined in considerable detail. In any case, a likely scenario of the planned construction methods should be described in the environmental document. At this early stage it may be possible to describe certain basic measures that would be taken to reduce the potential impact, for example, prohibiting the noisiest construction activities during nighttime. However, it may be prudent to defer final decisions on noise control measures until the project and construction plans are defined in greater detail during final design.

Qualitative Assessments. In cases where a qualitative construction noise assessment is appropriate, the following descriptions would be included:

- Duration of construction (overall and at specific locations)
- Equipment expected to be used, e.g., noisiest operations
- Schedule with limits on times of operation, e.g., daytime use only
- Monitoring of noise
- Forum for communicating with the public
- Commitments to limit noise levels to certain levels, including any local ordinances that apply
- Consideration of application of noise control treatments used successfully in other projects

Community relations will be important in these cases; early information disseminated to the public about the kinds of equipment, expected noise levels and durations will help to forewarn potentially affected neighbors about the temporary inconvenience. In these cases, a general description of the variation of noise levels during a typical construction day may be helpful. The criteria in Section 12.1.3 are not applied to qualitative assessments.

Quantitative Assessments. Factors that influence the decision to perform a quantitative construction noise assessment include the following:

- Scale of the project
- Proximity of noise-sensitive land uses to the construction zones

- Number of noise-sensitive receptors in the project area
- Duration of construction activities near noise-sensitive receptors
- Schedule (the construction days, hours and time periods)
- Method (e.g., cut-and-cover vs. bored tunneling)
- Concern about construction noise expressed in comments by the general public (scoping, public meetings)

A quantitative construction noise assessment requires information about source levels, operations, proximity of noise sensitive locations, and criteria against which the levels will be compared. These elements of assessment are described in the following sections.

12.1.1 Quantitative Noise Assessment Methods

A quantitative construction noise assessment is performed by comparing the predicted noise levels with impact criteria appropriate for the construction stage. The approach requires an appropriate descriptor, a standardized prediction method and a set of recognized criteria for assessing the impact.

The *descriptor* used for construction noise is the L_{eq}. This unit is appropriate for the following reasons:

- It can be used to describe the noise level from operation of each piece of equipment separately and is easy to combine to represent the noise level from all equipment operating during a given period.
- It can be used to describe the noise level during an entire phase.
- It can be used to describe the average noise over all phases of the construction.

The recommended *method* for predicting construction noise impact for major transit projects requires:

- An emission model to determine the noise generated by the equipment at a reference distance.
- A propagation model that shows how the noise level will vary with distance.
- A way of summing the noise of each piece of equipment at locations of noise sensitivity.

The first two components of the method are related by the following equation:

$$L_{eq}(equip) = E.L. + 10\log(U.F.) - 20\log(D/50) - 10G\log(D/50)$$

where: *L_{eq} (equip)* is the L_{eq} at a receiver resulting from the operation of a single piece of equipment over a specified time period

E.L. is the noise emission level of the particular piece of equipment at the reference distance of 50 feet, taken from Table 12-1

G is a constant that accounts for topography and ground effects, taken from Figure 6-5 (Chapter 6)

D is the distance from the receiver to the piece of equipment, and

U.F. is a usage factor that accounts for the fraction of time that the equipment is in use over the specified time period.

The combination of noise from several pieces of equipment operating during the same time period is obtained from decibel addition of the L_{eq} of each single piece of equipment found from the above equation.

General Assessment

The approach can be as detailed as necessary to characterize the construction noise by specifying the various quantities in the equation. For projects in an early assessment stage when the equipment roster and schedule are undefined, only a rough estimate of construction noise levels is practical.

The following assumptions are adequate for a general assessment of each phase of construction:

- Full power operation for a time period of one hour is assumed because most construction equipment operates continuously for periods of one hour or more at some point in the construction period. Therefore, U.F. = 1, and 10 log(U.F.) = 0.
- Free-field conditions are assumed and ground effects are ignored. Consequently, G = 0.
- Emission level at 50 feet, E.L., is taken from Table 12-1.
- All pieces of equipment are assumed to operate at the center of the project, or centerline, in the case of a guideway or highway construction project.
- The predictions include only the two noisiest pieces of equipment expected to be used in each construction phase.

Detailed Assessment

A more detailed approach can be used if warranted, such as when a large number of noise-sensitive sites are adjacent to a construction project or where contractors are faced with stringent local ordinances or heightened public concerns expressed in early outreach efforts. Additional details include:

- <u>Duration.</u> Long-term construction project noise impact is based on a 30-day average L_{dn}, the times of day of construction activity (nighttime noise is penalized by 10 dB in residential areas), and the percentage of time the equipment is to be used during a period of time which will affect U.F. For example, an 8-hour L_{eq} is determined by making U.F. the percentage of time each individual piece of equipment operates under full power in that period. Similarly, the 30-day average L_{dn} is determined from the U.F. expressed by the percentage of time the equipment is used during the daytime hours (7 a.m. to 10 p.m.) and nighttime (10 p.m. to 7 a.m.), separately over a 30-day period. However, to account for increased sensitivity to nighttime noise, the nighttime percentage is multiplied by 10 before performing the computation.

- Site Characteristics. Taking into account the site topography, natural and man-made barriers and ground effects will involve the factor G. Use Figure 6-5 (Chapter 6) to calculate G.

- Noise Sources. Measuring or certifying the emission level of each piece of equipment will refine E.L.

- Site Layout. Determining the location of each piece of equipment while it is working will specify the distance factor D more accurately.

- Combined Sources. Including all pieces of equipment in the computation of the 8-hour L_{eq} and the 30-day average L_{dn} will determine the total noise levels using Table 6-11 (Chapter 6).

12.1.2 Noise from Typical Construction Equipment and Operations

The noise levels generated by construction equipment will vary greatly depending on factors such as the type of equipment, the specific model, the operation being performed, and the condition of the equipment. The equivalent sound level (L_{eq}) of the construction activity also depends on the fraction of time that the equipment is operated over the time period of construction. The dominant source of noise from most construction equipment is the engine, usually a diesel, often without sufficient muffling. In a few cases, such as impact pile-driving or pavement-breaking, noise generated by the process dominates.

For considerations of noise assessment, construction equipment can be considered to operate in two modes, stationary and mobile. Stationary equipment operates in one location for one or more days at a time, with either a fixed power operation (pumps, generators, compressors) or a variable noise operation (pile drivers, pavement breakers). Mobile equipment moves around the construction site with power applied in cyclic fashion (bulldozers, loaders), or to and from the site (trucks). The movement around the site is handled in the construction noise prediction procedure discussed earlier in this chapter. Variation in power imposes additional complexity in characterizing the noise source level from a piece of equipment. This is handled by describing the noise at a reference distance from the equipment operating at full power and adjusting it based on the duty cycle of the activity to determine the L_{eq} of the operation. Standardized procedures for measuring the exterior noise levels for the certification of mobile and stationary construction equipment have been developed by the Society of Automotive Engineers. [1,2] Typical noise levels from representative pieces of equipment are listed in Table 12-1. These source levels can be used in FHWA’s Windows-based screening tool, “Roadway Construction Noise Model” (RCNM), for the prediction of construction noise.[3]

Construction activities are characterized by variations in the power expended by equipment, with resulting variation in noise levels with time. Variation in the power is expressed in terms of the previously mentioned "usage factor" of the equipment, which is the percentage of time during the workday that the equipment is operating at full power. Time-varying noise levels are converted to a single number (L_{eq}) for each piece of equipment during the operation. Besides having daily variations in activities, major construction projects are accomplished in several different phases. Each phase has a specific equipment mix depending on the work to be accomplished during that phase.

As a result of the equipment mix, each phase has its own noise characteristics; some have higher continuous noise levels than others, some have high impact noise levels. The purpose of the quantitative assessment is to determine not only the levels, but also the duration of the noise. The L_{eq} of each phase is determined by combining the L_{eq} contributions from each piece of equipment used in that phase. The impact and the consequent noise mitigation approaches depend on the criteria to be used in assessing impact, as discussed in the next section.

Table 12-1. Construction Equipment Noise Emission Levels

Equipment	**Typical Noise Level (dBA)** **50 ft from Source**
Air Compressor	81
Backhoe	80
Ballast Equalizer	82
Ballast Tamper	83
Compactor	82
Concrete Mixer	85
Concrete Pump	82
Concrete Vibrator	76
Crane, Derrick	88
Crane, Mobile	83
Dozer	85
Generator	81
Grader	85
Impact Wrench	85
Jack Hammer	88
Loader	85
Paver	89
Pile-driver (Impact)	101
Pile-driver (Sonic)	96
Pneumatic Tool	85
Pump	76
Rail Saw	90
Rock Drill	98
Roller	74

Table 12-1. Construction Equipment Noise Emission Levels (continued)	
Equipment	**Typical Noise Level (dBA) 50 ft from Source**
Saw	76
Scarifier	83
Scraper	89
Shovel	82
Spike Driver	77
Tie Cutter	84
Tie Handler	80
Tie Inserter	85
Truck	88
Table based on an EPA Report,[4] measured data from railroad construction equipment taken during the Northeast Corridor Improvement Project, and other measured data.	

12.1.3 Construction Noise Criteria

No standardized *criteria* have been developed for assessing construction noise impact. Consequently, criteria must be developed on a project-specific basis unless local ordinances can be found to apply. Generally, local noise ordinances are not very useful in evaluating construction noise. They usually relate to nuisance and hours of allowed activity and sometimes specify limits in terms of maximum levels, but are generally not practical for assessing the impact of a construction project. Project construction noise criteria should take into account the existing noise environment, the absolute noise levels during construction activities, the duration of the construction, and the adjacent land use. While it is not the purpose of this manual to specify standardized criteria for construction noise impact, the following guidelines can be considered reasonable criteria for assessment. If these criteria are exceeded, there may be adverse community reaction.

General Assessment

Estimate the combined noise level in one hour from the two noisiest pieces of equipment, assuming they both operate at the same time. Then identify locations where the level exceeds the following:

Land Use	One-hour L_{eq} (dBA)	
	Day	Night
Residential	90	80
Commercial	100	100
Industrial	100	100

Detailed Assessment

Where a more refined analysis is needed, predict the noise level in terms of 8-hour L_{eq} and 30-day averaged L_{dn} and compare to criteria in the following table:

Land Use	8-hour L_{eq} (dBA)		L_{dn} (dBA)
	Day	Night	30-day Average
Residential	80	70	75[a]
Commercial	85	85	80[b]
Industrial	90	90	85[b]

[a] In urban areas with very high ambient noise levels (L_{dn} > 65 dB), L_{dn} from construction operations should not exceed existing ambient + 10 dB.

[b] Twenty-four-hour L_{eq}, not L_{dn}.

12.1.4 Mitigation of Construction Noise

After using the above approaches to locate potential impacts from construction noise, the next step is to identify appropriate control measures. Three categories of noise control approaches, with examples, are given below:

1. *Design considerations and project layout:*
   - Construct noise barriers, such as temporary walls or piles of excavated material, between noisy activities and noise-sensitive receivers.
   - Re-route truck traffic away from residential streets, if possible. Select streets with fewest homes if no alternatives are available.
   - Site equipment on the construction lot as far away from noise-sensitive sites as possible.
   - Construct walled enclosures around especially noisy activities or clusters of noisy equipment. For example, shields can be used around pavement breakers and loaded vinyl curtains can be draped under elevated structures.

2. *Sequence of operations:*
   - Combine noisy operations to occur in the same time period. The total noise level produced will not be significantly greater than the level produced if the operations were performed separately.
   - Avoid nighttime activities. Sensitivity to noise increases during the nighttime hours in residential neighborhoods.

3. *Alternative construction methods:*

   - Avoid use of an impact pile driver where possible in noise-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver are quieter alternatives where the geological conditions permit their use.
   - Use specially-quieted equipment, such as quieted and enclosed air compressors and properly-working mufflers on all engines.
   - Select quieter demolition methods, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower cumulative noise levels than impact demolition by pavement breakers.

If possible, the environmental impact assessment should include descriptions of how each impacted location will be treated with one or more mitigation measures. However, with a large, complex project, the information available during the preliminary engineering phase may not allow final decisions to be made on all specific mitigation measures. In such cases, it is appropriate to describe and commit to a mitigation plan that will be developed during final design. The objective of the plan should be to minimize construction noise using all reasonable (i.e., cost vs. benefit) and feasible (i.e., physically achievable) means available. Components of the plan may include some or all of the following provisions which would be specified in construction contracts:

- *Equipment noise emission limits*. These are absolute noise limits applied to generic classes of equipment at a reference distance (typically 50 feet). The limits should be set no higher than what is reasonably achievable for well-maintained equipment with effective mufflers. Lower limits that require source noise control may be appropriate for certain equipment when needed to minimize community noise impact, if reasonable and feasible. Provisions could also be included to require equipment noise certification testing prior to use on site.
- *Lot-line construction noise limits*. These are noise limits that apply at the lot line of specific noise-sensitive properties. The limits are typically specified in terms of both noise exposure (usually Leq over a 20-30 minute period) and maximum noise level. They should be based on local noise ordinances, if applicable, as well as pre-construction baseline noise levels; limits that are 3-5 decibels above the baseline are often used.
- *Operational and/or equipment restrictions*. It may be necessary to prohibit or restrict certain construction equipment and activities near residential areas during nighttime hours. This is particularly true for activities that generate tonal, impulsive or repetitive sounds, such as back-up alarms, hoe ram demolition and pile-driving.
- *Noise abatement requirements*. In some cases specifications may be provided for particular noise control treatments, based on the results of the design analysis and/or prior commitments made to the public by civic authorities. An example would be the requirement for a temporary noise barrier to shield a particular community area from noisy construction activities.

- *Noise monitoring plan requirements*. Plans can be developed for pre-project noise monitoring to establish baseline noise levels at sensitive locations, as well as for periodic equipment and lot-line noise monitoring during the construction period. The plan should outline the measurement and reporting methods that will be used to demonstrate compliance with the project noise limits.
- *Noise control plan requirements*. For major construction projects, specifications have required the preparation and submission of noise control plans on a periodic basis (e.g., every six months). These plans should predict the construction noise at noise-sensitive receptor locations based on the proposed construction equipment and methods. If the analysis predicts that the specified noise limits will be exceeded, the plan should specify the mitigation measures that will be applied and should demonstrate the expected noise reductions these measures will achieve. The objective of this proactive approach is to minimize the likelihood of community noise complaints by ensuring that any necessary mitigation measures are included in the construction plans.
- *Compliance enforcement program*. If construction noise is a significant issue in the community, it is important that a program be put in place to monitor contractor compliance with the noise control specifications and mitigation plan. It is best that this function be performed by a construction management team on behalf of the public agency.
- *Public information and complaint response procedures*. To maintain positive community relations, the public should be kept informed about the construction plans and efforts to minimize noise, and procedures should be established for prompt response and corrective action with regard to noise complaints during construction.

Most of these provisions are appropriate for very large projects where construction activity will continue for many months, if not years. References 4 and 5 contain details on dealing with construction noise on major transportation projects. [5,6]

12.2 CONSTRUCTION VIBRATION ASSESSMENT

Construction activity can result in varying degrees of ground vibration, depending on the equipment and methods employed. Operation of construction equipment causes ground vibrations that spread through the ground and diminish in strength with distance. Buildings founded on the soil in the vicinity of the construction site respond to these vibrations, with varying results ranging from no perceptible effects at the lowest levels, low rumbling sounds and perceptible vibrations at moderate levels, and slight damage at the highest levels. As expressed previously in this chapter with respect to construction noise, the type of assessment – qualitative or quantitative – and the level of construction vibration analysis will be determined by factors related to the scale of the project and the sensitivity of the surrounding land use. A quantitative analysis should be conducted in cases where construction vibration may result in prolonged annoyance or building damage.

Ground vibrations from construction activities do not often reach the levels that can damage structures, but they can achieve the audible and feelable ranges in buildings very close to the site. A possible exception is the case of fragile buildings, many of them old, where special care must be taken to avoid damage. The construction vibration criteria include special consideration for such buildings. The construction activities that typically generate the most severe vibrations are blasting and impact pile-driving.

In cases where prolonged annoyance or damage from construction vibrations are not expected, a qualitative assessment is appropriate. Such an assessment should include a description of the duration and the type of equipment to be used during the construction, with an explanation of how the ground-borne vibration will be maintained at an acceptable level. For example, if the equipment is of the type that generates little or no ground vibration – air compressors, light trucks, hydraulic loaders, etc. – a simple explanation is sufficient and no quantitative analysis is necessary.

12.2.1 Quantitative Construction Vibration Assessment Methods

Construction vibration should be assessed quantitatively in cases where there is significant potential for impact from construction activities. Such activities include blasting, pile-driving, vibratory compaction, demolition, and drilling or excavation in close proximity to sensitive structures. The recommended procedure for estimating vibration impact from construction activities is as follows:

Damage Assessment

- Select the equipment and associated vibration source levels at a reference distance of 25 feet from Table 12-2.
- Make the propagation adjustment according to the following formula (this formula is based on point sources with normal propagation conditions):

$$PPV_{equip} = PPV_{ref} \times (25/D)^{1.5}$$

where: PPV (equip) is the peak particle velocity in in/sec of the equipment adjusted for distance

PPV (ref) is the reference vibration level in in/sec at 25 feet from Table 12-2

D is the distance from the equipment to the receiver.

- Apply the vibration damage criteria from Table 12-3.

Annoyance Assessment

- If desired for consideration of annoyance or interference with vibration-sensitive activities, estimate the vibration level L_v at any distance D from the following equation and apply the vibration impact criteria for General Assessment in Chapter 8 for vibration-sensitive sites:

$$L_v(D) = L_v(25 \text{ ft}) - 30\log(D/25)$$

12.2.2 Vibration Source Levels from Construction Equipment

Ground-borne vibration related to human annoyance is generally related to root mean square (rms) velocity levels expressed in VdB. However, a major concern with regard to construction vibration is building damage. Consequently, construction vibration is generally assessed in terms of peak particle velocity (PPV), as defined in Chapter 7.1.2. The relationship of PPV to rms velocity is expressed in terms of the "crest factor," defined as the ratio of the PPV amplitude to the rms amplitude. Peak particle velocity is typically a factor of 1.7 to 6 times greater than rms vibration velocity.

Various types of construction equipment have been measured under a wide variety of construction activities with an average of source levels reported in terms of velocity as shown in Table 12-2. In this table, a crest factor of 4 (representing a PPV-rms difference of 12 VdB) has been used to calculate the approximate rms vibration velocity levels from the PPV values. Although the table gives one level for each piece of equipment, it should be noted that there is a considerable variation in reported ground vibration levels from construction activities. The data provide a reasonable estimate for a wide range of soil conditions.

Table 12-2. Vibration Source Levels for Construction Equipment (From measured data.[7,8,9,10])

Equipment		PPV at 25 ft (in/sec)	Approximate L_v† at 25 ft
Pile Driver (impact)	upper range	1.518	112
	typical	0.644	104
Pile Driver (sonic)	upper range	0.734	105
	typical	0.170	93
Clam shovel drop (slurry wall)		0.202	94
Hydromill (slurry wall)	in soil	0.008	66
	in rock	0.017	75
Vibratory Roller		0.210	94
Hoe Ram		0.089	87
Large bulldozer		0.089	87
Caisson drilling		0.089	87
Loaded trucks		0.076	86
Jackhammer		0.035	79
Small bulldozer		0.003	58

† RMS velocity in decibels (VdB) re 1 micro-inch/second

12.2.2 Construction Vibration Criteria

For evaluating potential annoyance or interference with vibration-sensitive activities due to construction vibration, the criteria for General Assessment in Chapter 8 can be applied. In most cases, however, the primary concern regarding construction vibration relates to potential damage effects. Guideline vibration damage criteria are given in Table 12-3 for various structural categories.[10] In this table, a crest factor of 4 (representing a PPV-rms difference of 12 VdB) has been used to calculate the approximate rms vibration velocity limits from the PPV limits. These limits should be viewed as criteria that should be used during the environmental impact assessment phase to identify problem locations that must be addressed during final design.

Table 12-3. Construction Vibration Damage Criteria[11]

Building Category	**PPV (in/sec)**	**Approximate L_v**†
I. Reinforced-concrete, steel or timber (no plaster)	0.5	102
II. Engineered concrete and masonry (no plaster)	0.3	98
III. Non-engineered timber and masonry buildings	0.2	94
IV. Buildings extremely susceptible to vibration damage	0.12	90

† RMS velocity in decibels (VdB) re 1 micro-inch/second

12.2.3 Construction Vibration Mitigation

After using the above methods to locate potential human impacts or building damage from construction vibrations, the next step is to identify control measures. Similar to the approach for construction noise, mitigation of construction vibration requires consideration of equipment location and processes, as follows:

1. *Design considerations and project layout:*
   - Route heavily-loaded trucks away from residential streets, if possible. Select streets with fewest homes if no alternatives are available.
   - Operate earth-moving equipment on the construction lot as far away from vibration-sensitive sites as possible.
2. *Sequence of operations:*
   - Phase demolition, earth-moving and ground-impacting operations so as not to occur in the same time period. Unlike noise, the total vibration level produced could be significantly less when each vibration source operates separately.

- Avoid nighttime activities. People are more aware of vibration in their homes during the nighttime hours.

3. *Alternative construction methods:*

   - Avoid impact pile-driving where possible in vibration-sensitive areas. Drilled piles or the use of a sonic or vibratory pile driver causes lower vibration levels where the geological conditions permit their use (however, see cautionary note below).
   - Select demolition methods not involving impact, where possible. For example, sawing bridge decks into sections that can be loaded onto trucks results in lower vibration levels than impact demolition by pavement breakers, and milling generates lower vibration levels than excavation using clam shell or chisel drops.
   - Avoid vibratory rollers and packers near sensitive areas.

Pile-driving is one of the greatest sources of vibration associated with equipment used during construction of a project. The source levels in Table 12-2 indicate that sonic pile drivers may provide substantial reduction of vibration levels. However, there are some additional vibration effects of sonic pile drivers that may limit their use in sensitive locations. A sonic pile driver operates by continuously shaking the pile at a fixed frequency, literally vibrating it into the ground. Vibratory pile drivers operate on the same principle, but at a different frequency. However, continuous operation at a fixed frequency may be more noticeable to nearby residents, even at lower vibration levels. Furthermore, the steady-state excitation of the ground may induce a growth in the resonant response of building components. Resonant response may be unacceptable in cases of fragile buildings or vibration-sensitive manufacturing processes. Impact pile drivers, on the other hand, produce a high vibration level for a short time (0.2 seconds) with sufficient time between impacts to allow any resonant response to decay.

As with construction noise, in many cases the information available during the preliminary engineering phase will not be sufficient to define specific construction vibration mitigation measures. In such cases, it is appropriate to describe and commit to a mitigation plan that will be developed and implemented during the final design and construction phases of the project. The objective of the plan should be to minimize construction vibration damage using all reasonable and feasible means available. The plan should provide a procedure for establishing threshold and limiting vibration values for potentially affected structures based on an assessment of each structure’s ability to withstand the loads and displacements due to construction vibrations. The plan should also include the development of a vibration monitoring plan during final design and the implementation of a compliance monitoring program during construction.

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13. DOCUMENTATION OF NOISE AND VIBRATION ASSESSMENT

To be effective, the noise and vibration analysis must be presented to the public in a clear, yet comprehensive manner. The mass of technical data and information necessary to withstand scrutiny in the environmental review process must be documented in a way that remains intelligible to the public. Justification for all assumptions used in the analysis, such as selection of representative measurement sites and all baseline conditions, must be presented for review. For large-scale projects, the environmental document contains a condensation of essential information in order to maintain a reasonable size. For these projects, separate technical reports are usually prepared as supplements to the environmental impact statement (EIS) or environmental assessment (EA). For smaller projects, or ones with minimal noise or vibration impact, all the technical information may be presented in the environmental document itself. This chapter gives guidance on how the necessary noise and vibration information should be included in the project's environmental documentation.

13.1 THE TECHNICAL REPORT ON NOISE AND VIBRATION

A separate technical report is often prepared as a supplement to the environmental document (EIS or EA). A technical report is appropriate in cases when the wealth of data can not all be placed in the environmental document. The details of the analysis are important for establishing the basis for the assessment. Consequently, all the details in the technical report should be contained in a well-organized format for easy access to the information. While the technical report is not intended to be a primer on the subject, the technical data and descriptions should be presented in a manner that can be understood by the general public. All the necessary background information should be present in the technical report, including tables, maps, charts, drawings and references that may be too detailed for the environmental document, but which are important in helping to draw conclusions about the project's noise and vibration impacts and mitigation options.

13.1.1 Organization of Technical Report

The technical report on noise/vibration should contain the following major subject headings, along with the key information content described below. If both noise and vibration have been analyzed, it is generally preferable to separate the noise and vibration sections; as shown in this guidance manual, the approaches to the two topics are quite different.

- **Overview**: This section contains a brief description of the project and an overview of the noise/vibration concerns. It sets forth the initial considerations in framing the scope of the study.
- **Inventory of Noise/Vibration-Sensitive Sites**: The approach for selecting noise- and vibration-sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.
- **Measurements of Existing Noise/Vibration Conditions:** The basis for selecting measurement sites should be documented, along with tables of sites coordinated with maps showing locations of sites. If the measurement data are used to estimate existing conditions at other locations, the rationale and the method should be included. Measurement procedures should be fully described. Tables of measurement instruments should include manufacturer, type, serial number and date of most recent calibration by authorized testing laboratory. Measurement periods, including time of day and length of time at each site should be shown to demonstrate adequate representation of the ambient conditions. The measurement data should be presented in well organized form in tables and figures. A summary and interpretation of measured data should be included.
- **Special Measurements Related to the Project:** Some projects require specialized measurements at sensitive sites, such as outdoor-to-indoor noise level reduction of homes, or transmission of vibrations into concert halls and recording studios. Other projects may need special source-level characterization. Full description of the measurements and the results should be included.
- **Predictions of Noise/Vibration from the Project:** The prediction model used for estimating future project conditions should be fully described and referenced. Any changes or extensions to the models recommended in this manual should be fully described so that the validity of the adjustments can be confirmed. Specific data used as input to the models should be listed. Computed levels should be tabulated and illustrated by contours, cross-sections or shaded mapping. It is important to illustrate noise/vibration impacts with base maps at a scale with enough detail to provide location reference for the reader.
- **Noise/Vibration Criteria:** Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 8). In addition, any applicable local ordinances should be described. Tables specifying the criteria levels should also be included. If the project involves considerable construction, and a separate construction noise and vibration analysis will be included, then construction criteria should appear in a separate section with its own assessment.
- **Noise/Vibration Impact Assessment:** The impact assessment should be described according to the procedures outlined in this manual. A resulting impact inventory should be presented for each alternative mode or alignment in a format that allows ready comparison among alternatives. The

inventory should be tabulated according to the different types of land uses affected. The results of the assessment may be presented both before and after mitigation.

- **Noise/Vibration Mitigation:** The mitigation section of the technical report should begin with a summary of all treatments considered, even if some are not carried to final consideration. Final candidate mitigation treatments should be considered separately with description of the features of the treatment, costs, expected benefit in reducing impacts, locations where the benefit would be realized and discussion of practicality of implementing alternative treatments. With respect to noise impacts, enough information is to be included to allow the project sponsor and FTA to reach decisions on mitigation prior to issuance of the final environmental document.
- **Construction Noise/Vibration Impacts:** Criteria adopted for construction noise or vibration should be described, if appropriate. According to Chapter 12, these may be adopted on a project-specific basis. The method used for predicting construction noise or vibration should be described along with inputs to the models, such as equipment roster by construction phase, equipment source levels, assumed usage factors and other assumed site characteristics. The predicted levels should be shown for sensitive sites and short-term impacts should be identified. In cases where construction impacts appear to be problematic, feasible abatement methods should be discussed in enough detail such that construction contract documents could include mitigation measures.
- **References:** References should be provided for all criteria, approaches and data used in the analyses, including other reports related to the project which may be relied on for information, e.g., geotechnical reports.

13.2 THE ENVIRONMENTAL DOCUMENT

The environmental document typically includes noise and vibration information in three places: a section of the chapter on the affected environment (existing conditions) and two sections in the chapter on environmental consequences (the long-term impacts from operations and short-term impacts from construction activity). The noise and vibration information presented in the environmental document is a summary of the comprehensive information from the technical report with emphasis on presenting the salient points of the analysis in a format and style which affected property owners and other interested citizens can understand. Smaller projects may have all of the technical information contained within the environmental document, requiring special care in summarizing technical details to convey the information adequately.

The environmental document provides full disclosure of noise and vibration impacts, including identification of locations where impacts cannot be mitigated satisfactorily. An EIS describes significant impacts and tells what the Federal agency intends to do about them. For projects handled with EA’s, completion of the environmental review with a finding of no significant impact (FONSI) may depend on mitigation being incorporated in the proposed project. The specific way mitigation is handled in the environmental document depends on the type of impact (noise or vibration) and the stage of project development and environmental review.

In general, airborne noise impacts can be accurately predicted in the preliminary engineering stage. Since the environmental review for major investment projects is completed during preliminary engineering, it is possible to specify, and commit to implement, any needed noise mitigation measures in the final environmental document (Final EIS or FONSI). With major investments, as well as small projects like bus terminals and garages, it is expected that decisions on noise mitigation will be made before the final document is approved; thus timely development of design, feasibility and cost information needed to reach decisions on noise mitigation is essential. For major investments in the Alternatives Analysis/Draft EIS stage, the emphasis is not on mitigation but rather a broad comparison among the alternatives concerning the magnitude and extent of noise impacts. If it seems likely that mitigation would be required for at least some major investment alternatives, this can be discussed in a general way while touching on the remaining stages of project development and how decisions on mitigation fit in. Finally, there are other projects for which the preferred alternative is identified at the outset in the Draft EIS or EA. With the focus on a single alternative, noise impacts can be accurately identified in the draft document. If mitigation is needed, mitigation options should be explored in the draft; however firm decisions on mitigation can be deferred to the final document.

Predicting vibration impacts accurately is a more complex undertaking because ground-borne vibration may be strongly influenced by subsurface conditions. The geotechnical studies that reveal these conditions are normally undertaken during the final design stage after the NEPA process has been completed. Thus, for ground-borne vibration and noise, the final environmental document will usually not be able to state with certainty whether or not mitigation is needed. The final environmental document will rely on a General Assessment for ground-borne vibration and noise to identify potential problem areas. If there are such areas, there should be a commitment in the final document to conduct a Detailed Analysis during final design to complete the impact assessment and help determine the need for mitigation. The final environmental document should present a preliminary assessment using the vibration impact criteria for the General Assessment. If it appears the criteria cannot be met, the document would discuss various control measures that could be used and the likelihood that the criteria could be met through the use of one or more of the measures. It may be possible to state a commitment in the final environmental document to adhere to the impact criteria for the Detailed Analysis, while deferring the selection of specific vibration control measures until the completion of detailed studies in final design.

After a final environmental document is approved, the described mitigation measures are incorporated by reference in the actual grant agreements signed by FTA and the project sponsor. Thus, they become contractual conditions that must be adhered to by the project sponsor.

13.2.1 Organization of Noise and Vibration Sections of Environmental Documents

Chapter on Affected Environment (Existing Conditions)

This chapter describes the pre-project setting, including the existing noise and vibration conditions, that will likely be affected by one or more of the alternatives. The primary function of this chapter is to establish the focus and baseline conditions for later chapters discussing environmental impacts. Consequently, it is a good place to put basic information on noise and vibration descriptors and effects, as well as describing the characteristics in the vicinity of the project. Again, it is preferable to separate the noise and vibration sections.

- **Description of Noise/Vibration Descriptors, Effects and Typical Levels:** Information from Chapters 2 and 7 of this manual can be used to provide a background for the discussions of noise/vibration levels and characteristics to follow. Illustrative material to guide the reader in understanding typical levels is helpful.
- **Inventory of Noise/Vibration-Sensitive Sites:** The approach for selecting noise/vibration-sensitive sites should be described in sufficient detail to demonstrate completeness. Sites and site descriptions are to be included.
- **Noise/Vibration Measurements:** A summary of the site selection procedure should be included along with tables of sites coordinated with maps showing locations of sites. The measurement approach should be summarized with justification for the measurement procedures used. The measurement data should be presented in well organized form in tables and figures. To save space, the results are often included with the table of sites described above. In some cases, measurements may be supplemented or replaced by collected data relevant to the noise and vibration characteristics of the area. For example, soils information for estimating ground-borne vibration propagation characteristics may be available from other projects in the area. Fundamental to this section is a summary and interpretation of how the collected data define the project setting.

Chapter on Environmental Consequences.

The section on long-term impacts - the impacts due to operation of the project - should be organized according to the following order:

- **Overview of Approach:** A summary of the assessment procedure for determining noise/vibration impacts is provided as a framework for the following sections.
- **Estimated Noise/Vibration Levels:** A general description of prediction models used to estimate project noise/vibration levels should be provided. Any distinguishing features unique to the project, such as source levels associated with various technologies, should be described. The results of the predictions for various alternatives should be described in general terms first, followed by a detailed accounting of predicted noise levels. This information should be supplemented with tables and

illustrated by contours, cross-sections or shaded mapping. If contours are included in a technical report, then it is not necessary to repeat them here.

- **Criteria for Noise/Vibration Impact:** Impact criteria for the project should be fully described and referenced (refer to Chapters 3 and 8). In addition, any applicable local ordinances should be described. Tables listing the criterion levels should be included.
- **Impact Assessment:** The impact assessment can be a section by itself or can be combined with the section above. It is important to provide a description of locations where noise/vibration impact is expected to occur without implementation of mitigation measures, based on the predicted future levels, existing levels and application of the impact criteria. Inventory tables of impacted land uses should be used to quantify the impacts for comparisons among alternatives. The comprehensive list of noise/vibration-sensitive sites identified in the Affected Environment chapter should be included in this inventory table.
- **Noise/Vibration Mitigation Measures:** Perhaps the most significant difference between the technical report and the environmental document is in the area of mitigation. Whereas the technical report discusses options and may make recommendations, the environmental document provides the vehicle for reaching decisions on appropriate mitigation measures with consideration given to environmental benefits, feasibility and cost. This section should begin with a summary of the noise/vibration mitigation measures considered for the impacted locations. The specific measures selected for implementation should be fully described. Reasons for dismissing any abatement measures should also be clearly stated, especially if such non-implementation results in significant adverse effects. In cases where it is not possible to commit to a specific mitigation measure in the final environmental document, it may be possible to commit to a certain level of noise/vibration reduction, for example, adherence to the impact criteria specified in Chapters 3 and 8.
- **Unavoidable Adverse Environmental Effects:** If it is projected that adverse noise/vibration impacts will result after all reasonable abatement measures have been incorporated, these impacts are identified in this section.

Impacts During Construction

The environmental document may have a separate section on short-term impacts due to project construction, depending on the scale of the project. For a major project there may be a special section on construction noise/vibration impacts; this section should be organized according to the comprehensive outline described above. For projects with relatively minor effects, a briefer format should be utilized, with a section included in the chapter on Environmental Consequences.

APPENDICES

APPENDIX A. GLOSSARY OF TERMS[1, 2]

A-weighting – A standardized filter used to alter the sensitivity of a sound level meter with respect to frequency so that the instrument is less sensitive at low and high frequencies where the human ear is less sensitive. Also written as dBA.

Accelerometer – A transducer that converts vibratory motion to an electrical signal proportional to the acceleration of that motion.

Ambient – The pre-project background noise or vibration level.

Amplitude – Difference between the extremes of an oscillating signal.

Alignment – The horizontal location of a railroad or transit system as described by curved and tangent track.

At-grade – Tracks on the ground surface.

Automated Guideway Transit (AGT) – Guided steel-wheel or rubber-tired transit passenger vehicles operating singly or in multi-car trains with a fully automated system on fixed guideways along an exclusive right-of-way. AGT includes personal rapid transit, group rapid transit and automated people mover systems.

Auxiliaries – The term applied to a number of separately driven machines, operated by power from the main engine or electric generation. They include the air compressor, radiator fan, traction motor blower, and air conditioning equipment.

Ballast mat – A 2- to 3-inch-thick elastomer mat placed under the normal track ballast on top of a rigid slab or packed sub-grade.

Ballast – Granular material placed on the trackbed for the purpose of holding the track in line and at surface.

Bus Rapid Transit (BRT) - A type of limited-stop bus operation that relies on technology to help speed up the service. Buses can operate on exclusive transitways, high-occupancy-vehicle lanes, expressways, or ordinary streets.

Catenary – On electric railroad and light rail transit systems, the term describing the overhead conductor that is contacted by the pantograph or trolley, and its support structure.

Commuter rail – Conventional passenger railroad serving areas surrounding an urban center. Most commuter railroads utilize locomotive-hauled coaches, often in push-pull configuration.

Consist – The total number and type of cars, locomotives, or transit vehicles in a trainset.

Continuous welded rail – A number of rails welded together to form unbroken lengths of track without gaps or joints.

Corrugated rail – A rough condition of alternating ridges and grooves which develops on the rail head in service.

Crest factor - The ratio of peak particle velocity to maximum RMS amplitude in an oscillating signal.

Criteria – Plural form of “criterion,” the relationship between a measure of exposure (e.g., sound or vibration level) and its corresponding effect.

Cross tie – The transverse member of the track structure to which the rails are spiked or otherwise fastened to provide proper gage and to cushion, distribute, and transmit the stresses of traffic through the ballast to the trackbed.

Crossover – Two turnouts with the track between the frogs arranged to form a continuous passage between two nearby and generally parallel tracks.

Cumulative – The summation of individual sounds into a single total value related to the effect over time.

Cut – A term used to describe a trackbed at a lower level than the surrounding ground.

dB – see Decibel.

dBA – see A-weighting.

Decibel – The standard unit of measurement for sound pressure level and vibration level. Technically, a decibel is the unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm of this ratio. Also written as dB.

Descriptor – A quantitative metric used to identify a specific measure of sound level.

DMU – Diesel-powered multiple unit. See Multiple Unit.

DNL – see $L_{dn.}$

Electrification – A term used to describe the installation of overhead wire or third rail power distribution facilities to enable operation of trains.

Embankment – A bank of earth, rock or other material constructed above the natural ground surface.

Equivalent Level – The level of a steady sound which, in a stated time period and at a stated location, has the same sound energy as the time-varying sound. Also written as L_{eq}.

Ferry boat – A transit mode comprised of vessels to carry passengers and/or vehicles over a body of water.

Fixed guideway – A mass transit facility with a separate right-of-way for the exclusive use of public transportation and other high-occupancy vehicles.

Flange – The vertical projection along the inner rim of a wheel that serves, together with the corresponding projection of the mating wheel of a wheel set, to keep the wheel set on the track.

Floating slab – A special track support system for vibration isolation, consisting of concrete slabs supported on resilient elements, usually rubber or similar elastomer.

Frequency – The number of times that a periodically occurring quantity repeats itself in a specified period. With reference to noise and vibration signals, the number of cycles per second.

Frequency spectrum – Distribution of frequency components of a noise or vibration signal.

Frog – A track structure used at the intersection of two running rails to provide support for wheels and passageways for their flanges, thus permitting wheels on either rail to cross the other.

Gage (of track) – The distance between the rails on a track.

Grade crossing – The point where a rail line and a motor vehicle road intersect.

Guideway – Supporting structure to form a track for rolling or magnetically-levitated vehicles.

Head-End Power (HEP) – A system of furnishing electric power for a complete railway train from a single generating plant in the locomotive.

Heavy rail – See Rail Rapid Transit.

Hertz (Hz) -- The unit of acoustic or vibration frequency representing cycles per second.

Hourly Average Sound Level – The time-averaged A-weighted sound level, over a 1-hour period, usually calculated between integral hours. Also written as L_{1h}.

Hybrid Bus – A rubber-tired vehicle that features a hybrid diesel-electric propulsion system. A diesel engine runs an electric generator that powers the entire vehicle including electric drive motors that deliver power to the wheels.

Idle – The speed at which an engine runs when it is not under load.

Intermediate Capacity Transit (ICT) – A transit system with less capacity than rail rapid transit, but more capacity than typical bus operations. Examples of ICT include bus rapid transit (BRT), automated guideway transit (AGT), monorails and trolleys.

Intermodal facility – Junction of two or more modes of transportation where transfers may occur.

Jointed rail – A system of joining rails with steel members designed to unite the abutting ends of contiguous rails.

L_{1h} – see Hourly Average Sound Level

L_{dn} – Day-Night Sound Level. The sound exposure level for a 24-hour day calculated by adding the sound exposure level obtained during the daytime (7 a.m. to 10 p.m.) to 10 times the sound exposure level obtained during the nighttime (10 p.m. to 7 a.m.). This unit is used throughout the U.S. for environmental impact assessment. Also written as DNL.

L_{eq} – see Equivalent Level

Light Rail Transit (LRT) – A mode of public transit with tracked vehicles in multiple units operating in mixed traffic conditions on streets as well as sections of exclusive right-of-way. Vehicles are generally powered by electricity from overhead lines.

Locomotive – A self-propelled, non-revenue rail vehicle designed to convert electrical or mechanical energy into tractive effort to haul railway cars. (see also Power Unit)

Main line – The principal line or lines of a railway.

Maglev – Magnetically-levitated vehicle; a vehicle or train of vehicles with guidance and propulsion provided by magnetic forces. Support can be provided by either an electrodynamic system wherein a moving vehicle is lifted by magnetic forces induced in the guideway, or an electromagnetic system wherein the magnetic lifting forces are actively energized in the guideway.

Maximum Sound Level – The highest exponential-time-average sound level, in decibels, that occurs during a stated time period. Also written as L_{max}. The standardized time periods are 1 second for $L_{max, slow}$ and 0.125 second for $L_{max, fast}$.

Metric – Measurement value, or descriptor.

Monorail – Guided transit vehicles operating on or suspended from a single rail, beam or tube.

Multiple Unit (MU) – A term referring to the practice of coupling two or more diesel-powered or electric-powered passenger cars together with provision for controlling the traction motors on all units from a single controller.

Noise – Any disagreeable or undesired sound or other audible disturbance.

Octave band – A standardized division of a frequency spectrum in which the interval between two divisions is a frequency ratio of 2.

One-third octave band – A standardized division of a frequency spectrum in which the octave bands are divided into thirds for more detailed information. The interval between center frequencies is a ratio of 1.25.

Pantograph – A device for collecting current from an overhead conductor (catenary), consisting of a jointed frame held up by springs or compressed air and having a current collector at the top.

Park-and-ride facility – A parking garage and/or lot used for parking passengers' automobiles while they use transit agency facilities and vehicles.

Peak factor – see Crest factor.

Plan-and-profile – Mapping used by transportation planners that shows two-dimensional plan views (x- and y- axes) on the same page as two-dimensional profiles (x- and z-axes) of a road or track.

Peak Particle Velocity (ppv) – The peak signal value of an oscillating vibration velocity waveform. Usually expressed in inches/second in the United States.

Peak-to-Peak (P-P) Value – Of an oscillating quantity, the algebraic difference between the extreme values of the quantity.

Power unit – A self-propelled vehicle, running on rails and having one or more electric motors that drive the wheels and thereby propel the locomotive and train. The motors obtain electrical energy either from a rail laid near to, but insulated from, the track rails, or from a wire suspended above the track. Contact with the wire is made by a pantograph mounted on top of the unit.

Pure tone – Sound of a single frequency.

Radius of curvature – A measure of the severity of a curve in a track structure based on the length of the radius of a circle that would be formed if the curve were continued.

Rail – A rolled steel shape, commonly a T-section, designed to be laid end to end in two parallel lines on cross ties or other suitable supports to form a track for railway rolling stock.

Rail Rapid Transit – (often called "Heavy Rail Transit") A mode of public transit with tracked vehicles in multiple units operating in exclusive rights-of-way. Trains are generally powered by electricity from a third rail alongside the track.

Receiver/Receptor – A stationary far-field position at which noise or vibration levels are specified.

Resonance frequency – The phenomenon that occurs in a structure under conditions of forced vibration such that any change in frequency of excitation results in a decrease in response.

Right-of-Way – Lands or rights used or held for railroad or transit operation.

Root Mean Square (rms) – The square root of the mean-square value of an oscillating waveform, where the mean-square value is obtained by squaring the value of amplitudes at each instant of time and then averaging these values over the sample time.

RMS Velocity Level (L_V) – See "Vibration Velocity Level."

SEL – see Sound Exposure Level.

Sound Exposure Level – The level of sound accumulated over a given time interval or event. Technically, the sound exposure level is the level of the time-integrated mean square A-weighted sound for a stated time interval or event, with a reference time of one second. Also written as SEL.

Sound – A physical disturbance in a medium that is capable of detecting by the human ear.

Spectrum – See Frequency Spectrum.

Sub-Ballast – Any material of a superior character, which is spread on the finished subgrade of the roadbed and below the top-ballast, to provide better drainage, prevent upheaval by frost, and better distribute the load over the roadbed.

Subgrade – The finished surface of the roadbed below the ballast and track.

Suburban bus – Bus similar to an intercity bus with high-backed seats but no luggage compartment, used in express mode to city centers from suburban locations.

Switch – A track structure used to divert rolling stock from one track to another.

Tangent Track – Track without curvature.

Track – An assembly of rail, ties and fastenings over which cars, locomotives, and trains are moved.

Traction Motor – A specially designed direct current series-wound motor mounted on the trucks of locomotives and self-propelled cars to drive the axles.

Trainset – A group of coupled cars including at least one power unit.

Transducer – Device designed to receive an input signal of a given kind (motion, pressure, heat, etc.) and to provide an output signal of a different kind (electrical voltage, amperage, etc.) in such a manner that desired characteristics of the input signal appear in the output signal for measurement purposes.

Transit center – A fixed location where passengers interchange from one route or vehicle to another.

Trolley bus – A rubber-tired, electrically-powered bus operating on city streets drawing power from overhead lines.

Truck – The complete assembly of parts including wheels, axles, bearings, side frames, bolster, brake rigging, springs and all associated connecting components, the function of which is to provide support, mobility and guidance to a railroad car or locomotive.

Trunk line – See Mainline. The mainline of a commuter railroad where the branch line traffic is combined.

Turnout – An arrangement of a switch and a frog with closure rails, by means of which rolling stock may be diverted from one track to another.

VdB – see Vibration Velocity Level.

Vibration Velocity Level (L_V) – Ten times the common logarithm of the ratio of the square of the amplitude of the RMS vibration velocity to the square of the amplitude of the reference RMS vibration velocity. The reference velocity in the United States is one micro-inch per second. Also written as VdB.

Vibration – An oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

Wheel Flat – A localized flat area on a steel wheel of a rail vehicle, usually caused by skidding on steel rails, causing a discontinuity in the wheel radius.

Wheel Squeal – The noise produced by wheel-rail interaction, particularly on a curve where the radius of curvature is smaller than allowed by the separation of the axles in a wheel set.

REFERENCES

1. American National Standards Institute, "Acoustical Terminology," ANSI S1.1-1994

2. American Public Transportation Association, "Public Transportation Factbook," 55th Edition, March 2004.

APPENDIX B. BACKGROUND FOR TRANSIT NOISE IMPACT CRITERIA

The noise criteria, presented in Chapter 3 of this manual, have been developed based on well-documented criteria and research into human response to community noise. The primary goals in developing the noise criteria were to ensure that the impact limits be firmly founded in scientific studies, be realistically based on noise levels associated with new transit projects, and represent a reasonable balance between community benefit and project costs. This appendix provides the background information.

B.1 RELEVANT LITERATURE

Following is an annotated list of the documents that are particularly relevant to the noise impact criteria:

1. US Environmental Protection Agency "Levels Document":[1] This report identifies noise levels consistent with the protection of public health and welfare against hearing loss, annoyance, and activity interference. It has been used as the basis of numerous community noise standards and ordinances.

2. CHABA Working Group 69, "Guidelines for Preparing Environmental Impact Statements on Noise":[2] This report was the result of deliberations by a group of leading acoustical scientists with the goal of developing a uniform national method for noise impact assessment. Although the CHABA's proposed approach has not been adopted, the report serves as an excellent resource documenting research in noise effects. It provides a strong scientific basis for quantifying impacts in terms of L_{dn}.

3. American Public Transit Association Guidelines:[3] The noise and vibration sections of the APTA Guidelines have been used successfully in the past for the design of rail transit facilities. The APTA Guidelines include criteria for acceptable community noise and vibration. Experience has shown that meeting the APTA Guidelines will usually result in acceptable noise levels. However, there are some problems in using the APTA Guidelines for environmental assessment purposes. The criteria are in terms of L_{max} for conventional rail rapid transit vehicles and they cannot be used to compare among

different modes of transit. Since the APTA Guidelines are expressed in terms of maximum passby noise, they are not sensitive to the frequency or duration of noise events for transit modes other than conventional rail rapid transit operations with 5- to 10-minute headways. Therefore, the APTA criteria are questionable for assessing the noise impact of other transit modes which differ from conventional rapid transit with respect to source emission levels and operating characteristics (e.g., commuter rail, AGT and a variety of bus projects).

4. "Synthesis of Social Surveys on Noise Annoyance":[4] In 1978, Theodore J. Schultz, an internationally known acoustical scientist, synthesized the results of a large number of social surveys, each concerning annoyance due to transportation noise. Remarkable consistency was found in a group of these surveys, and the author proposed that their average results be taken as the best available prediction of transportation noise annoyance. This synthesis has received essentially unanimous acceptance by acoustical scientists and engineers. The "universal" transportation response curve developed by Schultz (Figure 2-7) shows that the percent of the population highly annoyed by transportation noise increases from zero at an L_{dn} of approximately 50 dBA to 100-percent when L_{dn} is about 90 dBA. Most significantly, this curve indicates that for the same increase in L_{dn}, there is a greater increase in the number of people highly annoyed at high noise levels than at low noise levels. In other words, a 5 dB increase at low ambient levels (40 - 50 dB) has less impact than at higher ambient levels (65 - 75 dB). A recent update of the original research, containing several railroad, transit and street traffic noise surveys, confirmed the shape of the original Schultz curve.[5]

5. HUD Standards:[6] The U.S. Department of Housing and Urban Development has developed noise standards, criteria and guidelines to ensure that housing projects supported by HUD achieve the goal of a suitable living environment. The HUD site acceptability standards define 65 dB (L_{dn}) as the threshold for a normally unacceptable living environment and 75 dB (L_{dn}) as the threshold for an unacceptable living environment.

B.2 BASIS FOR NOISE IMPACT CRITERIA CURVES

The lower curve in Figure 3-1 representing the onset of Moderate Impact is based on the following considerations:

- The EPA finding that a community noise level of L_{dn} less than or equal to 55 dBA is "requisite to protect public health and welfare with an adequate margin of safety."[1]

- The conclusion by EPA and others that a 5 dB increase in L_{dn} or L_{eq} is the minimum required for a change in community reaction.

- The research finding that there are very few people highly annoyed when the L_{dn} is 50 dBA, and that an increase in L_{dn} from 50 dBA to 55 dBA results in an average of 2% more people highly annoyed (see Figure 2-10 in Chapter 2).

Consequently, the change in noise level from an existing ambient level of 50 dBA to a cumulative level of 55 dBA caused by a project is assumed to be a minimal impact. Expressed another way, this is considered to be the lowest threshold where impact starts to occur. Moreover, the 2% increment represents the minimum measurable change in community reaction. Thus the curve's hinge point is placed at a project noise level of 53 dBA and an existing ambient noise level of 50 dBA, the combination of which yields a cumulative level of 55 dBA. The remainder of the lower curve in Figure 3-1 was determined from the annoyance curve (Figure 2-10) by allowing a fixed 2% increase in annoyance at other levels of existing ambient noise. As cumulative noise increases, it takes a smaller and smaller increment to attain the same 2% increase in highly annoyed people. While it takes a 5 dB noise increase to cause a 2% increase in highly annoyed people at an existing ambient noise level of 50 dB, an increase of only 1 dB causes the 2% increase of highly annoyed people at an existing ambient noise level of 70 dB.

The upper curve delineating the onset of Severe Impact was developed in a similar manner, except that it was based on a total noise level corresponding to a higher degree of impact. The Severe Noise Impact curve is based on the following considerations:

- The Department of Housing and Urban Development (HUD) in its environmental noise standards defines an L_{dn} of 65 as the onset of a normally unacceptable noise zone.[6] Moreover, the Federal Aviation Administration (FAA) considers that residential land uses are not compatible with noise environments where L_{dn} is greater than 65 dBA [7].

- The common use of a 5 dBA increase in L_{dn} or L_{eq} as the minimum required for a change in community reaction.

- The research finding that the foregoing step represents a 6.5% increase in the number of people highly annoyed (see Figure 2-10 in Chapter 2).

Consequently, the increase in noise level from an existing ambient level of 60 dBA to a cumulative level of 65 dBA caused by a project represents a change from an acceptable noise environment to the threshold of an unacceptable noise environment. This is considered to be the level at which severe impact starts to occur. Moreover, the 6.5% increment represents the change in community reaction associated with severe impact. Thus the upper curve's hinge point is placed at a project noise level of 63 dBA and existing ambient noise level of 60 dBA, the combination of which yields a cumulative level of 65 dBA. The remainder of the upper curve in Figure 3-1 was determined from the annoyance curve (Figure 2-10) by fixing the 6.5% increase in annoyance at all existing ambient noise levels.

Both curves incorporate a maximum limit for the transit project noise in noise-sensitive areas. Independent of existing noise levels, Moderate Impact for land use categories 1 and 2 is considered to occur whenever the <u>transit</u> L_{dn} equals or exceeds 65 dBA and Severe Impact occurs whenever the <u>transit</u> L_{dn} equals or exceeds 75 dBA. These absolute limits are intended to restrict activity interference caused by the transit project alone.

Both curves also incorporate a maximum limit for cumulative noise increase at low existing noise levels (below about 45 dBA). This is a conservative measure that reflects the lack of social survey data on people's reaction to noise at such low ambient levels. Similar to the FHWA approach in assessing the relative impact of a highway project, the transit noise criteria include caps on noise increase of 10 dB and 15 dB for Moderate Impact and Severe Impact, respectively, relative to the existing noise level.

Finally, it should be noted that due to the types of land use included in Category 3, the criteria allow the project noise for Category 3 sites to be 5 decibels greater than for Category 1 and Category 2 sites. This difference is reflected by the offset in the vertical scale on the right side of Figure 3-1. With the exception of active parks, which are clearly less sensitive to noise than Category 1 and 2 sites, Category 3 sites include primarily indoor activities and thus the criteria account for some noise reduction provided by the building structure.

B.3 EQUATIONS FOR NOISE IMPACT CRITERIA CURVES

The noise impact criteria can be quantified through the use of mathematical equations which approximate the curves shown in Figure 3-1. These equations may be useful when performing the noise assessment methodology through the use of spreadsheets, computer programs or other analysis tools. Otherwise, such mathematical detail is generally not necessary in order to properly implement the criteria, and direct use of Figure 3-1 is likely to be adequate and less time-consuming.

A total of four continuous curves are obtained from the criteria: two threshold curves ("Moderate Impact" and "Severe Impact") for Category 1 and 2; and two for Category 3. Note that for each level of impact, the overall curves for Categories 1 and 2 are offset by 5 dB from Category 3. While each curve is graphically continuous, it is defined by a set of three discrete equations which represent three "regimes" of existing noise exposure. These equations are approximately continuous at the transition points between regimes.

The first equation in each set is a linear relationship, representing the portion of the curve in which the existing noise exposure is low and the allowable increase is capped at 10 dB and 15 dB for Moderate Impact and Severe Impact, respectively. The second equation in each set represents the impact threshold over the range of existing noise exposure for which a fixed percentage of increase in annoyance is allowed, as described in the previous section. This curve, a third-order polynomial approximation derived from the Schultz curve,[(4)] covers the range of noise exposure encountered in most populated areas and is used in determining noise impact in the majority of cases for transit projects. Finally, the third equation in each of the four sets represents the absolute limit of project noise imposed by the criteria, for areas with high existing noise exposure. For land use category 1 and 2, this limit is 65 dBA for Moderate Impact and 70 dBA for Severe Impact. For land use category 3, the limit is 75 dBA for Moderate Impact and 80 dBA for Severe Impact.

The four sets of equations corresponding to the curves are given below. Each curve represents a threshold of noise impact, with impact indicated for points on or above the curve.

Threshold of Moderate Impact:

$$L_P = \begin{cases} 11.450 + 0.953L_E & L_E < 42 \\ 71.662 - 1.164L_E + 0.018{L_E}^2 - 4.088\times10^{-5}{L_E}^3 & 42 \le L_E \le 71 \\ 65 & L_E > 71 \end{cases} \Bigg\} \text{Category 1 and 2}$$

$$L_P = \begin{cases} 16.450 + 0.953L_E & L_E < 42 \\ 76.662 - 1.164L_E + 0.018{L_E}^2 - 4.088\times10^{-5}{L_E}^3 & 42 \le L_E \le 71 \\ 70 & L_E > 71 \end{cases} \Bigg\} \text{Category 3}$$

Threshold of Severe Impact:

$$L_P = \begin{cases} 17.322 + 0.940L_E & L_E < 44 \\ 96.725 - 1.992L_E + 3.02\times10^{-2}{L_E}^2 - 1.043\times10^{-4}{L_E}^3 & 44 \le L_E \le 77 \\ 75 & L_E > 77 \end{cases} \Bigg\} \text{Category 1 and 2}$$

$$L_P = \begin{cases} 22.322 + 0.940L_E & L_E < 44 \\ 101.725 - 1.992L_E + 3.02\times10^{-2}{L_E}^2 - 1.043\times10^{-4}{L_E}^3 & 44 \le L_E \le 77 \\ 80 & L_E > 77 \end{cases} \Bigg\} \text{Category 3}$$

where L_E is the existing noise exposure in terms of L_{dn} or $L_{eq}(h)$ and L_P is the project noise exposure which determines impact, also in terms of L_{dn} or $L_{eq}(h)$.

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3. American Public Transit Association, *1981 Guidelines for Design of Rapid Transit Facilities*, Section 2.7, "Noise and Vibration," 1981.

4. T.J. Schultz, "Synthesis of Social Surveys on Noise Annoyance," Journal of the Acoustical Society of America, Vol. 64, No. 2, pp. 377-405, August 1978.

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6. U.S. Department of Housing and Urban Development, "Environmental Criteria and Standards", 24 CFR Part 51,v 12 July 1979; amended by 49 FR 880, 6 January 1984.

7. U.S. Department of Transportation, Federal Aviation Administration, "Federal Aviation Regulations Part 150: Airport Noise Compatibility Planning," January 1981.

APPENDIX C. SELECTING RECEIVERS OF INTEREST

This appendix provides additional detail in selecting receivers of interest for those users desiring such detail. The general approach given in Chapter 6 includes the following guidelines:

- Every major public building or site with noise-sensitive indoor use within the noise study area should be selected as a separate receiver of interest.
- Each isolated residence and small outdoor noise-sensitive area within the noise study area should be selected as a separate receiver of interest in the same manner as for public buildings.
- In contrast, groups of residences and larger outdoor noise-sensitive areas within the noise study area should be "clustered" and a receiver of interest selected from each cluster. Clustering reduces the number of computations later needed, especially for large-scale projects where a great number of noise-sensitive sites may be affected. For this approach to work, however, it is essential that the receiver selected provide an accurate representation of the noise environment of the cluster.

This appendix elaborates on the clustering procedure. In brief: (1) Cluster boundaries are first drawn relative to the proposed project, either running parallel to a linear project or circling major stationary sources. These boundaries approximate contours of equal project noise. (2) Then a separate set of cluster boundaries is drawn parallel to, or circling, major sources of ambient noise to approximate contours of ambient noise. (3) Finally, a third set of cluster boundaries may further subdivide the noise study area, if there are changes in project layout or operations along the corridor.

Following are suggested procedures for drawing cluster boundaries and for selecting a receiver of interest from each cluster:

Boundaries along the proposed project. First draw cluster boundaries along the proposed project, to separate clusters based upon distance from the project. Draw such cluster boundaries for all sources that are listed as "Major" in Table 6-2.

Within both residential and noise-sensitive outdoor areas:

- **Primary project source.** Draw cluster boundaries at the following distances from the near edge of the primary project source: 0 feet, 50 feet, 100 feet, 200 feet, 400 feet, and 800 feet. If the primary project source is a linear source, such as a rail line, draw these boundaries as lines parallel to the proposed right-of-way line. Around major stationary sources, draw these boundaries as approximate circles around the source, starting at the property line. Do not extend boundaries beyond the noise study area, identified in the Screening Procedure of Chapter 4 or the General Assessment of Chapter 5.
- **Remaining project sources**. Repeat this for all other project sources listed as Major in Table 6-2, such as substations and crossing signals. If several project sources are located approximately together, only one need be considered here, since the others would produce approximately the same boundaries. It is good practice to optimize the number of clusters for a project, to avoid needlessly complicating the procedure.

Where rows of buildings parallel the transit corridor:

- Check that cluster boundaries fall between the following rows of buildings, counting back away from the proposed project:

  Between rows 1 and 2

  Between rows 2 and 3

  Between rows 4 and 5

  If not, add cluster boundaries between these rows.

Boundaries along sources of ambient noise. Next, draw cluster boundaries along all major sources of ambient noise, based upon distance from these sources.

- Along all interstates and major roadway arterials, draw cluster boundaries at the following distances from the near edge of the roadway: 0 feet, 100 feet, 200 feet, and 500 feet.
- Along all other roadways that have state or county numbering, draw cluster boundaries at 0 feet and 100 feet from the near edge of the roadway.
- For all major industrial sources of noise, draw cluster boundaries that circle the source, at the following distances from the near property line of the source: 0 feet, 100 feet, 200 feet, 400 feet.

Further boundaries based upon changes in project layout or operations along the corridor. Where proposed project layout or operating conditions change significantly along the corridor, further subdivision is needed to account for changes in project noise. Draw a cluster boundary perpendicular to the corridor, extending straight outward to both sides, at the following locations:

- Where parallel tracks, previously separated by more than 100 feet or so, come closer together
- Approximately where speed and/or throttle is reduced approaching stations and where steady service speed is reached after departing stations.
- Approximately 200 feet up and down the line from grade-crossing bells
- At transitions from jointed to welded rail
- At transitions from one type of cross section to another -- from among these types: on structure, on fill, at grade, and in cut.
- At transitions from open terrain to heavily wooded terrain
- At transitions between areas free of locomotive-horn noise and areas subject to this noise source
- Any other positions along the line where project noise is expected to change significantly -- such as up and down the line from tight curves where wheels may squeal

Selection of a receiver of interest from each cluster. The cluster boundaries divide the land area into clusters of miscellaneous shape. Each of these pieces constitutes an area that will be represented by a single receiver of interest.

- For residential clusters, locate this receiver of interest within the cluster at the house closest to the proposed project. If in doubt, select the one furthest from significant sources of ambient noise.
- For outdoor noise-sensitive clusters, such as an urban park or amphitheater, locate this receiver of interest within the cluster at the closest point of active noise-sensitive use. If in doubt, select the one furthest from significant sources of ambient noise.

In following the foregoing procedures, some clusters may fall between areas with receivers of interest. This could occur, for example, when operational changes or track layouts change in an open undeveloped area. Retain such clusters -- that is, do not merge them with adjacent ones -- but do not select a receiver of interest from them.

Example C-1. Receivers of Interest and Cluster Boundaries

An example of receivers of interest and cluster boundaries is shown in Figure C-1. In this hypothetical situation, a new rail transit line, labeled "new rail line," is proposed along a major urban street with commercial land use. A residential area is located adjacent to the commercial strip, starting about one-half block from the proposed transit alignment. A major arterial, labeled "highway," crosses the alignment.

Following the procedure described in this appendix, the first step is to draw cluster boundaries along the **proposed primary project source** (in this case, the new rail line) at distances of 0 feet from the right-of-way line (edge of the street in this example), 50 feet, 100 feet, 200 feet, 400 feet, and 800 feet. These lines are shown with distances labeled at the top of the figure. This is proposed to be a constant speed section of track, so there are no changes in boundaries due to changes in operations along the corridor. Moreover, no **other project sources** are shown here, although if there had been a station with a parking lot, lines would have been drawn enveloping the station site at the specified distances from the property line. However, this example does show **rows of buildings parallel** to the transit corridor. The first set of lines satisfies the requirement that cluster boundaries fall between rows 1 and 2, and between rows 2 and 3, but there is no line between rows 4 and 5. Consequently, a cluster boundary (labeled "R" at the top of the figure) has been drawn between the 4th and 5th row of buildings.

Next, cluster boundaries are to be drawn along major sources of ambient noise. The roadway arterial (labeled "highway") is the only major source of ambient noise shown. Again following the procedure described in this appendix, cluster boundaries are drawn at 0 feet, 100 feet, 200 feet and 500 feet from the near edge of the roadway, both sides. These lines are shown with distances labeled at the side of the figure.

The foregoing describes the procedures for drawing all the lines defining the cluster boundaries shown in Figure C-1. The next step is to **select a receiver of interest within each cluster**. These are shown as filled circles in the figure. Some receivers of interest are labeled for use as examples in Appendix D. Taking the shaded cluster with "Rec 3" as an example: the cluster is located at the outer edge of influence from the major source ("highway"), where local street traffic takes over from the highway as the dominant source for ambient noise, which would be verified by a measurement. "Rec 3" is chosen to represent this cluster because it is among the houses closest to the proposed project source in this cluster and it is in the middle of the block affected by the dominant local street. Ambient noise levels at one end of the cluster may be influenced more by the highway and the other end may be affected more by the cross street, but the majority of the cluster would be represented by receiver site "Rec 3."

End of Example C-1

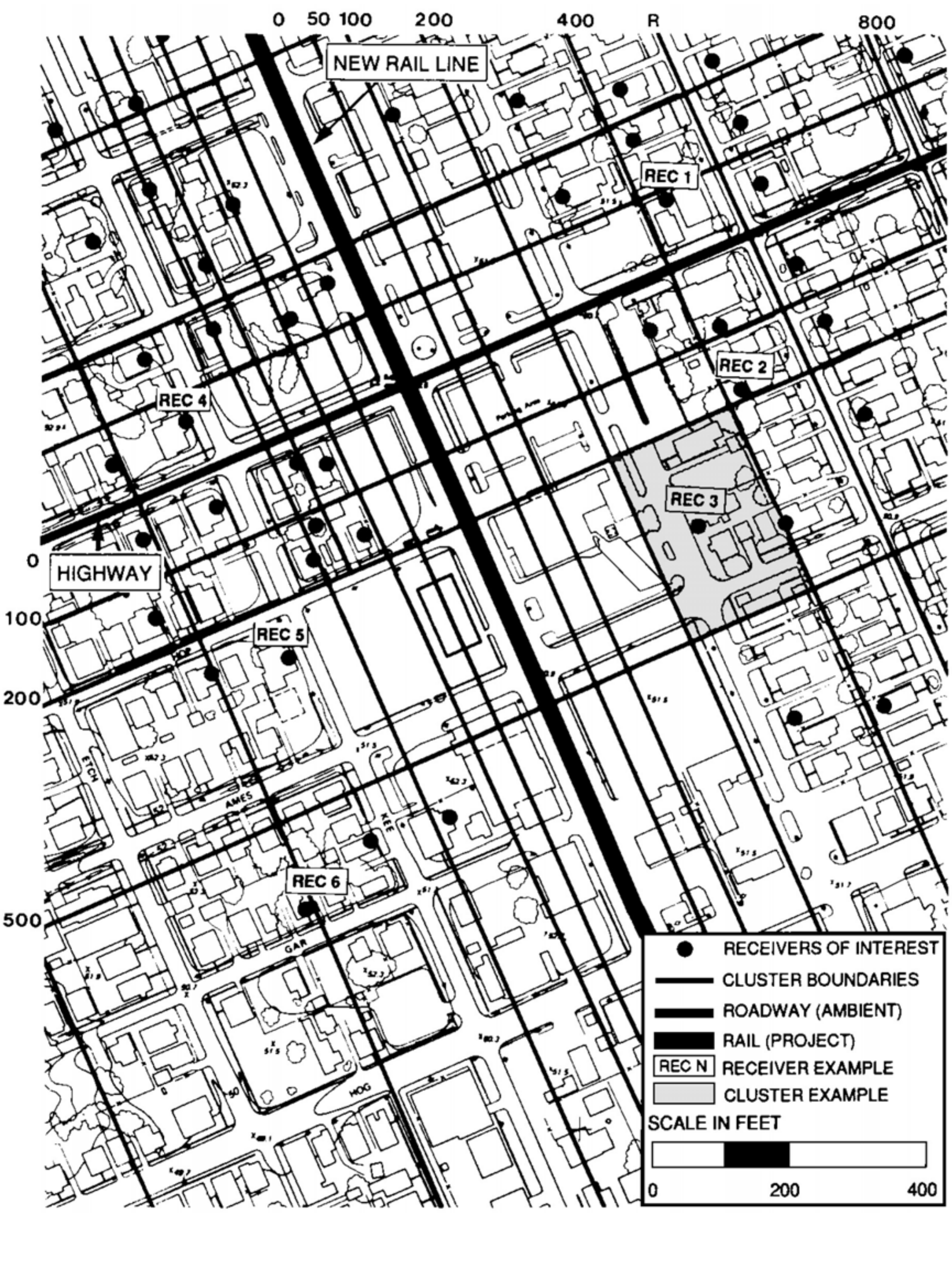

Figure C-1. Example of Receiver Map Showing Cluster Boundaries

APPENDIX D. DETERMINING EXISTING NOISE

This appendix provides additional detail in determining existing noise by: (1) full measurement, (2) computation from partial measurements, and (3) tabular look-up. Note that the words "existing noise" and "ambient noise" are often used interchangeably.

Continuing with the example from Figure C-1, the ambient noise at the selected receivers of interest, labeled "REC 1,2,3...," can be determined according to the following methods.

- Existing noise at REC 1 is due to the highway at the side of this church. L_{eq} during a typical church hour was measured in full. – OPTION 1 below
- Existing noise at REC 2, a residence, is due to a combination of the highway and local streets. L_{dn} was measured in full. – OPTION 2 below
- Existing noise at REC 3 is due to the street in front of this residence. L_{dn} was computed from three hourly L_{eq} measurements. – OPTION 3 below
- Existing noise at REC 4, a residence, is due to the highway. Since the highway has a predictable diurnal pattern, L_{dn} was computed from one hourly L_{eq} measurement. – OPTION 4 below
- Existing noise at REC 5, a residence, is due to Kee Street. L_{dn} was computed from L_{dn} at the comparable REC 3, which is also affected by local street traffic and is a comparable distance from the highway. – OPTION 5 below
- Existing noise at REC 6, a residence, is due to local traffic. L_{dn} was estimated by table look-up, based upon population density along this corridor. – OPTION 6 below

The full set of options for determining existing noise at receivers of interest is as follows:

- For non-residential land uses, measure a full hour's L_{eq} at the receiver of interest, during a typical hour of use on two non-successive days. The hour chosen should be the one in which maximum project activity will occur. The L_{eq} will be accurately represented.-- OPTION 1

- The three options for residential land uses are:
    - Measure a full day's L_{dn}. The L_{dn} will be accurately represented. – OPTION 2
    - Measure the hourly L_{eq} for three typical hours: peak traffic, midday and late night. Then compute the L_{dn} from these three hourly L_{eq}'s. The computed L_{dn} will be slightly underestimated. – OPTION 3
    - Measure the hourly L_{eq} for one hour of the day only, preferably during midday. Then compute the L_{dn} from this hourly L_{eq}. The computed L_{dn} will be moderately underestimated. – OPTION 4
- For all land uses, compute either the L_{eq} or the L_{dn} from a measured value at a nearby receiver – one where the ambient noise is dominated by the same noise source. The computed value will be represented with only moderate precision. – OPTION 5
- For all land uses, estimate either the L_{eq} or the L_{dn} from a table of typical values, depending upon distance from major roadways or upon population density. The resulting values will be significantly underestimated. – OPTION 6

Option 1: For non-residential land uses, measure the hourly L_{eq} for the hour of interest

Full one-hour measurements are the most precise way to determine existing noise for non-residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full hour's L_{eq} at the receiver of interest on at least two non-successive days during a typical hour of use. This would generally be between noon Monday and noon Friday, but weekend days may be appropriate for places of worship. On both days, the measured hour must be the same as that for which project noise is computed: the loudest facility hour that overlaps hours of noise-sensitive activity at the receiver.
- At all sites, locate the measurement microphone as shown in Figure 6-9, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice.

Option 2: For residential land uses, measure the L_{dn} for a full 24 hours

Full 24-hour measurements are the most precise way to determine ambient noise for residential receivers of interest. Such full-duration measurements are preferred over all other options. The following procedures apply to full-duration measurements:

- Measure a full 24-hour's L_{dn} at the receiver of interest, for a single weekday (generally between noon Monday and noon Friday).
- At all sites, locate the measurement microphone as shown in Figure 6-9, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice.

Option 3: For residential land uses, measure the hourly L_{eq} for three hours and then compute L_{dn}

An alternative way to determine L_{dn}, less precise than its full-duration measurement, is to measure hourly L_{eq}'s for three typical hours of the day and then to compute the L_{dn} from these three hourly L_{eq}'s. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during each of the following time periods: once during peak-hour roadway traffic, once midday between the morning and afternoon roadway-traffic peak hours, and once during late night between midnight and 5 am.
- Compute L_{dn} with the following equation:

$$\boxed{L_{dn} \approx 10\log\left[(3)\cdot 10^{\frac{L_{eq}(\text{peakhour})-2}{10}} + (12)\cdot 10^{\frac{L_{eq}(\text{midday})-2}{10}} + (9)\cdot 10^{\frac{L_{eq}(\text{latenight})+8}{10}}\right] - 13.8}$$

  This value of L_{dn} will be slightly underestimated due to the subtraction of 2 decibels from each of the measured levels before their combination. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to its full-duration measurement.

- At all sites, locate the measurement microphone as shown in Figure 6-9, depending upon the relative orientation of project and ambient sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice.

Option 4: For residential land uses, measure the hourly L_{eq} for one hour and then compute L_{dn}

The next level down in precision is to determine L_{dn} by measuring the hourly L_{eq} for one hour of the day and then to compute L_{dn} from this hourly L_{eq}. This method is useful when there are many sites in a General

Assessment, or when checking whether a particular receiver of interest represents a cluster in a Detailed Analysis. The following procedures apply to this partial-duration measurement option for L_{dn}:

- Measure the one-hour L_{eq} during any hour of the day. The loudest hour during the daytime period is preferable. If this hour is not selected, then other hours may be used with less precision.
- Convert the measured hourly L_{eq} to L_{dn} with the applicable equation:

$$\begin{array}{r}\text{For measurements between 7am and 7pm}: L_{dn} \approx L_{eq} - 2\\ \text{For measurements between 7pm and 10pm}: L_{dn} \approx L_{eq} + 3\\ \text{For measurements between 10pm and 7am}: L_{dn} \approx L_{eq} + 8\end{array}$$

  The resulting value of L_{dn} will be moderately underestimated due to the use of the adjustment constants in these equations. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to the more precise methods of determining L_{dn}.

- At all sites, locate the measurement microphone as shown in Figure 6-9, depending upon the relative orientation of project and existing sources. Desired is a microphone location that is shielded somewhat from the ambient source. At such locations, ambient noise will be measured at the quietest location on the property for purposes of noise impact assessment so that noise impact will be assessed most critically.
- Undertake all measurements in accordance with good engineering practice

Option 5: For all land uses, compute either L_{eq} or L_{dn} from a nearby measured value

A computation method comparable in precision to Option 4 is to determine the ambient noise, either L_{eq}(h) or $L_{dn,}$ from a measured value at a nearby receiver – one where the ambient noise is dominated by the same noise source. This method is used to characterize noise in several neighborhoods by using a single representative receiver. Care must be taken to ensure that the measurement site has a similar noise environment to all areas represented. If measurements made by others are available, and the sites are equivalent, they can be used to reduce the amount of project noise monitoring. The following procedures apply to this computation of ambient noise at the receiver of interest:

- Choose another receiver of interest, called the "comparable receiver," at which:
  - o The same source of ambient noise dominates.
  - o The ambient $L_{CompRec}$ was measured with either OPTION 1 or OPTION 2 above.
  - o The ambient measurement at the comparable receiver was made in direct view of the major source of ambient noise, unshielded from it by noise barriers, terrain, rows of buildings, or dense tree zones.

- From a plan or aerial photograph, determine: (1) the distance $D_{CompRec}$ from the comparable receiver to the near edge of the ambient source, and (2) the distance $D_{ThisRec}$ from this receiver of interest to the near edge of the ambient source.
- Also determine N, the number of rows of buildings that intervene between the receiver of interest and the ambient source.
- Compute the ambient level at this receiver of interest with the applicable equation:

If roadway sources dominate: $$L_{ThisRec} \approx L_{CompRec} - 15\log\left(\frac{D_{ThisRec}}{D_{CompRec}}\right) - 3N$$

If other sources dominate: $$L_{ThisRec} \approx L_{CompRec} - 25\log\left(\frac{D_{ThisRec}}{D_{CompRec}}\right) - 3N$$

The resulting value of $L_{ThisRec}$ will be moderately underestimated. As explained previously, this underestimate is intended to compensate for the reduced precision of the computed L_{dn} here, compared to the more precise methods of determining ambient noise levels.

Option 6: For all land uses, estimate either L_{eq}(h) or L_{dn} from a table of typical values

The least precise way to determine the ambient noise is to estimate it from a table. A tabular look-up can be used to establish baseline conditions for a General Noise Assessment if a noise measurement can not be made. It should not be used for a Detailed Noise Analysis. For this estimate of ambient noise:

- Read the ambient noise estimate from the relevant portion of Table 5-7. These tabulated estimates depend upon distance from major roadways, rail lines or upon population densities. In general, these tabulated values are significant underestimates. As explained previously, underestimates here are intended to compensate for the reduced precision of the estimated ambients, compared to the options that incorporate some degree of measurements.

APPENDIX E. COMPUTING SOURCE REFERENCE LEVELS FROM MEASUREMENTS

This appendix contains the procedures for computing source reference levels (SEL_{ref}) from source measurements in cases where the Source Reference Tables in Chapter 6 indicate measurements are preferred.

For vehicle passbys, the closeby source measurements may be either of the vehicle's sound exposure level (SEL) or of its maximum noise level (L_{max}). Both these descriptors can be measured directly by commonly available sound level meters. L_{max}'s are allowed here for several reasons. Often L_{max} measurements are available from transit-equipment manufacturers. For some transit systems, equipment specifications will limit closeby L_{max}'s to some particular value. And in some situations, closeby source measurements may be taken as part of the environmental study for more precision than is possible with the reference-level table.

For non-passby sources, the closeby source measurements must be of the source's SEL over one source "event." The source "event" duration may be chosen for measurement convenience; it will subtract out of the computation when the measured value is converted to reference operating conditions later in this section.

This manual does not specify elaborate methods for undertaking such closeby source measurements, nor that these measurements be at the reference conditions discussed in the main text. Required are measurements that conform to good engineering practice, guided by the standards of the American National Standards Institute and other such organizations (see References 2, 3 and 4 of Chapter 6).

For passbys of both highway and rail vehicles, the following conditions are required in addition to good engineering practice:

- Measured vehicles must be representative of project vehicles in all aspects, including representative acceleration and speed conditions for buses.

- Track must be relatively free of corrugations and train wheels relatively free of flats, unless these conditions are typical of the proposed project.
- Road surfaces must be smooth and dry, unless these conditions are typical of the proposed project.
- Perpendicular distance between the measurement position and the source's centerline must be 100 feet or less.
- Vehicle speed must be 30 miles per hour or greater, unless typical project speeds are less than that.
- No noise barriers, terrain, buildings, or dense tree zones may break the lines-of-sight between the source and the measurement position.

For sources other than vehicle passbys, the following conditions are required in addition to good engineering practice:

- Measured source operations must be representative of project operations in all aspects.
- The following ratio must be 2 or less:

  distance to the furthest source component
  divided by
  distance to the closest source component

  In addition, the distance to the closest source component must be 200 feet or less. If both these conditions cannot simultaneously be met, then separate closeby measurements must be made of individual components of this source, for which these distance conditions can be met.

- The following ratio must be 2 or less:

  lateral length of the source area, measured perpendicular to the general line-of-sight between source and measurement position
  divided by
  distance to the closest source component

  If this condition cannot be met, then separate closeby measurements must be made of individual components of this source, for which this condition can be met.

- No noise barriers, terrain, buildings, or dense tree zones may break the lines-of-sight between the source and the measurement position.

When closeby source measurements are made under non-reference conditions, the equations in Table E-1 are used to convert the measured values to Source Reference Levels. Detailed procedures follow. Note that each vehicle type must be measured and converted separately. Note that this computation requires that all measured vehicles be of the same type. For trains of mixed consists, see Appendix F. For rail vehicles, measure/convert a group of locomotives **or** a group of cars separately.

<u>If SEL was measured for a highway-vehicle passby, or a passby of a group of identical rail vehicles:</u>

- Collect the following input information:
    - SEL_{meas}, the measured SEL for the vehicle passby
    - N, the consist of the measured group of rail cars or group of locomotives
    - T, the average throttle setting of the measured diesel-powered locomotive(s)
    - S_{meas}, the measured passby speed, in miles per hour
    - D_{meas}, the closest distance between the measurement position and the source, in feet
- Compute the Source Reference Level -- SEL_{ref} -- from the **first** equation in Table E-1.

Example E-1. Computation of SEL_{ref} from SEL Measurement of Fixed-Guideway Source

A passby of two diesel-powered locomotives was measured at

SEL_{meas} = 90 dBA.

For this measurement,

N = 2
T = 6
S_{meas} = 55 miles per hour, and
D_{meas} = 65 feet.

The resulting SEL_{ref} = 86.5 dBA.

End of Example E-1

<u>If SEL was measured for a stationary noise source:</u>

- Collect the following input information:
    - SEL_{meas}, the measured SEL for the noise source, for whatever source "event" is convenient to measure
    - E_{meas}, the event duration, in seconds
    - D_{meas}, the closest distance between the measurement position and the source, in feet
- Compute the Source Reference Level -- SEL_{ref} -- from the **second** equation in Table E-1.

Example E-2. Computation of SEL_{ref} from SEL Measurement of Stationary Source

A signal crossing was measured for a 10-second "event" at

SEL_{meas} = 70.

For this measurement,

E_{meas} = 10 seconds and
D_{meas} = 25 feet.

The resulting SEL_{ref} = 89.5 dBA.

End of Example E-2

If L_{max} was measured for a passby of a group of identical rail vehicles:

- Collect the following input information:
  - L_{max}, measured for the group passby
  - N, the consist of the measured group of rail cars or group of locomotives
  - T, the average throttle setting of the measured diesel-powered locomotive(s)
  - S_{meas}, the measured passby speed, in miles per hour
  - D_{meas}, the closest distance between the measurement position and the source, in feet
  - L_{meas}, the total length of the measured group of locomotives or group of rail cars, in feet

- Compute the Source Reference Level -- SEL_{ref} -- from the **third or fourth** equations in Table E-1, depending on whether the sources are locomotives or rail cars.

Example E-3. Computation of SEL_{ref} from L_{max} Measurement of Fixed-Guideway Source

A passby of a 4-car consist of 70-ft long rail cars was measured at

L_{max} = 90.

For this measurement,

N = 4
S_{meas} = 70 miles per hour
D_{meas} = 65 feet, and
L_{meas} = 280 feet.

Using the fourth equation in Table E-1,

$\propto$ = 1.14

and the resulting SEL_{ref} = 86.7 dBA.

End of Example E-3

<u>If L_{max} was measured for a highway-vehicle passby:</u>

- Collect the following input information:
  - L_{max}, measured for the highway-vehicle passby
  - S_{meas}, the vehicle speed, in miles per hour
  - D_{meas}, the closest distance between the measurement position and the source, in feet
- Compute the Source Reference Level -- SEL_{ref} -- from the **fifth** equation in Table E-1.

Example E-4. Computation of SEL_{ref} from L_{max} Measurement of Highway Vehicle Source

A bus was measured at

L_{max} = 78 dBA.

For this measurement,

S_{meas} = 40 miles per hour and
D_{meas} = 80 feet.

Using the fifth equation in Table E-1, the resulting SEL_{ref} = 87.8 dBA.

End of Example E-4

Table E-1. Conversion to Source Reference Levels at 50 feet for Transit Noise Sources

Measured Quantity	Noise Source	Equation
SEL	Vehicle passby	$SEL_{ref} = SEL_{meas} + 10\log\left(\frac{S_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) + C_{consist} + C_{emissions}$
	Stationary noise source	$SEL_{ref} = SEL_{meas} - 10\log\left(\frac{E_{meas}}{3600}\right) + 20\log\left(\frac{D_{meas}}{50}\right)$
L_{max}	Rail-vehicle passby, locomotives only	$SEL_{ref} = L_{max} + 10\log\left(\frac{L_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) - 10\log(2\propto) + C_{consist} + C_{emissions} + 3.3$
	Rail-vehicle passby, cars only	$SEL_{ref} = L_{max} + 10\log\left(\frac{L_{meas}}{50}\right) + 10\log\left(\frac{D_{meas}}{50}\right) - 10\log\left[2\propto + \sin(2\propto)\right] + C_{consist} + C_{emissions} + 3.3$
	Highway-vehicle passby	$SEL_{ref} = L_{max} + 20\log\left(\frac{D_{meas}}{50}\right) + C_{emissions} + 3.3$

Vehicle Type	Expression for $C_{consist}$	Expression for $C_{emissions}$
Locomotives	-10 log (N)	0 For T<6 -2(T-5) For T ≥ 6
Rail Cars	-10 log (N)	$-30\log\left(\frac{S_{meas}}{50}\right)$
Buses	0	$-25\times\log\left(\frac{S_{meas}}{50}\right)$
Automobiles	0	$-38.1\times\log\left(\frac{S_{meas}}{50}\right)$

N = consist, (number of locomotives *or* rail cars in the measured group)
T = average throttle setting of measured diesel – electric locomotive(s)
D_{meas} = closest distance between measurement position and source, in feet
E_{meas} = event duration of measurement, in seconds
L_{meas} = total length of measured group of locomotives *or* rail cars, in feet
S_{meas} = speed of measured vehicle(s), in miles per hour

$\propto = \arctan\left(\frac{L_{meas}}{2D_{meas}}\right)$, in radians

APPENDIX F. COMPUTING MAXIMUM NOISE LEVEL (L_{max}) FOR A SINGLE TRAIN PASSBY

This appendix provides procedures for the computation of L_{max} for a single train passby, for those readers desiring such procedures. Table F-1 contains the equations to compute L_{max}. The procedure is summarized as follows.

- Collect the following input information:
  - SEL_{ref}'s from Chapter 6, specific to both the locomotive type and car type of the train
  - N_{locos}, the number of locomotives in the train
  - N_{cars}, the number of cars in the train
  - L_{locos}, the total length of the train's locomotive(s), in feet (or N_{locos}(unit length)
  - L_{cars}, the total length of the train's set of rail car(s), in feet (or N_{cars}(unit length)
  - S, the train speed, in miles per hour
  - D, the closest distance between the receiver of interest and the train, in feet
- Compute $L_{max,locos}$ from the locomotive(s) using the first equation in Table F-1.
- Compute $L_{max,cars}$ from the rail car(s) using the second equation in Table F-1.
- Choose the larger of the two L_{max}'s as the L_{max} for the total train passby.

Table F-1. Conversion to L_{max} at the Receiver, for a Single Train Passby

Source	Equation
Locomotives	$L_{\max,locos} = SEL_{locos} + 10\log\left(\frac{S}{50}\right) - 10\log\left(\frac{L}{50}\right) + 10\log(2\propto) - 3.3$
Rail Cars	$L_{\max,cars} = SEL_{cars} + 10\log\left(\frac{S}{50}\right) - 10\log\left(\frac{L}{50}\right) + 10\log\left[2\propto + \sin(2\propto)\right] - 3.3$
Total Train	$L_{\max,total} = \max\left[L_{\max,locos}\ or\ L_{\max,cars}\right]$
D	= closest distance between receiver and source, in feet
L	= total length of measured group of locomotive(s) *or* rail car(s), in feet
S	= vehicle speed, in miles per hour
$\propto$	$= \arctan\left(\frac{L}{2D}\right)$, in radians

Example F-1. Computation of L_{max} for Train Passby

A commuter train will pass by a receiver of interest and its L_{max} is desired. For this train, the following conditions apply:

SEL_{ref}	=	92 dB for locomotives and
	=	82 dB for rail cars
N_{locos}	=	1
N_{cars}	=	6
S	=	43 miles per hour
D	=	125 feet.

The locomotive and rail cars each have a unit length of 70 feet. Therefore,

L_{locos}	=	70 feet
L_{cars}	=	420 feet

Using the equations in Table F-1,

$\propto_{locos}$	=	0.27
$\propto_{cars}$	=	1.03

and the resulting Lmax's are as follows:

$L_{max,locos}$	=	84 dBA
$L_{max,cars}$	=	74 dBA
$L_{max,total}$	=	84 dBA.

End of Example F-1

Federal Transit Administration
U.S. Department of Transportation
http://www.fta.dot.gov

Environmental Noise Assessment

Homewood Snowmaking

Placer County, California

Job # 2008-232

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January 14, 2009

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INTRODUCTION

This section analyzes the existing noise environment associated with snowmaking operations at the Homewood Mountain Resort and Ski Area. Homewood Mountain Resort encompasses 1260 acres, utilized for downhill snow recreation in winter months, and full service event facilities year round. Figure 1 shows the project site.

The intent of this report is to establish the existing noise environment, general ambient background noise levels, and existing snowmaking noise levels on the project site. This section also discusses the applicable regional and local noise level criteria.

ACOUSTICAL TERMINOLOGY[1]

Fundamentals of Acoustics

Acoustics is the science of sound. Sound may be thought of as mechanical energy of a vibrating object transmitted by pressure waves through a medium to human (or animal) ears. If the pressure variations occur frequently enough (at least 20 times per second), then they can be heard and are called sound. The number of pressure variations per second is called the frequency of sound, and is expressed as cycles per second or Hertz (Hz).

Noise is a subjective reaction to different types of sounds. Noise is typically defined as (airborne) sound that is loud, unpleasant, unexpected or undesired, and may therefore be classified as a more specific group of sounds. Perceptions of sound and noise are highly subjective: one person's music is another's headache.

Measuring sound directly in terms of pressure would require a very large and awkward range of numbers. To avoid this, the decibel scale was devised. The decibel scale uses the hearing threshold (20 micropascals), as a point of reference, defined as 0 dB. Other sound pressures are then compared to this reference pressure, and the logarithm is taken to keep the numbers in a practical range. The decibel scale allows a million-fold increase in pressure to be expressed as 120 dB, and changes in levels (dB) correspond closely to human perception of relative loudness.

The perceived loudness of sounds is dependent upon many factors, including sound pressure level and frequency content. However, within the usual range of environmental noise levels, perception of loudness is relatively predictable, and can be approximated by A-weighted sound levels. There is a strong correlation between A-weighted sound levels (expressed as dBA) and the way the human ear perceives sound. For this reason, the A-weighted sound level has become the standard tool of environmental noise assessment. All noise levels reported in this section are in terms of A-weighted levels, but are expressed as dB, unless otherwise noted.

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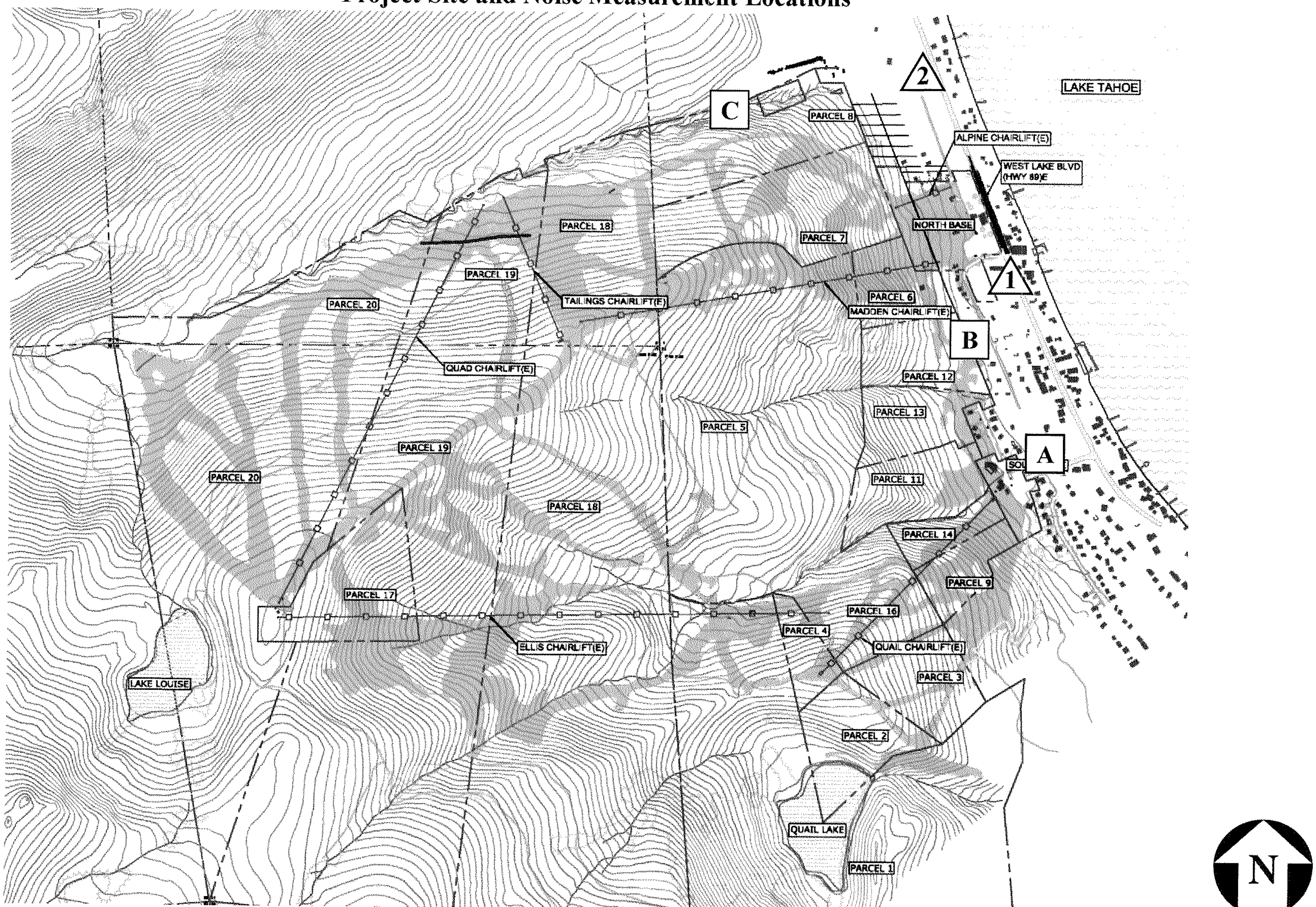
[1] For an explanation of these terms, see Appendix A: "Acoustical Terminology"

Figure 1
Homewood Mountain Resort
Project Site and Noise Measurement Locations



△ : Short Term Noise Measurement Location

□ : Continuous Noise Measurement Location

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Community noise is commonly described in terms of the ambient noise level, which is defined as the all-encompassing noise level associated with a given environment. A common statistical tool to measure the ambient noise level is the average, or equivalent, sound level (L_{eq}), which corresponds to a steady-state A weighted sound level containing the same total energy as a time varying signal over a given time period (usually one hour). The L_{eq} is the foundation of the composite noise descriptor, L_{dn}, and shows very good correlation with community response to noise.

The Community Noise Equivalent Level (CNEL) descriptor is used by the TRPA for determining a significant noise impact. The CNEL is defined as the 24-hour average noise level with noise occurring during evening hours (7:00 p.m. – 10:00 p.m.) weighted by a factor of three, and nighttime hours (10:00 p.m. – 7:00 a.m.) weighted by a factor of 10, prior to the averaging.

Table 1 lists several examples of the noise levels associated with common situations. Appendix A provides a summary of acoustical terms used in this report.

Table 1
Typical A-Weighted Sound Levels of Common Noise Sources

Loudness Ratio Level	A-Weighted Sound Level (dBA)	
128	130	Threshold of pain
64	120	Jet aircraft take-off at 100 feet
32	110	Riveting machine at operators position
16	100	Shot-gun at 200 feet
8	90	Bulldozer at 50 feet
4	80	Diesel locomotive at 300 feet
2	70	Commercial jet aircraft interior during flight
1	60	Normal conversation speech at 5-10 feet
1/2	50	Open office background level
1/4	40	Background level within a residence
1/8	30	soft whisper at 2 feet
1/16	20	Interior of recording studio

REGULATORY SETTING

Tahoe Regional Planning Agency Criteria:

The Tahoe Regional Planning Agency (TRPA) has adopted environmental thresholds for the Lake Tahoe Region. The noise standards, or "Thresholds" as they are commonly referred to, are numerical CNEL values for various land use categories and transportation corridors.

As a form of zoning, the TRPA has divided the Lake Tahoe Region into more than 175 separate Plan Areas. Boundaries for each of the Plan Areas have been established based on similar land uses and the unique character of each geographic area. For each Plan Area, a "Statement" is made as to how that particular area should be regulated to achieve regional environmental and land use objectives. As a part of each Statement, an outdoor CNEL standard is established. The project site is located within Plan Area 157 (Homewood/Tahoe Ski Bowl). The project site is bordered to the south and east by Plan Area 156 (Chambers Landing) and to the north and northeast by Plan Area 160 (Homewood/Residential). The Plan Area Statement noise level criteria are shown in Table 2.

Table 2
Project and Adjoining Plan Area Statement Noise Level Criteria

Plan Area #	Plan Area Name	TRPA Noise Level Criteria
157	Homewood/Tahoe Ski Bowl	55 dB CNEL for entire Plan Area
156	Chambers Landing	55 dB CNEL for entire Plan Area
160	Homewood/Residential	55 dB CNEL for entire Plan Area

Placer County General Plan

The Placer County General Plan Policies pertaining to noise are designed to protect County residents from the harmful and annoying effects of exposure to excessive noise. Those policies which would be applicable to this project are reproduced below:

1. *The County shall not allow development of new noise-sensitive uses where the noise level due to non-transportation noise sources will exceed the noise level standards of* Table 3 *(Table 9-1 of the Placer County General Plan Noise Element) as measured immediately within the property line of the new development, unless effective noise mitigation measures have been incorporated into the development design to achieve the standards specified in* Table 3.

2. *The County shall require that noise created by new non-transportation noise sources be mitigated so as not to exceed the noise level standards of* Table 3 *(Table 9-1 of the Placer County General Plan) as measured immediately within the property line of lands designated for noise-sensitive uses.*

3. *Impulsive noise produced by blasting should not be subject to the criteria listed in* Table 3 *(Table 9-1 of the Placer County General Plan). Single event impulsive noise levels produced by gunshots or blasting shall not exceed a peak linear overpressure of 122 dB, or a C-weighted Sound Exposure Level (SEL) of 98 dBC. The cumulative noise level from impulsive sounds such as gunshots and blasting shall not exceed 60 dB LCDN or CNEL on any given day. These standards shall be applied at the property line of a receiving land use.*

Table 3
(Table 9-1 of the Placer County General Plan)
Allowable Ldn Noise Levels Within Specified Zone Districts
Applicable to New Projects Affected by or Including Non-Transportation Noise Sources

Zone District of Receptor	Property Line of Receiving Use	Interior Space
Residential adjacent to industrial	60 dBA	45 dBA
Other Residential	50 dBA	45 dBA
Office/Professional	70 dBA	45 dBA
Neighborhood Commercial	70 dBA	45 dBA

Notes for Table 10-4:
1. Except where noted otherwise, noise exposures will be those which occur at the property line of the receiving use.
2. Interior spaces are defined as any locations where some degree of noise-sensitivity exists. Examples include all habitable rooms of residences, and areas where communication and speech intelligibility are essential, such as classrooms and offices.

EXISTING LAND USES IN THE PROJECT VICINITY

The Homewood Mountain Resort is located on the west shoreline of Lake Tahoe, six miles south of Tahoe City along Highway 89, in Placer County. Existing land uses in the immediate Project vicinity include limited commercial/retail areas to the east, and residential uses along the north, south and southeast. Highway 89 is directly adjacent to the North Lodge Building, on the Resort site.

EXISTING NOISE ENVIRONMENT IN THE PROJECT VICINITY

Snowmaking Operations

Snowmaking operations can be separated into two categories. The first is the air/water guns which consist of high pressure air and water which are mixed at the nozzle. These types of snowmaking guns can be fairly loud, with the primary noise source being the compressed air at the nozzle. In addition, this requires fairly large compressors and in some cases diesel generators. In the late 1980's and early 1990's, Homewood ski area used this type of snowmaking equipment. The air/water nozzle fleet was generally made up of Omichron and Ratnik brand air/water nozzles. Each nozzle has varying performance characteristics for snowmaking and noise emissions. Most of the nozzles are mounted to skids, and can be connected to any of the snowmaking hydrants on the mountain.

The other type of snowmaking equipment is characterized as fan-gun technology. The fan guns are electrically powered, with either compressors located in a main building or small compressors located on each fan gun. This technology is significantly quieter than the air/water nozzles. With the recent reconfiguration, the Homewood snowmaking fleet consists exclusively of fan guns, such as the Super Polecat, the Super Wizzard, and the Viking Snowtower. In general, fan gun snowmaking equipment is 10dB to 20dB quieter than the air/water nozzle equivalent.

Existing Ambient Noise Environment

To quantify existing snowmaking noise levels and background noise levels in the vicinity of the Ski Area, j.c. brennan & associates, Inc. conducted continuous noise monitoring for 4 consecutive days at three locations between the dates of December 18-21, 2008. Table 4 shows a summary of the continuous hourly noise monitoring results. Appendix B graphically shows the continuous 24-hour ambient noise measurement data.

Noise measurement equipment consisted of Larson Davis Laboratories (LDL) Model 820 precision integrating sound level meters. The measurement systems were calibrated using a LDL Model CAL200 acoustical calibrator before testing. The measurement equipment meets all of the pertinent requirements of the American National Standards Institute (ANSI) for Type 1 (precision) sound level meters.

Table 4 Existing Continuous Ambient and Snowmaking Noise Monitoring Results												
			Average Measured Hourly Noise Levels, dBA									
				Daytime (7:00 am - 7:00 pm)			Evening (7:00 pm–10:00pm)			Nighttime (10:00 pm – 7:00 am)		
Site	Location	Date	CNEL/* (dBA)	Leq	L50	Lmax	Leq	L50	Lmax	Leq	L50	Lmax
A	Residential uses near South Base	December 18, 2008	65.1/60.0*	57.6	52.7	71.6	54.5	53.7	66.9	58.8	49.2	65.1
		December 19, 2008	65.8/62.7*	61.4	56.8	73.0	54.2	53.9	60.3	59.1	55.8	70.0
		December 20, 2008	65.4/59.9*	54.1	42.8	65.2	35.5	29.1	49.2	59.5	49.4	66.3
		December 21, 2008	58.6/**	51.0	42.1	65.7	44.1	42.5	60.3	52.4	30.6	55.7
B	Eastern Project Boundary	December 18, 2008	62.5/51.6*	56.6	43.9	78.5	60.4	48.0	87.2	54.9	42.1	67.5
		December 19, 2008	61.7/55.8*	55.9	47.4	75.7	45.0	41.8	64.4	55.3	48.6	72.1
		December 20, 2008	55.0/48.0*	55.2	38.3	71.2	36.9	28.4	49.4	45.9	40.0	61.5
		December 21, 2008	52.5/**	45.0	39.1	54.5	48.6	45.4	60.3	45.6	29.4	56.0
C	Northeastern Project Boundary	December 18, 2008	50.3/48.1*	42.5	36.0	59.2	47.4	45.0	64.1	43.1	33.1	48.1
		December 19, 2008	55.9/52.7*	54.2	42.2	66.9	32.2	30.0	49.8	48.4	43.5	59.8
		December 20, 2008	43.3/35.4*	44.7	33.5	58.6	36.3	29.0	49.9	31.2	29.3	46.4
		December 21, 2008	44.7/**	39.8	38.1	50.7	39.5	38.5	53.6	37.6	28.5	49.8
Appendix B graphically shows the continuous 24-hour ambient noise measurement results. *Indicates the CNEL due to snowmaking operations. **No Snowmaking occurred during this day Source – j.c. brennan & associates, Inc. - 2008												

The CNEL values shown in Table 4 show the overall ambient CNEL value as well as the CNEL value associated with snowmaking operations. Due to the fact that the measured noise levels included numerous noise sources, including snowmaking operations, roadway traffic, snowmobile operations, etc., the overall CNEL values associated with snowmaking were calculated using the measured L50 values. The hourly L50 values identify the steady-state noise associated with the snowmaking operations, while excluding the temporary and short-term noise events, such as snowmobile pass-bys and roadway traffic.

In conversations with Homewood Ski Resort, snowmaking was continuous from December 18th till 10:30 a.m. on December 20th. No snowmaking operations occurred on December 21st.

Short-Term Noise Monitoring

In addition to the continuous hourly noise level measurements, j.c. brennan & associates, Inc. conducted two sets of short-term noise measurements adjacent to the eastern boundary of the ski area, and S.R. 89 on December 22, 2008. The noise measurements were conducted while snowmaking operations occurred along the face of face of Homewood Ski Area. The noise measurement sites are shown on Figure 1.

Noise measurements were conducted using an LDL Model 824 precision integrating sound level meter, which was equipped with 1/3 Octave band filters. Table 5 shows the results of the short term noise measurements, and the predicted CNEL value based upon 24-hours of snowmaking operations.

Table 5
Short-term Snowmaking Operations Noise Measurement Results and Predicted CNEL Values

Site	Site Description	Measured Leq	Predicted CNEL*
1	Adjacent to S.R. 89, & East of Madden Chairlift	58 dB	64.6 dB
2	Adjacent to S.R. 89, & at North Boundary of Homewood	60 dB	66.6 dB

Source: j.c. brennan & associates, Inc. 2009
* CNEL is calculated based upon 24-hours of operations.

Individual Noise Measurements of Snowmaking Equipment

The staff of j.c. brennan & associates, Inc. have conducted noise measurements of the snowmaking equipment used at the Homewood Ski Area. Noise level data was collected at 3 locations. The locations were at 50 feet in front, side and rear of the equipment. Table 6 shows the results of the noise level data associated with the snowmaking equipment.

Table 6
Snowmaking Equipment Noise Levels

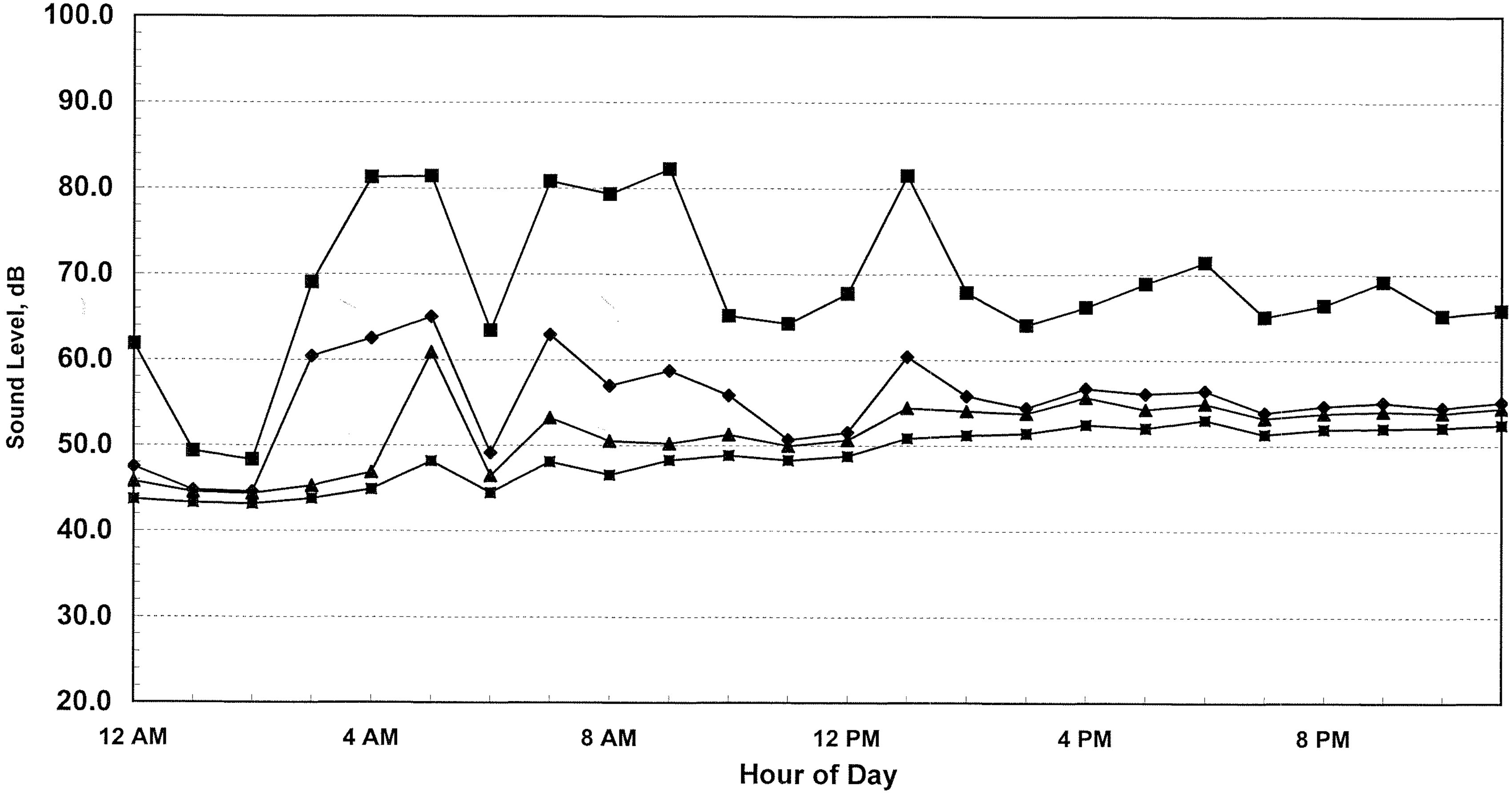
		Noise Levels at Position		
Snowmaking Equipment	Type	Front @ 50'	Side @ 50'	Rear @ 50'
Super Polecat 25 HP	Fan Gun	75 dBA	71 dBA	77 dBA
Super Wizzard 25 HP	Fan Gun	76 dBA	70 dBA	76 dBA
Viking Snowtower	Fan Gun	78 dBA	70 dBA	65 dBA

Appendix A

Acoustical Terminology

Acoustics	The science of sound.
Ambient Noise	The distinctive acoustical characteristics of a given space consisting of all noise sources audible at that location. In many cases, the term ambient is used to describe an existing or pre-project condition such as the setting in an environmental noise study.
Attenuation	The reduction of an acoustic signal.
A-Weighting	A frequency-response adjustment of a sound level meter that conditions the output signal to approximate human response.
Decibel or dB	Fundamental unit of sound, A Bell is defined as the logarithm of the ratio of the sound pressure squared over the reference pressure squared. A Decibel is one-tenth of a Bell.
CNEL	Community Noise Equivalent Level. Defined as the 24-hour average noise level with noise occurring during evening hours (7 - 10 p.m.) weighted by a factor of three and nighttime hours weighted by a factor of 10 prior to averaging.
Frequency	The measure of the rapidity of alterations of a periodic signal, expressed in cycles per second or hertz.
Ldn	Day/Night Average Sound Level. Similar to CNEL but with no evening weighting.
Leq	Equivalent or energy-averaged sound level.
Lmax	The highest root-mean-square (RMS) sound level measured over a given period of time.
L(n)	The sound level exceeded a described percentile over a measurement period. For instance, an hourly L50 is the sound level exceeded 50% of the time during the one hour period.
Loudness	A subjective term for the sensation of the magnitude of sound.
Noise	Unwanted sound.
Peak Noise	The level corresponding to the highest (not RMS) sound pressure measured over a given period of time. This term is often confused with the "Maximum" level, which is the highest RMS level.
RT_{60}	The time it takes reverberant sound to decay by 60 dB once the source has been removed.
Sabin	The unit of sound absorption. One square foot of material absorbing 100% of incident sound has an absorption of 1 sabin.
Threshold of Hearing	The lowest sound that can be perceived by the human auditory system, generally considered to be 0 dB for persons with perfect hearing.
Threshold of Pain	Approximately 120 dB above the threshold of hearing.
Impulsive	Sound of short duration, usually less than one second, with an abrupt onset and rapid decay.
Simple Tone	Any sound which can be judged as audible as a single pitch or set of single pitches.

Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site A
December 18, 2008



CNEL = 65.1 dB

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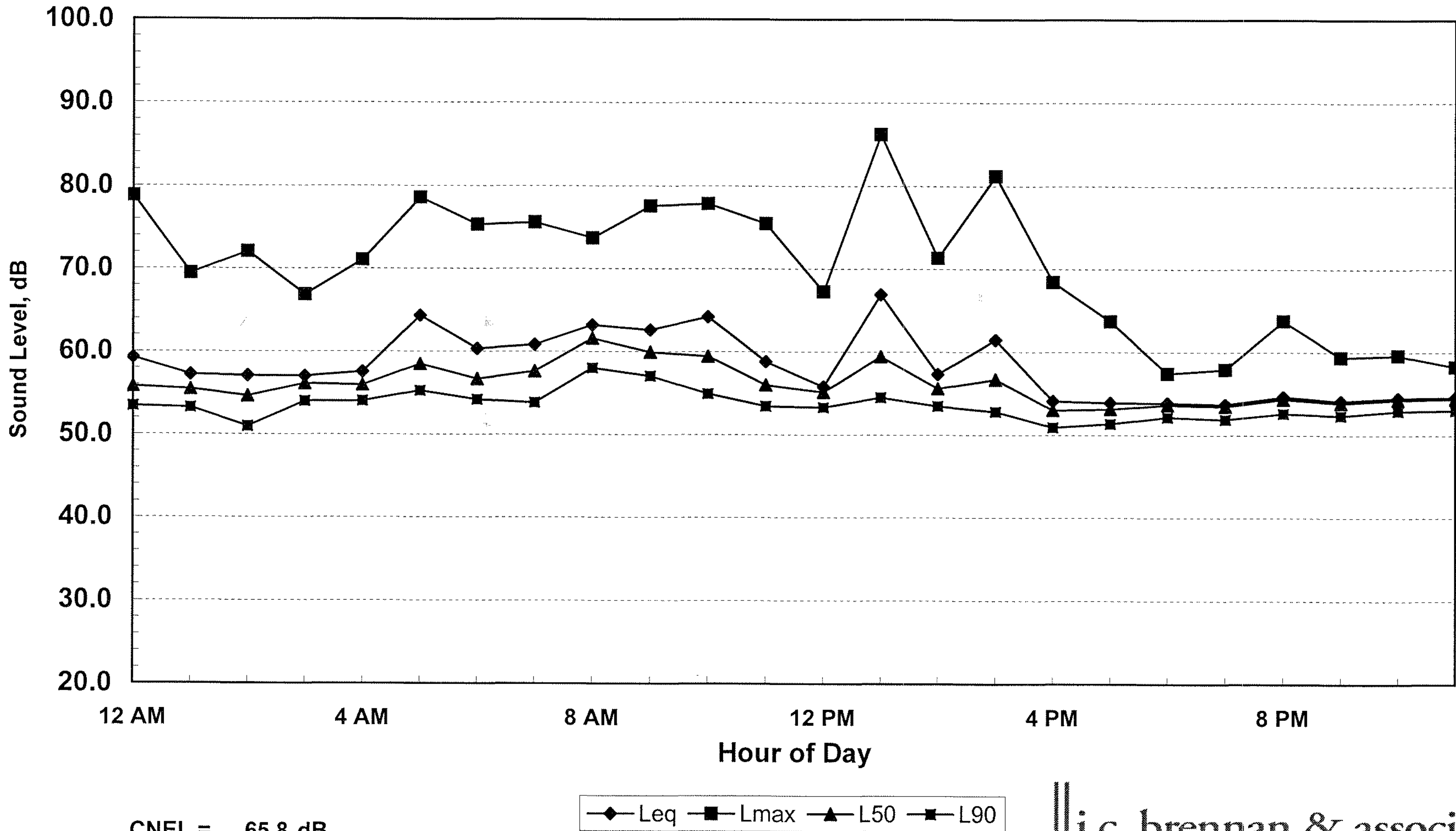
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site A
December 19, 2008



CNEL = 65.8 dB

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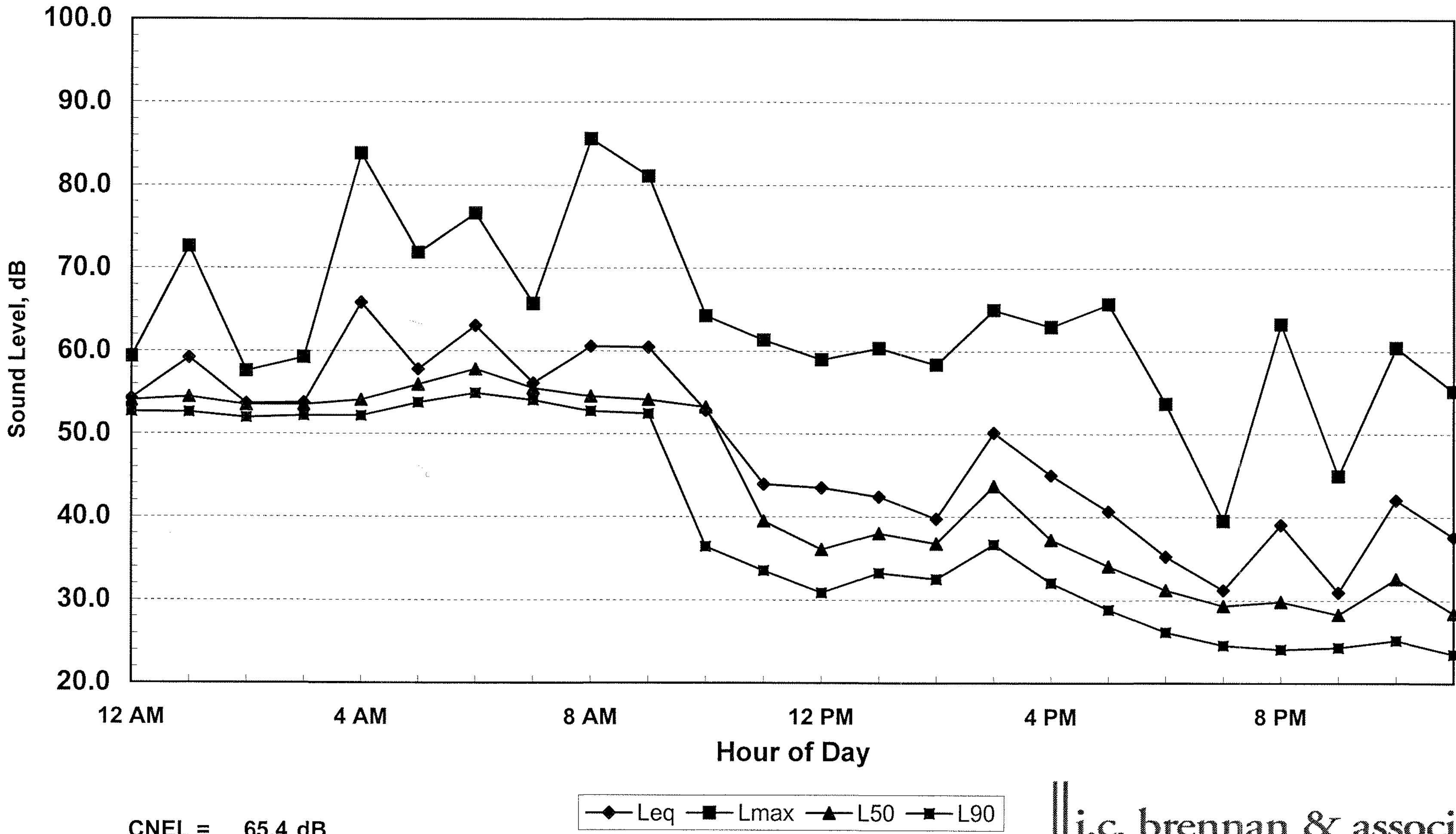
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site A
December 20, 2008



CNEL = 65.4 dB

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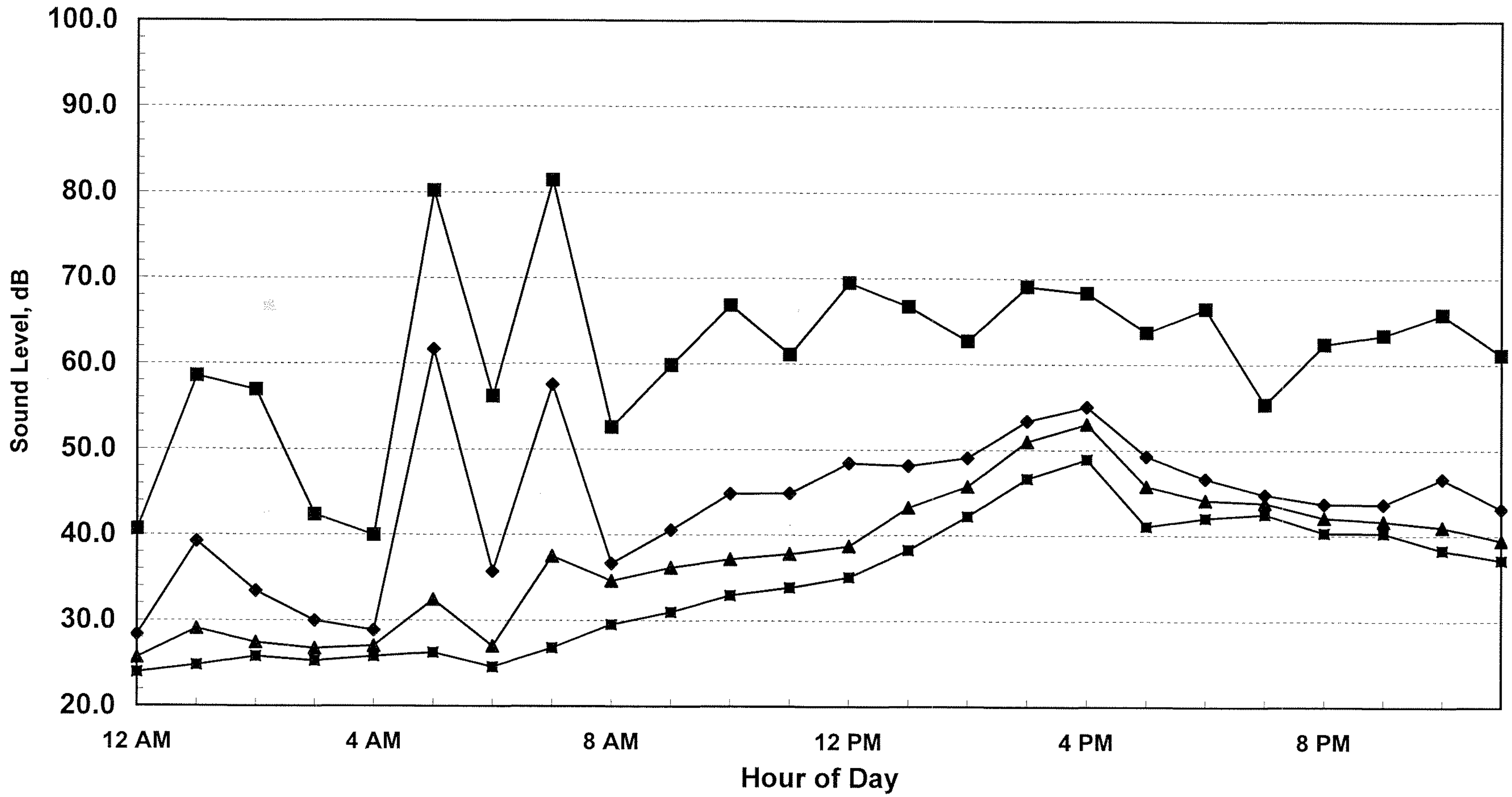
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site A
December 21, 2008



CNEL = 58.6 dB

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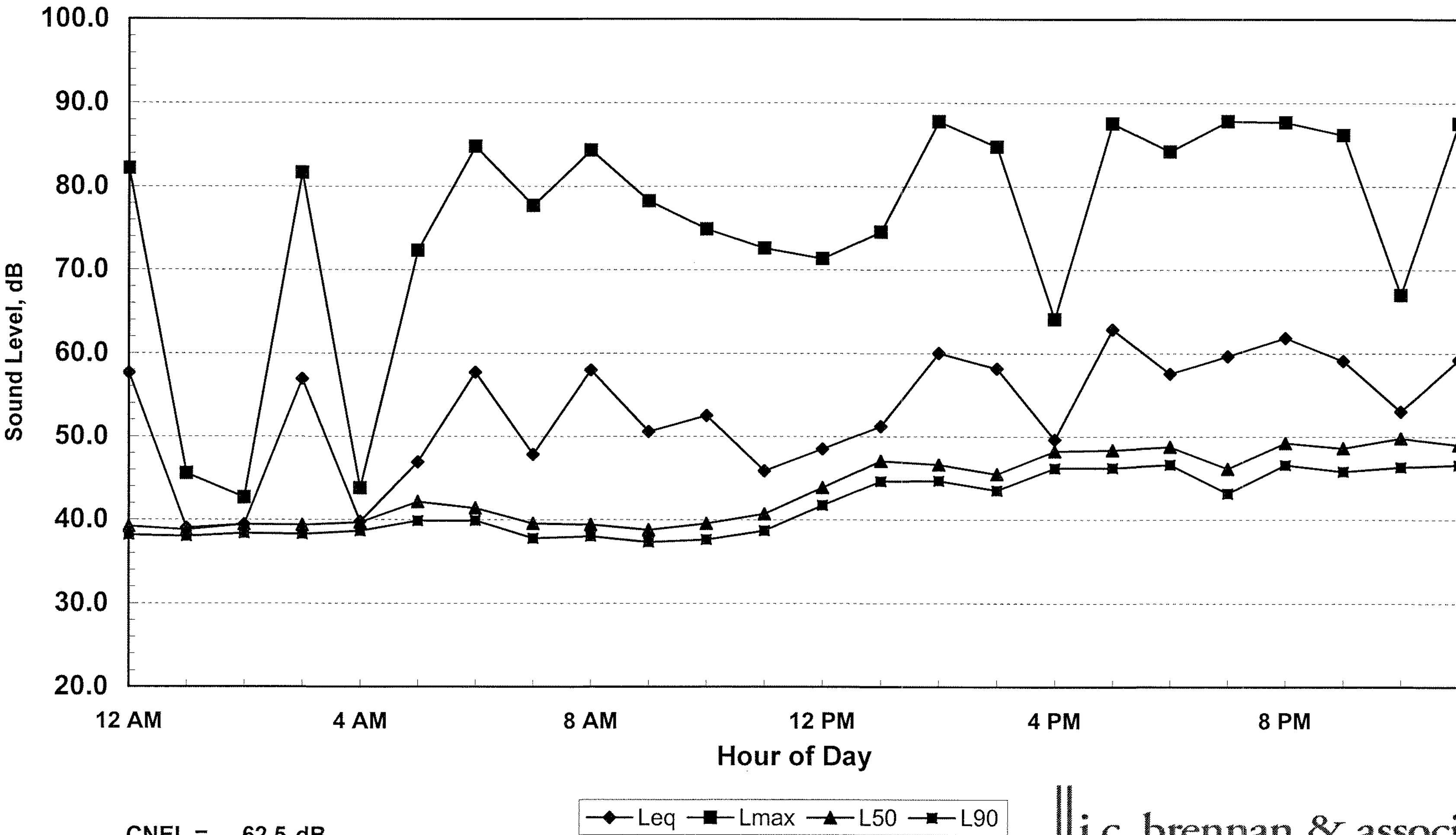
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site B
December 18, 2008



CNEL = 62.5 dB

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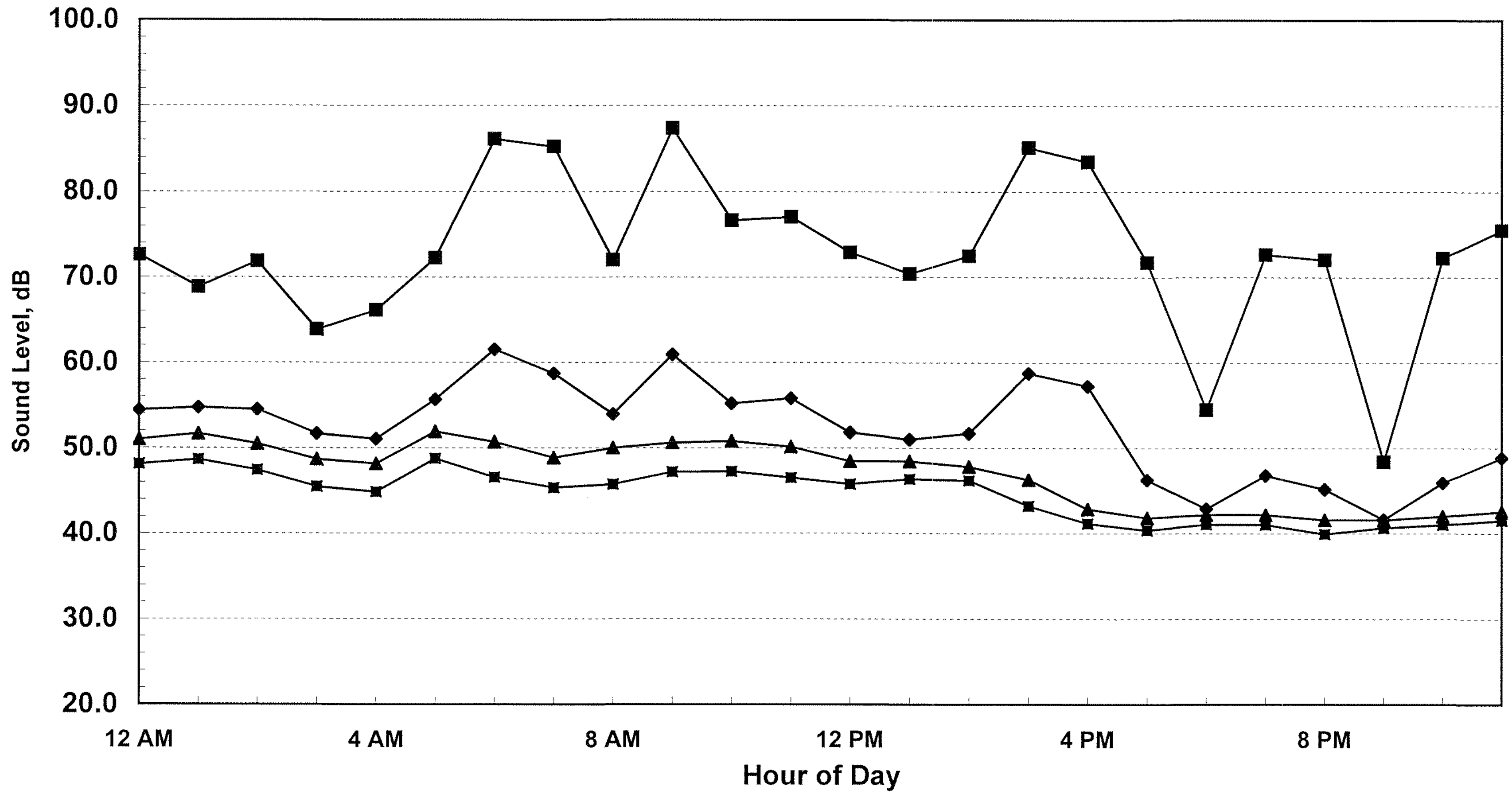
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site B
December 19, 2008



CNEL = 61.7 dB

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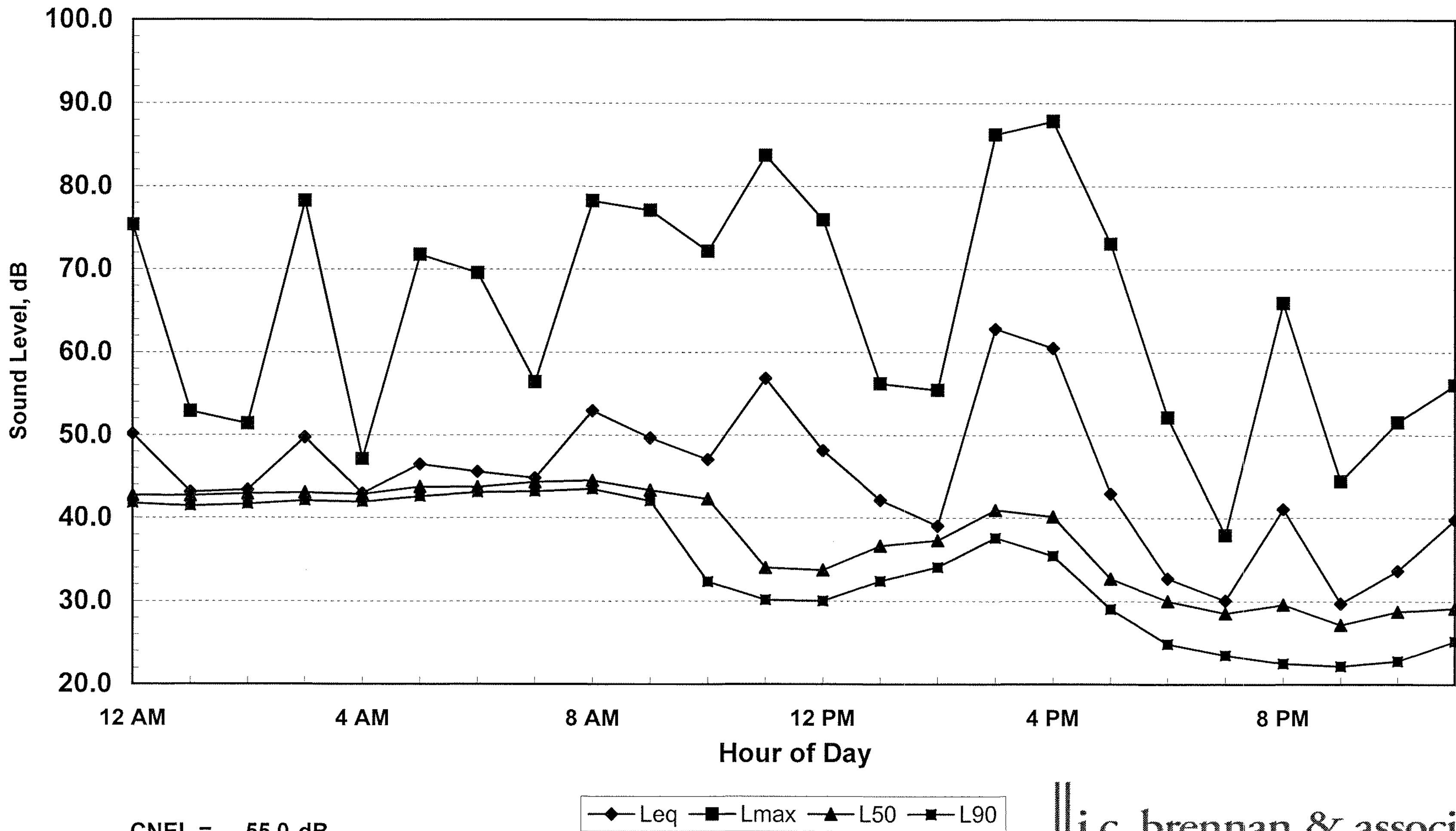
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site B
December 20, 2008



CNEL = 55.0 dB

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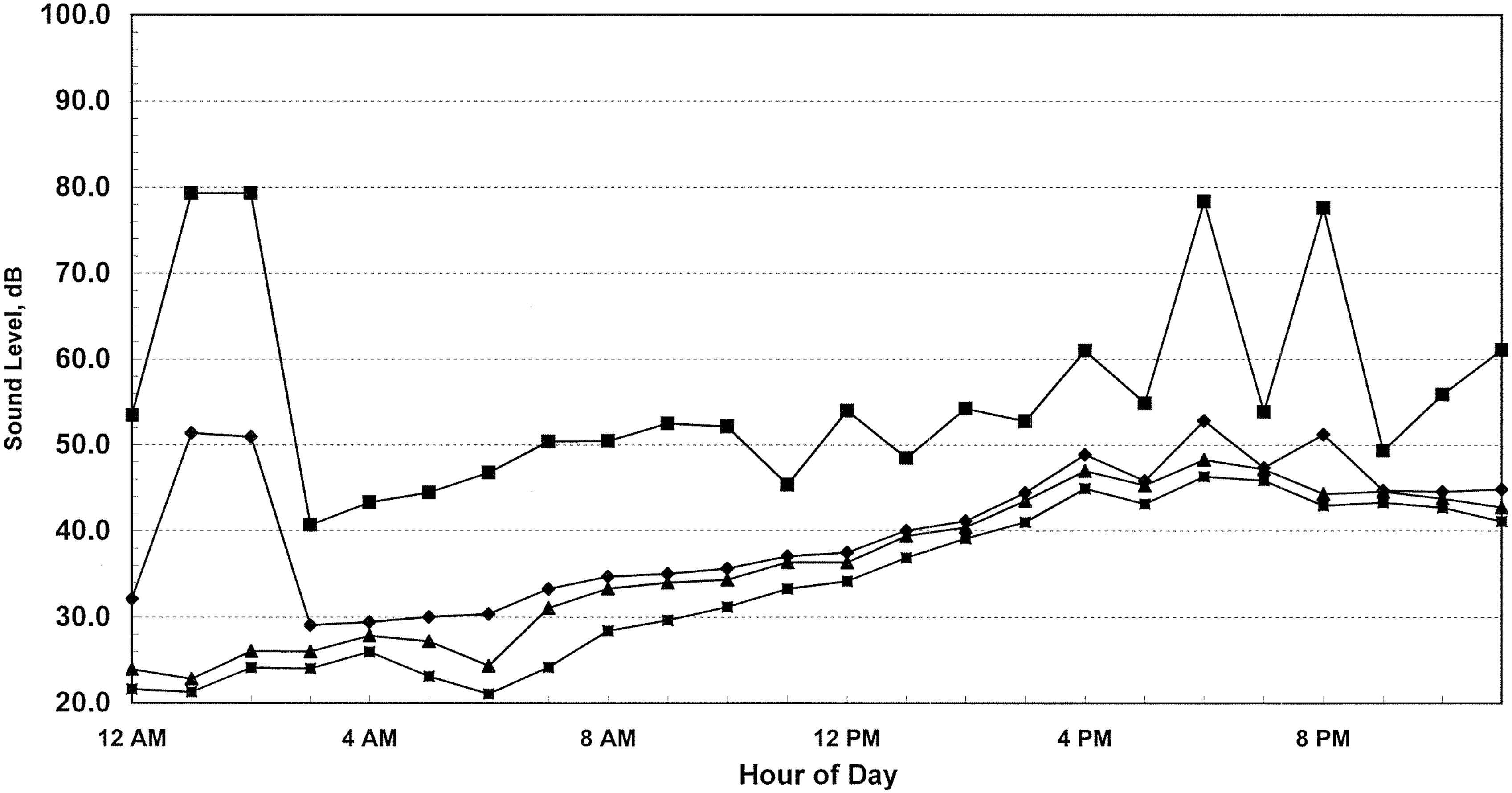
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site B
December 21, 2008



CNEL = 52.5 dB

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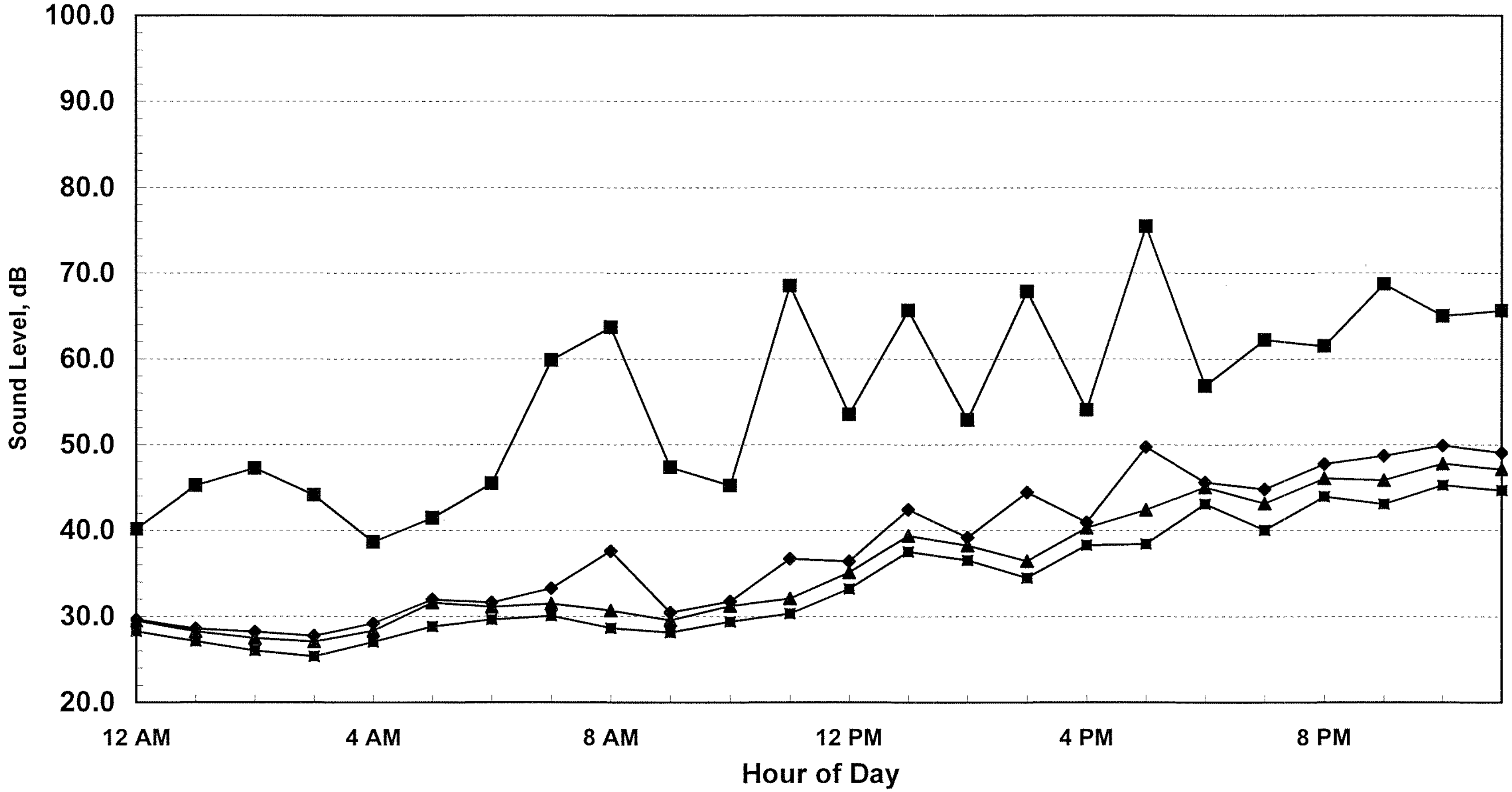
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site C
December 18, 2008



CNEL = 50.3 dB

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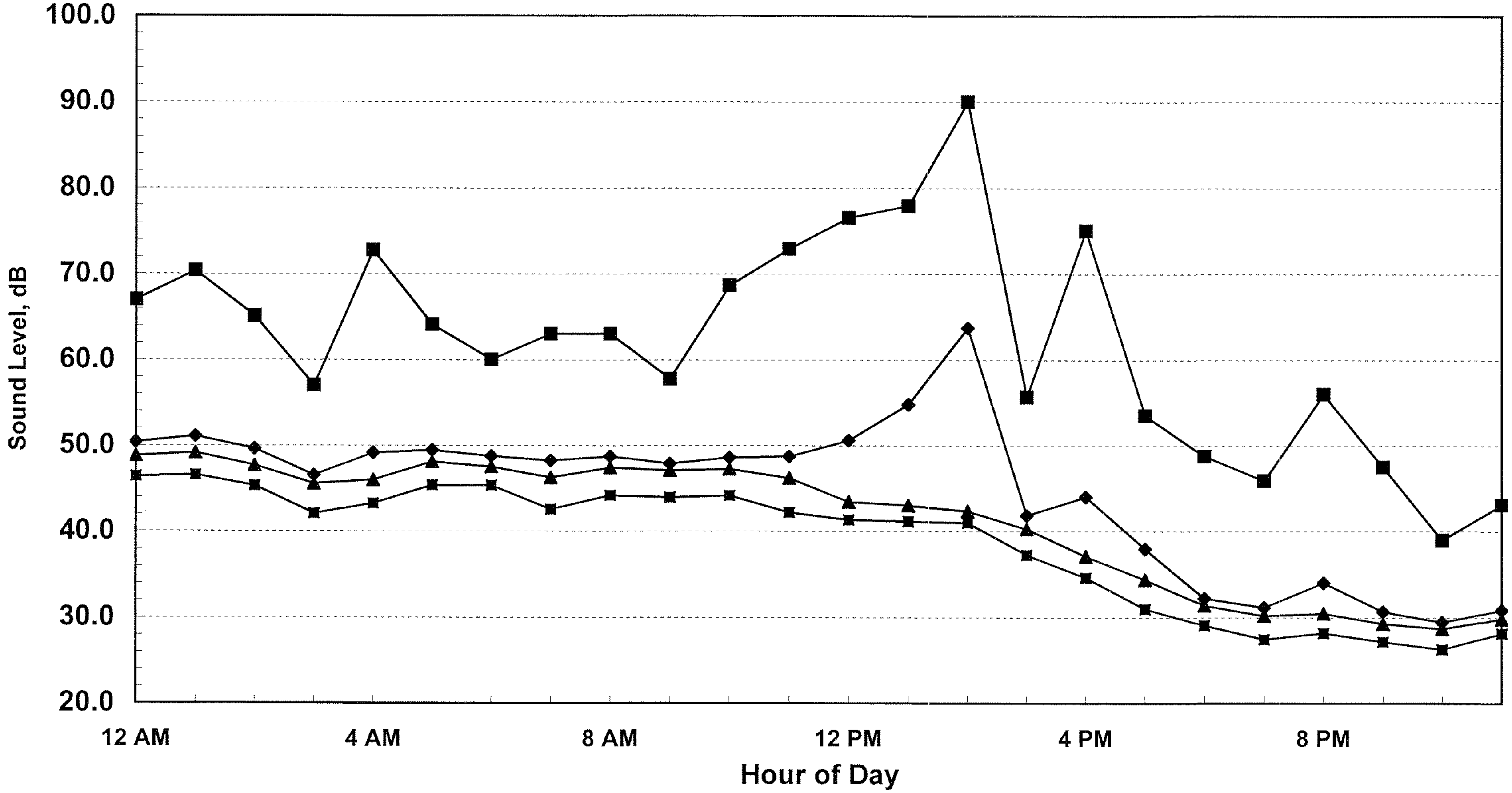
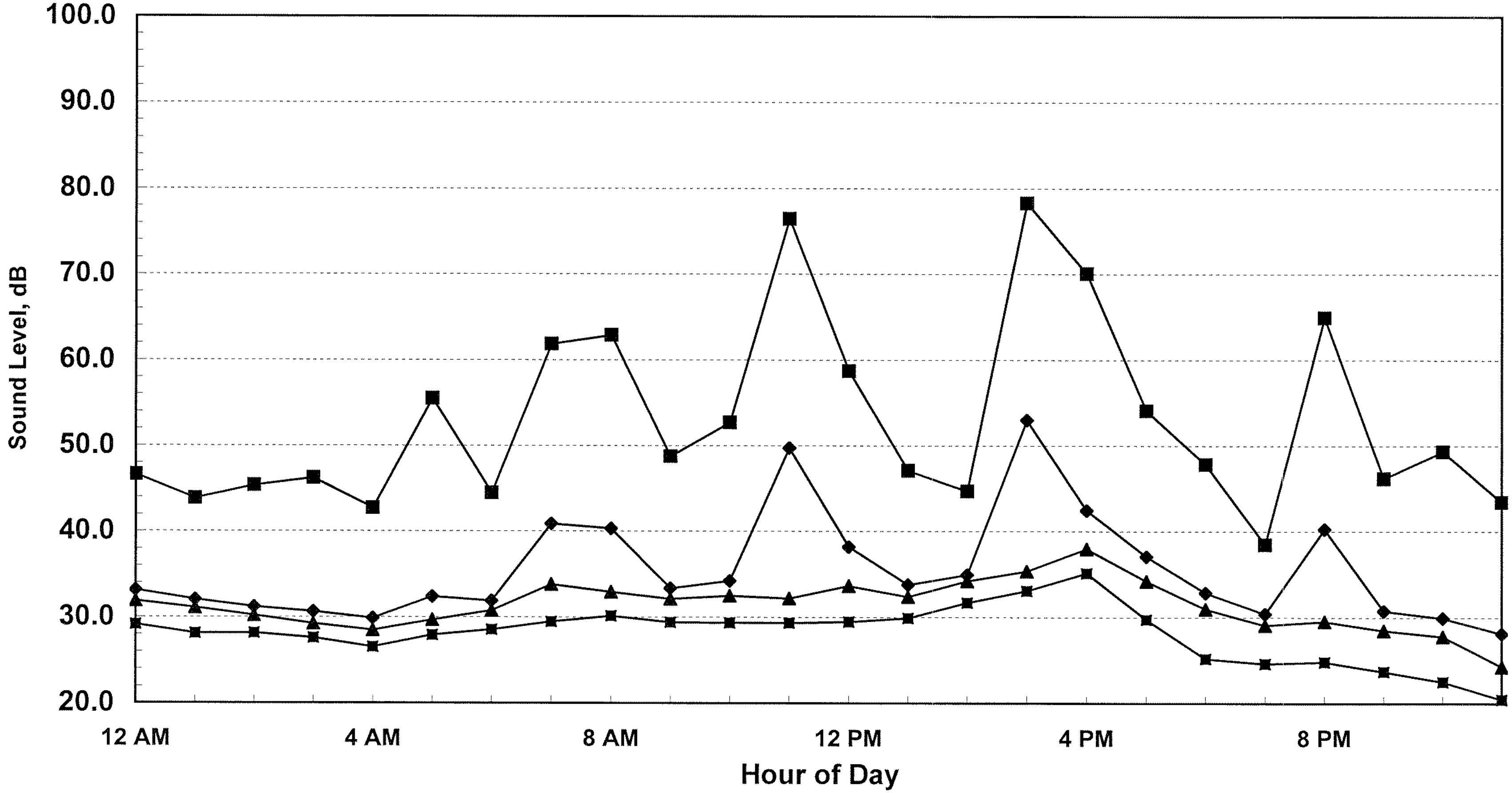
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site C
December 19, 2008



CNEL = 55.9 dB

j.c. brennan & associates
consultants in acoustics

Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site C
December 20, 2008



CNEL = 43.3 dB

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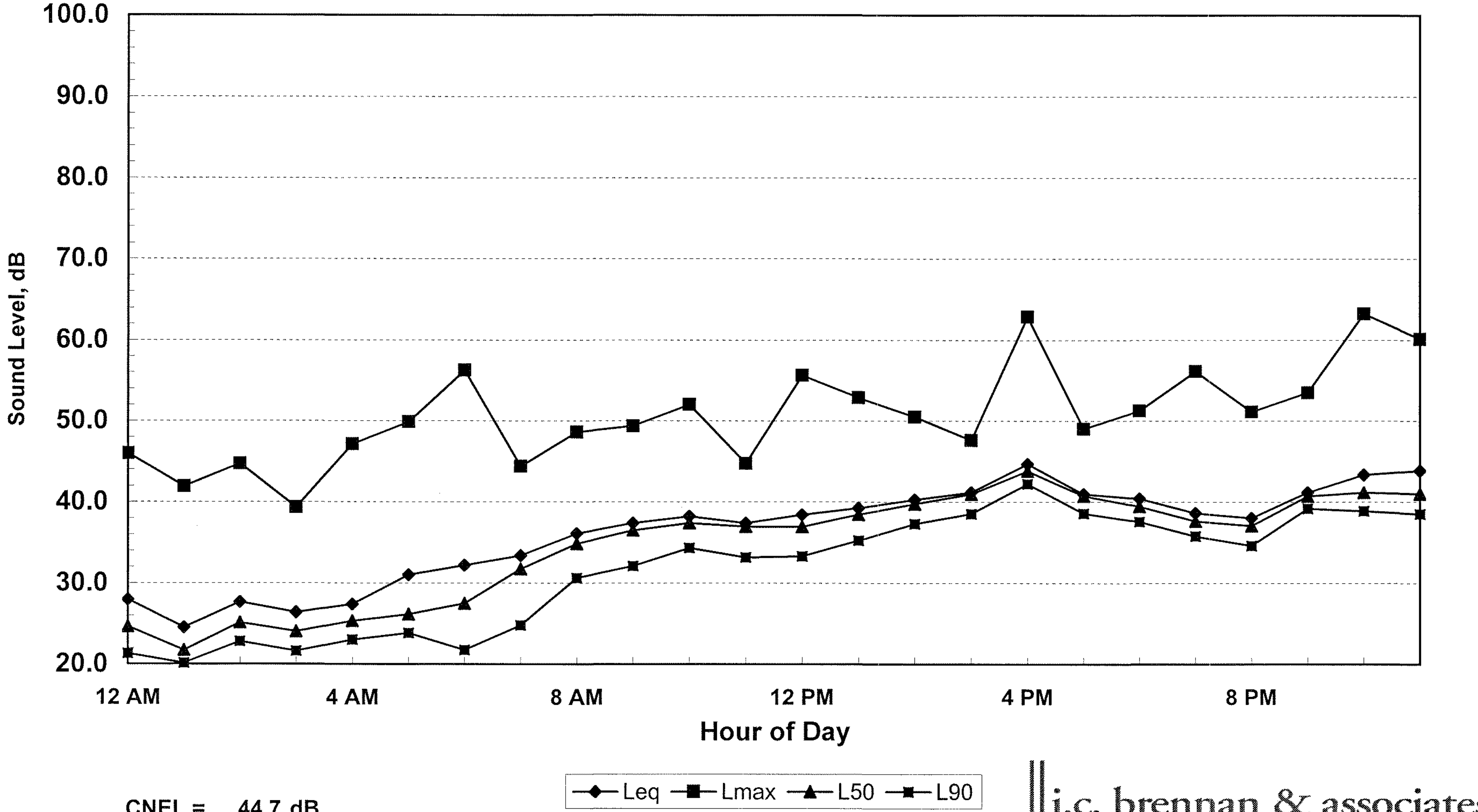
Appendix B
Homewood Snowmaking Monitoring
Continous 24 Hr Monitoring, Site C
December 21, 2008



CNEL = 44.7 dB

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SECTION 9

NOISE

Goal 9.A: To protect County residents from the harmful and annoying effects of exposure to excessive noise.

Policies

9.A.1. The County shall not allow development of new noise-sensitive uses where the noise level due to non-transportation noise sources will exceed the noise level standards of Table 9-1 as measured immediately within the property line of the new development, unless effective noise mitigation measures have been incorporated into the development design to achieve the standards specified in Table 9-1.

9.A.2. The County shall require that noise created by new non-transportation noise sources be mitigated so as not to exceed the noise level standards of Table 9-1 as measured immediately within the property line of lands designated for noise-sensitive uses.

9.A.3. The County shall continue to enforce the State Noise Insulation Standards (California Code of Regulations, Title 24) and Chapter 35 of the Uniform Building Code (UBC).

9.A.4. Impulsive noise produced by blasting should not be subject to the criteria listed in Table 9-1. Single event impulsive noise levels produced by gunshots or blasting shall not exceed a peak linear overpressure of 122 db, or a C-weighted Sound Exposure Level (SEL) of 98 dBC. The cumulative noise level from impulsive sounds such as gunshots and blasting shall not exceed 60 dB LCdn or CNELC on any given day. These standards shall be applied at the property line of a receiving land use.

9.A.5. Where proposed non-residential land uses are likely to produce noise levels exceeding the performance standards of Table 9-1 at existing or planned noise-sensitive uses, the County shall require submission of an acoustical analysis as part of the environmental review process so that noise mitigation may be included in the project design. The requirements for the content of an acoustical analysis are listed in Table 9-2.

9.A.6. The feasibility of proposed projects with respect to existing and future transportation noise levels shall be evaluated by comparison to Figure 9-1.

9.A.7. The County shall purchase only new equipment and vehicles which comply with noise level performance standards based upon the best available noise reduction technology.

9.A.8. New development of noise-sensitive land uses shall not be permitted in areas exposed to existing or projected levels of noise from transportation noise sources, including airports, which exceed the levels specified in Table 9-3, unless the project design includes effective mitigation measures to reduce noise in outdoor activity areas and interior spaces to the levels specified in Table 9-3.

TABLE 9-1

ALLOWABLE Ldn NOISE LEVELS WITHIN SPECIFIED ZONE DISTRICTS[1]
Applicable to New Projects Affected by or Including
Non-Transportation Noise Sources

Zone District of Receptor	Property Line of Receiving Use	Interior Spaces[2]
Residential Adjacent to Industrial[3]	60	45
Other Residential[4]	50	45
Office/Professional	70	45
Transient Lodging	65	45
Neighborhood Commercial	70	45
General Commercial	70	45
Heavy Commercial	75	45
Limited Industrial	75	45
Highway Service	75	45
Shopping Center	70	45
Industrial	---	45
Industrial Park	75	45
Industrial Reserve	---	---
Airport	---	45
Unclassified	---	---
Farm	(see footnote 6)	---
Agriculture Exclusive	(see footnote 6)	---
Forestry	---	---
Timberland Preserve	---	---
Recreation & Forestry	70	---
Open Space	---	---
Mineral Reserve	---	---

Notes:

- Except where noted otherwise, noise exposures will be those which occur at the property line of the receiving use.
- Where existing transportation noise levels exceed the standards of this table, the allowable Ldn shall be raised to the same level as that of the ambient level.
- If the noise source generated by, or affecting, the uses shown above consists primarily of speech or music, of if the noise source is impulsive in nature, the noise standards shown above shall be decreased by 5 dB.
- Where a use permit has established noise level standards for an existing use, those standards shall supersede the levels specified in Table 9-1 and Table 9-3. Similarly, where an existing use which is not subject to a use permit causes noise in excess of the allowable levels in Tables 9-1 and 9-3, said excess noise shall be considered the allowable level. If a new development is proposed which will be affected by noise from such an existing use, it will ordinarily be assumed that the noise levels already existing or those levels allowed by the existing use permit, whichever are greater, are those levels actually produced by the existing use.

- Existing industry located in industrial zones will be given the benefit of the doubt in being allowed to emit increased noise consistent with the state of the art5 at the time of expansion. In no case will expansion of an existing industrial operation be cause to decrease allowable noise emission limits. Increased emissions above those normally allowable should be limited to a one-time 5 dB increase at the discretion of the decision making body.

- The noise level standards applicable to land uses containing incidental residential uses, such as caretaker dwellings at industrial facilities and homes on agriculturally zoned land, shall be the standards applicable to the zone district, not those applicable to residential uses.

- Where no noise level standards have been provided for a specific zone district, it is assumed that the interior and/or exterior spaces of these uses are effectively insensitive to noise.

[1] Overriding policy on interpretation of allowable noise levels: Industrial-zoned properties are confined to unique areas of the County, and are irreplaceable. Industries which provide primary wage-earner jobs in the County, if forced to relocate, will likely be forced to leave the County. For this reason, industries operating upon industrial zoned properties must be afforded reasonable opportunity to exercise the rights/privileges conferred upon them be their zoning. Whenever the allowable noise levels herein fall subject to interpretation relative to industrial activities, the benefit of the doubt shall be afforded to the industrial use.

Where an industrial use is subject to infrequent and unplanned upset or breakdown of operations resulting in increased noise emissions, where such upsets and breakdowns are reasonable considering the type of industry, and where the industrial use exercises due diligence in preventing as well as correcting such upsets and breakdowns, noise generated during such upsets and breakdowns shall not be included in calculations to determine conformance with allowable noise levels.

[2] Interior spaces are defined as any locations where some degree of noise-sensitivity exists. Examples include all habitable rooms of residences, and areas where communication and speech intelligibility are essential, such as classrooms and offices.

[3] Noise from industrial operations may be difficult to mitigate in a cost-effective manner. In recognition of this fact, the exterior noise standards for residential zone districts immediately adjacent to industrial, limited industrial, industrial park, and industrial reserve zone districts have been increased by 10 dB as compared to residential districts adjacent to other land uses.

For purposes of the Noise Element, residential zone districts are defined to include the following zoning classifications: AR, R-1, R-2, R-3, FR, RP, TR-1, TR-2, TR-3, and TR-4.

[4] Where a residential zone district is located within an -SP combining district, the exterior noise level standards are applied at the outer boundary of the -SP district. If an existing industrial operation within an -SP district is expanded or modified, the noise level standards at the outer boundary of the -SP district may be increased as described above in these standards.

Where a new residential use is proposed in an -SP zone, an Administrative Review Permit is required, which may require mitigation measures at the residence for noise levels existing and/or allowed by use permit as described under "NOTES," above, in these standards.

[5] State of the art should include the use of modern equipment with lower noise emissions, site design, and plant orientation to mitigate offsite noise impacts, and similar methodology.

[6] Normally, agricultural uses are noise insensitive and will be treated in this way. However, conflicts with agricultural noise emissions can occur where single-family residences exist within agricultural zone districts. Therefore, where effects of agricultural noise upon residences located in these agricultural zones is a concern, an Ldn of 70 dBA will be considered acceptable outdoor exposure at a residence.

TABLE 9-2

REQUIREMENTS FOR AN ACOUSTICAL ANALYSIS
(See Policy 9.A.5)

An acoustical analysis prepared pursuant to Policy 9.A.5 shall:	
1.	Be the financial responsibility of the applicant.
2.	Be prepared by a qualified person experienced in the fields of environmental noise assessment and architectural acoustics.
3.	Include representative noise level measurements with sufficient sampling periods and locations to adequately describe local conditions and the predominant noise sources.
4.	Estimate existing and projected cumulative (20 years) noise levels in terms of Ldn or CNEL and/or the standards of Table 9-1, and compare those levels to the policies in this section. Noise prediction methodology must be consistent with the Placer County Acoustical Design Manual.
5.	Recommend appropriate mitigation to achieve compliance with the policies and standards of this section, giving preference to proper site planning and design over mitigation measures which require the construction of noise barriers or structural modifications to buildings which contain noise-sensitive land uses. Where the noise source in question consists of intermittent single events, the report must address the effects of maximum noise levels in sleeping rooms in terms of possible sleep disturbance.
6.	Estimate noise exposure after the prescribed mitigation measures have been implemented.
7.	Describe a post-project assessment program which could be used to evaluate the effectiveness of the proposed mitigation measures.

TABLE 9-3

MAXIMUM ALLOWABLE NOISE EXPOSURE
Transportation Noise Sources

Land Use	Outdoor Activity Areas[1]	Interior Spaces	
	Ldn/CNEL, dB	Ldn/CNEL,dB	Leq, dB[2]
Residential	60[3]	45	--
Transient Lodging	60[3]	45	--
Hospitals, Nursing Homes	60[3]	45	--
Theaters, Auditoriums, Music Halls	--	--	35
Churches, Meeting Halls	60[3]	--	40
Office Buildings	--	--	45
Schools, Libraries, Museums	--	--	45
Playgrounds, Neighborhood Parks	70	--	--

[1] Where the location of outdoor activity areas is unknown, the exterior noise level standard shall be applied to the property line of the receiving land use.
[2] As determined for a typical worst-case hour during periods of use.
[3] Where it is not possible to reduce noise in outdoor activity areas to 60 dB Ldn/CNEL or less using a practical application of the best-available noise reduction measures, an exterior noise level of up to 65 dB Ldn/CNEL may be allowed provided that available exterior noise level reduction measures have been implemented and interior noise levels are in compliance with this table.

9.A.9. Noise created by new transportation noise sources, including roadway improvement projects, shall be mitigated so as not to exceed the levels specified in Table 9-3 at outdoor activity areas or interior spaces of existing noise-sensitive land uses.

9.A.10. Where noise-sensitive land uses are proposed in areas exposed to existing or projected exterior noise levels exceeding the levels specified in Table 9-3 or the performance standards of Table 9-1, the County shall require submission of an acoustical analysis as part of the environmental review process so that noise mitigation may be included in the project design. At the discretion of the County, the requirement for an acoustical analysis may be waived provided that all of the following conditions are satisfied:

a. The development is for less than five single-family dwellings or less than 10,000 square feet of total gross floor area for office buildings, churches, or meeting halls;

b. The noise source in question consists of a single roadway or railroad for which up-to-date noise exposure information is available. An acoustical analysis will be required when the noise source in question is a stationary noise source or airport, or when the noise source consists of multiple transportation noise sources;

c. The existing or projected future noise exposure at the exterior of buildings which will contain noise-sensitive uses or within proposed outdoor activity areas (other than outdoor sports and recreation areas) does not exceed 65 dB Ldn (or CNEL) prior to mitigation. For outdoor sports and recreation areas, the existing or projected future noise exposure may not exceed 75 dB Ldn (or CNEL) prior to mitigation;

d. The topography in the project area is essentially flat; that is, noise source and receiving land use are at the same grade; and

e. Effective noise mitigation, as determined by the County, is incorporated into the project design to reduce noise exposure to the levels specified in Table 9-1 or 9-3. Such measures may include the use of building setbacks, building orientation, noise barriers, and the standard noise mitigations contained in the Placer County Acoustical Design Manual. If closed windows are required for compliance with interior noise level standards, air conditioning or a mechanical ventilation system will be required.

9.A.11. The County shall implement one or more of the following mitigation measures where existing noise levels significantly impact existing noise-sensitive land uses, or where the cumulative increase in noise levels resulting from new development significantly impacts noise-sensitive land uses:

a. Rerouting traffic onto streets that have available traffic capacity and that do not adjoin noise-sensitive land uses;
b. Lowering speed limits, if feasible and practical;
c. Programs to pay for noise mitigation such as low cost loans to owners of noise-impacted property or establishment of developer fees;
d. Acoustical treatment of buildings; or
e. Construction of noise barriers.

9.A.12. Where noise mitigation measures are required to achieve the standards of Tables 9-1 and 9-3, the emphasis of such measures shall be placed upon site planning and project design. The use of noise barriers shall be considered as a means of achieving the noise standards only after all other practical design-related noise mitigation measures have been integrated into the project.

Goal 9.B: To ensure that areas designated for industrial uses pursuant to Goal 1.E. and Policy 1.E.1. are protected from encroachment by noise-sensitive land uses.

Policies

9.B.1. The County shall require that new noise-sensitive land uses established next to existing industrial areas be responsible for self-mitigating noise impacts from industrial activities.

9.B.2. The County shall apply noise standards in a manner consistent with encouraging the retention, expansion, and development of new businesses pursuant to Goal 1.N. and Policy 1.N.2.

9.B.3. Because many industrial activities and processes necessarily produce noise which will likely be objectionable to nearby non-industrial land uses, existing and potential future industrial noise emissions shall be accommodated in all land use decisions.

9.B.4. Whenever noise exposure standards herein fall subject to interpretation relative to industrial activities, the benefit of the doubt shall be afforded to the industrial use.

Implementation Measures

9.1. The County shall develop and employ procedures to ensure that noise mitigation measures required pursuant to an acoustical analysis are implemented in the project review process and, as may be determined necessary, through the building permit process.

Responsibility:	Division of Environmental Health Planning Department Building Department
Time Frame:	Ongoing
Funding:	Permit fees

9.2. The County shall develop and employ procedures to monitor compliance with the standards of the Noise section of the Policy Document after completion of projects where noise mitigation measures were required.

Responsibility:	Division of Environmental Health
Time Frame:	Ongoing
Funding:	Permit fees

9.3. The County shall periodically review and update the Noise section of the Policy Document to ensure that noise exposure information and specific policies are consistent with changing conditions within the community and with noise control regulations or policies enacted after the adoption of the General Plan.

Responsibility:	Division of Environmental Health Planning Department
Time Frame:	Ongoing
Funding:	Permit fees

MASTER

Report of Investigations 8485

Structure Response and Damage Produced by Airblast From Surface Mining

By David E. Siskind, Virgil J. Stachura, Mark S. Stagg, and John W. Kopp

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Bureau of Mines
Report of Investigations 8485

STRUCTURE RESPONSE AND DAMAGE PRODUCED BY AIRBLAST FROM SURFACE MINING

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ERRATA

Page 13 (table 1): Insert under Notes for both Bruel and Kjaer 2209 and GenRad 1933 "Recording device is optional."

Page 51 (figure 38): Caption should include "(Numbers in parentheses correspond to regression lines in table 9.)"

Page 52 (figure 39): Caption should refer to "table 9" instead of "table 5."

Page 55, Title for fourth paragraph should read "Criteria."

Page 61 (figure 40): Caption should read "Numbers in parentheses correspond to references."

Page 76, Line 8 from bottom should read "...function of depth as given..."

Page 76, APP equation should have "D_{cg}" as part of exponent.

Page 76, following the APP equation, it should read "for small-scale blasts in limestone, where D_{cg} is the distance..."

Page 76, last sentence should read "Wiss quantified the confinement effect from full-scale coal mine blasts:"

Page 77, equation at top of page should be $APP + SRP = K_2 e^{-1.0} B_s$.

This publication has been cataloged as follows:

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(Report of investigations ; 8485)

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Supt. of Docs. no.: I 28.23:8485.

1. Blast effect. 2. Blasting—Safety measures. 3. Blasting—Noise control. 4. Strip mining. I. Siskind, D. E. II. Series: United States. Bureau of Mines. Report of investigations ; 8485.

TN23.U43 [TA654.7] 622'.08s [622'.31] 79-607810

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

TABLES--Continued

STRUCTURE RESPONSE AND DAMAGE PRODUCED BY AIRBLAST FROM SURFACE MINING

by

David E. Siskind,[1] Virgil J. Stachura,[1] Mark S. Stagg,[2] and John W. Kopp[3]

ABSTRACT

The Bureau of Mines studied airblast from surface mining to assess its damage and annoyance potential, and to determine safe levels and appropriate measurement techniques. Research results obtained from direct measurements of airblast-produced structure responses, damage, and analysis of instrument characteristics were combined with studies of sonic booms and human response to transient overpressures. Safe levels of airblast were found to be 134 dBL (0.1 Hz), 133 dBL (2 Hz), 129 dBL (6 Hz), and 105 dB C-slow. These four airblast levels and measurement methods are equivalent in terms of structure response, and any one could be used as a safe-level criterion. Of the four methods, only the 0.1-Hz high-pass linear method accurately measures the total airblast energy present; however, the other three were found to adequately quantify the structure response and also represent techniques that are readily available to industry. Where a single airblast measuring system must be used, the 2-Hz linear peak response is the best overall compromise. The human response and annoyance problem from airblast is probably caused primarily by wall rattling and the resulting secondary noises. Although these will not entirely be precluded by the recommended levels, they are low enough to preclude damage to residential structures and any possible human injury over the long term.

INTRODUCTION

Airblast, like ground vibrations, is an undesirable side effect of the use of explosives to fragment rock for mining, quarrying, and excavation. Blasts at large surface mines and quarries can produce noticeable airblasts at large distances, particularly when weather conditions are favorable for propagation. Because of these variations in propagation, and the strong relationship between blast confinement and airblast character and levels, prediction and control are often more difficult for airblast than for such other adverse blast effects as ground vibrations, dust, and fumes.

[1]Geophysicist.
[2]Civil engineer.
[3]Mining engineer.
All authors are with the Twin Cities Research Center, Bureau of Mines, Twin Cities, Minn.

FIGURE 1. - Occupied residences near an operating surface mine.

This report summarizes research by the Bureau of Mines on airblast effects on residential structures. Discussed is research by the Bureau and other institutions on ground vibration response and damage, human response, sonic booms, airblast generation and propagation, and instrumentation as they apply directly to the airblast-tolerance problem. Reports are being prepared on blast-vibration generation and propagation, ground vibration damage, and instrumentation methodology, and while work is continuing on many other aspects of the blasting problem including blast design and human annoyance.

Research in areas related to airblast was also analyzed-specifically, sonic booms and human response to transient overpressures. Most of this work is in general agreement with the Bureau's results; however, it was mainly supportive data because of characteristic differences in the sources and their resulting effects.

An understanding of how residential structures respond to airblast and the airblast characteristics most closely related to this response will enable blasts to be designed to minimize these adverse effects. The mining industry needs not only appropriate design levels for blast effects, but also practical techniques to attain these levels. At the same time, environmental agencies responsible for blasting control and noise abatement must be provided with reasonable, appropriate, and technologically established and supportable criteria on which to base their regulations. Finally, neighbors around mines and other blasting operations require protection of their health and property (fig. 1).

ACKNOWLEDGMENTS

The authors wish to acknowledge the very generous assistance of regulatory agencies, engineering consultants, powder companies, homeowners, and mine and quarry operators. Paul D. Schomer of the Corps of Engineers and George W. Kamperman Associates made helpful suggestions in the area of measurement techniques. Special thanks are due to the Illinois Environmental Protection Agency for demonstrating the immediate need for this airblast research. Much of the fieldwork and data reduction was done by student employees Alvin J. Engler, Steven J. Sampson, David M. Purdham, Patrick G. Corser, Stephen Lepp, and Michael P. Sethna, who put in long hours. Philip D. Murray, whose thesis material was referenced in the structure-character analysis, also provided additional support.

AIRBLAST CHARACTERISTICS

Causes of Airblast

Airblast is an impulsive sound generated by an explosive blast and resulting rock fragmentation and movement. Four causes of airblast overpressures are generally recognized: (1) direct rock displacement at the face or mounding at the blasthole collar, (2) vibrating ground, (3) gas escaping from the detonating explosive through the fractured rock, and (4) gas escaping from the blown-out stemming. Wiss labels these four contributions to the total airblast (1) air pressure pulse (APP), (2) rock pressure pulse (RPP), (3) gas release pulse (GRP), and (4) stemming release pulse (SRP) (83)[4]. Their characteristics have been described in various other studies (53, 58, 83). The GRP is also termed the gas vent pulse (58).

The air pressure pulse (APP) will dominate in a properly designed blast, and will only be absent for cases of total confinement (that is, underground blasts). Each blasthole acts as an APP source. Close-in or front-of-face airblast measurements with wide-band systems usually detect a series of APP pulses corresponding in time to the interval between the top decks or front-row holes. At large distances or behind the face, dispersion and refraction mask the individual pulses and the blast timing becomes less evident. The time histories then lose their APP spikes and associated high frequencies.

The rock pressure pulse (RPP) is theoretically generated by the vertical components of the ground vibration summed over all the area, which acts as a large vibrating piston. A simple relationship was found by Wiss (53, 83) between RPP and the vertical ground vibration V_v:

[4]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

$$RPP = 0.0015\ V_v\ ,$$

with RPP in pounds per square inch (lb/in^2) and V_v in inches per second (in/sec). Normally, RPP has the least amplitude of the airblast components; however, it is typically of higher frequency (identical to the V_v which spawns it), and enables us to predict the minimum airblast level expected (for example, 1.0 in/sec V_v will generate 0.0015 lb/in^2, or 114 dB-peak). It arrives at the receiver simultaneously with the ground vibration and prior to APP.

The gas release pulse (GRP) and stemming release pulse (SRP) are the most undesirable and theoretically controllable parts of the airblast, since they involve the blast design variables of stemming, spacing, burden, and detonation velocity. SRP and/or GRP result from a blowout and appear as a spike or series of spikes superimposed on the APP. Because they have rise times of only a few milliseconds, they are rich in unwanted high-frequency airblast energy. Snell (58) reports that simply the use of an AN-FO explosive contributes to the irregular occurrence of SRP because of its slow detonation. Other conditions that may contribute to this effect are small-diameter holes (lower detonation velocities), wet holes, long columns, and high propagation velocities of the rock. Consequently, SRP would be more of a potential problem for quarries than coal strip mines. Figure 2 shows a coal mine production blast soon after

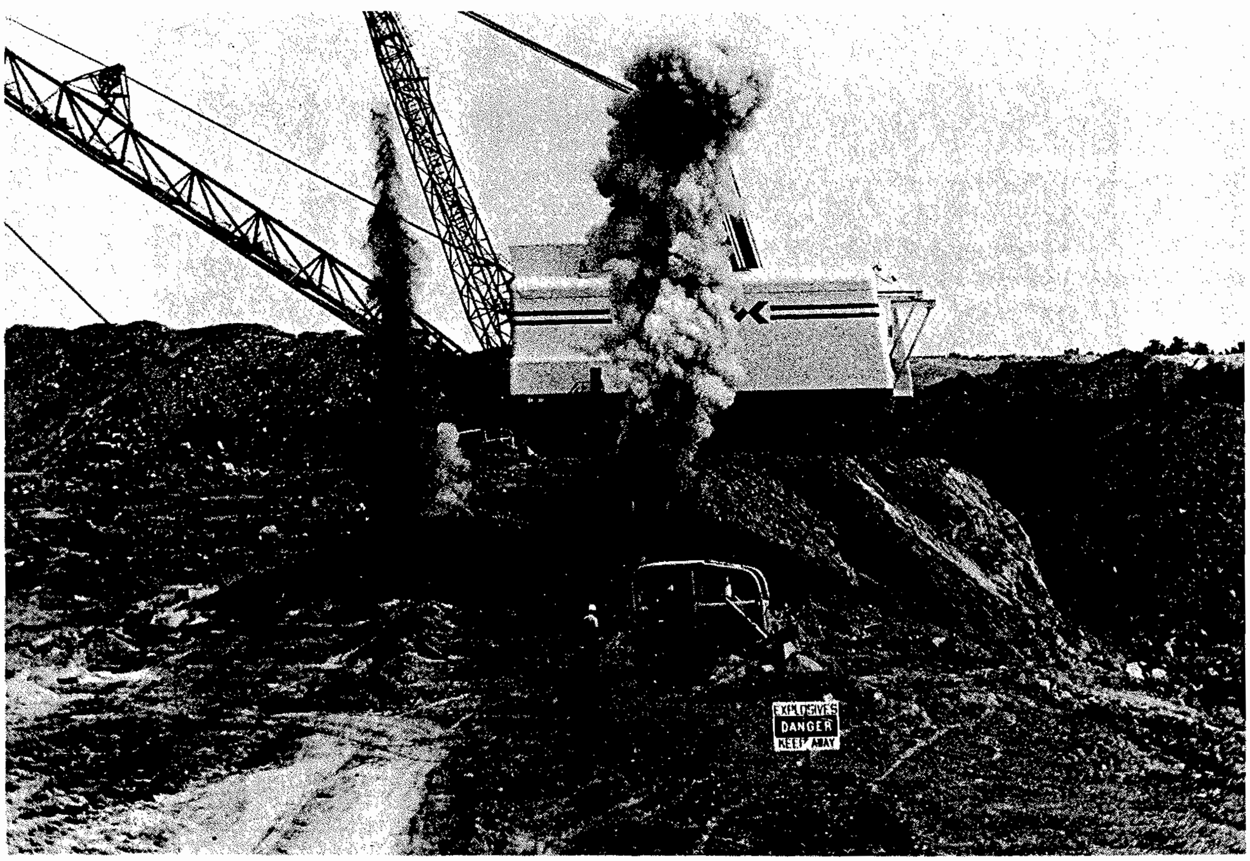

FIGURE 2. - A production blast in a surface coal mine.

initiation. The mounding which produces APP energy and the stemming plume are both visible, signifying that less than total confinement was obtained.

Surface detonating cord is a potential source of high-frequency airblast, and at small to moderate distances may be the dominant source. It is easily controlled by increasing the ground cover, and its effects diminish with distance.

Airblast Types Observed In Mining

Airblasts from surface mines have been classified according to their frequency character (53). Figure 3 shows the time history and spectra of a type 1 airblast which has prominent APP pulses resulting from almost line-of-sight propagation conditions, and exhibits a 15-Hz spectral peak corresponding to the 60-msec separation betwen hole detonations. This 15-Hz peak in the spectra is not the largest, but it is the most important in terms of its noticeability and effects on structures. The magnitude of the APP peaks is a fundamental result of the rock fragmentation process, and cannot be appreciably reduced. However, the delay interval and the resulting airblast frequency are part of the blast design and can be controlled. A type 2 airblast is shown in figure 4, with the APP pulses spread out into a single, very-low-frequency overpressure. This type of airblast typically occurs at large distances and behind the rock face. For quarries, APP pulses are produced by rock movement directly away from, and in front of, the face. The relatively high frequency airblast energy represented by the APP spikes cannot readily diffract behind and around obstacles, including the face itself. Consequently, type 1 airblasts are typically encountered in front of the face, and type 2, behind. An exception to this noted by Stachura (61) involved a high face across the pit from the blast. The face served as a simultaneous reflector and high-pass filter and returned the APP pulses as a ghost type 1 airblast. For coal mine highwall shots in area strip mines, where little or no rock displacement occurs, the heaving of the bench at the collar of each hole generates some APP, which should not be as horizontally directional as it is in contour mines or quarries. For all blasts, the air is a dispersive and selectively absorptive medium for sound transmission. The high frequencies are attentuated at a higher rate, and all airblasts become similar to type 2 at large distances.

The time history and spectra of a coal mine highwall shot producing a blowout and significant SRP appear in figure 5. This sharp pulse caused a large structural response and a high level of sound. Theoretically, blasts can be designed to prevent the generation of SRP and GRP; however, the natural variability of the blasted material (mainly, its nonhomogeneity and anisotropic character) makes it impossible to control SRP at all times.

Small blasts such as those used in construction and coal-mine-parting shots are particularly troublesome, not only for the high levels of airblast they can produce, but also because they are of high frequency (as much as 5-25 Hz compared with the usual 0.5-1.5 Hz). Obtaining sufficient confinement is the usual problem with these shots.

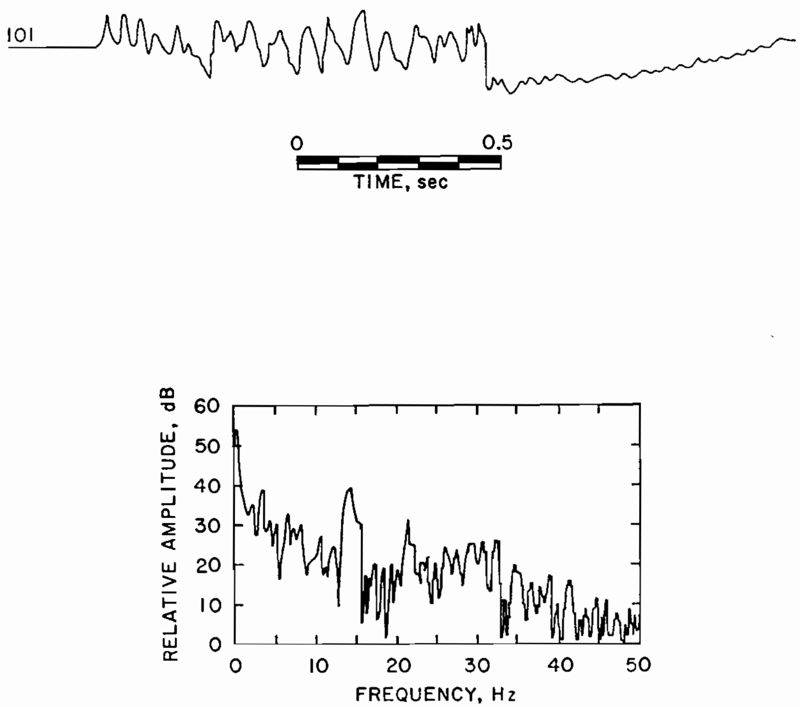

FIGURE 3. - Airblast time history and spectrum of a type 1 airblast (shot 101).

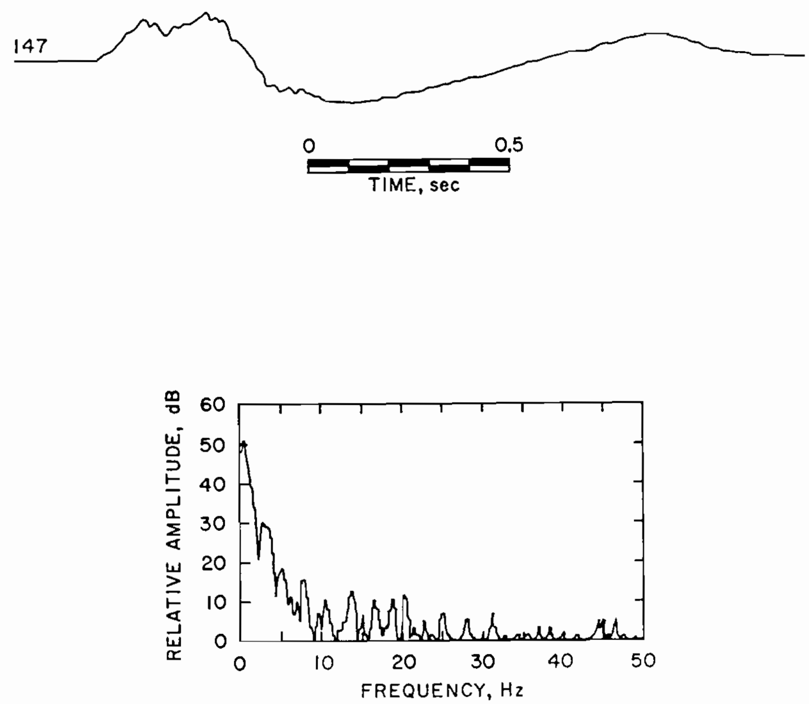

FIGURE 4. - Airblast time history and spectrum of a type 2 airblast (shot 147).

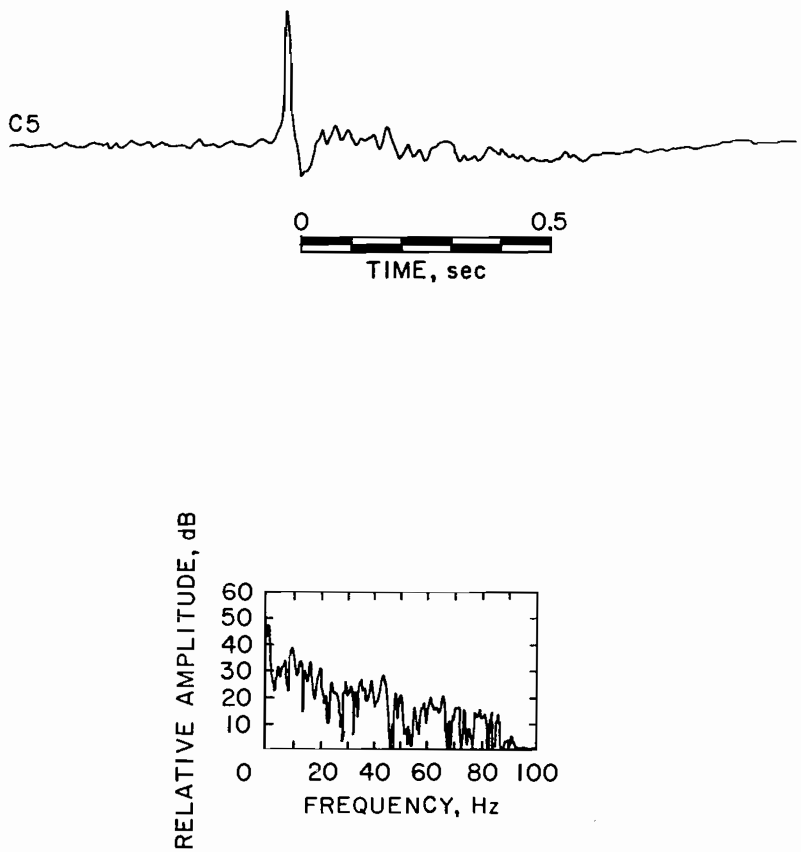

FIGURE 5. - Airblast time history and spectrum of a blowout (shot C5).

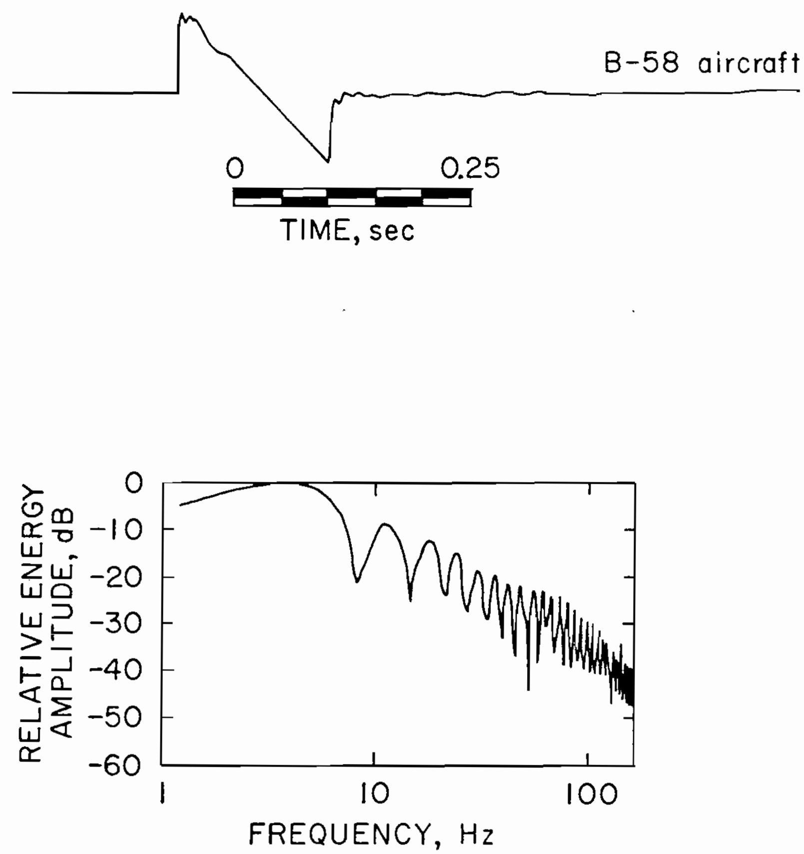

FIGURE 6. - Airblast time history and spectrum of a sonic boom.

Unconfined Blasts

Even more serious than poorly confined blasts is the problem of totally unconfined blasts exemplified by artillery, open-air detonations, uncovered surface detonating cord, and explosive testing. These produce high-frequency airblast and the highest levels per amount of explosive. Studies of the effects of unconfined airblast cannot readily be applied to the mining airblast problem, except possibly to provide a worst case or, when unconfined blasts are observed at large distances, to simulate confined blasts (58). These studies are discussed in the "Human Tolerance" section.

Sonic Booms

A typical sonic boom time history (N-wave) and spectra are shown in figure 6 (86). Considerable work has been done on the damage from and response of structures and humans to sonic booms. With caution, these results can be applied to the blasting problem.

The period of a sonic boom depends on the aircraft size and ranges from 75 msec for an F-104 to 206 msec for an XB-70. The spectrum is smoother than an airblast and like it contains much low-frequency energy. Sonic booms do not have isolated frequency spikes as do SRP and APP, and probably should not be directly equated in effect to type 1 or blowout-dominated airblasts. Most sonic boom spectra drop off at 12 dB per octave in pressure from the spectral peak, which can be roughly determined by inverting the N-wave duration and typically ranges between 4 and 11 Hz.

MEASUREMENT AND INSTRUMENTATION

Airblast is a transient time-varying overpressure, which can be expressed in any units of pressure. Various types of studies have specified pounds per square foot, pounds per square inch, millibars, and Newtons per square meter, and various expressions of relative sound levels, in decibels (dB). An equivalence and conversion chart for overpressure units is shown in figure 7.

Sound Pressure Levels

Shown in figure 7 is a line representing the sound pressure level (L_p) defined by the standardized relationship:

$$L_p = 20 \log_{10} \frac{P}{P_0},$$

where P_0 is the reference pressure of 20×10^{-6} N/m^2 or 2.9×10^{-9} lb/in^2 (5, 38, 61). Airblast time histories (figs. 3-6) plot pressure versus time with amplitudes proportional to changes around the zero line (ambient pressure). The measurement of sound is a complex subject involving factors of weighting (filtering), short-term integrations (fast or slow), long-term averaging (L_{dn}), root mean square (RMS), impulse and peak values, and a multitude of special descriptors (5, 38, 48, 53, 60, 70). Stachura (61) describes these measurement factors as they pertain to airblast.

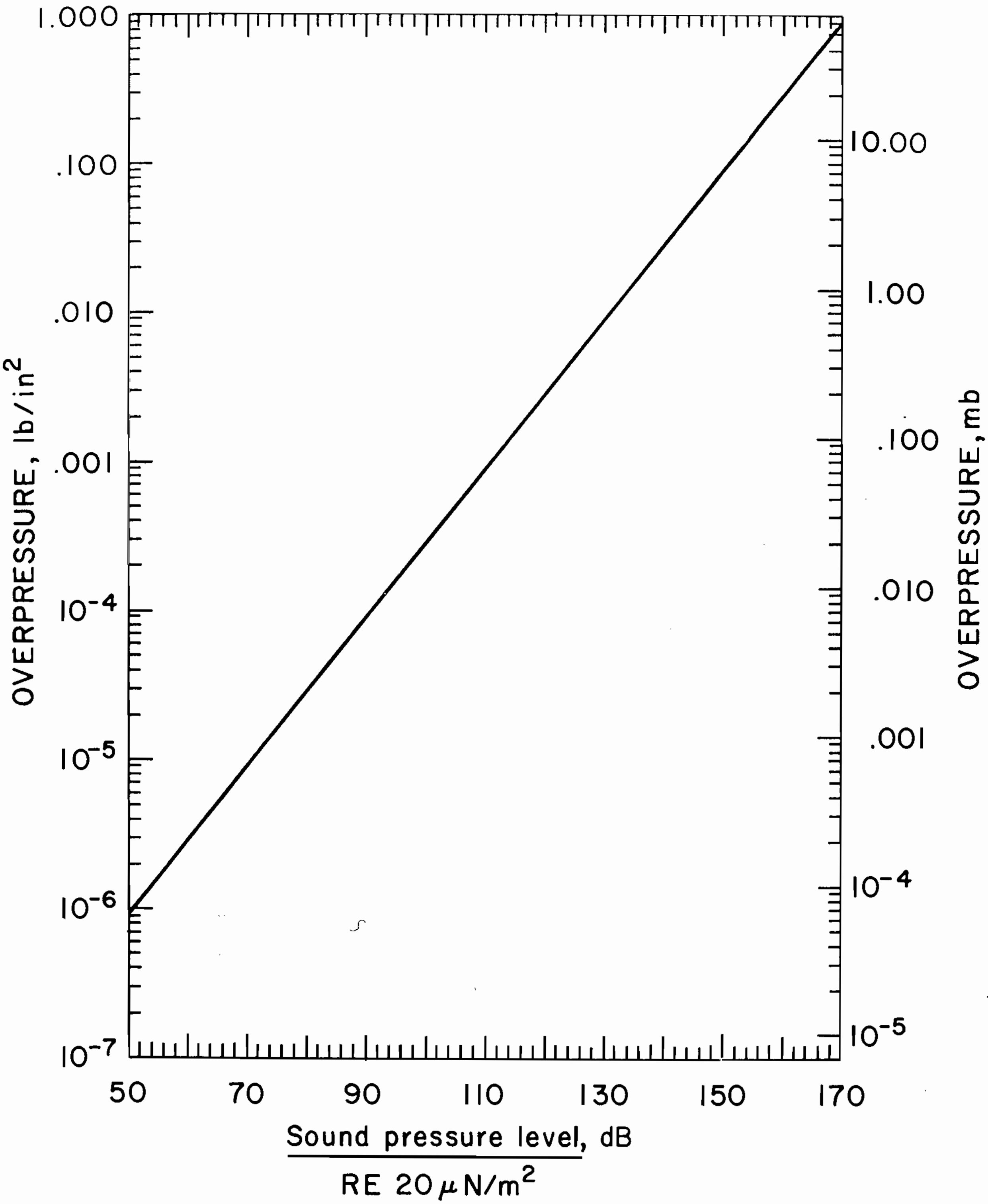

FIGURE 7. - Airblast level conversion and equivalence.

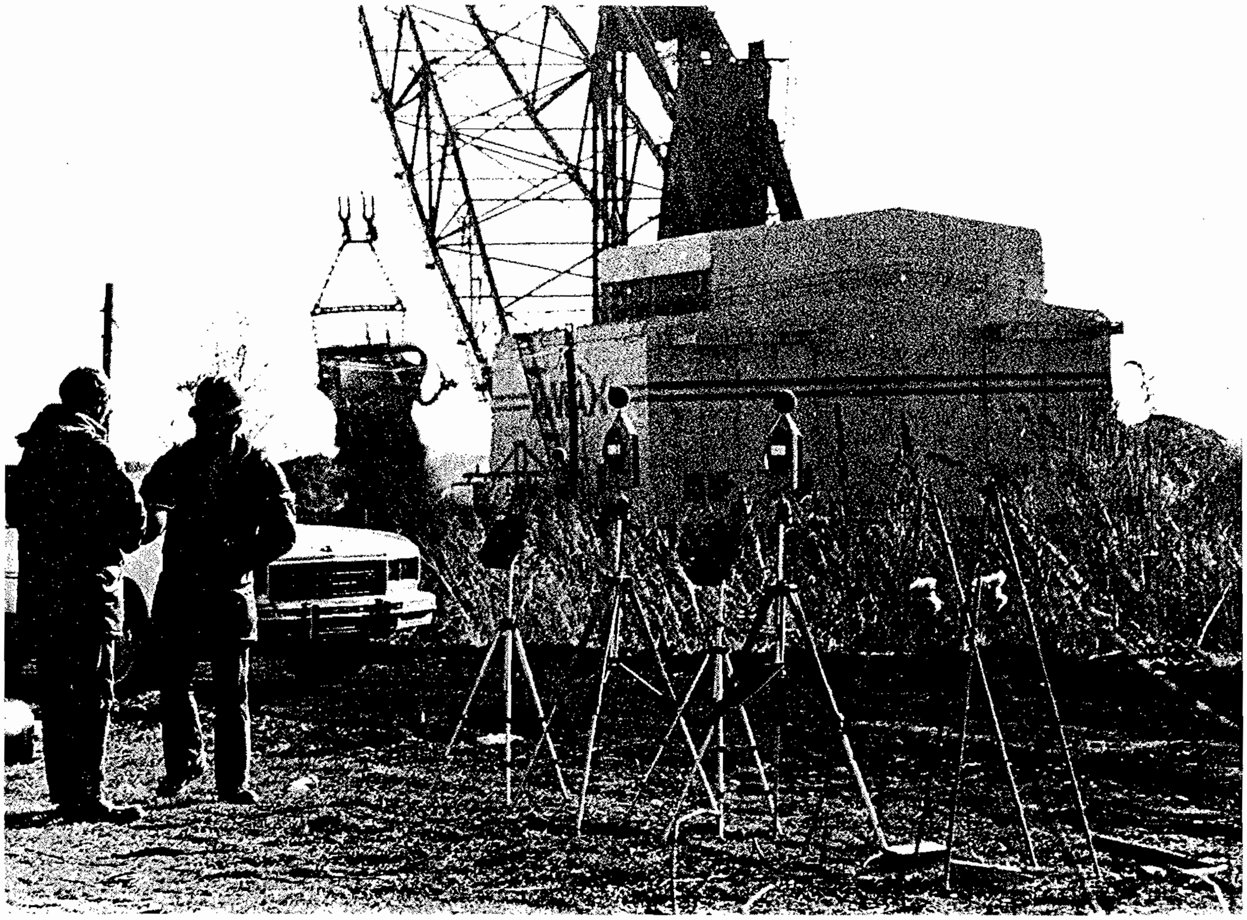

FIGURE 8. - Instrumentation for measuring airblasts.

Survey Instrumentation

The measurement and recording systems used for the Bureau of Mines airblast studies have been described in interim reports (54, 55). Low-frequency pressure transducers of 0.1- to 380-Hz response were used in 7- and 14 channel FM recording systems (figs. 8-9). From these "ultralinear" airblast time histories, other "linear" measurements were generated by appropriate filtering. The 0.1-Hz low-frequency response was required for research purposes to measure accurately the 1-Hz energy often present in the airblasts (8, 53, 56). The high-frequency response of the measuring system could be a problem for some sources (detonating cord, SRP), although in practice, only a 200-Hz response is required (23). The 0.1-Hz airblast time histories were processed by playback through various analysis systems (including the filtering networks of standard sound-level meters,) and then correlated with measured structure responses. Supplementing these values were direct measurements using a 0.1-8,000-Hz sonic boom measuring system (B&K 2631)[5] and sound level meters giving

[5]Reference to specific brand names is made for identification only and does not imply endorsement by the Bureau of Mines.

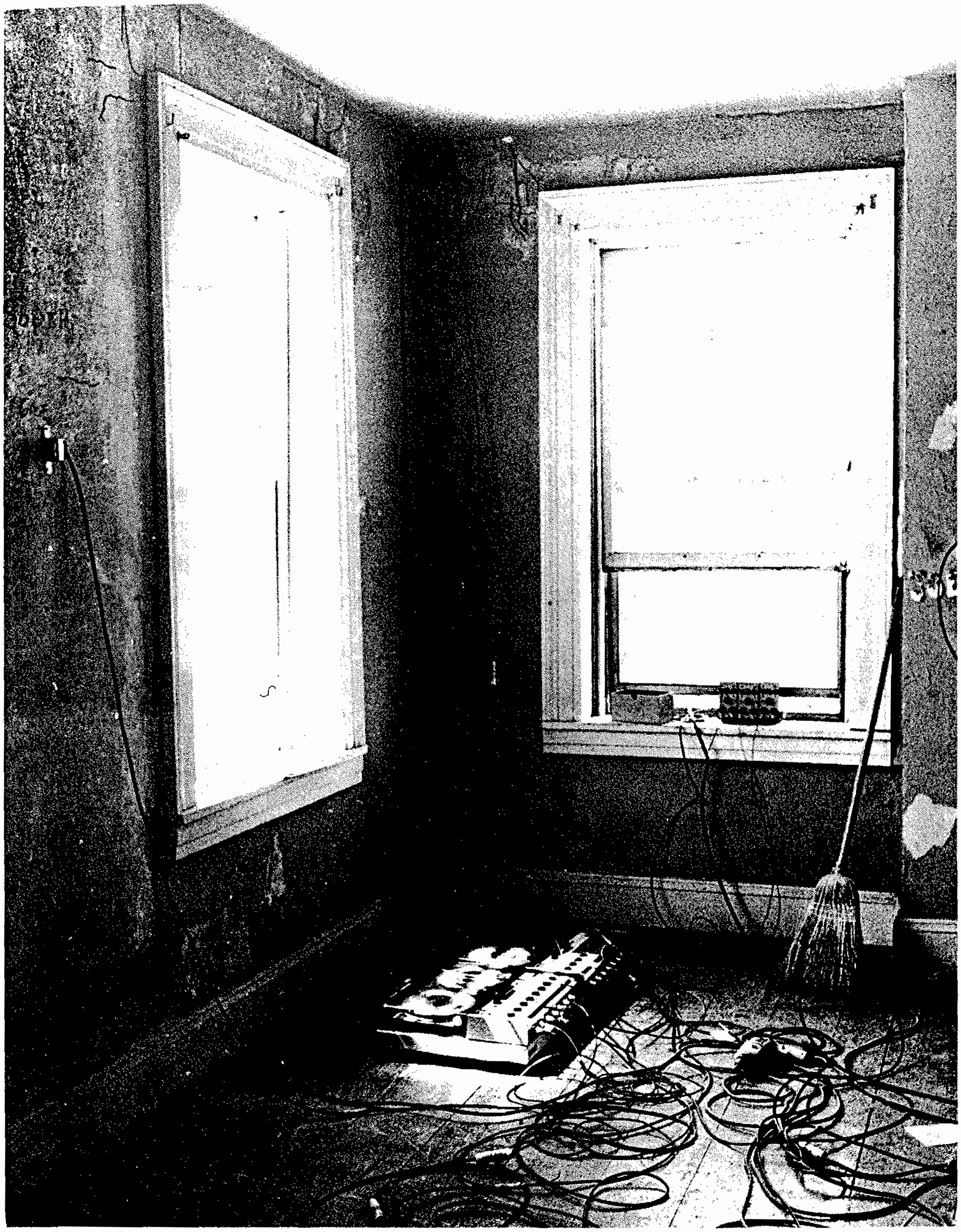

FIGURE 9. - Measurement and recording system for structure response.

2-Hz, 5-Hz, 6-Hz linear, and C-weighted-slow values. The analyses are further described in the section on processing airblast time histories, and also in Stachura's report (61).

Structure responses and ground motions were measured by direct-reading velocity gages of 2.5- and 4.75-Hz natural frequencies (Vibra-Metrics 120 and 124) with flat frequency responses of 3-500 Hz and 5-2,000 Hz (-3 dB), respectively (62).

The airblast measuring instruments and their application (table 1) are discussed in other reports (5, 38, 54, 61). It is often convenient to measure airblast with blasting seismographs, most of which have an airblast channel as well as three components of ground vibration. They typically give permanent film or paper records, but often limit the choices of weighting, integrating times, and frequency ranges. Stagg (62) and Stachura (61) describe these systems, many of which have been frequency-calibrated by the Bureau of Mines. Two of the devices in table 1 are not complete systems, but transducers which require some type of recorder (B&K 2631 and Validyne DP-7). Two are impulse-precision sound level meters with multi-function capability (B&K 2209 and GenRad 1933). Permanent records can be obtained by using a suitable recorder on their outputs; however, the sound level meters give only numerical readings. The B&K 2209 has a "hold" capability which greatly facilitates the reading of transients. The acoustic monitor (Dallas AR-2) is designed for long-term unattended recording. The ultralinear system is the only one which accurately measures the true waveform, and should be used wherever later processing is required.

TABLE 1. - Airblast-measurement systems

Name	Quantities measured	Output	Time history capability	Permanent record capability	Frequency response (± 3dB), linear or flat setting	Weight, lb	Notes
Brüel and Kjaer 2209.	A-, B-, C-weighted RMS; flat, peak, and impulse; fast and slow response	Direct sound-level-readings and voltage.	No............	No............	With 4145 (1-in) microphone, it is 2 Hz-18 kHz or 6 Hz-18 kHz selectable; with 4165 (½-in) microphone, it is 3.5 Hz-20 kHz or 5.5 Hz-20 kHz selectable.	6	Sound-level meter, hold capability on meter, battery operation.
GenRad 1933.	A-, B-, C-weighted RMS; flat, peak, and impulse; fast and slow response; octave band levels (10).	.....do......	No............	No............	With 1961-9601 (1-in) microphone, 5 Hz-12 kHz; with 1962-9601 (½-in) microphone, 5 Hz-19 kHz.	5.5	Sound-level meter, does not hold peak readings, battery, operation.
Brüel and Kjaer 2631.	Overpressures.	Voltage proportional to pressure.	Yes, when used with ancillary recorder.	Yes, when used with ancillary recorder.	With 4146 (1-in) microphone; 0.1 Hz-8 kHz.	4.3	Sonic boom system. Recording device is required (oscilloscope, oscillograph, tape recorder).
Validyne DP-7 pressure gage with CD-16 carrier demodulator.	Overpressures.	.....do.....	.....do.......	.....do.......	Selectable low frequency to 380 Hz.	3.3	Do.
Dallas Instruments AR-2 acoustic monitor. slow response.	A-, B-, C-weighted RMS: flat and peak; slow response	Bar graph, not printed.	No............	Yes...........	5 Hz-8 kHz.	23	30-day recording monitor. Runs 5-7 days on internal battery, 1-2 months on 12-volt automotive battery.

TEST STRUCTURES

A total of 56 different structures were studied for airblast and ground vibration response and damage (table 2). All were houses, except No. 54, which was a mobile home. In addition, structures 13, 15, 16, and 50 were somewhat larger than single-family residences. Some structures (19 and 20) were studied for a variety of blasts, highwalls, parting, and surface. The response of structures 1-6 were described in an earlier study (55). Of the 56 structures, only 17 had significant and identifiable levels of airblast response (figs. 10-24). In many cases, the blasting did not result in high airblast levels and/or high-frequency airblasts. Measurements were generally made near the blasts since ground vibration were also being sought. Time separation between the ground vibration and the airblast was not always sufficient to identify the latter response. The coal-mine-parting and quarry shots usually produced good airblast data, as did the coal highwall shots with long delay intervals.

TABLE 2. - Test structures and their measured dynamic properties

Structure	Number of stories	Dimensions, feet: Plan dimensions, NS x EW	Dimensions, feet: Overall height	Construction: Superstructure	Construction: Exterior covering	Construction: Interior covering	Construction: Foundation	Total structure: Natural frequency, Hz: N-S	Total structure: Natural frequency, Hz: E-W	Total structure: Damping, pct: N-S	Total structure: Damping, pct: E-W	Midwall: Natural frequency, Hz	Midwall: Damping, pct	Shot numbers (table 3)	Air-blast response
1	1	22 x 30	14	Wood frame.......	Wood siding.	Gypsum wall-board.	Full basement.					16		13,14,17, 18	X
2	1	30 x 70	14	Masonry and wood.	Stone...	..do....	..do......							15	
3	1-1/2	35 x 35	16	Wood frame.......	Brick and wood.	..do....	..do......					13		16	
4	2	30 x 40	22	.....do..........	Wood siding.	..do....	Full basement.	8.2		2.0		19,22		17,18	X
5	2	40 x 40	22	.....do..........	Brick and wood siding.	..do....	Partial basement.					19		19	
6	1	40 x 40	14	.....do..........	Wood siding.	..do....	Full basement.	9.6				32		19	
7	1	48 x 25	15	.....do..........	Asbestos siding.	..do....	..do......							33	
8	1	15 x 10	12	.....do..........	Wood siding.	..do....	Concrete slab.							33	
9	1	61 x 29	14	.....do..........	..do.....	..do....	Full basement.							34	
10	2	44 x 29	22	.....do..........	Asphalt sheathing.	Plaster.	..do......							35	
11	2	26 x 32	30	.....do..........	Masonite siding.	Gypsum wall-board.	..do......					36		35	
12	1-1/2	27 x 36	20	.....do..........	Cedar shakes.	..do....	..do......					25		35	X
13	1	34 x 100	16	.....do..........	Brick and stucco.	..do....	Slab and crawl-space							35	
14	1-1/2	35 x 35	23	.....do..........	Wood siding.	..do....	Full basement.	10.4		6.5		14		36,38	X
15	1	125 x 25	12	Steel frame......	Steel.....	..do....	Concrete slab.	5.6		2.8		17		36,38	
16	1	80 x 80	17		Brick and stucco.	..do....	Full basement.					8.3		36	
17	1-1/2	19 x 40	20	Wood frame.......	Wood shingles.	..do....	..do......	10	8.6	4.5	6.7	18		37,146	
18	1	44 x 28	13	.....do..........	Wood siding.	..do....	Pillars in dirt.	8.8	8.0	2.3	4.3	11.4		37,146	
19	2	33 x 35	24	.....do..........	Wood siding.	Plaster and lathe.	Partial basement.	4.1	3.9	3.9	7.0	13,17	4.5, 5.1	39-48, 59-96	X
20	1-1/2	39 x 29	21	.....do..........	..do......	Gypsum wall-board.	Full basement.	8.3	7.6	3.0	3.6	20	3.1	42-58	X
21	1	48 x 28	15	.....do..........	..do......	..do....	..do......	8.0	6.4	2.9	3.3	13.4, 14.5	2.9, 2.3	97-102 110,111, 113,114, 117, 135,136	X
22	2	27 x 76	26	.....do..........	Brick and masonite.	Gypsum and pan-eling.	Crawlspace	7.5	6.5	2.1	1.8	12.3, 13.1	2.0, 3.0	103,104	X
23	1	62 x 26	14	.....do..........	Asbestos shingles.	Gypsum wall-board.	..do......	7.4	7.3	2.8	4.9	18.5		103-105	X
24	1	24 x 55	15	.....do..........	Brick.....	..do....	Crawlspace	10.6	5.9	1.7	3.3			106	
25	1-1/2	41 x 24	22	.....do..........	Wood siding.	..do....	Full basement.	8.1	10.1	3.3	3.2	13.7, 16.3	1.8, 3.6	106	
26	1	40 x 31	15	.....do..........	Aluminum siding.	..do....	Crawlspace							107	
27	1	51 x 30	15	.....do..........	Wood siding.	Plaster and lathe.	Partial basement.	7.2	6.3	6.2	6.3	17,24		C.1-C.11	X
28	1	42 x 28	14	.....do..........	Wood and aluminum.	Gypsum wall-board.	Crawlspace	7.0	10.1	1.7	1.3			108,122	
29	2	26 x 35	22	.....do..........	Wood	..do....	..do......	6.6	7.9	2.2	1.9	17.7, 13.0	1.1, 2.2	109,120, 121	
30	1	34 x 48	16	.....do..........	Stone.....	..do....	Full basement.							112	
31	1	35 x 44	13	.....do..........	Wood siding.	..do....	Crawlspace	8.1	5.9	2.9	2.2	12.2, 16.6	1.5, 1.2	115,116, 118	
32	1-1/2	58 x 26	22	.....do..........	Brick and masonite.	Panel-ing and wall-board.	Concrete slab.							119	
33	1-1/2	69 x 27	24	.....do..........	Stone.....	Gypsum wall-board.	Full basement	7.5	7.9	1.6	3.0	16.0, 19.7	1.5, 2.1	124,125, 132-134, 137-139	
34	1	33 x 33	18	.....do..........	Asphalt sheathing.	Plaster.	Crawlspace	7.1	6.4		3.4			126,127, 130,131	X
35	1	32 x 37	18	.....do..........	..do.......	Gypsum wall-board.	..do......	7.1	6.1	1.4	4.0			128,129, 140	X

TABLE 2. - Test structures and their measured dynamic properties--Continued

Structure	Number of stories	Dimensions, feet: Plan dimensions, NS x EW	Dimensions, feet: Overall height	Construction: Superstructure	Construction: Exterior covering	Construction: Interior covering	Construction: Foundation	Total structure: Natural frequency, Hz: N-S	Total structure: Natural frequency, Hz: E-W	Total structure: Damping, pct: N-S	Total structure: Damping, pct: E-W	Midwall: Natural frequency, Hz	Midwall: Damping, pct	Shot numbers (table 3)	Air-blast response
36	1	28 x 40	14	.....do..........	Asphalt shingle.	..do......	..do......	6.3	7.1	3.0		14,17		141-145	X
37	1-1/2	32 x 26	20	.....do..........	Wood siding.	Plaster and lathe.	Full basement.	8.6	10.0	2.0	1.9	18.5,20		146,150	X
38	2	28 x 32	20	Masonry and wood.	Brick and aluminum	Wood paneling.	Concrete slab.	4.6	5.5	3.8	3.0			147,148	X
39	1	34 x 29	15	Wood frame.......	Masonite siding.	Paneling and wall-board.	Full basement.	5.0	4.8	7.3		14		147	
40	1-1/2	28 x 31	18	.....do..........	Stucco...	Plaster and lathe.	Partial basement.	5.5	7.5	2.6	2.4	13.6		148	
41	2	40 x 28	22	.....do..........	Wood siding.	Gypsum and plaster.	Full basement.	9.9	8.1	2.5	2.3	16.6		149	
42	1-1/2	44 x 30	20	.....do..........	..do.....	Paneling.	..do......	5.4	6.7	4.7	3.7	11.9, 13.9		151-153	
43	1-1/2	28 x 46	23	.....do..........	..do.....	..do......	..do......	8	5.1			18,18		154	X
44	1	--	15	.....do..........	..do.....	--	..do......					11,11		156-156	
45	2	55 x 44	32	Solid brick......	Brick....	Plaster on brick	..do......	6.3	7		8.1			157-159	
46	1-1/2	38 x 40	21	Concrete block...	Concrete block.	Plaster....	..do......					11,11			
47	1	87 x 38	15	Wood frame.......	Brick....	Gypsum wall-board.	..do......					12.5, 13.3		160	
48	1-1/2	36 x 24	22	.....do..........	Wood siding.	..do.......	..do......		8.3			16.7, 16.7		161	X
49	1-1/2	41 x 35	27	.....do..........	..do.....	Gypsum wall-board and plaster.	..do......	5.4	5	10	4.2	18.2, 18.2		162,164-166,172	
50	1	46 x 180	14	.....do..........	Aluminum siding.	Gypsum wall-board.	Concrete slab.							163	
51	2	50 x 43	28	Solid rock.......	Brick....	Plaster on brick and lathe.	Full basement.	8.3						167-171, 173-182	
52	1	37 x 24	16	Wood frame.......	--	Wood paneling.	..do......							183	
53	1	24 x 35	15	.....do..........	Wood siding.	--	Crawlspace							184	
54	1	12 x 60	15	Metal walls......	Metal....	Paneling...	None......							186,187, 189-192	
55	1-1/2	40 x 31	23	Wood frame.......	Wood siding.	--	Full basement.							193	
56	1-1/2	34 x 57	20	.....do..........	Wood siding.	--	..do......							194,196	

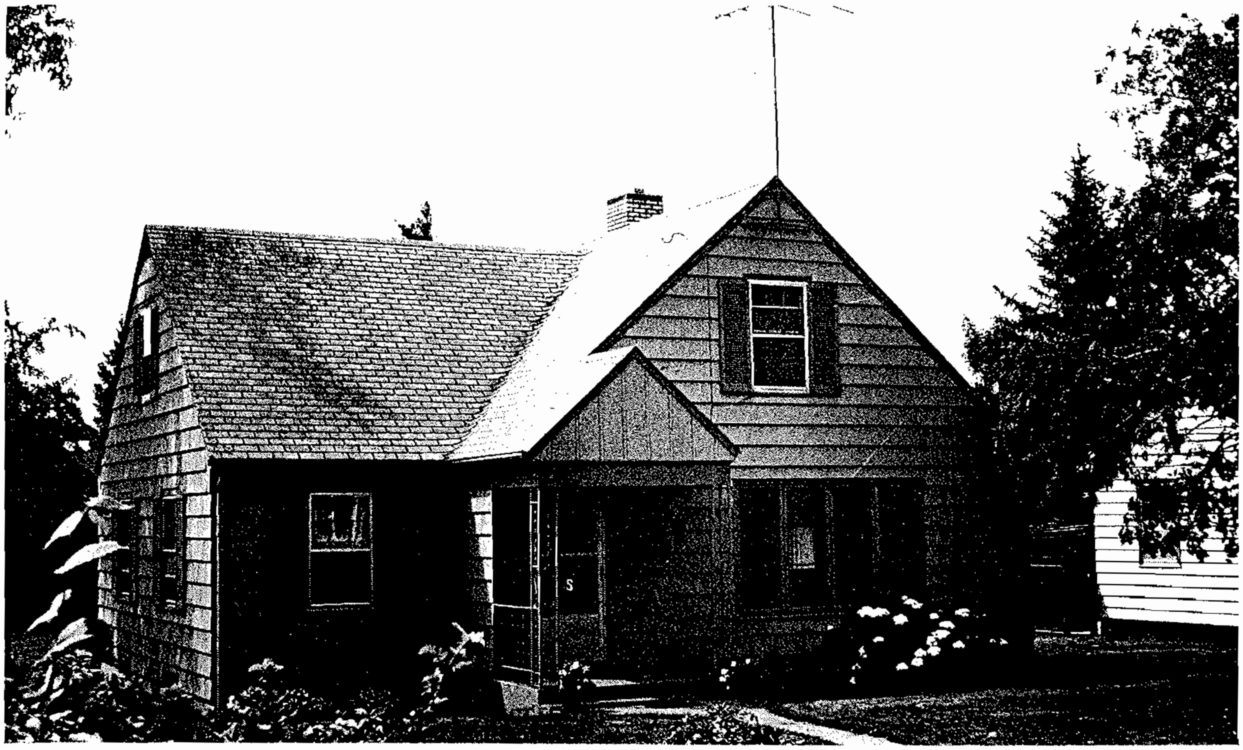

FIGURE 10. - Test structure 12, metal mine.

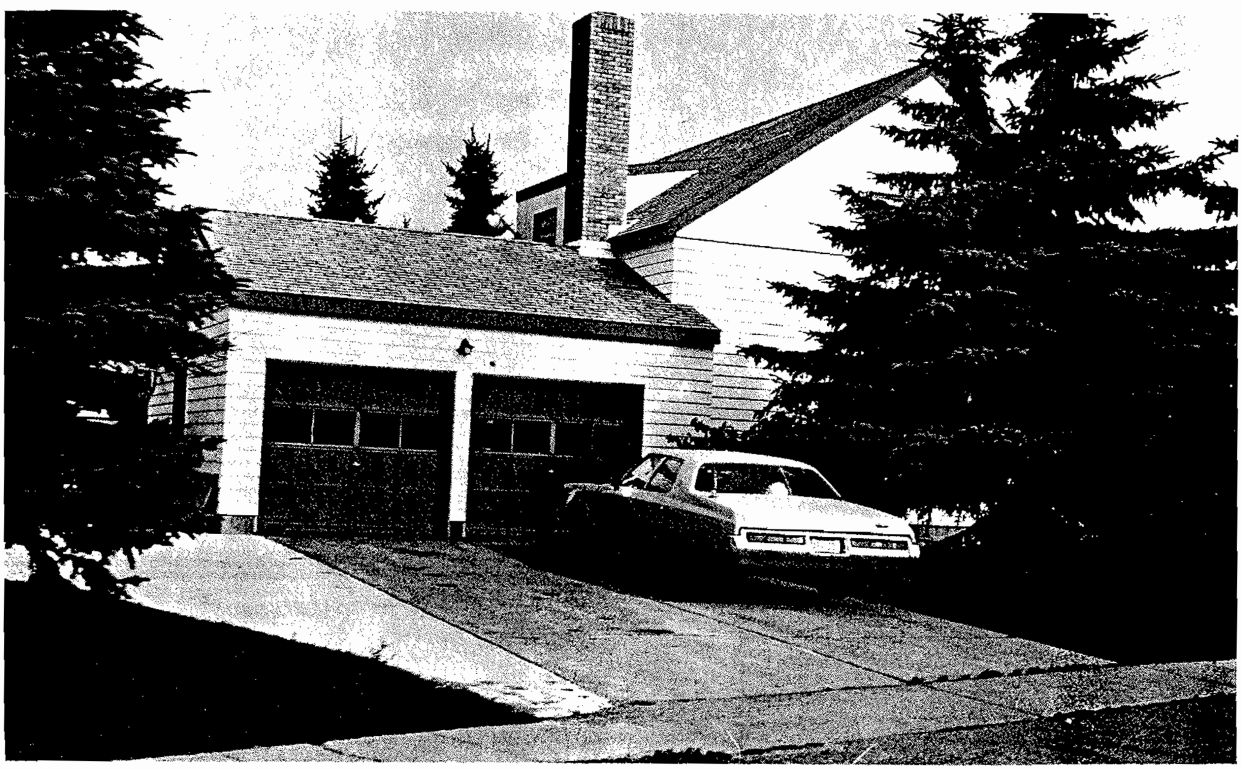

FIGURE 11. - Test structure 14, metal mine.

FIGURE 12. - Test structure 19, coal mine.

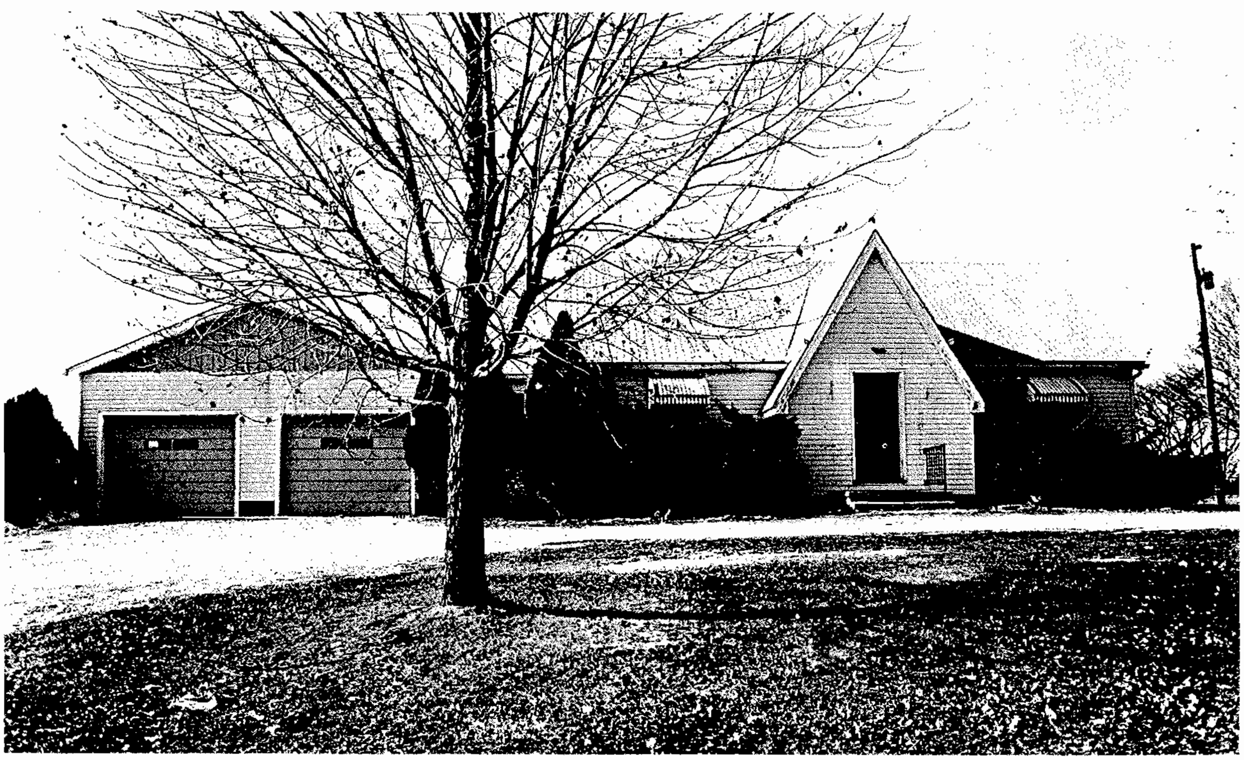

FIGURE 13. - Test structure 20, coal mine.

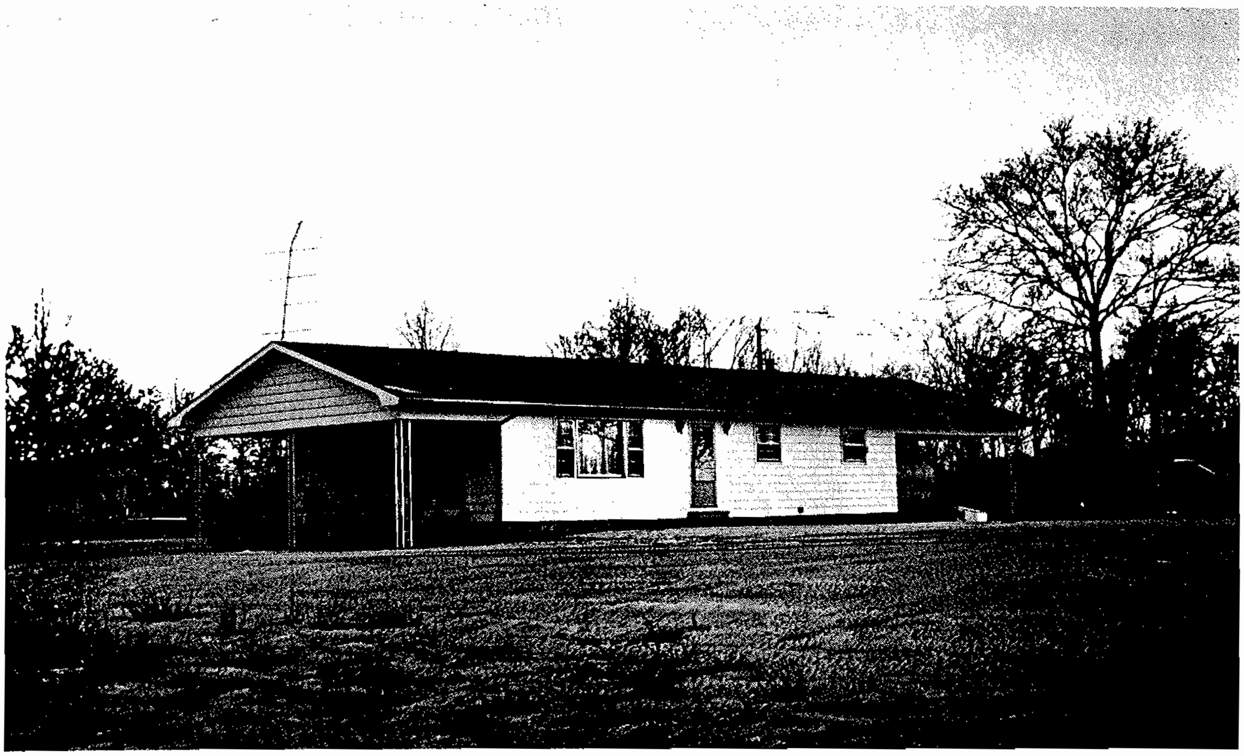

FIGURE 14. - Test structure 21, coal mine.

FIGURE 15. - Test structure 22, stone quarry.

FIGURE 16. - Test structure 23, stone quarry.

FIGURE 17. - Test structure 27, coal mine.

FIGURE 18. - Test structure 34, coal mine.

FIGURE 19. - Test structure 35, coal mine.

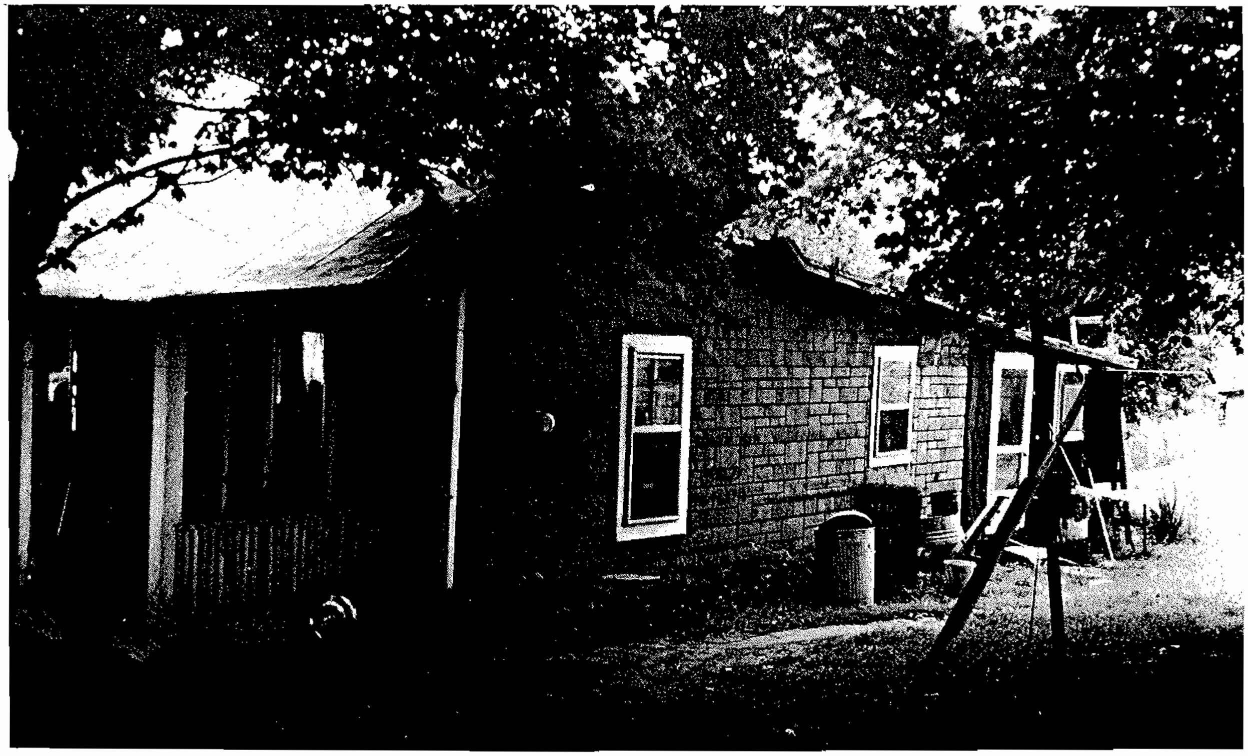

FIGURE 20. - Test structure 36, coal mine.

FIGURE 21. - Test structure 37, metal mine.

FIGURE 22. - Test structure 38, metal mine.

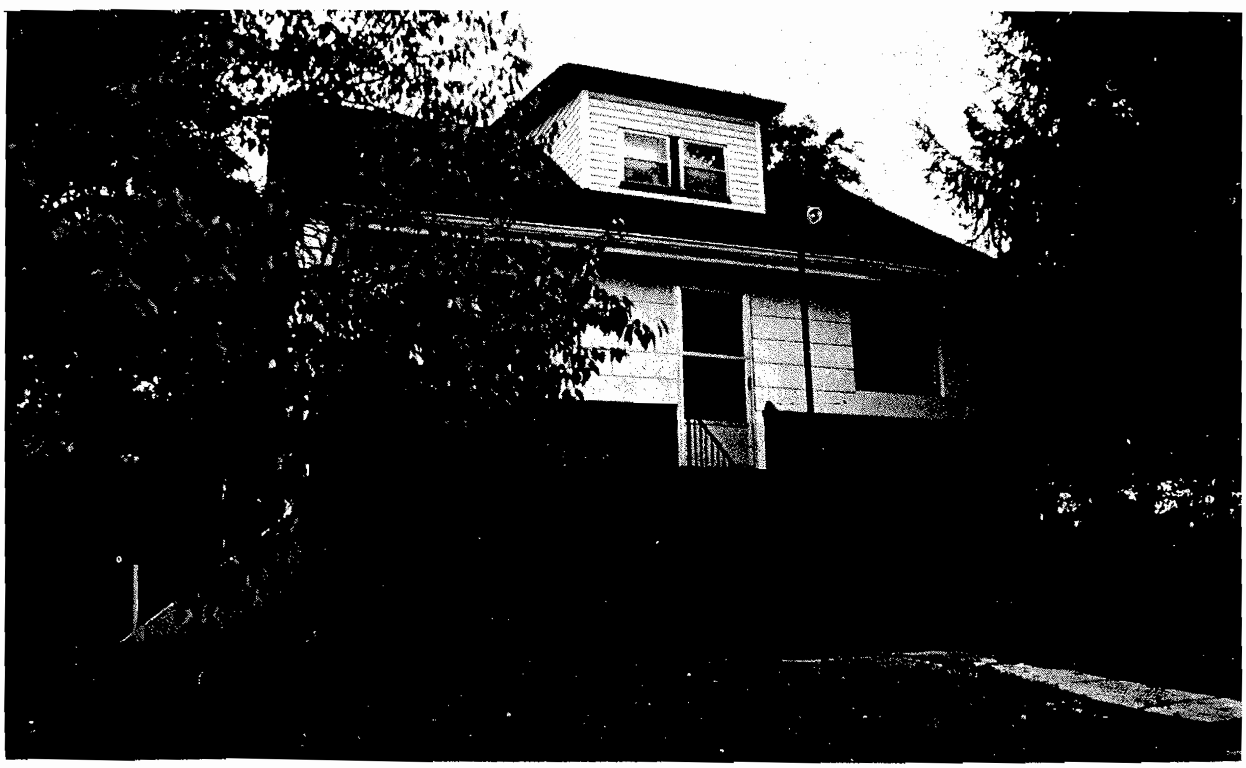

FIGURE 23. - Test structure 43, coal mine.

FIGURE 24. - Test structure 48, coal mine.

Instrumenting For Response

Outside ground vibration, airblast, and corner and midwall responses of the structure were measured for each shot. The ground vibration was measured by three orthogonal 2.5-Hz velocity gages buried about 12 inches into the soil next to the foundation (62). Outside airblast was measured with at least one DP-7 gage, and two sound level meters (one reading C-slow). The structures were instrumented for horizontal motions by a pair of gages mounted low on the first-floor vertical walls in the corner closest to the blast and one or more mid-walls. Typically, the vertical motion was measured in the same corner. Additional channels were usually available and used for various additional corner-motion measurements at mid-heights, near the ceiling, or on the next floor; additional floor-motion measurements such as mid-floor verticals; basement wall horizontal measurements; opposite-corner responses (for rotational motions); and inside noise.

Corner measurements assessed the racking motions (distortion) of the structure. Essentially all blast damage occurs where stresses and deformations are produced within the planes of the wall as shear stresses. Consequently,

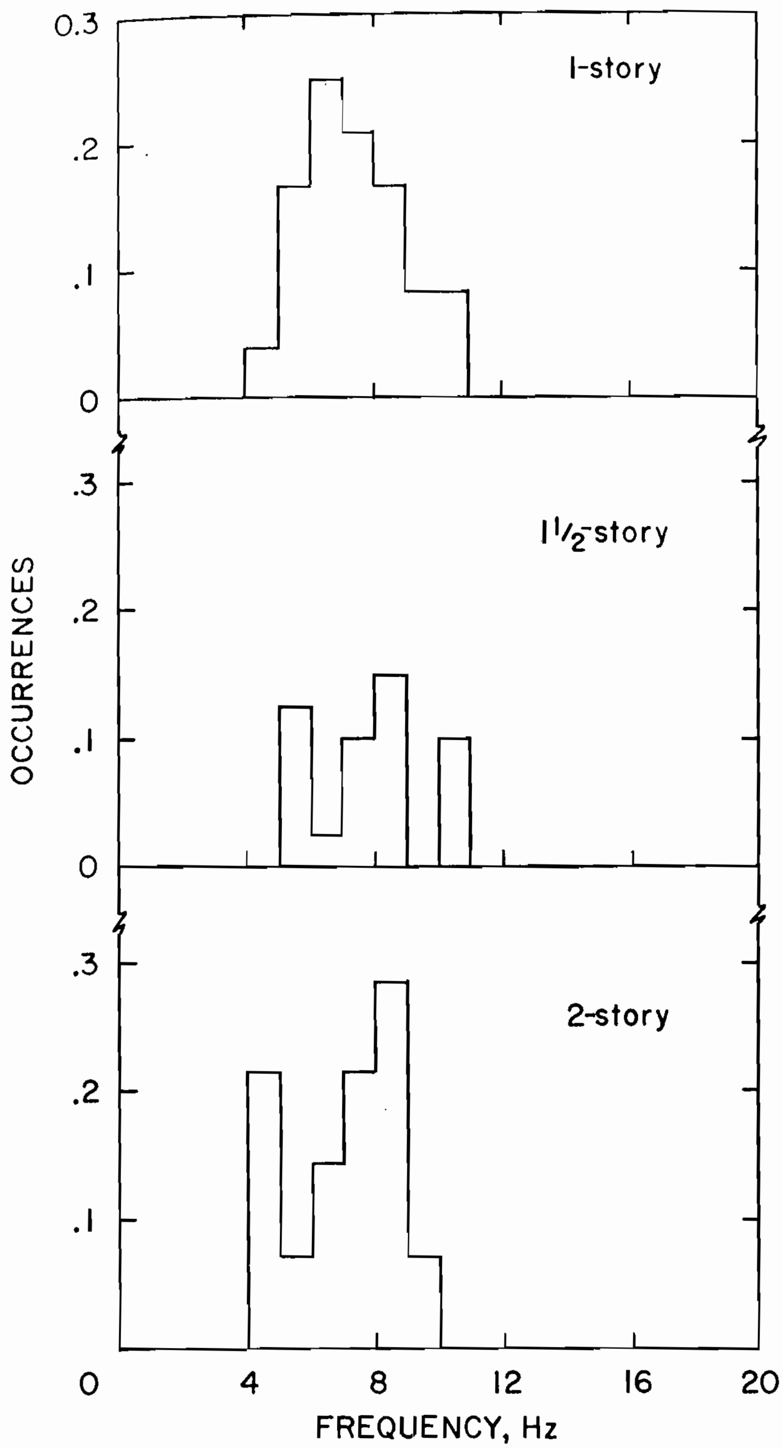

FIGURE 25. - Natural frequencies of residential structures.

the vibration measurements made in the corners were assumed to indicate damage potential, because they measured whole-structure response. Other types of response caused different but consequential results. Midwall motions (perpendicular to the wall surface) are primarily responsible for window sashes rattling, picture frames tilting, dishes jiggling, and knick-knacks falling. Midwall accelerations in excess of 0.4 g (12.8 ft/sec^2) are occasionally generated and could cause items to fall off shelves. These midwall motions are not necessarily dangerous to the structure since walls can vibrate in this mode without producing high levels of stress. Midwall motions are mostly annoying. Floor motions present a problem similar to midwalls. Like them, they also produce secondary noises and can lift hanging objects off nails and cause them to drop to the floor. Structures are designed to resist normal vertical load, so vertical corner motions of less than 1 g should not warrant serious concern.

Natural Frequencies and Damping

Natural frequency and damping are the most important structure-response characteristics. The natural frequencies of the structures as measured from blast-produced corner motions are summarized in figure 25, with individual values listed in table 2. Structures continue to vibrate after the sources (ground vibration and airblast) decay, and natural frequencies and damping can be measured from the time histories. The vibrations of structures, especially midwalls, are approximately sinusoidal; therefore, the natural frequencies are calculated by inverting their periods (in seconds). The damping values are given by

$$B = \frac{100}{2\pi m} \text{Ln} \; (A_n / A_{n+m}),$$

where B is the percentage of critical damping, A is the peak amplitude at the n^{th} cycle, and m is any number of cycles later. Murray (28) discussed the general problem of structure frequencies and damping and also computed many of the values in table 2. He noticed that damping values were level-dependent, indicating that friction was nonlinear.

Little difference in natural frequencies was observed between 1-, 1-1/2-, and 2-story houses. Medearis (27) measured frequencies and damping values for 61 houses and found similar results, except for some higher frequencies for the 1- and 1-1/2-story homes. He found frequency ranges of 8-18 Hz (1 story), 7-14 Hz (1-1/2 stories), and 4-11 Hz (2 stories). Two potential problems exist in Medearis' data. He utilized bumping and door slamming for his vibration sources, and these might excite only parts of the structure (unlike blasting). Bureau measurements of bumping vibrations also gave higher and more scattered values than the blast-produced responses. In addition, midwall frequencies are higher than the vibration frequencies of the structure as a whole (fig. 26), and could contribute to the corner vibration measurements, as was the case with the corner mid-height horizontal measurements. Damping is summarized in figure 27.

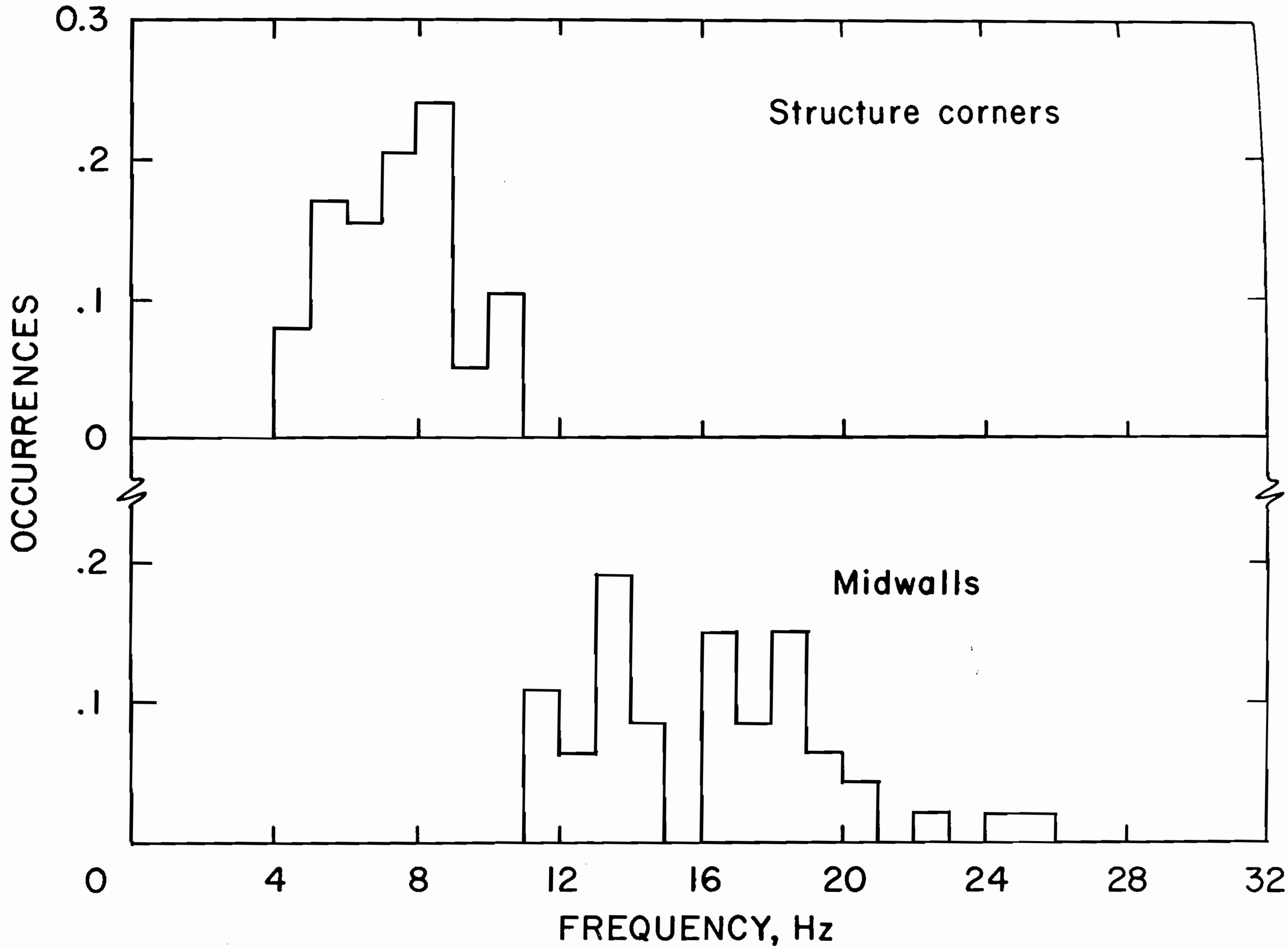

FIGURE 26. - Summary of natural frequencies of residential structures.

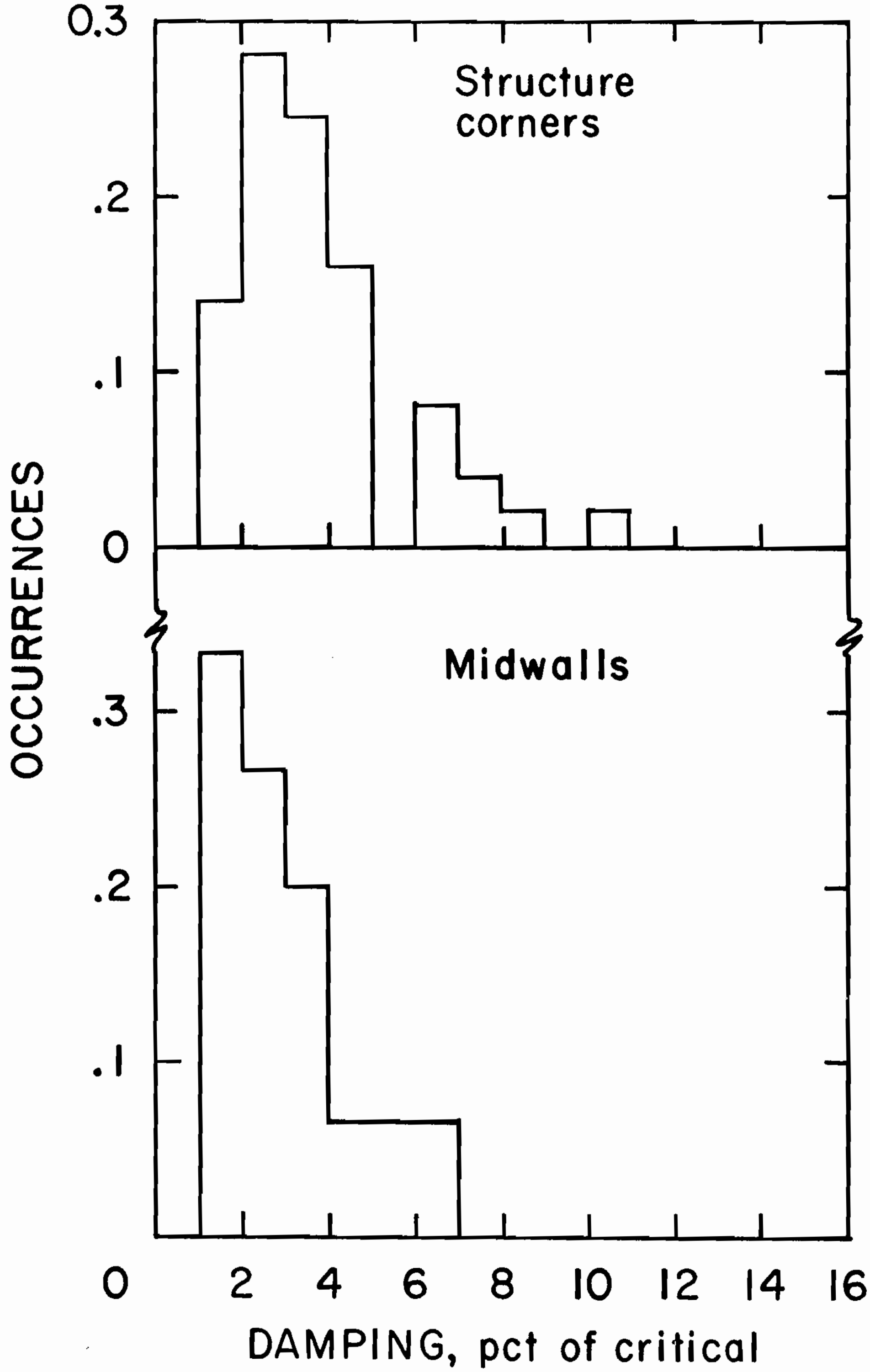

FIGURE 27. - Damping values of residential structures, corners and midwalls.

PRODUCTION BLASTING

Table 3 lists 196 production blasts. The first 12 shots were used for airblast instrumentation calibration, and are not included. A wide range of charge sizes, distances, and blast types produced airblasts of various peak values, durations, and frequency character. Quarries typically had a high free face, with strong directional effects. Quarries in urban areas used multiple decks, and hole diameters seldom exceeded 6 inches. Shots 21 to 30 were in an isolated quarry with high airblast levels at the close-in measuring locations, but no house vibration measurements were made.

Coal mine highwall blasts varied from well-confined blasts producing no throw whatsoever, to quarry-type blasts with three free faces (top, front, and one side). Where ground vibration appeared to be more serious than airblast, emphasis was put on sufficient relief. Parting shots involve blasting a thin, often hard, rock layer, and can produce high levels of airblast. The difficulty in obtaining sufficient confinement has resulted in some parting blasts being almost as loud as with unconfined explosive.

The metal mines produced a wide range of airblast concerns, depending on the proximity of residences. One operation (shots 36 and 38) had no structures nearby that were not company owned, and consequently loaded to the collar in order to fragment hard rock near the surface.

The operators recognized the airblast problem created by exposed surface detonating cord; none of the coal or stone quarry shots had uncovered cord. A few shots were designed with long delays which greatly influenced the airblast frequency character (for example, shot 101 (fig. 3)).

An extensive study was made by Wiss (83) of the blast design factors of noise and vibration. These are summarized in appendix B of this report, and reference 56.

PROCESSING OF AIRBLAST TIME HISTORIES

Descriptors for Sound

A variety of descriptors characterize levels of sound; however, no consensus exists on the appropriate measurement methodologies for impulsive noise sources. The nonuniformity of symbols among studies also complicates the problem, so the Environmental Protection Agency (EPA) has recently recommended standard terminology (59).

Stachura (61) defines and discusses various sound descriptors for impulsive noises. The applicability of these descriptors to blast-produced noise is discussed in this report in the section on tolerable airblast levels.

Perceived Noise Level (L_{pn}), also labeled PNdB, was analyzed by Kryter (19) for aircraft and nonimpulsive sources. Kryter (20) later examined a modified L_{pn}, which included a time and tone correction, calling it "Effective Perceived Noise Level" (L_{epn}), which he labeled EPNdB. Both L_{pn} and L_{epn} have been correlated with peak sonic boom levels by subjective assessment of test subjects (19-20, 48, 50).

TABLE 3. - Production blasts and airblast measurements

Shot No.	Facil- ity	Shot type	Blast design: Total charge weight, lb	Lb/ delay	Dis- tance, ft	Scaled distance: Ft/lb$^{1/2}$	Scaled distance: Ft/lb$^{1/3}$	Sound levels, dB: Peak linear 0.1-Hz high pass	Peak linear 2-Hz high pass	Peak linear 5-Hz high pass	C-slow	Per- ceived level, PLdB	Rock pres- sure pulse (RPP)	Structure response from airblast: Peak corner motion, in/sec	Peak midwall motion, in/sec	Structures monitored	Orien- tation of gage to blast free- face	Airblast type
13[1]	Quarry	High- wall.	2,033	280	400	24	61	130			105	88	111		0.70	1		1
14	..do..	..do..	4,353	218	900	61	149	125	116		<110	79	102			1		1,2
15	..do..	..do..	1,995	303	900	52	134	111	114		<90		102			2	90°	2
16	..do..	..do..	2,850	187	1,200	88	210	125				84				3		1;2
17	..do..	..do..	5,047	200	1,400	99	239	131	126	124		97			.41	1	270°	1,2
17	..do..	..do..	5,047	200	1,800	129	308	130				87	101		.28	4	270°	1,2
18	..do..	..do..	2,367	305	400	23	59	128		125			107			1		1,2
18	..do..	..do..	2,367	305	800	46	119	115					105			4		1,2
19	..do..	..do..	2,450	160	1,100	86	204	124		119		89	106			5	270°	1
19	..do..	..do..	2,450	160	1,500	119	276	116								6	270°	
21	..do..	..do..	4,240	1,470	240	6.3	21	143				103						
21	..do..	..do..	4,240	1,470	620	16.2	54	144									270°	
21	..do..	..do..	4,240	1,470	260	6.8	23	154									270°	
21	..do..	..do..	4,240	1,470	475	12.4	42		134									
21	..do..	..do..	4,240	1,470	75	2.0	6.6	140									90°	
22	..do..	..do..	3,560	790	425	15.1	46		133		116						0°	
22	..do..	..do..	3,560	790	260	9.3	28	149									270°	
22	..do..	..do..	3,560	790	610	22	66	144									270°	
22	..do..	..do..	3,560	790	290	10.3	32	139									180°	
22	..do..	..do..	3,560	790	82	3.0	8.9	140				110					90°	
23	..do..	..do..	5,540	985	210	6.7	21	143									270°	
23	..do..	..do..	5,540	985	400	12.7	40	160									180°	
23	..do..	..do..	5,540	985	705	22.4	71	153										
23	..do..	..do..	5,540	985	230	7.3	23	156	142		115	137					0°	
23	..do..	..do..	5,540	985	110	3.5	11.1	143										
24	..do..	..do..	3,500	580	750	31	75	123	120								0°	
24	..do..	..do..	3,500	580	550	23	66	139									270°	
24	..do..	..do..	3,500	580	190	7.9	23	126									180°	
24	..do..	..do..	3,500	580	250	10.4	30	130									270°	
25	..do..	..do..	4,600	790	440	15.7	48	127									0°	
25	..do..	..do..	4,600	790	550	20	60	138				104					270°	
25	..do..	..do..	4,600	790	410	14.6	45	124									90°	
25	..do..	..do..	4,600	790	550	20	60	125	117									
26	..do..	..do..	3,620	790	238	10.1	26	133									0°	
26	..do..	..do..	3,620	790	365	13.0	40	136									270°	
26	..do..	..do..	3,620	790	590	21	64	142									270°	
26	..do..	..do..	3,620	790	105	3.8	11.4	137									180°	
26	..do..	..do..	3,620	790	142	5.1	15.5	131	115	115							90°	
27	..do..	..do..	3,500	755	480	17.5	53	134									0°	
27	..do..	..do..	3,500	755	530	19.3	58	140									270°	
27	..do..	..do..	3,500	755	209	7.6	23	137									180°	
27	..do..	..do..	3,500	755	238	8.7	26	130	126	123	103						90°	
28	..do..	..do..	2,900	402	215	10.7	29	138									0°	
28	..do..	..do..	2,900	402	650	32	88	140									270°	
28	..do..	..do..	2,900	402	300	15.0	41	135									180°	
28	..do..	..do..	2,900	402	280	14.0	38	126									90°	
28	..do..	..do..	2,900	402	395	19.7	54	134		127	106						180°	
29	..do..	..do..	3,960	860	115	3.9	12.1	142									0°	
29	..do..	..do..	3,960	860	440	15.0	46	147									270°	
29	..do..	..do..	3,960	860	179	6.1	18.8	141									180°	
29	..do..	..do..	3,960	860	139	4.7	14.6	136									90°	
29	..do..	..do..	3,960	860	440	15.0	46	133		120	103						180°	
30	..do..	..do..	3,520	402	498	25	67	130	127	125								
31	..do..	..do..	4,470	115	150	14.0	31	135									0°	
31	..do..	..do..	4,470	115	645	60	133	128									270°	
31	..do..	..do..	4,470	115	130	12.1	27	132									180°	
31	..do..	..do..	4,470	115	470	44	97	123	116									
31	..do..	..do..	4,470	115	400	37	82	130									90°	
32	..do..	..do..	4,320	110	312	30	65	143										
32	..do..	..do..	4,320	110	390	37	82	142										
32	..do..	..do..	4,320	110	120	11.4	25	153										
32	..do..	..do..	4,320	110	300	29	63	144									90°	
33	..do..	..do..	8,762	700	3,300	125	372	117								7,8		
34	..do..	..do..	1,985	68	1,200	146	294	112								9		
35	Metal.	High- wall.	507,060	4,200	1,160	18	72	129					119			10	180°	
35	..do..	..do..	507,060	4,200	1,600	24.7	99				109							
35	..do..	..do..	507,060	4,200	3,440	53	213	122	116	115	97	77	100			11,12,13		
36	..do..	..do..	592,150	21,000	18,800	130	681	129	121	116	88	74			.081	14,15		2
36	..do..	..do..	592,150	21,000	7,000	48	254	132			105					16		
37	..do..	..do..	184,240	2,184	4,000	86	308	122			96		104			18		
37	..do..	Test..	2	2	4,000	2,828	3,176	117			96					17		
38	..do..	High- wall.	212,990	15,530	41,700	335	1,671	123			86		100			14		
38	..do..	..do..	212,990	15,530	42,700	343	1,712	122								15		
39	Coal..	High- wall.	20,300	2,300	3,084	64	234	122					97			19		
40	..do..	Part- ing.	648	72	6,506	767	1,564	114		113	93					19		
41	..do..	High- wall.	21,800	2,600	2,979	58	217	125					99			19		
43	..do..	..do..	20,700	2,600	2,872	56	210	124	121		93		101			19		
43	..do..	..do..	20,700	2,600	2,241	44	163	123	117		98		107			20		
44	..do..	..do..	20,600	2,300	2,757	57	209	123	119		90		100			19		
44	..do..	..do..	20,600	2,300	2,287	48	173	121			94		108			20		
45	..do..	..do..	20,700	2,300	2,651	55	201	121	115		90		98			19		

See footnotes at end of table.

TABLE 3. - Production blasts and airblast measurements--Continued

Shot No.	Facility	Shot type	Blast design: Total charge weight, lb	Blast design: Lb/delay	Blast design: Distance, ft	Blast design: Scaled distance Ft/lb$^{1/2}$	Blast design: Scaled distance Ft/lb$^{1/3}$	Sound levels, dB: Peak linear 0.1-Hz high pass	Sound levels, dB: Peak linear 2-Hz high pass	Sound levels, dB: Peak linear 5-Hz high pass	Sound levels, dB: C-slow	Sound levels, dB: Perceived level, PLdB	Sound levels, dB: Rock pressure pulse (RPP)	Structure response from airblast: Peak corner motion, in/sec	Structure response from airblast: Peak midwall motion, in/sec	Structures monitored	Orientation of gage to blast free-face	Airblast type
45	..do..	..do..	20,700	2,300	2,347	49	178	120	114	113	93	75			0.020	20		2
46	..do..	Ditch.	3,600	600	2,231	91	265	111	113				87			19		
46	..do..	..do..	3,600	600	1,753	72	208				88					20		
47	..do..	Highwall.	21,600	2,600	2,535	50	184	123	120		87		98			19		
47	..do..	..do..	21,600	2,600	2,413	47	176		115		90					20		
48	..do..	..do..	20,600	2,300	2,430	51	184	120	117		89		99			19		
48	..do..	..do..	20,600	2,300	2,480	52	188		113		92					20		
49	..do..	..do..	19,800	2,200	2,548	54	196	117	109		87		105			20		
50	..do..	..do..	19,700	2,200	2,617	56	201	119	114		91		105			20		
51	..do..	..do..	19,300	2,200	2,687	57	207	113	110		84		103			20		
52	..do..	Parting.	384	24	3,347	683	1,162		106		87					20		
53	..do..	..do..	264	24	3,042	621	1,055	108	106		88					20		
54	Coal..	Parting.	360	36	2,547	425	772	>113	108	112	93					20		
55	..do..	Highwall.	18,400	2,100	2,764	60	216	118	112		85		103			20		
56	..do..	..do..	17,700	2,000	2,843	64	226	116	111		84		103			20		
57	..do..	..do..	6,000	2,000	2,912	65	231	114	110		89		98			20		
58	..do..	Parting.	480	30	2,434	444	782				97					20		
59	..do..	..do..	294	30	4,314	788	1,389		117		98					19		
60	..do..	Highwall.	21,400	2,000	1,696	38	135	125					111			19		
61	..do..	..do..	24,700	2,100	1,608	35	125		127		104					19		
62	..do..	Sweetner.	1,500	150	1,696	138	318	127	127	124	99	74		.13	.40	19		1
63	..do..	Parting.	384	24	4,127	842	1,431	112	115	112	96					19		
64	..do..	Highwall.	24,600	2,100	1,501	33	117	128	122	120	100	87	111		.53	19		1,2
65	..do..	..do..	15,700	2,200	1,428	30	110	126	124		97		111			19		
66	..do..	..do..	15,800	1,900	1,339	31	108	128	126		102		115			19		
67	..do..	..do..	13,540	1,900	1,248	29	101	129	126	123	103	73	107		.70	19		1,2
68	..do..	Parting.	300	30	3,904	713	1,256	107	108	106	83					19		
69	..do..	Highwall.	11,040	2,000	1,160	26	92	121	117		96		110			19		
70	..do..	Sweetner.	2,100	300	1,485	86	222	129	126	124	101	87		.06	.56	19		2
71	..do..	Hilltop.	9,020	410	1,359	67	183	131	129	125	103	87	97	.11	.28	19		1,2
72	..do..	Ditch.	3,060	510	2,096	93	263	113	111				88			19		
73	..do..	Highwall.	19,600	2,000	1,093	24	87	132	128		105					19		
74	..do..	..do..	17,100	2,000	1,011	23	80	129	125				114			19		
75	..do..	Ditch.						118	114		89		92			19		
76	..do..	..do..	3,360	280	1,549	93	238	126	123				<90			19		
77	..do..	..do..	1,200	220	1,519	102	251	117	115		90					19		
78	..do..	Highwall.	22,200	2,100	928	20	72	129	124	120	103	95	114		1.10	19		1
79	..do..	..do..	24,900	2,200	853	18.2	66	132	129	126	107	91	120		1.18	19		1,2
80	..do..	..do..	25,100	2,300	801	16.7	61	132	127	124	108	93	109		1.50	19		1,2
81	..do..	Sweetner.	3,240	360	699	37	99	126	126	123	106	99	98		.70	19		1,2
82	..do..	Hilltop.	27,000	1,000	699	22	70		133				112			19		
83	..do..	Ditch.	2,040	340	1,487	81	213	122	120		99					19		
84	..do..	Highwall.	25,600	2,200	754	16.1	58	134	130	126	116	108	>110		1.40	19		2
85	..do..	..do..	25,400	2,200	732	15.6	56	133	128	125	109	97	120	.22	1.04	19		2
86	..do..	..do..	25,900	2,200	716	15.3	55	135	132	130	107	92	119	.24	2.50	19		2
87	..do..	Ditch.	1,320	220	1,459	98	241	120	120		95		88			19		
88	..do..	Parting.	360	36	2,593	433	786	125			108					19		
89	..do..	..do..	360	36	2,229	372	675	114			94					19		
90	..do..	Highwall.	25,500	2,200	720	15.4	55	129	124	120	104	86	121		.49	19		2
91	..do..	..do..	31,500	2,200	738	15.7	57	132	128		105		119			19		
92	..do..	Ditch.						131	129	128	104	93	93	.12	.58	19		1
93	..do..	Parting.	114	12	2,167	626	947	110	109	111	94					19		
94	..do..	Highwall.	30,700	2,200	800	17.1	62	133	130	127	104	88	108		.30	19		2
95	..do..	..do..	26,600	2,200	840	17.9	65	128	123	120	101	83	114		.59	19		2
96	..do..	..do..	20,500	2,000	906	19.3	72	132			102		115			19		
97	..do..	..do..	9,000	450	2,500	118	326	119	115		91					21		
98	..do..	..do..	14,400	450	2,700	127	352	120	121		95					21		
99	..do..	Parting.	20,880	773	1,400	50	153	128	125	123	96	88	99		.72	21		2
100	..do..	..do..	18,000	200	750	53	128	118	114	112	97		112			21		
101	..do..	..do..	17,500	350	1,800	96	255	121	120	118	102	83	98	.10	.91	21		1
102	..do..	..do..	27,040	208	700	48	118	119	120		100		117			21		
103	Quarry	Highwall.	4,956	632	1,558	62	182	122		121	94	84	103	.070	.28	22	0°	

See footnotes at end of table.

TABLE 3. - Production blasts and airblast measurements--Continued

Shot No.	Facility	Shot type	Blast design: Total charge weight, lb	Blast design: Lb/delay	Blast design: Distance, ft	Blast design: Scaled distance Ft/lb$^{1/2}$	Blast design: Scaled distance Ft/lb$^{1/3}$	Sound levels, dB: Peak linear 0.1-Hz high pass	Sound levels, dB: Peak linear 2-Hz high pass	Sound levels, dB: Peak linear 5-Hz high pass	Sound levels, dB: C-slow	Sound levels, dB: Perceived level, PLdB	Sound levels, dB: Rock pressure pulse (RPP)	Structure response from airblast: Peak corner motion, in/sec	Structure response from airblast: Peak midwall motion, in/sec	Structures monitored	Orientation of gage to blast free-face	Airblast type
103R[4]	..do..	..do..	4,956	632	1,558	62	182	124	120	121	98	88	103	0.089	0.65	22	270°	
103	..do..	..do..	4,956	632	701	28	82	133	132	130	106	99	110	.25	.60	23		
103R[3]	..do..	..do..	4,956	632	701	28	82	131			108	92	110	.16	.87	23	270°	
104	..do..	..do..	5,752	632	1,481	59	173	121			<90					22	270°	
104	..do..	..do..	5,752	632	646	26	76	133								23	270°	
105	..do..	..do..	4,350	615	550	22	64	132	130	126	101	89	113	.34	.46	23	0°	
105R[2]	..do..	..do..	4,350	615	550	22	64	126			103	87	113	.10	.40		270°	
106	..do..	..do..	17,604	852	4,208	144	443	133	124		<100					24	270°	
106	..do..	..do..	17,605	852	2,304	79	243	121	113		<90		102			25	90°	
107	Coal..	Highwall.						127	123		100		105			26	90°	
108	..do..	..do..						122					112			28	90°	
109	..do..	..do..		300	1,811	105	271	105			<80					29	90°	
110	..do..	Parting.	21,600	240	800	52	129	118	115	116	98		114			21		
111	..do..	..do..	112,200	320	1,000	56	146	120	122	121	98		106			21		
112	..do..	Highwall.		300	1,409	81	210	111	111		<90		103			30	90°	
113	..do..	Parting.	112,200	320	1,100	61	161	120	120	117	96		112			21		
114	..do..	..do..	23,680	370	1,300	68	181	119	113	114	94		105			21		
115	..do..			21	1,801	393	653	124								31	90°	
116	..do..	Highwall.	12,000	300	652	38	97	114	117		94		105			31	90°	
117	..do..	Parting.	14,400	360	3,000	158	422	120	112	114	92					21	90°	
119	Quarry	Highwall.	16,608	782	4,301	154	467	124	123		<90					32	270°	
120	Coal..	..do..	15,120	120	1,443	132	293		115		92					29	90°	
122	..do..			15	1,698	439	689	122	111		<90		97			28	90°	
124	..do..	Parting.	1,340	20	2,000	447	737	130			111			.09	1.77	33	90°	
125	..do..	Highwall.	10,200	200	2,000	141	342	114	113	112	95					33		
126	..do..	Parting.	1,200	20	1,750	391	645	136	135	133	115	103		.14	1.71	34		
127	..do..	Highwall.	12,000	400	..do.	88	238	108	106							34		
128	..do..	Parting.	1,500	20	3,250	727	1,197	127	127	125	102	89	98	.13	1.80	35		
129	..do..	Highwall.	15,000	350	3,100	166	440	113					94			35		
130	..do..	Parting.	890	20	1,750	391	645	127	128	127	107	91		.040	1.09	34		
131	..do..	Highwall.	10,800	400	1,750	88	238	111	108							34		
132	..do..	Parting.	1,300	30	1,200	219	386	130	130	131	113					33		
133	..do..	Highwall.	24,000	400	1,200	60	163	98								33		
134	..do..	Highwall.	2,300	400	2,000	60	163	113	113	111	92		106			33		
135	..do..				2,000			127					113			21		
136	..do..	Parting.	29,700	900	500	16.7	52	126	128	125	108					21		
137	..do..	Parting.	2,300	20	2,000	447	737	122		122	97					33		
138	..do..	..do..	2,300	20	2,000	447	737	119		119	98		106			33		
139	..do..	Highwall.	19,200	400	2,000	100	271	116	116				97			33		
140	..do..	Parting.	1,000	20	3,500	783	1,289	116	116	113						35		
141	..do..	..do..	1,000	20	2,400	537	884	124	125	123	101	86		.025	.86	36		
142	..do..	..do..	1,000	20	2,400	537	884	121		119	95					36		
143	..do..	Highwall.	40,000	400	2,400	120	326	111					94			36		
144	..do..	Parting.	2,400	10	2,400	759	1,114	118	115	113	92					36		
145	..do..	Highwall.	40,000	400	2,400	120	326	109	106		82		91			36		
146	Iron mine.	Highwall.	573,610	4,580	5,800	86	350	117	112	108	87	62	104		.15	17,18		2
146	..do..	..do..	573,610	4,580	6,400	95	387	116	111		85		104			37		
147	..do..	..do..	524,030	8,800	6,900	74	336	131	123		93		102			38,39		
148	..do..	..do..	593,720	8,230	6,730	74	332	131	127	124	95	81	94	.12	.47	38,40		1
149	..do..	..do..	58,000	2,500	11,050	221	814	117	112		86					41		

See footnotes at end of table.

TABLE 3. - Production blasts and airblast measurements--Continued

Shot No.	Blast design: Facility	Blast design: Shot type	Blast design: Total charge weight, lb	Blast design: Lb/delay	Blast design: Distance, ft	Blast design: Scaled distance Ft/lb^1/2	Blast design: Scaled distance Ft/lb^1/3	Sound levels, dB: Peak linear 0.1-Hz high pass	Sound levels, dB: Peak linear 2-Hz high pass	Sound levels, dB: Peak linear 5-Hz high pass	Sound levels, dB: C-slow	Sound levels, dB: Perceived level, PLdB	Sound levels, dB: Rock pressure pulse (RPP)	Structure response from airblast: Peak corner motion, in/sec	Structure response from airblast: Peak midwall motion, in/sec	Structures monitored	Orientation of gage to blast free-face	Airblast type
150	..do..	..do..	184,500	3,260	5,820	102	393	127	123	120	94	84	92	0.082	0.246	37		2
152	Coal..	..do..	3,585	255	2,110	132	333	111			88					42		
153	..do..	..do..	3,783	152	2,110	171	395	117	105		90		106			42		
154	..do..	..do..	3,000	125	575	51	115	125	121	118	97	82	107		.85	43		
155	..do..	..do..	5,400	120	475	43	95	122	121				102			44		
156	..do..	..do..	3,600	80	365	41	85	126	122				109			44		
157	..do..	..do..	4,500	75	1,100	127	261	115		112	94					45		
157	..do..	..do..	4,500	75	450	52	107	124			96					46		
158	..do..	..do..	2,460	41	1,150	180	334	112		108			91			45		
158	..do..	..do..	2,460	41	360	56	104	123	122		98		110			46		
159	..do..	..do..	920	23	1,200	250	422	104		106	86		88			45		
159	..do..	..do..	920	23	250	52	88	125	123		102		108			46		
160	..do..	..do..	5,460	78	450	51	105	119		116	98		94			47		
161	..do..	..do..	3,280	41	215	34	63	130	130	128	112	94			1.25	48		
162	..do..	..do..	13,040	602	1,500	61	177	119	112		<90		102			49		
163	Iron mine.	..do..	210,600	8,530	600	6.5	29	155	154	152	129		129	1.19	3.78	50		
164	Coal..	..do..	3,510	351	835	45	119	121	119		97	85	98		.40	49		
165	..do..	..do..	4,914	351	815	44	116	115			<90					49		
166	..do..	..do..						117			91		101			49		
167	..do..	..do..	1,750	35	301	51	92	119	119		97		107			51		
168	..do..	..do..	4,300	86	250	27	57	128			108		112			51		
169	..do..	..do..	4,300	86	178	19.2	40	129		127	108		112			51		
170	..do..	..do..	4,300	86	150	16.2	34	129		127	>110		115			51		
171	..do..	..do..	1,775	71	150	17.8	36	129		127	105		115			51		
172	..do..	..do..						120			<90		103			49		
173	..do..	..do..	2,150	86	249	27	56	122	125		101		107			51		
174	..do..	..do..	4,300	86	192	21	44				106		112			51		
175	..do..	..do..	5,150	212	144	9.9	24	135	134	135	112		124			51		
176	..do..	..do..	3,550	71	58	6.9	14.0	133		132	114		121			51		
177	..do..	..do..	3,240	36	58	9.7	17.6	127		126	110					51		
178	..do..	..do..	1,320	33	260	45	81	121	119		<100					51		
179	..do..	..do..	2,145	33	180	31	56	128	124	125	,103					51		
180	..do..	..do..	1,620	18	17	4.0	6.5	137	133	135	112					51		
181	..do..	..do..	1,980	22	87	18.5	31	136	125	128	104					51		
182	..do..	..do..	1,620	18	14	3.3	5.3	132	129	131	110					51		
183	..do..	Contour.	2,375	125	2,300	206	460	106								52		
184	..do..	..do..	18,500	200	2,600	184	445	121	116		<90					53		
185	..do..	..do..	545	5	600	268	351	110	110	109	91							
186	..do..	..do..	350	35	750	127	230	105			<90		87			54		
187	..do..	..do..	350	35	750	127	230	108	108		86		81			54		
188	..do..	..do..	9,450	175	1,500	113	268	117	117		94							
189	..do..	..do..	360	40	750	119	220	121	121		94		89			54		
190	..do..	..do..	720	40	750	119	220	105			86		87			54		
191	..do..	..do..	400	40	750	119	220	118	116		93		89			54		
192	..do..	..do..	960	40	750	119	220	106			84		84			54		
193	..do..	..do..	9,780	60	280	36	71	125			101					55		
194	..do..	..do..	320	40	1,100	174	322	111	108		87					56		
195	..do..	..do..	424	40	1,100	174	322	106	105		85					56		
196	..do..	..do..	680	40	1,100	174	322	113	111		90					56		
[3]C-1	..do..	Highwall.	6,000	500	851	38	107	117								27	90°	
C-2	..do..	..do..	7,200	600	796	33	94	123								27	90°	
C-3	..do..	..do..	7,800	650	743	29	86	125								27	90°	
C-4	..do..	..do..	7,200	1,200	695	20	65	131	127	128	108	100			.53	27	90°	1
C-5	..do..	..do..	7,800	1,300	652	18.1	60	139	138	135	112	103	109	.58	2.30	27	90°	Blowout
C-6	..do..	..do..	7,800	650	615	24	71	121					111			27	90°	
C-7	..do..	..do..	7,800	650	585	23	68	127								27	90°	
C-9	..do..	..do..	6,600	550	552	22	67	127								27	90°	
C-10	..do..	..do..	5,400	450	555	26	72	132	132	129	108	96	113	.20	.64	27	90°	1
C-11	..do..	..do..	3,600	300	564	33	84	126								27	90°	

[1]The first 12 shots were for instrumentation-calibration only.
[2]R = Airblast which had been reflected from the highwall accross the pit.
[3]Additional shots, not to be confused with the calibration shots previously mentioned.

Young (85) examined human tolerance to impulsive sources designed to simulate artillery firing. He used sound exposure levels (L_{SC}, L_{SA}, L_{D2}, for C, A, and D_2 weightings, respectively). C-weighted sound exposure levels, also labeled variously L_{CE} and CSEL, have been suggested as appropriate discriptors for assessing structure response from airblast (17, 46, 53, 60). Although it is recognized that the C-weighting cuts off the low frequencies above the house response frequencies, it is the closest of the standardized sound weightings to the desired frequency range.

One advantage of L_{SC} methods for regulating blast noise is that they are normalized to 1 second, which penalizes excessively long events (3 dB per doubling of duration), and allows higher levels for short duration events. Direct measurement of L_{SC} is complex. Kamperman (17) states that standard sound level meters on slow response can be used to measure L_{SC} and L_{SA} for events up to 1-second duration, within 2 dB accuracy.

Schomer (46) and von Gierke (70) have used day-night average sound levels, L_{dn}, to characterize the annoyance potential of impulsive sources involving long-term averages. This requires a minimum of 24-hour integration and both C-weighting (46, 70) and A-weighting (46). This technique may be applicable to quasi-static sources (a pile driver), but is probably not meaningful for infrequent blasting.

Higgins and Carpenter (14) analyzed Perceived Levels (PLdB) which are calculated from factors of sonic boom sharpness, such as rise time and peak values. The authors also give PLdB values for various levels of acceptability.

Airblast Processing For Structure Response

Airblast time histories were recorded with a system having ±3 dB linearity of at least 0.1 to 380 Hz as described in the section on survey instrumentation. Early tests with a 0.1- to 8,000-Hz sonic boom system (B&K 2631) verified that little significant airblast energy was present above 100 Hz at the distance of concern. Time histories from shot No. 86, with three components of ground vibrations, three corner motions, two midwalls, and the outside airblast appear in figure 28. The structure responded to both ground vibration and the airblast. As was typical, most corner responses were of lesser particle velocity amplitude than the incoming ground vibration. This was also true for measurements made in lower, upper, and second floor corners. The mid-height corner measurement appears to be a combination of corner and midwall responses. Midwalls experienced roughly equal amounts of ground vibration and airblast produced vibration response for this particular shot. Isolating the airblast effects requires good time separation between the two kinds of vibration, as well as an airblast of sufficiently high-level and high-frequency energy (for example, 10 Hz as in shot 86).

Many of the linear airblasts, including all which produced measureable structure responses, were further processed in order to determine the most

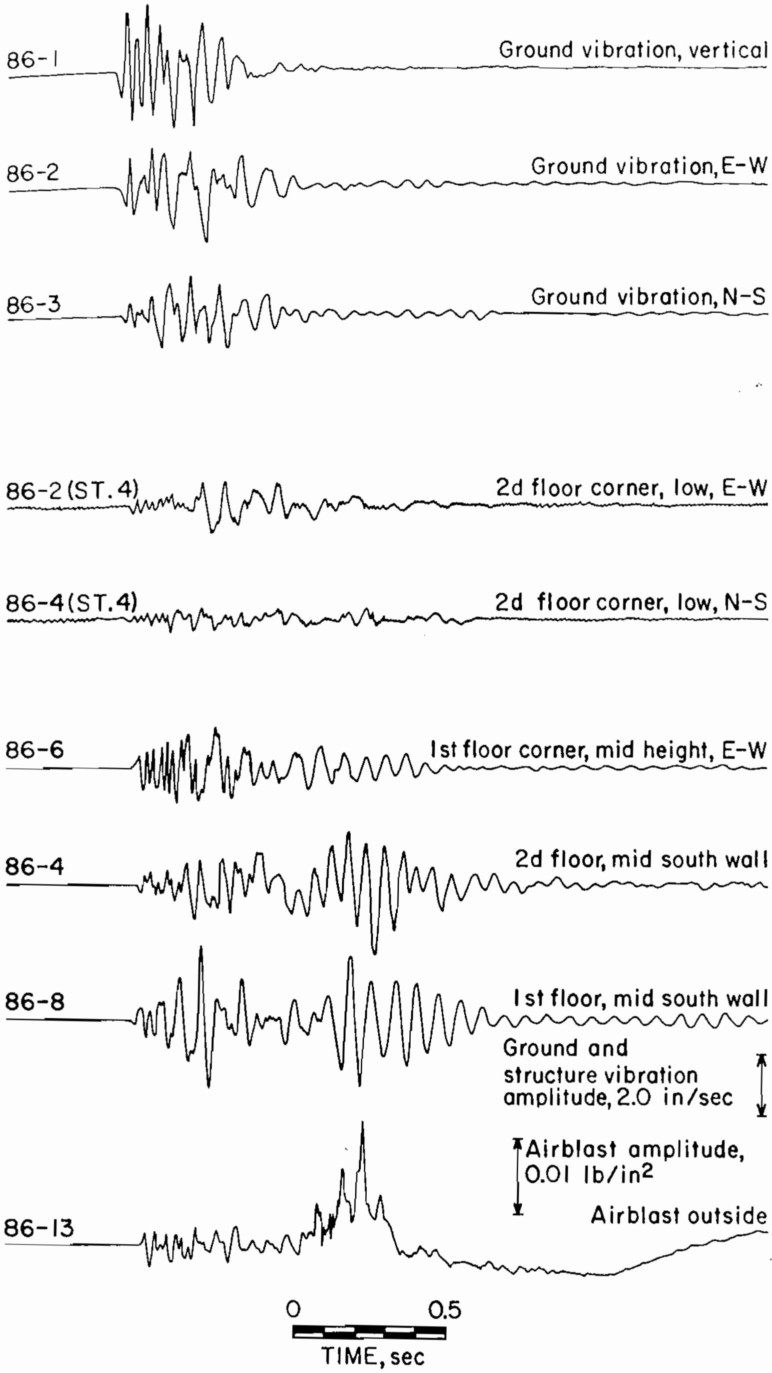

FIGURE 28. - Ground vibration, structure vibration, and airblast time histories from a coal mine highwall shot (shot 86).

appropriate structure-response descriptors (table 3). Playback of linear records through the two commercial sound-level meters gave "linear" sound levels with 2-, 5-, and 6-Hz low-frequency cutoffs. These laboratory-derived values agreed well with direct field sound level measurements made with the same meters (typically ±1 dB). Much of the airblast energy is below the low-frequency cutoffs of the linear range, and phase distortion as well as filtering will occur. However, the RMS value quantifies the energy in the airblast and is independent of phase distortion. Therefore, sound exposure levels (RMS values) with both special filtering and C-weighting were determined. A 0.1-Hz linear airblast time history with 500 msec of RPP and a combination type 1 and 2 APP character is shown in figure 29. The 5-Hz highpass (low frequency, 3 dB cut-off) removes the dominant low frequency (≈1 Hz), also distorting the waveform. C-weighting further filters the airblast's low frequencies, and the 1-sec averaging of the C-weighted sound would be dominated by the RPP in this case.

Sound exposure levels were determined by an RMS detecting and filtering system described by Stachura (61) and defined by:

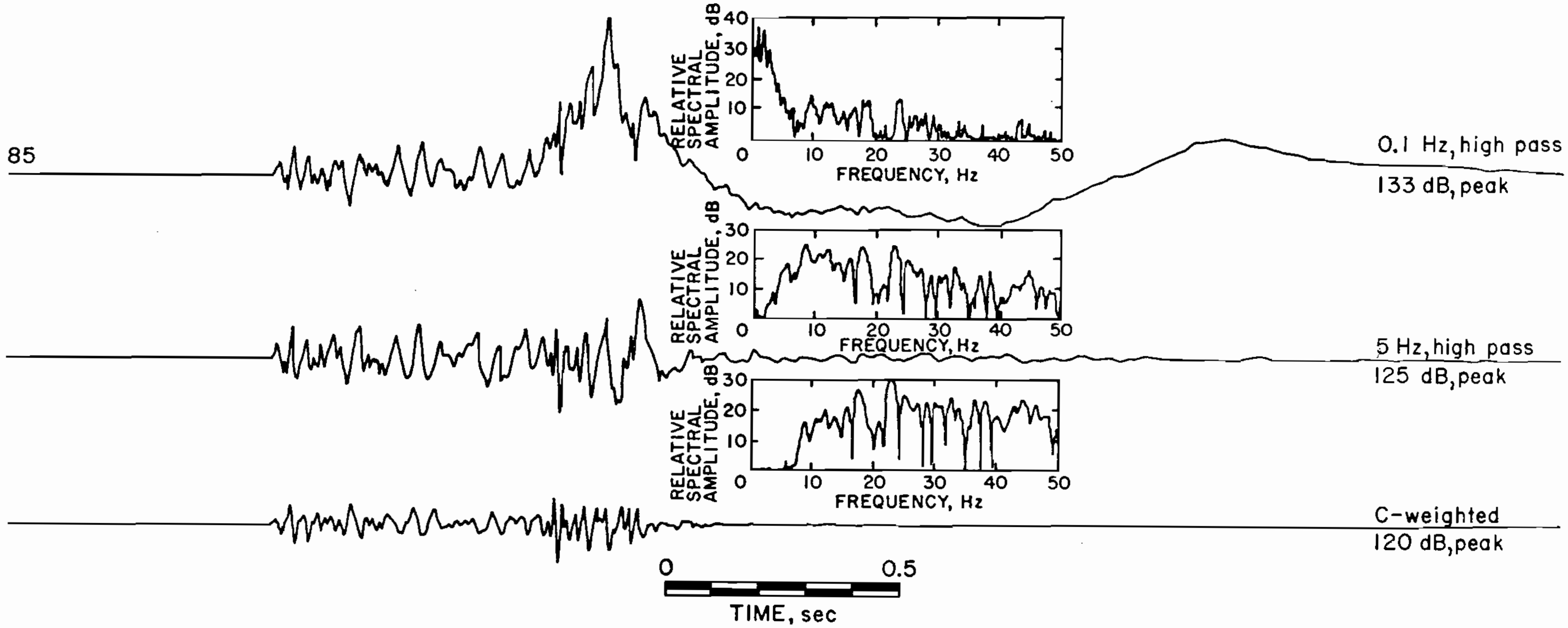

FIGURE 29. - Filtering of a complex airblast from a highwall production blast (shot 85).

$$L_s = 10 \log_{10} \left[\frac{1}{t_o} \int \frac{P_w^2}{P_o^2} \, dt \right],$$

where t_o = 1 second, p_w = weighted sound pressure, and $p_o = 20 \times 10^{-6}$ N/m^2. Analysis was made of the standard C-weighting sound levels as well as 3.5-10 Hz, 10-24 Hz, and 4-40 Hz band pass, with integration times of 1/8, 1/4, 1/2, and 4 seconds. These values plus peak 0.1-, 2, 5, and 6-Hz linear sound levels were correlated with peak corner and midwall motions, and also with the structures velocity exposure levels (VEL) determined with the various filtering and integration times used for SEL (see "Structure Response"). SEL values are given in table A-1.

Percieved levels (PLdB) were also calculated and included in table 3 for those airblasts with observable structure response, using the Higgins and Carpenter (14) formula:

$$\text{PLdB} = 55 + 20 \log_{10} \frac{\Delta p}{\tau},$$

where Δp = pressure change, in pounds per square foot, and τ = rise time, in seconds, corresponding to Δp.

PROPAGATION AND GENERATION OF AIRBLASTS

Much research has been done on airblast generation (72, 75-78) confinement and depth of burial effects (36, 40, 42, 73 -74), airblast propagation (24, 34, 36, 39, 42-44, 58, 77, 81), and weather influences on airblast levels and character (2, 11, 18, 36, 37, 39, 50). Much of this work applies only indirectly to airblast from mining, since the experiments were designed to study other situations. A comprehensive study was recently completed by Wiss which examined many of the blast design and environmental factors influencing the generation and propagation of surface mine-produced airblast and ground vibration (83). Bureau of Mines and other research on airblast generation and propagation are described in Appendix B, Blast Design and Airblast Generation; Appendix C, Weather Effects on Propagation; and Appendix D, Terrain Effects on Propagation.

STRUCTURE RESPONSE FROM AIRBLAST

The response of structures, primarily residential, is the most critical indicator of troublesome or potential damaging airblast. There is little direct evidence that infrequent short-duration impulsive noises contribute directly to annoyance. All studies at occupied houses have found that damage and fear of damage are of primary concern. Some sonic boom tolerance tests indicate that booms may have a relatively different effect than airblasts on humans inside and outside structures, and that for sonic booms, an annoyance criterion may be more appropriate than a damage criterion. Relevant to the airblast problem are the whole-building response (corner measurements indicating racking effects on the frame) and midwall responses (best correlated with secondary effects; such as window sashes rattling, dishes and knick-knacks falling, etc.).

Measured structural response from mine and quarry airblasts are shown in figures 30 through 37. They are separated into corner and midwall responses

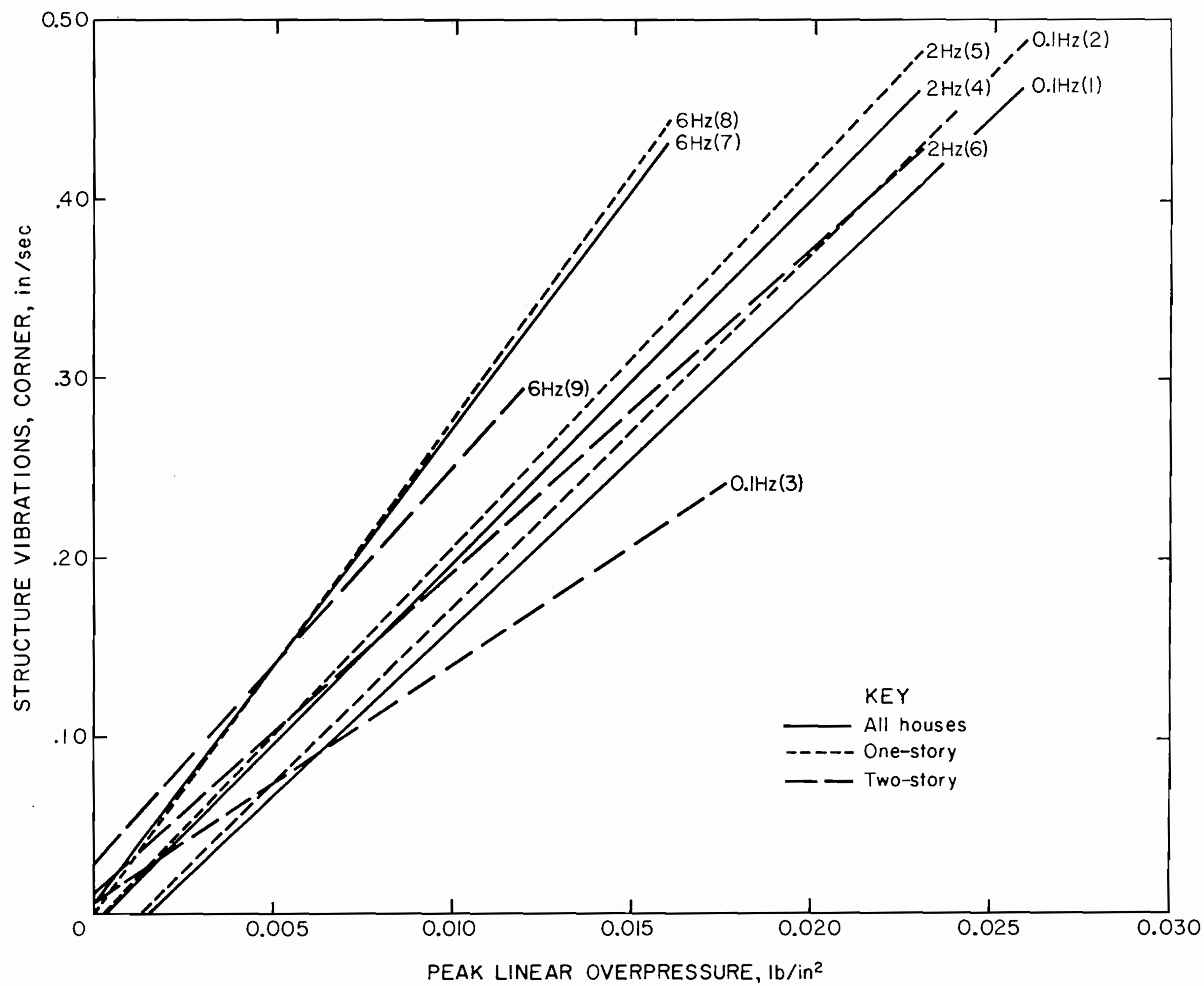

FIGURE 30. - Structure responses (corners) from peak linear overpressures, regressions. (Numbers in parentheses correspond to regression lines in table 4.)

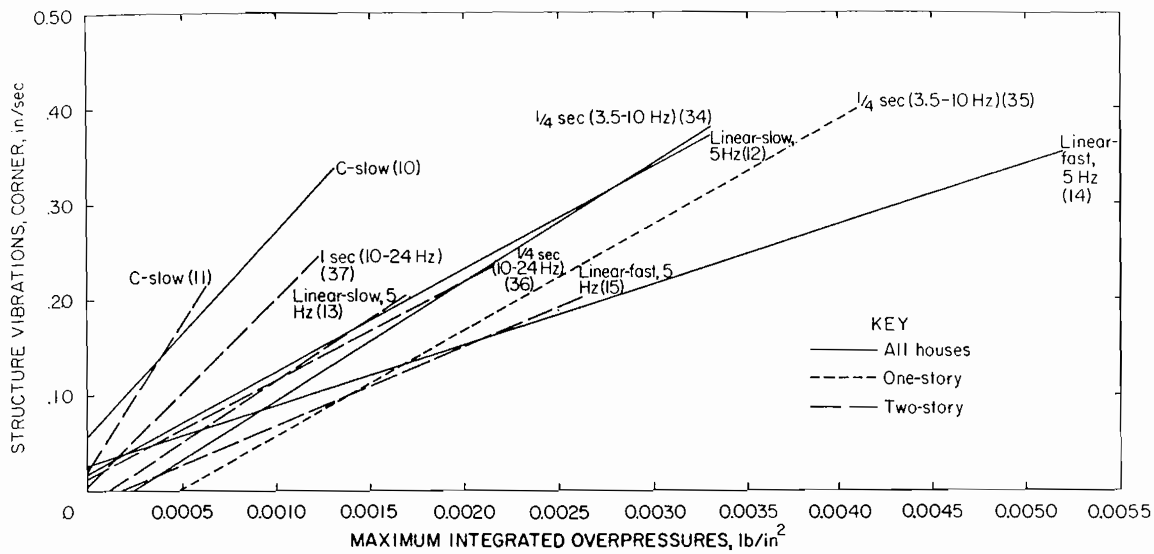

FIGURE 31. - Structure responses (corners) from maximum integrated overpressures, regressions. (Numbers in parentheses correspond to regression lines in table 4.)

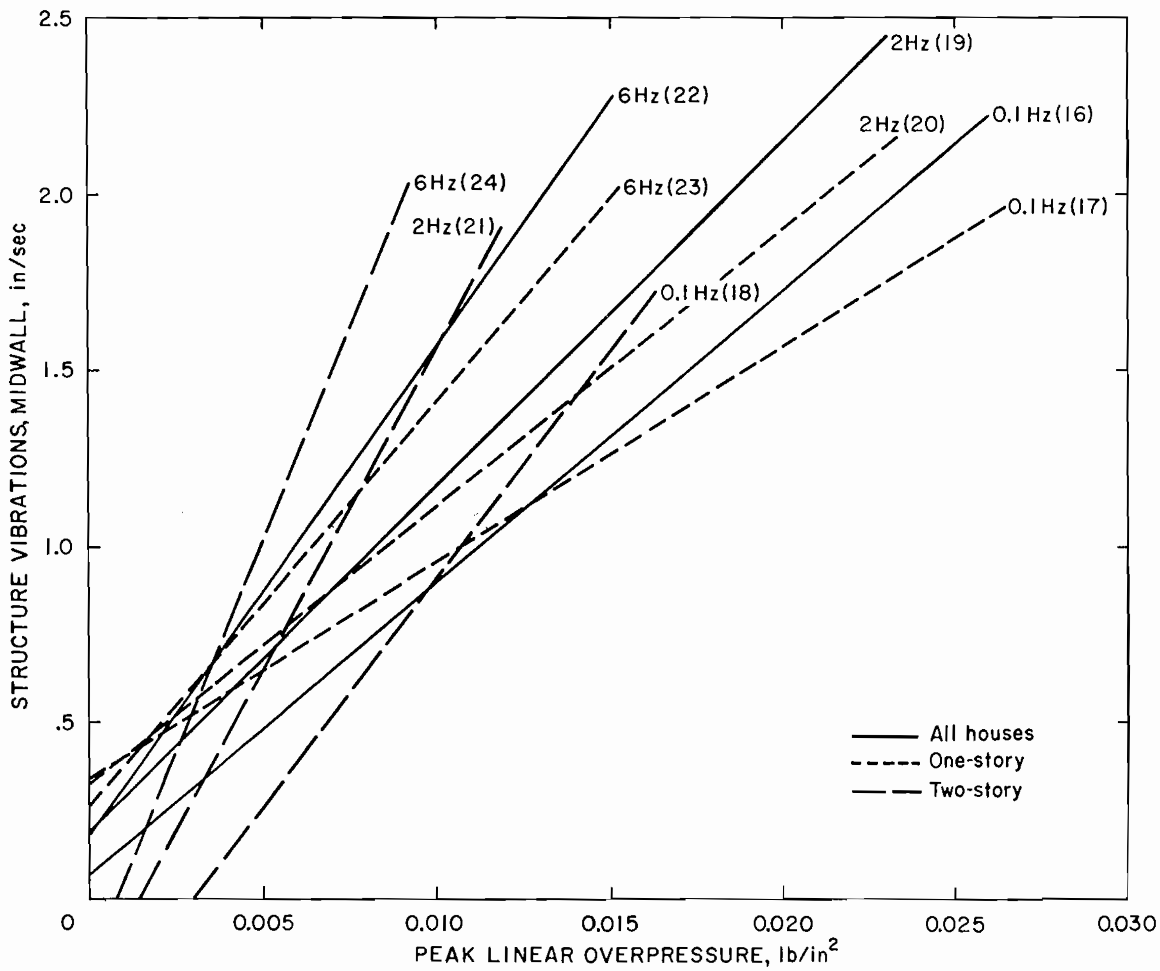

FIGURE 32. - Midwall responses from peak linear overpressures, regressions. (Numbers in parentheses correspond to regression lines in table 5.)

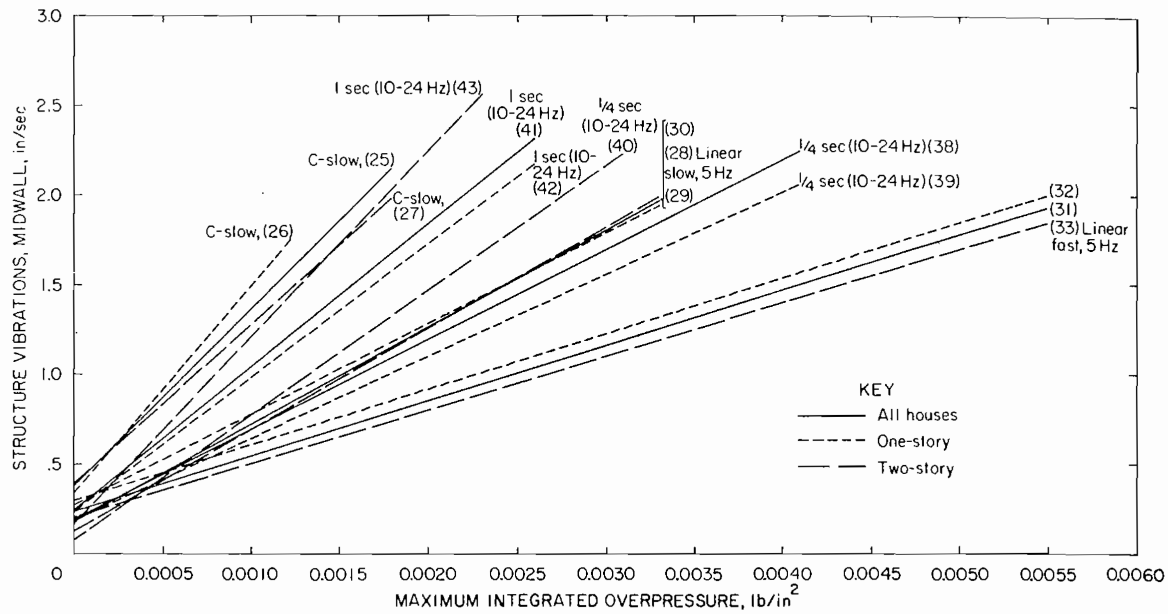

FIGURE 33. - Midwall responses from maximum integrated overpressures, regressions. (Numbers in parentheses correspond to regression lines in table 5.)

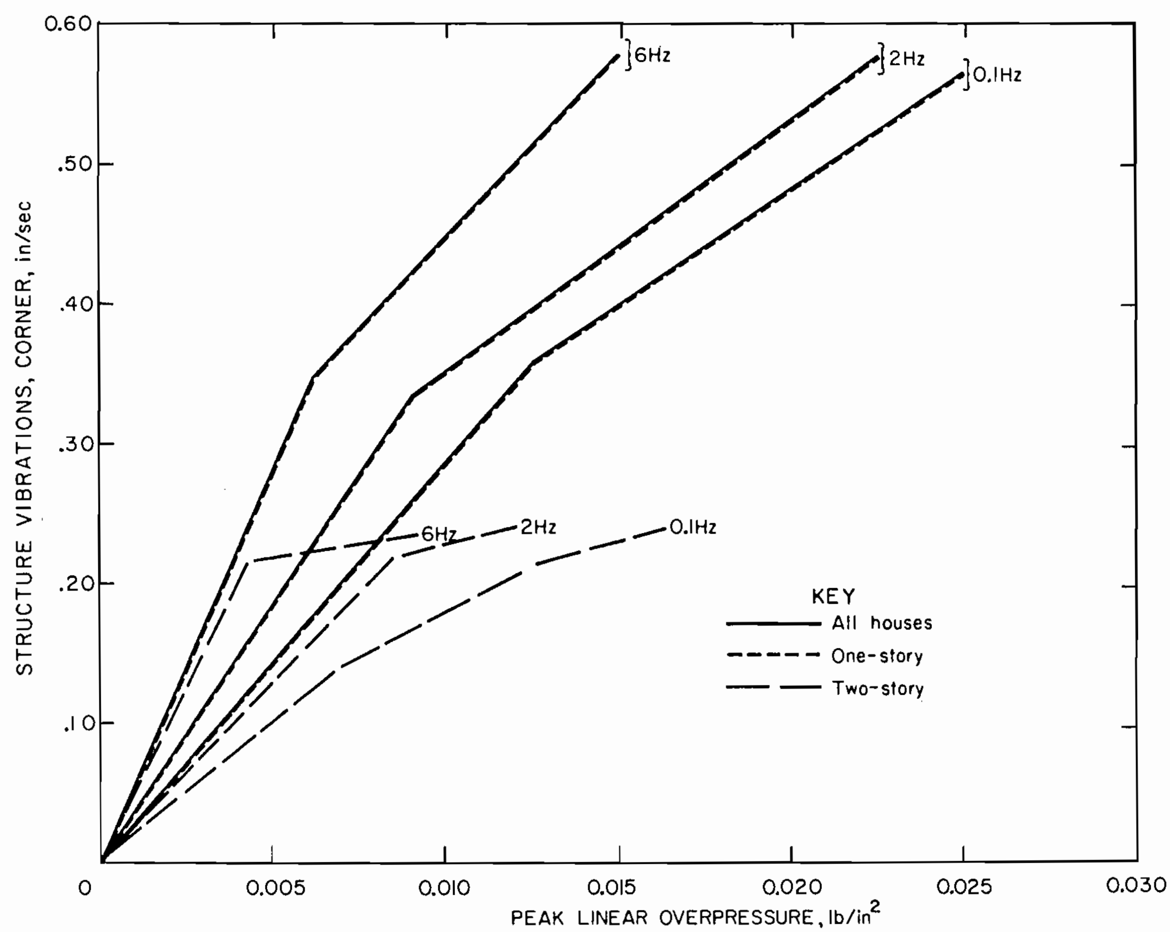

FIGURE 34. - Structure responses from peak overpressures, envelopes of maximum value.

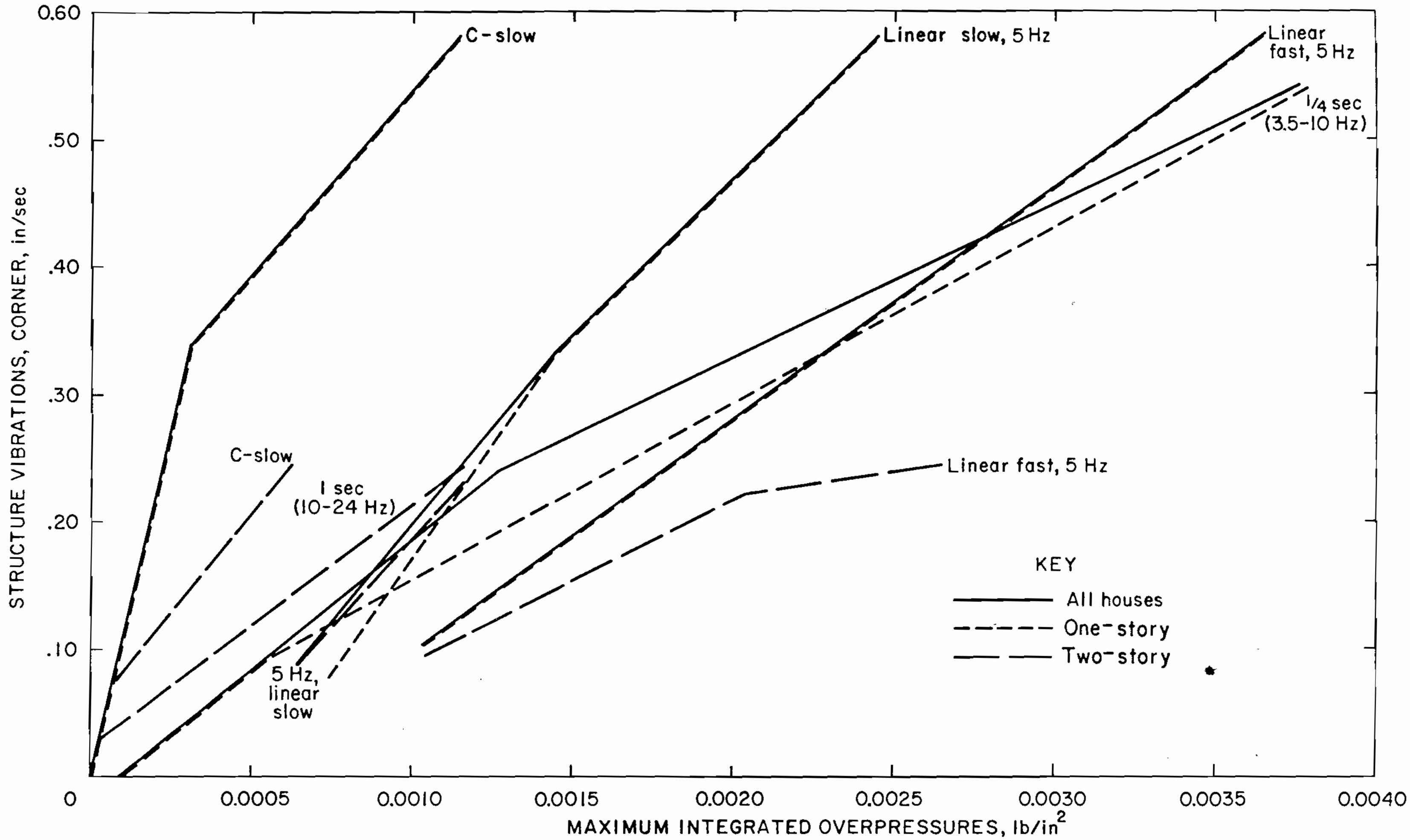

FIGURE 35. - Structure responses from maximum integrated overpressures, envelopes of maximum values.

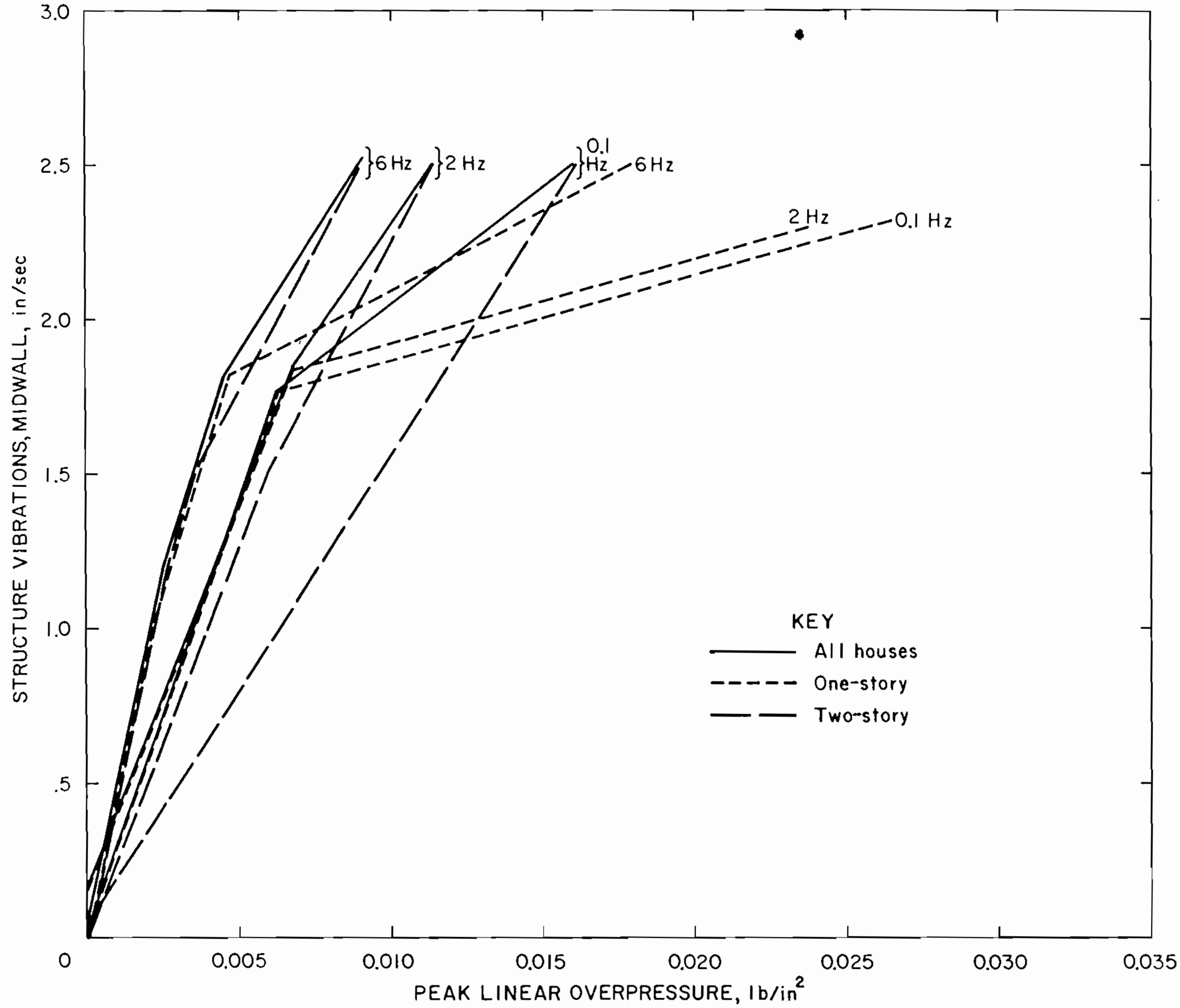

FIGURE 36. - Midwall responses from peak overpressures, envelopes of maximum values.

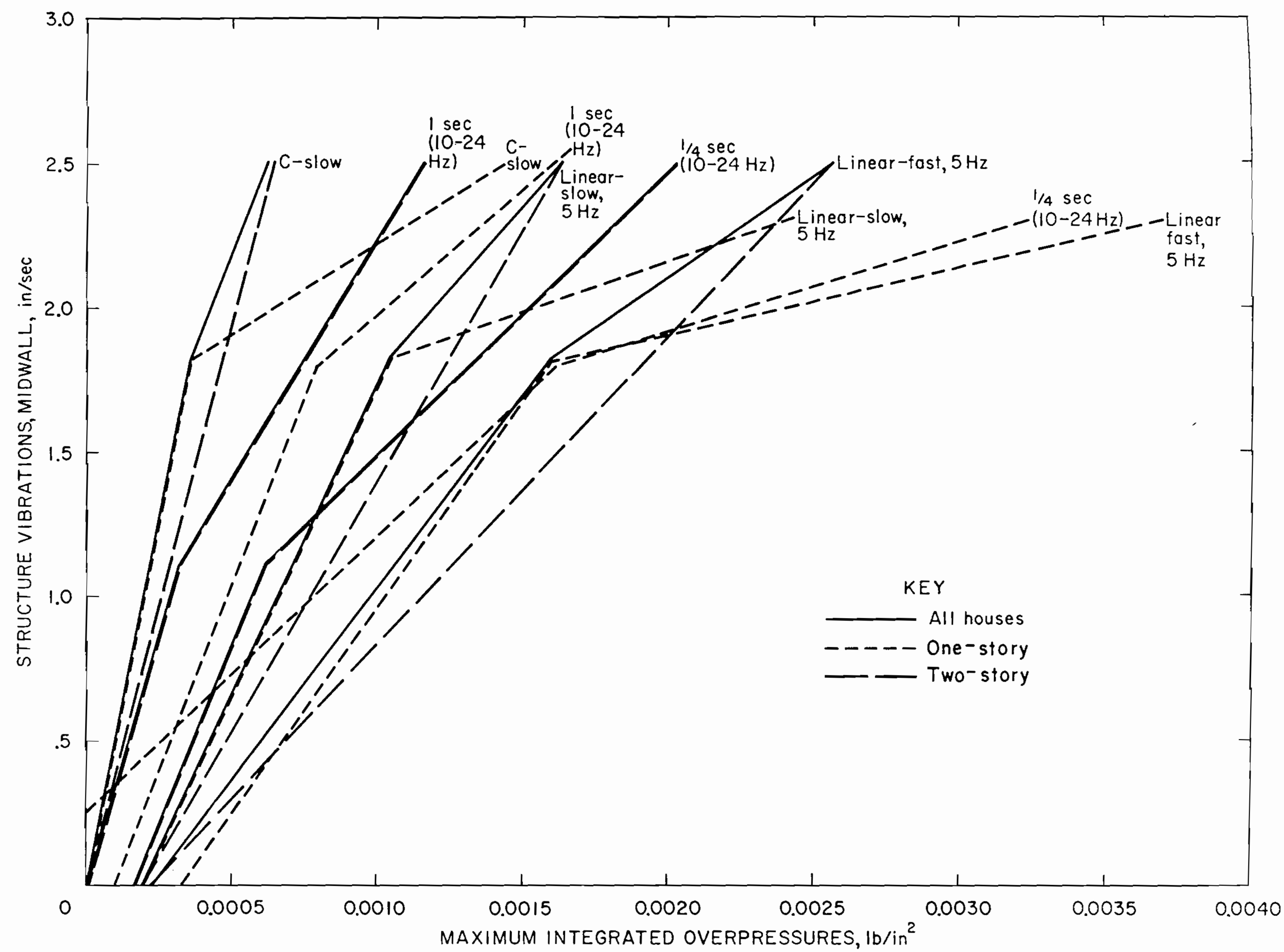

FIGURE 37. - Midwall responses from maximum integrated overpressures, envelopes of maximum values.

of one-story, two-story, and all homes, and the best of the 27 sound descriptors studied. (The airblast values used in the response plots are given in table 3.) A total of 222 correlations were made between measured responses and the various airblast descriptors. Those with the highest correlation coefficients and lowest standard errors (standard deviations) were plotted in figures 30 through 33; the equations and statistics for the plots are in tables 4 (corner or structural) and 5 (midwall). The remaining correlations are given in appendix tables E-1 (peak structural responses), E-2 (integrated structural responses), E-3 (peak midwall responses), and E-4 (integrated midwall responses). No standard error bars are shown on the response curves to avoid confusion; however, the values are given in tables 4-5, and E-1 through E-4. Comparisons were required between the various descriptors, some of which involved operations on the dependent variable. Therefore, a normalized standard error was calculated by dividing the standard error by the mean of the dependent variable. Comparisons between the descriptors of peak structure motions (tables 4-5, E-1 and E-3) and the integrated structure motions (tables E-2 and E-4), and also between the various integrated methods, require examination of the normalized standard errors. However, the statistics for peak structure motions can be compared using either the normalized or conventional standard error values.

TABLE 4. - Equations and statistics for peak corner structure vibration (SV) responses from airblasts - best results

		Equation[1]	Correlation coefficient	Standard error	Normalized standard error	Regression line
		ALL HOMES				
Peak SV (corner) versus	Peak AB (0.1 Hz)....	SV=-0.0274 + 18.8 AB	0.824	0.0760	0.458	1
	Peak AB (2 Hz)......	SV=- .0044 + 20.9 AB	.795	.0820	.482	4
	Peak AB (6 Hz)......	SV= .0073 + 26.6 AB	.676	.100	.586	7
	Maximum C-slow AB...	SV= .0584 +213 AB	.537	.114	.671	10
	Maximum linear-slow AB (5 Hz).	SV= .0166 +107 AB	.535	.112	.699	12
	Maximum linear-fast AB (5 Hz).	SV= .0271 + 62.9 AB	.502	.115	.612	14
	Maximum 1/4-sec integrated AB (3.5-10 Hz).	SV=- .0247 + 98.4 AB	.750	.0838	.513	34
	Maximum 1-sec integrated AB (3.5-10 Hz).	SV= .0353 +118 AB	.502	.110	.680	--
		ONE-STORY HOMES				
Peak SV (corner) versus	Peak AB (0.1 Hz)....	SV=-0.0265 + 19.9 AB	0.821	0.100	0.491	2
	Peak AB (2 Hz)......	SV=- .0058 + 21.2 AB	.784	.109	.535	5
	Peak AB (6 Hz)......	SV=- .00040+ 27.6 AB	.642	.135	.660	8
	Maximum C-slow AB...	SV= .0769 +188 AB	.433	.158	.774	--
	Maximum linear-slow AB (5 Hz).	SV= .0553 + 98.4 AB	.454	.157	.817	--
	Maximum linear-fast AB (5 Hz).	SV= .0550 + 54.8 AB	.405	.161	.838	--
	Maximum 1/4-sec integrated AB (3.5-10 Hz).	SV=- .0519 +109.5 AB	.785	.0989	.518	35
	Maximum 1-sec integrated AB (3.5-10 Hz).	SV= .0269 +129 AB	.515	.137	.720	--
		TWO-STORY HOMES				
Peak SV (corner) versus	Peak AB (0.1 Hz)....	SV= 0.0062 + 13.4 AB	0.855	0.0360	0.267	3
	Peak AB (5 Hz)......	SV= .0121 + 18.1 AB	.771	.0450	.332	6
	Peak AB (6 Hz)......	SV= .0274 + 22.3 AB	.736	.0480	.353	9
	Maximum C-slow AB...	SV= .0215 +304 AB	.917	.0280	.209	11
	Maximum linear-slow AB (5 Hz).	SV= .0135 +131 AB	.693	.0460	.371	13
	Maximum linear-fast AB (5 Hz).	SV=- .0127 + 81.8 AB	.738	.0430	.348	15
	Maximum 1/4-sec integrated AB (10-24 Hz).	SV= .0133 +103 AB	.843	.0360	.277	36
	Maximum 1-sec integrated AB (10-24 Hz).	SV= .00490+196 AB	.956	.0202	.152	37

[1]SV = Structure vibration , in/sec.
[2]AB = Airblast overpressure, lb/in.

TABLE 5. - Equations and statistics for peak midwall structure vibration (SV) responses from airblasts - best results

		Equation	Correlation coefficient	Standard error	Normalized standard error	Regression line
ALL HOMES						
Peak SV (midwall) versus	Peak AB (0.1 Hz)....	SV= 0.0662+ 83.0 AB	0.669	0.439	0.538	16
	Peak AB (2 Hz)......	SV= .193 + 97.8 AB	.700	.422	.509	19
	Peak AB (6 Hz)......	SV= .177 + 139 AB	.713	.415	.500	22
	Maximum C-slow AB...	SV= .368 + 987 AB	.618	.465	.560	25
	Maximum linear-slow AB (5 Hz).	SV= .180 + 540 AB	.613	.465	.579	28
	Maximum linear-fast AB (5 Hz).	SV= .234 + 309 AB	.569	.473	.589	31
	Maximum 1/4-sec integrated AB (10-24 Hz).	SV= .186 + 501 AB	.728	.392	.490	38
	Maximum 1-sec integrated AB (10-24 Hz).	SV= .224 + 802 AB	.686	.416	.519	41
ONE-STORY HOMES						
Peak SV (midwall) versus	Peak AB (0.1 Hz)....	SV= 0.342 + 61.3 AB	0.623	0.481	0.510	17
	Peak AB (2 Hz)......	SV= .327 + 78.3 AB	.733	.418	.433	20
	Peak AB (6 Hz)......	SV= .262 + 115 AB	.722	.425	.451	23
	Maximum C-slow AB...	SV= .650 +1090 AB	.660	.462	.489	26
	Maximum linear-slow AB (5 Hz).	SV= .270 + 503 AB	.626	.476	.512	29
	Maximum linear-fast AB (5 Hz).	SV= .298 + 308 AB	.619	.479	.515	32
	Maximum 1/4-sec integrated AB (10-24 Hz).	SV= .187 + 455 AB	.757	.384	.424	39
	Maximum 1-sec integrated AB (10-24 Hz).	SV= .237 + 743 AB	.716	.412	.453	42
TWO-STORY HOMES						
Peak SV (midwall) versus	Peak AB (0.1 Hz)....	SV=-0.381 + 129 AB	0.779	0.369	0.497	18
	Peak AB (2 Hz)......	SV=- .256 + 181 AB	.764	.384	.517	21
	Peak AB (6 Hz)......	SV=- .139 + 234 AB	.782	.370	.500	24
	Maximum C-slow AB...	SV= .384 + 889 AB	.570	.489	.660	27
	Maximum linear-slow AB (5 Hz).	SV= .129 + 560 AB	.581	.467	.647	30
	Maximum linear-fast AB (5 Hz).	SV= .211 + 597 AB	.557	.476	.660	33
	Maximum 1/4-sec integrated AB (10-24 Hz).	SV= .0617+ 693 AB	.738	.388	.528	40
	Maximum 1-sec integrated AB (10-24 Hz).	SV= .168 + 1037 AB	.675	.424	.577	43

Both peak and integrated structure motions were compared to the various airblast descriptors, also expressed as peak and various integrations. The integrated values are variously filtered "velocity exposure levels" (VEL) analogous to sound exposure levels (SEL) for sound. They are an indication of energy represented by the structure vibration, as opposed to the simple quantities of peak velocity, acceleration, and displacement. A prior assumption was not made that peak particle velocity would most appropriately indicate damage and annoyance potential. Consequently, it was considered appropriate to analyze VEL of the structures. However, the computed VEL levels did not correlate well with the SEL or various peak linear overpressures. Additionally, all studies of structure damage and response had quantified the structure responses in terms of peak motions and/or strains. No VEL damage data exists. The VEL response equations and statistics are presented in tables E-2 for structures, and E-4 for midwalls, but do not presently appear useful.

Measured Corner Responses

The corner responses from linear-peak airblasts are shown in figure 30. The 0.1-Hz (high-pass, or low-frequency -3-dB point) peak-linear measurement required a pressure transduce or a sonic boom system (such as the B&K 2631). The 2-Hz values were obtained with a standard type 1 commercial sound level meter (B&K 2209) set to peak-linear-hold, and the 6-Hz measurements were obtained with standard sound level meters (such as B&K 2209 and GenRad 1933) or other systems as described by Stachura (61). A complete analysis was also made of the 5-Hz peak-linear measurement, but it was essentially identical to the 6-Hz; therefore, the responses given for 6 Hz are assumed to apply to 5 Hz as well.

Responses from integrated methods of sound measurement (sound exposure levels) are shown in figure 31. The linear-slow, linear-fast, and C-weighted-slow were measured with type 1 meters, and the 1-second integrations approximated by the "slow" setting.

Special filter ranges were studied, in the hope of finding an ideal sound descriptor for structure response. Three frequency ranges were examined--4 to 40 Hz for overall response, 3.5 to 10 Hz for corner response, and 10 to 24 Hz for midwall response. Because of phase distortion, the filtered peak values did not appear meaningful; therefore, sound exposure values were measured from the airblast recordings, using the three filter ranges plus C-weighted, with integration times of 1/8, 1/4, 1, 2, and 4 seconds. Stachura (61) describes the system used for this analysis. Standard sound level meters can measure SEL values for C-weighting and also with external filters for special frequency ranges. The slow and fast responses approximate 1-second and 1/8-second integrations, respectively. Other integration times cannot be measured without a complex processing system or a modified sound level meter (61).

The statistics for the various sound measurement methods for the different sets of structures are in table 4. Depending on the criterion of superiority, different descriptors appear better. In addition to the maximum correlation coefficient and the minimum standard error, a better prediction is suggested by a small intercept in the equation, since theory predicts that this term

TABLE 6. - Ranking of best airblast descriptors for structure response

Homes	Ranking	Correlation coefficient		Standard error		Zero intercept	
		PEAK STRUCTURE VIBRATION (CORNERS)					
All	1	Peak, 0.1 Hz	0.824	Peak, 0.1 Hz	0.076	Peak, 2 Hz	0.0044
	2	Peak, 2 Hz	.795	Peak, 2 Hz	.082	Peak, 6 Hz	.0073
	3	1/4-sec, 3.5-10 Hz	.750	1/4-sec, 3.5-10 Hz	.084	Linear-slow, 5 Hz	.0166
	4	Peak, 6 Hz	.676	Peak, 6 Hz	.100	1/4-sec, 3.5-10 Hz	.0246
1-Story	1	Peak, 0.1 Hz	.821	1/4-sec, 3.5-10 Hz	.099	Peak, 6 Hz	.00040
	2	1/4-sec, 3.5-10 Hz	.785	Peak, 0.1 Hz	.100	Peak, 2 Hz	.0058
	3	Peak, 2 Hz	.784	Peak, 2 Hz	.109	Peak, 0.1 Hz	.0265
	4	Peak, 6 Hz	.642	Peak, 6 Hz	.135	1-sec, 3.5-10 Hz	.0269
2-Story	1	1-sec, 10-24 Hz	.956	1-sec, 10-24 Hz	.0202	1-sec, 10-24 Hz	.0049
	2	C-Slow	.917	C-Slow	.028	Peak, 0.1 Hz	.0062
	3	Peak, 0.1 Hz	.855	Peak, 0.1 Hz	.036	Peak, 2 Hz	.0121
	4	1/4-sec, 10-24 Hz	.843	1/4-sec, 10-24 Hz	.036	Linear-fast, 5 Hz	.0127
		PEAK MIDWALL VIBRATIONS					
All	1	1/4-sec, 10-24 Hz	0.728	1/4-sec, 10-24 Hz	0.392	Peak, 0.1 Hz	0.0662
	2	Peak, 6 Hz	.713	Peak, 6 Hz	.415	Peak, 6 Hz	.177
	3	Peak, 2 Hz	.700	1-sec, 10-24 Hz	.416	Linear-slow, 5 Hz	.180
	4	1-sec, 10-24 Hz	.686	Peak, 2 Hz	.422	1/4-sec, 10-24 Hz	.186
1-Story	1	1/4-sec, 10-24 Hz	.757	1/4-sec, 10-24 Hz	.384	1/4-sec, 10-24 Hz	.187
	2	Peak, 2 Hz	.733	1-sec, 10-24 Hz	.412	1-sec, 10-24 Hz	.237
	3	Peak, 6 Hz	.722	Peak, 2 Hz	.418	Peak, 6 Hz	.262
	4	1-sec, 10-24 Hz	.716	Peak, 6 Hz	.425	Linear-slow, 5 Hz	.270
2-Story	1	Peak, 6 Hz	.782	Peak, 0.1 Hz	.369	1/4-sec, 10-24 Hz	.062
	2	Peak, 0.1 Hz	.779	Peak, 6 Hz	.370	Linear-slow, 5 Hz	.129
	3	Peak, 2 Hz	.764	Peak, 2 Hz	.384	Peak, 6 Hz	.139
	4	1/4-sec, 10-24 Hz	.738	1/4-sec, 10-24 Hz	.388	Linear-fast, 5 Hz	.211

Measured Midwall Responses

Figures 32 and 33 show midwall responses from various peak and integrated airblasts, respectively, analogous to the corner responses of figures 30 and 31. Statistics and equations are given in table 5 and , like those for the corner responses, indicate that neither unanimity nor major differences exist among the methods. The methods are ranked in table 6. As expected, the 10 to 24 Hz SEL correlated well with midwall motions; however, the 2 Hz and 6 Hz peak methods were consistently good. For the two-story homes, 0.1 Hz peaks was also excellent. Because of scatter in all the measurements, small differences among values of the correlation coefficients and standard errors have no meaning, so the ranking of one method over the next is not always significant.

The low-frequency response systems (0.1 and 2 Hz) are generally best for assessing likely corner responses, and the higher one (6 Hz) and SEL values (integrated sound levels) correlate better with midwall responses. This suggests that the damage potential of airblasts should be measured with the low-frequency sound systems, which have a flat response down to at least 2 Hz. The annoyance potential is strongly influenced by midwall responses and should be measured with special integrated sound levels or with systems having a flat response down to 6 Hz. The statistical differences between many of the descriptors are small (table 6), which would allow the use of one or more of several linear and integrated measurement methods for airblasts. The most practical existing measurement methods are linear-peak with 2- and 6-Hz (or 5-Hz) low-frequency response and C-slow (type 1 precision impulse).

Envelopes of Maximum Airblast Responses

The most severe cases of residential-type structure response are shown in figures 34 through 37 as the envelopes of maximum response values. Predictions could also be made by taking some number of standard deviations from the response plots (figs. 30-33), although the scatter (indicated by the correlation coefficients) introduces much uncertainty about some of the descriptors.

Comparison of Responses From All Sources

The racking and midwall responses from airblasts and other impulsive noise sources are summarized in tables 7 and 8. All responses, including those in the previous investigations (Appendix F), have been converted to vibration levels in the structures per pound per square inch (lb/in^2) overpressure. It is not possible to assess the reliability of many of the responses since some are based on very few individual measurements, and all involve various instrumentation and measurement techniques. Some descriptors were calculated on the assumption of simple harmonic motion (usually good for midwall motions and fair for racking motions) and measured frequencies, where available. Where frequencies were not given by the authors, the racking and midwall frequencies were assumed to 8 and 16 Hz, respectively. Sonic boom and large blast studies typically use wide-band instrumentation; therefore, the Bureau of Mines response data in tables 7 and 8 are from the 0.1 Hz low-frequency cut-off plots of figures 30 and 32.

TABLE 7. - Racking response of structures from various impulsive noise sources

Author	Displacement, in/psi	Velocity, in/sec/psi	Strain, µin/in/psi	Source of noise
				Production blasts:
This research......		17.8		All homes.
Do...............		18.8		1-story homes.
Do...............		13.8		2-story homes.
				Sonic booms:
Kryter (19)........	0.461	[1] 23.0		B-58.
Wiggins (80).......	.050-0.096	[1] 2.59- 4.90	488-1,125	B-58 and F-104.
Newberry (33)......	.107	[1] 5.38		FD-2, roof response.
Clarkson (7).......	<.486	[1] <24.4		Shear response at 2d floor.
Blume (3)..........	.245- .326	[1] 12.3 -16.4		B-58 and F-104, roofline.

[1] Calculated.

TABLE 8. - Midwall response from various impulsive noise sources

Author	Dis-placement, in/psi	Acceleration, g/psi	Velocity, in/sec/psi	Stress, lb/in^2/psi	Strain µin/in/psi	Source of noise
This research.	[1] 0.852	[1] 22.3	85.6			Production blasts: All homes.
Do..........	[1] .744	[1] 19.4	74.8			1-story homes.
Do..........	[1] 1.04	[1] 27.3	105			2-story homes.
Kamperman (18)	[1] .165		16.6			Floor motion.
Kryter (19)...	1.01		[1] 101			Sonic booms: B-58 Ceiling.
Do..........	1.53		[1] 154			B-58, midwall.
Wiggins (80)..	.302-0.634		[1] 30.2-63.4			B-58 and F-104 midwall.
Do..........	5.7-18.7		[1] 197-646		864-3,312	8x10-ft window.
Newberry (33).	1.15		[1] 116			FD-2, walls.
Leigh (22)....	2.13	40.2	[1] 124-223			XB-70, walls.
Do..........					446-677	Gypsum panels.
Mayes (25)....				4,752-7,200		Sonic boom.
Do..........				2,016-2,347		Single charge blast.
Clarkson (7)..	<1.04	7.2-28.8	<[1] 104			Sonic booms: XB-70, B-58, F-104. Exterior walls.
Do..........	<.45		<[1] 45			Interior walls.
Do..........	<.875		<[1] 87.5			Window, 5 x 10 ft x 0.25 in.
Blume (3).....	.87	41.0	[1] 117			B-58 and F-104 walls.
Do..........					4,320	Window.

[1] Calculated.

The racking responses (table 7) produced by sonic booms and blasting appear comparable on the basis of the Kryter (19), Blume (3), and Clarkson (7) studies. The Wiggins (80) and Newberry (33) values are comparable to each other and to about one-third of the others. (Newberry measured roof response, as opposed to corners or walls.)

Midwall responses also show reasonably good agreement between production blasts and sonic booms, despite the widely varying frequency character in sources, geometric factors of orientation, wall surface area, etc.

Kamperman's (18) floor response is about one-fifth of the vertical wall response, as expected. The Wiggins (80) midwall response is somewhat low, but within the scatter of the blast responses. Window responses are either much greater according to Wiggins (80), or comparable as found by Clarkson and Mayes (7). In summary, the sonic boom produced responses (peak particle velocities) range from the same as production blasting to about three times higher; the average was greater by a factor of 1.8.

STRUCTURE RESPONSE FROM GROUND VIBRATION

Structure and midwall responses from production mine blasting (figs. 38-39) can be compared with analysis of the airblast responses. In all cases,

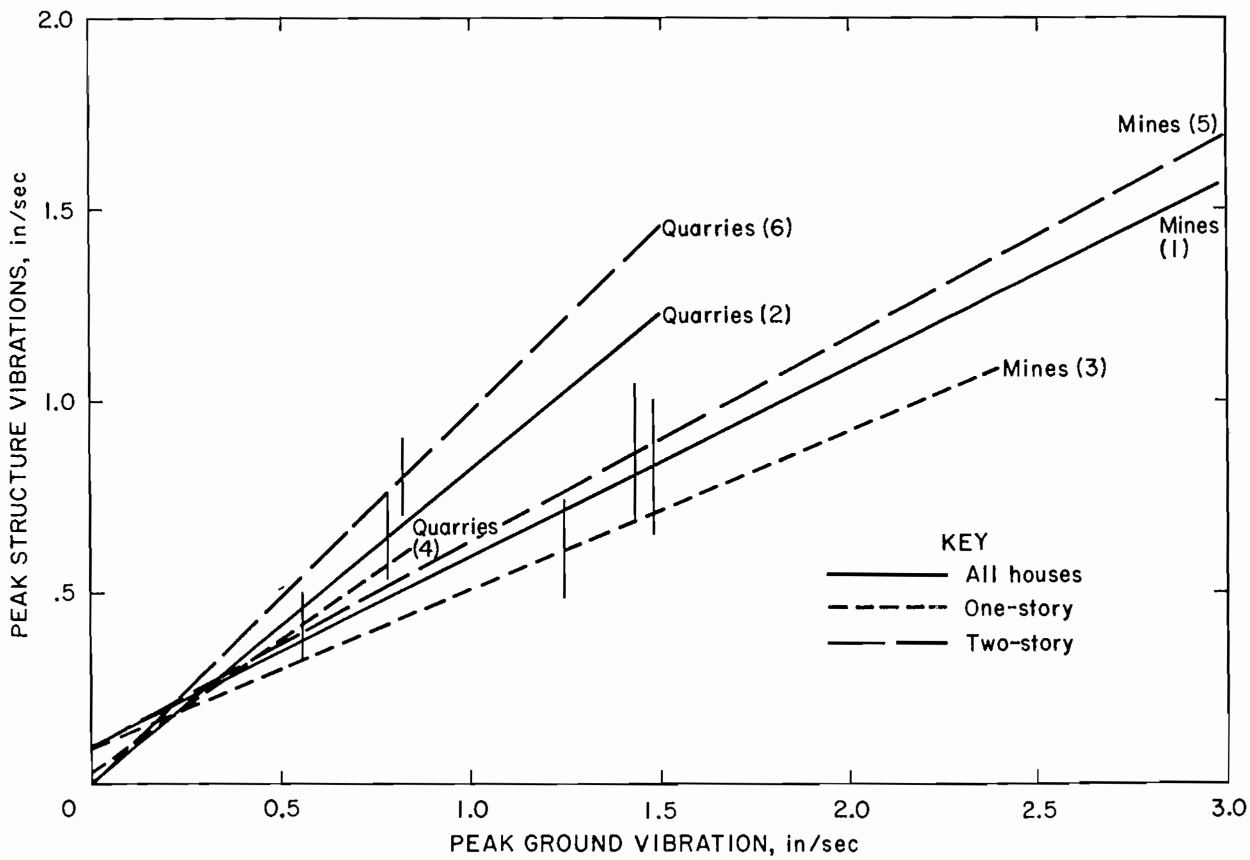

FIGURE 38. - Structure responses (horizontal corner motions) from peak ground vibrations.

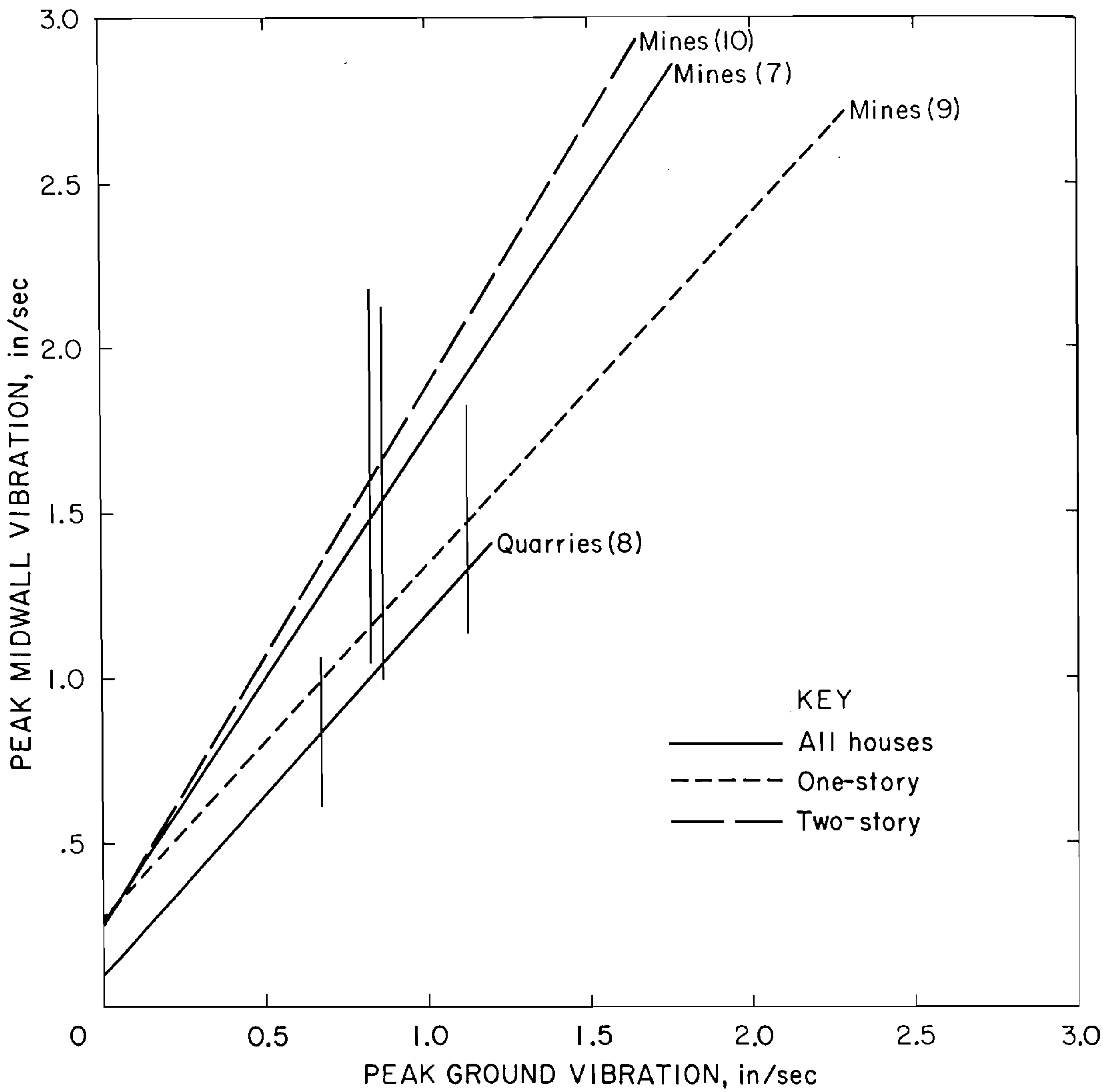

FIGURE 39. - Midwall responses from peak ground vibrations. (Numbers in parentheses correspond to regression lines in table 5.)

the largest corner and midwall responses from any given blast were plotted against the largest of three ground vibration components, to give the worst cases. The horizontal components did not necessarily correspond to the true radial (or longitudinal) and transverse, the velocity gages were oriented parallel to the structure walls.

Most interesting is that the racking response (corner or structure vibration) as shown in figure 38 is significantly lower than the input ground vibration velocity, when measured either on the first or second floor. The difference between the data from quarries and surface coal and metal mines was significant. For both kinds of mine blasts, responses were greater for two-story than one-story structures, probably resulting from significant low-frequency energy in the ground vibrations. Midheight corner measurements could not be used to evaluate the structural motions because of contamination by the higher amplitude midwall vibrations.

The midwall responses from the blast vibrations have an amplification effect as indicated by the slopes exceeding 45° (figure 32). They also show more scatter than the corner motion plot. In contrast to the corner vibrations, both types of mines produced greater structure vibration levels than the quarries. Summarized in table 9 are the equations and statistics for ground vibration-structure response plots in figures 38 and 39.

TABLE 9. - Equations and statistics for peak structure vibration (SV) responses from ground vibration

Sites	Homes	Equation	Correlation coefficient	Standard error	Normalized standard error	Regression line
PEAK STRUCTURE VIBRATION (CORNER) VERSUS PEAK GROUND VIBRATION						
Mines.....	All homes.	SV=0.101 + 0.491 GV	0.887	0.177	0.394	1
Quarries..	..do......	SV= .011 + .838 GV	.934	.112	.378	2
All sites.	..do......	SV= .101 + .497 GV	.886	.175	.405	
Mines.....	1-story...	SV= .097 + .410 GV	.925	.123	.300	3
Quarries..	..do......	SV= .035 + .686 GV	.956	.088	.324	4
All sites.	..do......	SV= .101 + .415 GV	.920	.125	.310	
Mines.....	1-1/2- and 2-story.	SV= .100 + .532 GV	.893	.183	.396	5
Quarries..	..do......	SV= .008 + .965 GV	.950	.106	.383	6
All sites.	..do......	SV= .098 + .539 GV	.892	.182	.407	
PEAK STRUCTURE VIBRATION (MIDWALL) VERSUS PEAK GROUND VIBRATION						
Mines.....	All homes.	SV=0.261 + 1.47 GV	0.863	0.574	0.427	7
Quarries..	..do......	SV= .097 + 1.09 GV	.832	.229	.453	8
All sites.	..do......	SV= .202 + 1.50 GV	.866	.550	.449	
Mines.....	1-story...	SV= .267 + 1.07 GV	.910	.345	.324	9
Quarries..	..do......	SV= .112 + 1.17 GV	.861	.245	.422	
All sites.	..do......	SV= .222 + 1.10 GV	.910	.324	.340	
Mines.....	1-1/2- and 2 story.	SV= .246 + 1.62 GV	.881	.570	.401	10
Quarries..	..do......	SV= .107 + .937 GV	.787	.208	.505	
All sites.	..do......	SV= .193 + 1.64 GV	.882	.559	.423	

A complete analysis of the Bureau's ground vibration response and damage study is available in a separate report (56).

It is necessary to note that all the responses discussed in this paper are applicable to residential-type structures with frame superstructures. The airblast or ground vibration response values may not apply to multi-story steel frame structures or large structures with masonry load-supporting walls. The natural frequencies of vibration of a large-span structure such as warehouse would be considerably lower than the 4 to 24-Hz range for residences and their midwalls. The larger structures will not only be more responsive to the low frequency airblast, but the responses will not correlate with the various sound discriptors in the same way as do the small residential structures.

TOLERABLE LEVELS OF AIRBLAST

Several research areas have developed data that apply to the problem of safe and tolerable levels of impulsive noise. These studies have used a variety of sound descriptors that are not readily comparable, and results have been based on different criteria of acceptability. Much work has been done on glass breakage, because glass is the element in a typical home most sensitive to airblast damage. Human and structural tolerance to sonic booms was extensively studied in the event of increased supersonic air traffic. The Army has long been interested in tolerable exposure to short-term impulse noise as from artillary firing. Environmental agencies, concerned with protecting the quality of life and property, are also aware of economic and social costs in the regulation of such adverse environmental effects as blast noise. The considerable work done on structural vibration and damage from ground vibration applies to the airblast problem, as the findings can be related through structure responses.

Comparisons Between Airblast and Ground Vibration Responses

Ground Vibration Damage

The Bureau has recently completed an extensive study of the response and damage from blast-produced ground vibrations (56). Ten data sets were analyzed, including three described in earlier damage analyses done by the Bureau (9, 34), an additional Canadian study (35), Dvorak's analysis of brick structures (10), and new residential damage data from surface coal mines obtained by the Bureau of Mines (56). The previously recommended 2-in/sec safe blasting criterion still appears applicable to those blasting situations which produce only high-frequency ground vibrations at the receiving structures >40 Hz. Such situations include small-scale blasting (excavation and construction) and homes sitting directly on rock at small distances (< 300 ft). A 5-pct minor damage probability level for these high-frequency blasts as measured by both Langefors (21) and recent Bureau work is approximately 2 to 3 in/sec, and no damage has been observed below 2 in/sec (56).

Significant problems exist for blasting where the ground vibration frequencies are close to the structure response frequencies (4 to 25 Hz). This is well demonstrated by the differences in the scatter for the two types of damage data analyzed in the earlier Bureau of Mines summaries (fig. 3.7 of reference 34). Both the minor and major damage threshold have a small amount of scatter for the high-frequency vibrations, indicating that the use of particle velocity in this frequency range is a good damage descriptor. In a response-spectrum analysis, this is the velocity-bound range of particle velocity frequencies. However, at lower frequencies (2.5 to 40 Hz), the particle velocity alone results in significant scatter (large standard deviations), and the statistically determined probability of damage at 2 in/sec for such data alone can exceed 10 pct. This problem results from both the structural resonances and large particle displacements occurring at these low frequencies. The British have noted the need for a displacement-bound criterion at low frequencies, and use 0.008 and 0.016 inches peak displacement as caution and maximum levels, respectively, for safe blasting (56). Assuming simple harmonic motions, these convert to 0.5 in/sec and 1.0 in/sec peak particle velocities at 10 Hz.

Direct measurement of blast damage and reanalysis of the nine previous studies have demonstrated that a stricter safe vibration level is required for low-frequency situations. In addition, the concept of a threshold for the most superficial types of damage needs to be reintroduced in the light of the latest data. Nonstructural cracks on interior walls are the most sensitive indicators of blast damage, and have a threshold level (with a 95-pct confidence of nondamage) of 0.75 in/sec. Inclusion of the Bureau's shaker tests (66) and the Dvorak blast data (10) lowers this to approximately 0.5 in/sec, although the shaker tests are somewhat suspect since they produce only localized vibrations and last longer than blasts. This lower criterion is applicable to sensitive residential structures (plaster interior walls), superficial damage (hairline plaster cracks), and low-frequency ground vibrations (structure on soft ground or thick overburden, and/or at long distances). Wallboard (gypsum Drywall) is more damage resistant than plaster by a factor of approximately two, and as previously discussed the high-frequency damage threshold is considerably higher (2 to 3 in/sec).

Data was collected from many shots for some structures; in one example, there were 12 nondamaging blasts exceeding 1 to 2 in/sec. However, this study did not fully address the long-term fatigue problem or the characteristics of masonry response. Consequently, the conservative 0.5-in/sec criterion is justified for long-term blasting under the conditions described. Modern construction (Drywall) should be afforded the same degree of protection at peak particle velocity of approximately 1.0 in/sec. Further work on long-term blasting and fatigue is continuing.

Airblast Criterian From Response Analysis of Structures

Airblast criteria have been developed from these ground vibration criteria and from comparisons between the airblast responses (figs. 30-33) and ground vibration responses (figs. 38-39), with equivalent damage risks. One method involves comparing the mean values of the airblast and ground vibration plots. Airblast levels equivalent to the 0.5-in/sec peak particle velocity in terms of whole-structure response are 135 dB (0.1 Hz), 134 dB (2 Hz), 132 dB (6 Hz), and 112 dB C-slow (table 10).

TABLE 10. - Airblast sound levels for control of structure response based on ground vibration response and damage levels

Type of blasting	Structures	Equivalent vibration, in/sec	Sound levels, lb/in^2 (dB) 0.1 Hz	2 Hz	6 Hz	C-slow	Assumptions
Mine......	All.....	0.50	0.0195 (137)	0.0171 (135)	0.0126 (133)	0.00133 (113)	Utilized mean values of both airblast response and ground vibration response.
	1-story.		.0164 (135)	.0144 (134)	.0109 (132)		
	2-story.		.0272 (139)	.0198 (137)	.0154 (135)	.00115 (112)	
Quarry....	All.....		.0237 (138)	.0210 (137)	.0156 (135)	.0017 (115)	
	1-story.		.0206 (137)	.0183 (136)	.0138 (134)		
	2-story.		>.018 (>136)	.026 (139)	.024 (138)	.0012 (112)	
Mine......	All.....		.0093 (130)	.0073 (128)	.0045 (124)	.00037 (102)	Based on 5-percent probability of strong response to airblast and weak response to ground vibration. This is the least favorable airblast case. All other predictions give higher airblast levels.
	1-story.		.0080 (129)	.0063 (127)	.0039 (123)		
	2-story.		.0153 (135)	.0107 (131)	.0080 (129)	.00065 (107)	
Quarry....	All.....		.0161 (135)	.0136 (133)	.0094 (130)	.00088 (110)	
	1-story.		.0131 (133)	.0110 (132)	.0076 (128)		
	2-story.		>.017 (>135)	.0207 (137)	>.012 (>132)	.00130 (113)	
Mine......	All.....	1.0	.0225 (138)	.0193 (137)	.0139 (134)	.00144 (114)	
	1-story.		.0186 (136)	.0160 (135)	.0116 (132)		
	2-story.		>.017 (>135)	>.020 (137)	>.012 (>132)	>.0015 (>114)	
Quarry....	All.....		>.025 (>139)	>.020 (137)	>.015 (>134)	>.0015 (>114)	
	1-story.		>.025 (>139)	>.020 (137)	>.015 (>134)	>.0015 (>114)	
	2-story.		>.017 (>135)	>.020 (137)	>.015 (>134)	>.0015 (>114)	
Mine......	All.....	0.75	.0193 (136)	.0166 (135)	.0109 (132)	.00077 (109)	Based on maximum airblast values (envelope of measured data) and mean ground vibration responses.
	1-story.		.0151 (134)	.0127 (133)	.0082 (129)	.00053 (105)	
	2-story.		>.020 (>137)	>.020 (>137)	>.020 (>137)	>.0007 (>108)	
Quarry....	All.....		~.029 (140)	~.029 (140)	~.029 (140)	>.0012 (>112)	
	1-story.		.0241 (138)	.0211 (137)	.014 (134)	.00105 (111)	
	2-story.		>.020 (>137)	>.020 (>137)	>.020 (>137)	>.0007 (>108)	

A more statistically rigorous analysis can be made by taking 0.76 standard deviation for each of the two responses using the most unfavorable case (with a probability of occurrence of only 5.0 pct), and projecting the resulting airblast levels. Statistically, this is equivalent to the simultaneous occurrence of a strong airblast response and a small ground vibration response. This resulting 5-pct occurrence probability could be combined with the 5-pct damage probability level (0.50 in/sec for blasting) for a very conservative set of airblast criteria with an overall probability of 0.25 pct. The resulting average airblast levels for mines (all mines) are 130 dB (0.1 Hz), 128 dB (2 Hz), 124 dB (6 Hz), and 102 dB C-slow for all structures. The same analysis, using the more appropriate ground vibration criterion of 1.0 in/sec for modern construction, gives mining airblast levels of 138 dB (0.1 Hz), 137 dB (2 Hz), 134 dB (6 Hz), and 114 dB C-slow (table 10). Again, it is necessary to note that these represent the levels with a small chance of the most superficial type of damage, and also correspond to the assumption of a ground vibration response in the most risky situations of low-frequency vibrations and structural foundations on soft ground.

A third method of determining safe airblast levels is to not assume any distribution of airblast responses, but use the envelopes of maximum values (figs. 34-35) and the mean values of the ground vibration responses. This strategy yields airblast levels of 134 dB (0.1 Hz), 133 dB (2 Hz), 129 dB (6 Hz), and 105 dB C-slow for the worst response case (one-story structures) and corresponds to a ground vibration of 0.75 in/sec (table 10). The same analysis, when used to obtain equivalence to 1.0 in/sec, gives airblast levels which are 3 dB higher for each measurement method.

It is necessary to note that the analysis performed for the levels in table 10 does not apply to individual shots. For each type of response, from both airblast and ground vibration, the mean values represent what is expected from the shots that were favorable for response (dominant and distinctly measureable). It is characteristic of the analyses that cases of small or nonexistent responses do not show up in table 3 or on the response graphs. Consequently, the response comparison techniques actually include a factor of safety for any individual shot, because strong confinement, which typically can increase ground vibration, will also lead to lesser airblast. For example, a coal mine parting shot produces high levels of airblast and small amounts of ground vibration.

The three analysis techniques for assessing airblast impact are summarized in table 10, based on measured corner (structure) responses to both airblast and ground vibration. Any other combination of airblast descriptors, levels, responses, and ground vibration responses can be made by direct comparison between figures 30 to 37 and figures 38 and 39. With the exception of the conservative case of the combination of 5-pct chance-of-occurrence and the 0.5-in/sec peak particle velocity, the three cases result in quite similar air-blast levels for the four measurement methods. From the lowest (safest) of the three cases, overall safe airblast criteria based on structural response and potential damage become 134 dB (0.1 Hz), 133 dB (2 Hz), 129 dB (6 Hz), and 105 dB C-slow. These levels correspond to essentially zero (< 1 pct chance probability of damage, (even superficial) in a typical residential structure.

As with the responses, no assumption should be made that these values are safe for larger structures or those with totally different response characteristics.

Airblast Criteria From Midwall Responses

Similar comparisons were made between airblast- and ground-vibration-produced midwall responses. Table 11 shows the predicted airblast levels derived from the mean values of the two sets of responses. Most evident is that they are lower than the corresponding values from the corner responses, showing that airblasts are relatively efficient generators of midwall motion. Consequently, the regulation of airblast based on an equivalence to ground vibration effects on midwalls would result in lower tolerance levels for airblast. As noted, the problem with midwall motions is that they produce annoyance from the secondary effects of rattling of objects and the motion and occasional fall of wall-mounted items. These results demonstrate that airblast is probably responsible for much of these secondary effects through its midwall responses.

A more direct evaluation of airblast-produced midwall motion could be made by determining the midwall motions required to produce rattling and the other secondary effects. Accelerations that cause something to rattle, move, and tilt, vary from 0.1 to 1.0 g, depending on the shape, center of gravity, and natural frequencies of the vibrating items. A wall acceleration of 0.5 g is sufficient to shake most items, and this roughly corresponds to the maximum safe airblast levels based on whole-structure responses. Table 11 lists airblast levels corresponding to 0.2- and 0.5-g wall motions computed at the typical wall natural frequency of 16 Hz, and derived from the midwall response plots in figures 32 and 33. These values are consistent with the observation that complaints about rattling occur at airblast levels exceeding about 120 dB (6 Hz), roughly corresponding to wall acceleration of 0.1 to 0.2 g. It is evident that the safe airblast levels as determined from structure response and damage are still high enough to produce secondary vibration effects. Similar rattling can be produced by truck traffic, airplanes, and normal household activities. The general problem of annoyance is discussed under the section on "Human Tolerance to Airblast."

TABLE 11. - Airblast sound levels for midwall response based on ground vibration levels and midwall accelerations

Type of blasting	Structure	Equivalent ground vibration, in/sec	Sound levels, lb/in^2 (dB)				Assumptions
			0.1 Hz	2 Hz	6 Hz	C-slow	
Mine......	All.....	0.5	0.0102 (131)	0.0073 (128)	0.0053 (125)	0.00133 (105)	Utilized mean values of both airblast response and ground vibration response.
	1-story.		.0076 (128)	.0061 (127)	.0048 (124)		
	2-story.		.0012 (132)	.0073 (128)	.0052 (125)	.00115 (108)	
Quarry....	All.....		.0069 (128)	.0046 (124)	.0033 (121)	.00027 (99)	
	1-story.						
	2-story.						
Mine......	All.....	1.0	.021 (137)	.0157 (135)	.0112 (132)	.00138 (114)	
	1-story.		.0162 (135)	.0127 (133)	.0093 (130)	.00097 (110)	
	2-story.		>.0165 (>135)	.0117 (132)	.0086 (129)	.00153 (114)	
Quarry....	All.....		.0134 (133)	.0101 (131)	.0072 (128)	.00082 (109)	
	1-story.						
	2-story.						
All.......	All.....		.0086 (129)	.0060 (126)	.0043 (123)	.00043 (103)	0.2 g wall acceleration; 0.772 in/sec at 16 Hz.
	1-story.		.0071 (128)	.0057 (126)	.0045 (124)	.00043 (103)	
	2-story.		.0090 (130)	.0057 (126)	.0040 (123)	.00037 (102)	
All.......	All.....		.0225 (138)	.0178 (136)	.0127 (133)	.00158 (115)	0.5 g wall acceleration; 1.93 in/sec at 16 Hz.
	1-story.		.026 (139)	.0204 (137)	.0146 (134)	.00174 (116)	
	2-story.		>.017 (>135)	.012 (133)	.0089 (130)	>.00125 (>113)	

Airblast Damage Summary

Many studies have been made of glass and structural damage from impulsive noises including airblasts (Appendix G) and sonic booms (Appendix H). Despite the widely varied source characteristics, assumptions of damage probabilities, and experimental design, and also the differing interpretations among the studies, there is a consensus that damage becomes improbable below approximately 0.030 lb/in^2 (140 dB). The various safe airblast and sonic boom damage criteria are summarized in table 12, based on no greater damage risk than one chance in a thousand. The apparently greater damage risk from sonic boom is probably an artifact of the analyses, with large populations sampled with few preboom damage inspections.

TABLE 12. - Summary of maximum safe overpressures from all sources

Author	Overpressure source	Maximum safe Lb/in^2	Overpressure dB	Sensitive element
Windes (82).....	Single unconfined charges.	0.100	151	Glass, poorly mounted.
Perkins (36)....	.....do........	.100	151	Do.
Poulter (39)....	.....do........	.032	141	Do.
Reed (43).......	Large surface blasts.	.017	136	<64-ft^2 window 1 chance in 10^3.
Reed (42).......	General........	.029	140	Glass.
ANSI (1)........	Single unconfined charges.	.057	146	Do.
von Gierke (70).	Confined blasts	.047	144	<1 chance in 10^5 1,000 people impacted, glass.
Redpath (41)....	Blasts.........	.060	141	<1 chance in 10^4 3.5 ft window.
Sutherland (63).	Steady-state sources, fatigue.	>.041	>143	Wood frame and concrete walls.
Taylor (64).....	Small line charges.	<.029	<140	35,000 panes in 30 greenhouses 0.7% damaged.
Do............	General........	.014	134	Threshold.
Sutherland (63).	Sonic booms....	.045	144	Plaster.
Do............	.....do........	.053	145	Glass.
Wiggins (80)....	.....do........	.015	134	Paint fleck fell.
Do............	.....do........	.035	142	Plaster, new.
Do............	.....do........	.056	146	Glass,
Kryter (19).....	.....do........	.035	142	39-ft^2 window.
Clarkson (7)....	.....do........	.076	148	Plaster.
Leigh (22)......	.....do........	>.069	>148	Plaster.
Blume (3).......	.....do........	.026	139	Glass.
This research...	Production blasting.	.014	134	Based on response and ground vibration.

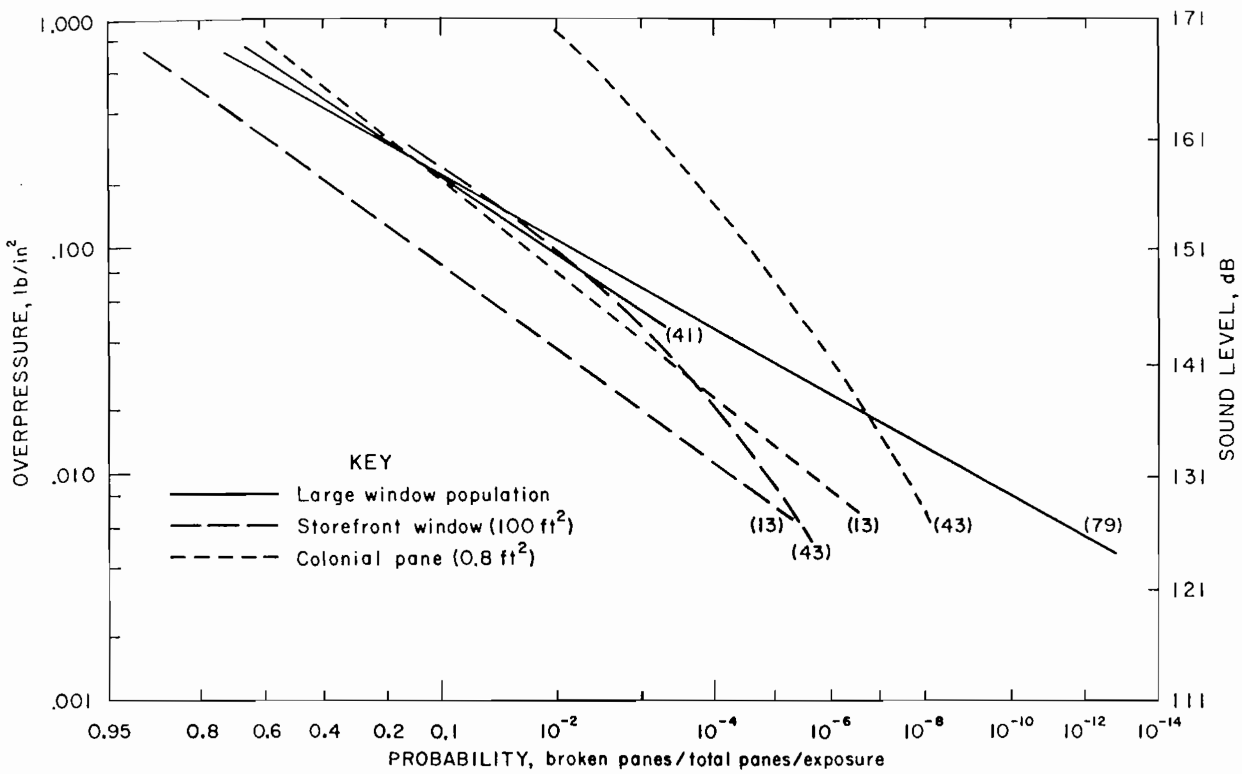

FIGURE 40. - Glass breakage probability from sonic booms and airblasts. (Numbers in parentheses correspond to regression lines in table 5.)

The glass-breakage probabilities versus airblast overpressures, as computed from several models and based on observed failures for large populations, are given in figure 40. Damage probabilities are again very small below 0.030 lb/in^2 (140 dB).

Human Tolerance to Airblasts and Impulsive Sounds

Health Risks

Hirsch assessed the injury and hearing damage risk from impulsive noise (15). He concluded that the thresholds of ear drum rupture and inner ear damage were 2 to 4 lb/in^2 and 5 lb/in^2 (178-184 dB and 185 dB), respectively. The U.S. Army has been concerned with hearing conservation amid impulsive noise sources such as gunfire, and has published noise limits (67). The Army's safe impulsive noise criteria are based on peak overpressure and the two time parameters of positive phase duration (A), and total time during which the signal is within 20 dB of the peak values (B). No ear protection is required for peak levels below 140 dB, regardless of the number of events per day or the A and B durations.

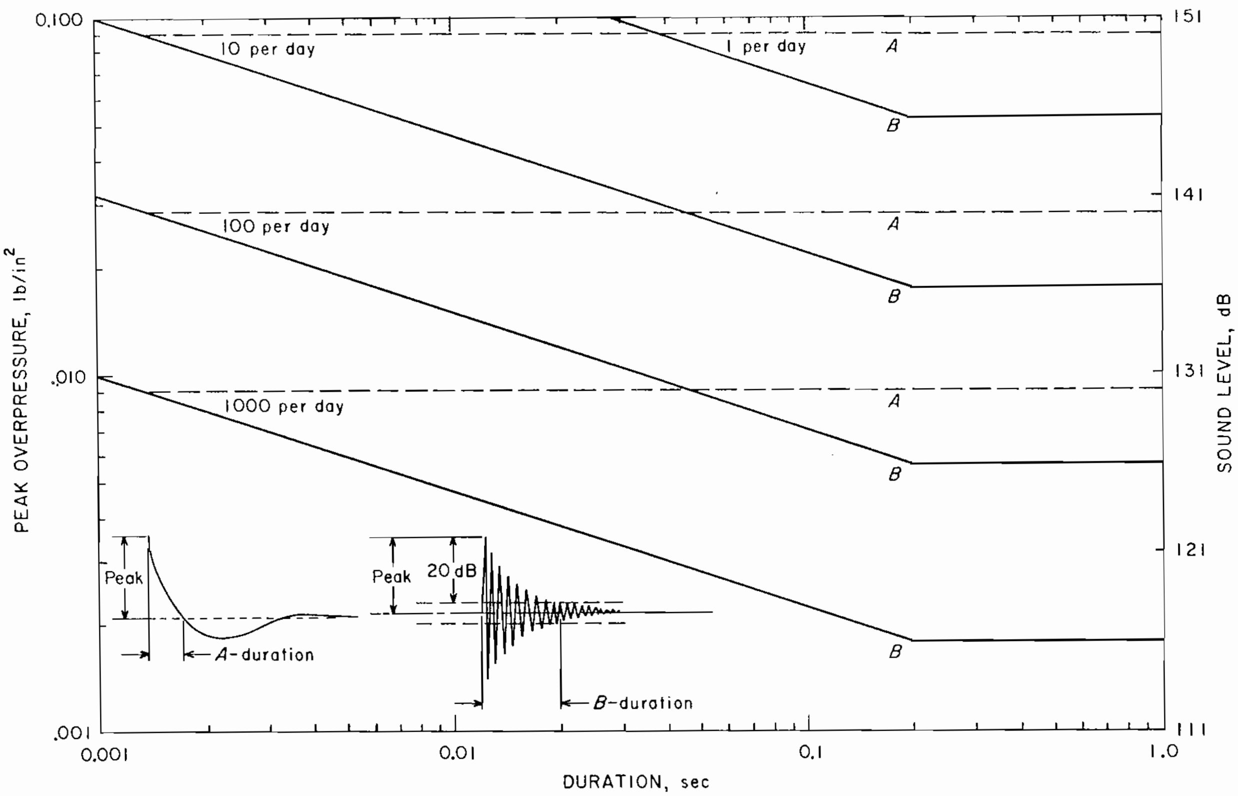

FIGURE 41. - Human tolerance to impulsive noise.

An evaluation of environmental noise and public health was made by the U.S. Environmental Protection Agency (68). Discussed were both the 1968 CHABA[6] damage risk criterion for impulsive noise, which was the basis of the Army specifications, and also a modified criterion for additional protection. The modified criterion is based on a maximum of 5 dB NIPTS (noise-induced permanent threshold shift)[7] at 4,000 Hz in 10 pct of the people after 20 years. The original criterion specified a maximum of 20 dB NIPTS at 3,000 Hz in 5 pct of the people affected, which allows higher noise levels by 12 dB.

Figure 41 shows the modified CHABA impulsive noise tolerance for humans, based on the A- and B-durations and the number of events per day. The criterion in figure 41 can be applied to mine production blasting even though it was designed for noise sources with rather different characteristics. The typical type 1 airblast appears as a series of spikes with A durations of 0.050 sec or less. Since there are no significant negative phases or oscillations for this type of airblast, the B durations are not meaningful. A large coal mine could have as many as four shots per day over the long run, each producing 10 to 15 type 1 spikes. This rather extreme case involving 40 to 60 "events" per

[6] Committee on Hearing, Bioacoustics, and Biomechanics, Washington, D.C.
[7] Threshold shifts represent hearing losses, or changes in minimum levels at which sounds can be heard. A certain amount of threshold shift occurs naturally with age.

day would result in a maximum allowable peak level of 142 dB, using the graph in figure 41. A large taconite mine could possibly produce type 1 airblasts with 100 spikes; however, these mines produce blast only a few times a month. Quarries are similar to metal mines in that they blast infrequently (usually not more than two or three times per week), and use blasts with up to 10 to 20 front-row holes (20 type 1 spikes, maximum). Consequently, the quarries could produce 5 to 10 "events" per day of 50-msec A duration, at a maximum peak level of 150 dB. More prevalent is the production of type 2 airblasts, which have very long B durations caused by their infrasonic (low-frequency) wave train. The resulting one event per blast (four per day maximum), gives an allowable peak level of 139 dB.

The recommended maximum 134 dB (0.1 Hz) peak airblast for minimum damage risk to structures and window glass is also low enough to meet the most strict CHABA criteria for human health. Furthermore, 134 dB (0.1 Hz) is a maximum level rather than a design level, which gives an additional factor of safety in actual practice. The modified CHABA criterion for human tolerance allows a maximum of 400 type 1 events per day or 16 type 2 shots per day, both at 134 dB (0.1 Hz). For type 1, the "events" would be the front-row holes on separate delays (or spikes countable on the airblast time histories), multiplied by the number of shots per day.

Airblast from confined, surface-mine blasts consists mostly of acoustic energy below 20 Hz, where human hearing becomes less acute. This infrasonic sound can still be perceived as harmonics generated by distortion of the middle and inner ear. Johnson (16) has evaluated the human tolerance for this kind of sound, noting also that its presence is not at all rare. A 6-inch change of height associated with jogging produces a 90-dB "sound" with a frequency of 2 to 3 Hz; a 3-inch change of depth while swimming produces 140 dB. Any activity or condition which produces a change in the pressure field acts as an infrasonic sound source: examples include elevator rides, aircraft flights, open windows in autos, wind, and barometric pressure changes. Laboratory studies of humans have indicated that infrasonic sound could be heard at least down to 1 Hz, with a rolloff of approximately 13 dB per octave below 20 Hz (16, 71). No threshold shifts have been found for subjects at levels of 150 dB (1 to 8 Hz) and 130 to 139 dB (1.5 Hz) for 5-minute exposures.

An analysis was made of impulsive infrasound from sonic booms by von Geirke and Nixon (71) who found no adverse effects from levels up to 1.34 x $10^3 N/m^2$ (157 dB) from 1,800 booms at White Sands, N. Mex., and up to 6.9 x $10^3 N/m^2$ (171 dB) at Tonopah, Nev.

Annoyance

Little research has been done on the problem of subjective reactions to blast noise, although annoyance surveys have been made for sonic booms and other impulsive sources and applied to blasting with various degrees or justification. A major problem is to define just what is objectionable about the noise, and separate those factors from other psychological and physiological reactions. In contrast to many noises, mine blasts are infrequent, typically one a week to a few a day. They generate impulsive noises with much energy outside the usual hearing frequency range, are of short duration (typically 300 msec), and affect relatively few people over a long period of time. Other types of blasting (such as construction and excavation) may be louder and more frequent, but are generally accepted as being temporary nuisances. The usual reasons for objecting to noise, such as speech, radio, and TV interference, do not generally apply to airblasts. Similarly, the discomfort descriptors of "unpleasant", "uncomfortable", and "fatiguing" also don't apply. Since blasting is usually restricted to daylight hours, sleep interference is only a potential problem for the fraction of the population who sleep during the daytime. Most objections to blasting are based on damage to houses and fear of damage to homes. Fright from fear of property damage is the primary reaction of citizens near blasting sites. "Startle" and "Fright" are the only discomfort descriptors clearly applicable to blasting.

The variable nature of airblast propagation creates special problems. Occasional weather conditions can cause anomalous noise levels at locations that do not usually receive strong enough airblast to rattle buildings. Since the airblast is predominantly infrasonic and sometimes totally so beyond a few miles, ground vibrations are usually blamed for shaking the house. The degree to which the noise is considered essential and unavoidable strongly influences public reaction. Where jobs and economy are tied to local mines, tolerances are considerably higher. For mining or quarrying, the general population is sufficiently removed from the end product that they fail to understand the necessity for blasting or problems inherent to the industry. Complicating the noise-response problem are the other problems associated with have a mine in one's neighborhood, such as truck and rail traffic, noise, dust, fumes, and possible unsightliness.

Studies made on annoyance from impulsive noises are discussed in Appendix I. The overall consensus was a composite of five impulse noise studies. The maximum safe levels, as given in this report and derived from structural response and damage considerations, would be acceptable to 95 pct of the population for relatively infrequent events (1-2 per day) (table 13). With variations between sources (sonic booms and unconfined, partially, and full confined blasts), and the number of events actually produced per day, the intolerable percentage at the maximum airblast levels will range from 0 to 10 pct.

TABLE 13. - Summary of airblast levels considered 95 pct acceptable

Author	Overpressure source	Maximum Levels		Basis
		Lb/in^2	dB	
von Gierke (70).	General	-	57 $dBL_{C\,dn}$	5 pct annoyed. Equivalent to 1 sec duration 107 dBC Event
Higgins (14)....	Coal highwall.	0.0205	137 dBL	5pct annoyed. Equivalent to PLdB level as per Table I-1. All dBL values are with 0.1 Hz high pass system.
	Coal parting..	.0115	132 dBL	
	Quarry........	.0183	136 dBL	
	Overall.......	.0145	134 dBL	
Kryter (19-20)..	General.......	.015-0.0216	135-137 dBL	Just acceptable. Equivalent to 0.0105 lb/in^2 (131 dBl) sonic boom
Borsky (4)......		.0145	134 dBL	5 pct more than moderately annoyed (fig. I-1).
Schomer (47)....		-	108 dBC-slow	

In summarizing the airblast annoyance problem, it is evident that the results of other related studies are only roughly applicable and that additional research is needed. Specifically, the annoyance factors from airblast and resulting rattling effects should be quantified and a survey for blasting similar to Borsky's (4) should be made. The attitudes of both the blaster and the neighbors are quite significant. As Borsky found for sonic booms, the belief that the source is necessary and unavoidable, the blaster's public relations role, and possible economic connections may have greater effect on airblast tolerance than specific levels, number per day, etc. It is theoretically possible to obtain total protection of neighbors by regulating the allowable levels to those lower than can be detected outside the mine's property line. Not only is this impractical, it is also unreasonable since other noise sources are not restricted in this manner. However, it is possible to minimize any real impact by careful control of blasting and a responsive public relations program.

CONCLUSIONS

Safe airblast levels have been determined from an analysis of structure response and damage including applicable studies of ground vibrations, sonic booms, mining, quarrying and construction blasts, surface and accidental explosions, and laboratory studies of fatigue and damage. Based on a minimal probability of the most superficial type of damage in residential-type structures, any of the following represent safe maximum airblast levels:

0.1-Hz high-pass system	134 dB
2-Hz high-pass system	133 dB
5- or 6-Hz high-pass system	129 dB
C-slow (events not exceeding 2-sec duration)	105 dB

These criteria could be lowered at locations with many large plate glass windows. The single best airblast descriptor is the 2 Hz, although many of the existing instruments were designed to be linear down to only 5 Hz.

Levels exceeding 120 dB will produce some annoyance from rattling and fright, with as much as 5 to 10 pct of homes exhibiting such disturbances at the maximum level of 134 dBL (0.1-Hz high-pass). Public reaction depends strongly on the blaster's public relations and the general attitudes of the neighbors to the economic and social requirement for the blasting. Tolerance increases where jobs are involved. Trade-offs between the costs and benefits of more restrictive criteria may have to be made.

In the absence of monitoring, the following minimum cube-root-scaled distances should be maintained:

Coal highwall	180 $ft/lb^{1/3}$
Coal parting	500 $ft/lb^{1/3}$
Quarries and mines	250 $ft/lb^{1/3}$
Construction and excavation	500 $ft/lb^{1/3}$
Unconfined blasting	800 $ft/lb^{1/3}$

Because these are necessarily restrictive, it would be an advantage to monitor enough blasts to determine typical site values, particularly for the highly variable parting shots.

Airblast character and level are dominated by factors of charge weight, distance, delay intervals, face orientation, explosive confinement, and weather. The following conditions require additional caution because of anomalously high levels (HL) or high frequencies (HF) that are in the range of structure response (5 to 25 Hz):

Large charge weight delay	HL
Effective delay too short (reinforcement)	HL
Effective delay too long (> 25 msec)	HF
Face toward receiver	HL, HF
Insufficient confinement	HL, HF
Wind toward receiver	HL
Severe temperature inversions	HL

The type 1 airblast is most serious in terms of potential damage and response, because of its resulting high frequency. Where its presence is unavoidable, effective delays should be chosen outside the range of 25 to 250 msec. The conditions which favor production of type 1 airblast often result in higher levels too. Where possible, a change in the face orientation may be helpful.

All blasting conditions that have low confinement require special precautions. Surface blasts, thin partings, exposed detonating cord, explosives testing, and construction blasting are all potentially serious. The worst case can be determined from the "unconfined" line in the propagation summary (fig. B-5).

Wind direction and speed are most critical weather influences on airblast propagation; inversions are secondary. Strong winds blowing from the sound source toward the receiver can increase the sound level by over 20 dB from the normal cube-root-scaled propagation.

It is necessary to emphasize that the safe levels specified in this report for both airblast and ground vibration levels are based on the worst cases of damage and response, and are therefore conservative levels for typical modern homes and the average blast effects. Previously, safe maximum levels of 140 dBL-peak and 2.0 in/sec provided sufficient protection in most cases, although they were high enough for significant annoyance. The new recommended levels in this report should provide 95 to 99 pct nondamage probability and 90 to 95 pct annoyance acceptability.

Airblast is an undesirable side effect of blasting rock for mining, quarrying, construction, and excavation. Since blasting is the most economic and presently the only practical way to fragment rock, it is the responsibility of the mining industry and others to design their blasting programs for minimum environmental impact. At the same time, those affected are part of a social, technological, and economic system that depends on mining and quarrying for a myriad of products, some far removed from raw material sites. This assessment of airblast levels and effects was made to provide guidelines for the industry which uses explosives, the regulatory agencies which are charged with control of environmental degradation, and the general population which must always bear the ultimate cost.

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APPENDIX A.--SOUND AND VELOCITY EXPOSURE LEVELS FOR AIRBLAST RESPONSE

Shot	Site	Peak air-blast, dB (0.1-Hz high-pass)	Sound exposure levels (L_s, L_{sc}), dB														Peak particle velocity, in/sec		Velocity exposure level (L_v), in/sec							
			4-40 Hz				3.5-10 Hz				10-24 Hz				C-weighting				Midwalls				Corners			
			Integration, sec				Integration, sec				Integration, sec				Integration, sec		velocity, in/sec		Integration, sec				Integration, sec			
			1/8	1/4	1	2	1/8	1/4	1	2	1/8	1/4	1	2	1	4	Mid-wall	Corner	1/8	1/4	1	2	1/8	1/4	1	2
35	12	122	110	109	108	107	107	106	103	101	107	106	105	103	97	94	0.19		0.10	0.11	0.07	0.07				
36	14	129	115	110	98	98	112	112	107	104	101	101	95	93	88	86	.081		.068	.068	.042	.030				
45	20	120	118	118	113	109	103	102	99	97	103	102	96	94	94	92	.20		.13	.13	.12	.07				
62	19	127	116	116	109	107	115	115	108	106	112	112	107	105	99	93	.40	0.13	.26	.15	.08		0.06	0.04	0.03	0.02
64	19	128	112	109	105	103	112	111	106	104	105	103	98	96	99	94	.53		.24	.21	.17	.09				
67	19	129	116	114	109	106	117	116	110	109	108	106	101	99	99	94	.70		.49	.37	.23					
70	19	129	115	115	108	107	117	114	110	107	113	111	104	103	97	92	.56	.06	.24	.21	.13	.11	.028	.024	.014	.014
71	19	131	117	116	111	110	119	117	112	110	111	111	105	103	99	94	.28	.11	.14	.12	.08		.06	.06	.04	.04
78	19	129	113	112	107	105	113	113	106	103	110	107	101	100	100	95	1.10		.47	.42	.24					
79	19	132	118	118	113	109	116	116	111	109	117	115	108	106	104	100	1.18		.54	.46	.23	.18				
80	19	132	112	111	106	106	113	111	106	104	114	113	106	104	103	97	1.50		.82	.54	.47	.36				
81	19	126	113	113	106	104	114	113	107	105	112	109	104	101	102	96	.70		.50	.40	.25	.19				
84	19	134	124	123	118	116	122	121	118	117	122	119	115	114	116	110	1.40		.70	.61	.35					
85	19	133	118	116	111	107	117	117	109	106	114	114	111	106	106	101	1.04	.22	.60	.52			.16	.14	.09	
86	19	135	120	118	113	110	114	113	108	105	120	117	112	110	107	102	2.50	.24	1.67	1.27	.96	.63	.105	.098	.060	.053
90	19	129	114	113	109	107	111	109	105	103	114	111	108	106	99	96	.49		.18	.19	.17					
92	19	131	120	115	111	109	118	117	113	109	115	114	108	104	102	96	.58	.12	.34	.27	.19	.14	.07	.06	.05	.04
94	19	133	121	118	112	109											.30									
95	19	128	113	109	108	106	104	103	99	97	104	104	100	98	97	95	.59		.33	.31	.20		.09	.06		
99	21	128	117	116	109	108	116	116	110	107	110	110	105	102	94	90	.72		.32	.30	.17					
101	21	121	112	112	109	108	110	106	104	102	111	111	108	106	102	97	.91	.10	.53	.50	.40	.30	.07	.06	.05	.03
103	22	122	107	106	101	99	107	106	102	99	103	102	98	94	94		.28	.07	.14	.12	.09		.03	.03	.02	
103R	22	124	113	112	106	104	111	110	105	103	110	107	103	100	98	95	.65	.09	.25	.25	.13	.12	.04	.04	.03	.02
103	23	133	122	120	115	113	121	121	115	111	116	116	110	107	106	101	.60	.25	.32	.21			.13	.10	.08	
103R	23	131	122	120	115	115	117	116	111	109	117	117	111	110	108	101	.87	.16	.40	.34	.21	.21	.08	.08	.06	
105	23	132	120	120	112	111	119	119	113	111	113	112	106	103	101	95	.46	.34	.23	.20	.15		.15		.08	.06
105R	23	126	116	114	110		113	113	107	105	114	112	107	104	103	98	.40	.10	.20	.18	.14	.10	.05	.05	.03	
126	34	136	129	125	121	118	124	121	118	115	126	123	119	117	113	107	1.71	.14	1.16	1.00	.66	.50	.09	.08	.04	.03
128	35	127	121	118	111	109	116	115	108	106	116	115	109	106	102	96	1.80	.13	1.22	.80	.46	.40	.08	.05	.04	.03
130	34	127	122	119	113	111	113	111	107	104	119	117	111	110	107	101	1.09	.04	.45	.42	.25	.19	.020	.019	.009	.006
141	36	124	117	114	109	106	110	110	106	103	115	112	107	103	100	94	.86	.025	.55	.42	.20	.15	.015	.012	.009	.007
146	37	117	102	101	98	96	107	106	102	101	101	101	99	99	88	87	.15		.11	.09	.07	.05				
148	38	131	121	117	113	112	121	119	116	113	110	109	103	102	97	93	.47	.12	.20	.17	.12	.10	.043	.040	.026	.023
150	37	127	115	111	109	107	117	112	109	108	115	106	101	99	93	87	.246	.082	.213	.185	.116	.088	.077	.067	.038	.033
154	43	125	114	113	109	106	112	109	107	104	108	107	104	102	93	88	.85		.53	.40						
161	48	131	121	119	117	115	115	114	111	109	117	115	112	109	112	107	1.25		.78	.58						

APPENDIX B.--BLAST DESIGN AND AIRBLAST GENERATION

Vortman has made several studies of the generation of explosive-produced airblast, mainly for nonmining situations. He examined close-in airblast (77) and propagation both along the line and perpendicular to a row of charges fired with no delays between charges (75, 78). He found airblast reinforcement when measured perpendicular to the array (overpressures were multiplied by the number of holes), and partial addition of overpressures for the in-line case (75). Snell (58) reviewed Vortman's work on spacing and orientation. He concluded that reinforcement, or simultaneous arrival of airblasts from different holes would not occur for delay periods (T) given by:

$$T_{sec} = 0.53 \cdot \frac{S}{V_s},$$

where S is the spacing (ft) and V_s is the sonic velocity in air (ft/sec).

This relationship represents supersonic detonation down the face as successive holes fire before the arrival of airblast from adjacent holes. This case, and that of near-sonic velocity (with the spacing divided by the effective delay, equaling the velocity of sound), lead to airblast reinforcement in specific directions. For mining, a highly subsonic succession of detonations is recommended:

$$Tsec \geq 2\frac{S}{V_s}$$

Good blast design also calls for 1-3 msec per foot of burden between rows of holes, to allow sufficient relief. Even greater time separation is sometimes used for deep multiple-row blasts, although there is increased risk of hole cut-offs.

As discussed previously, the degree of blast confinement strongly influences both airblast levels and frequency character. Vortman (73) discusses the airblast components produced by the venting (GRP) and ground shock (APP) for alluvium, clay, sand, and basalt, and also by confinement of very large blasts (40,000 lb) (74). Reed (42) also studied confinement in his analysis of cratering and excavation and noted that airblast amplitudes are 5 to 35 pct of free air levels. Other investigators have examined confinement and airblast generation for various depths of burial (36, 40). Wiss (83) intensively investigated airblast from mining production blasts with various degrees of confinement. He determined relationships for burden and stemming, both important confinement factors. The APP pulse, which dominates airblasts that have no stemming release or gas venting, is a function of burden as given by:

$$APP = K_1 \; e^{-0.13} \; D_{cg}$$

where D_{cg} is distance (in feet) to the charge weight center of gravity and K is a constant. The stemming length has a far greater effect on resulting airblast levels, with a confined SRP being approximately one-tenth of the APP, and unconfined SRP, about two and one-half times the APP (83). Wiss quantified the confinement effect:

$$SRP = K_2 e^{-1.0\ B_s},$$

where B_s is the scaled depth of burial ($ft/lb^{1/3}$).[1] The B_s values can be computed from--

$$B_s = D_{cg} / W^{1/3}$$

for stemming lengths shorter than explosive charge lengths, and--

$$B_s = \frac{3}{2} \frac{S^{2/3}}{W^{1/3}}$$

for stemming lengths longer than explosive charge lengths, where S is the stemming length (in feet) and W is the charge weight (in pounds). Wiss's study quantified the reduction of airblast by burial as follows:

2.3 $ft/lb^{1/3}$ scale depth of burial......... 20 dB reduction (1/10)
4.6 $ft/lb^{1/3}$ scale depth of burial......... 40 dB reduction (1/100)
6.8 $ft/lb^{1/3}$ scale depth of burial......... 60 dB reduction (1/1000)

for 9-12 inch horizontal and vertical holes of up to 120 ft in length. An analysis (36) for spherically shaped charges found that lesser depths were required for similar reductions:

0.75 $ft/lb^{1/3}$ scale depth of burial.......... 20 dB reduction
1.50 $ft/lb^{1/3}$ scale depth of burial.......... 40 dB reduction

Although these reductions may vary considerably at sites with differing geologies, they demonstrate how confinement dominates airblast levels.

Airblast levels as measured with four different low-frequency cut-offs (high-pass frequencies) for two types of coal-mine production blasts are shown in figure B-1. Most obvious is the higher levels resulting from the parting blasts, which are frequently underconfined. These airblasts are 10 to 15 dB higher in level than the highwall shots, although still approximately 10 dB lower than the free air levels (unconfined). They are also typically of high frequency and resemble type 1 airblast. These data have a moderate amount of scatter, as they represent few measurements from each of many sites, with varying weather conditions, geology, and blast designs. The primary purpose of this study was to analyze response and damage. These propagation data (83) used an array of gages with many measurements at a few sites, resulting in less scatter.

Airblasts from coal mine highwall airblasts are shown in figure B-2. Lines one through six are different sites or blast designs of the Wiss study (83). Line seven is a compilation of values from this study, where all shots are decked. The Bureau's results show slightly more scatter than Wiss; however, decking evidently produces higher airblast levels for a given charge

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[1]Note that the units of scaled depth of burial are the same as cube-root-scaled distance.

RI 8485 (1980)

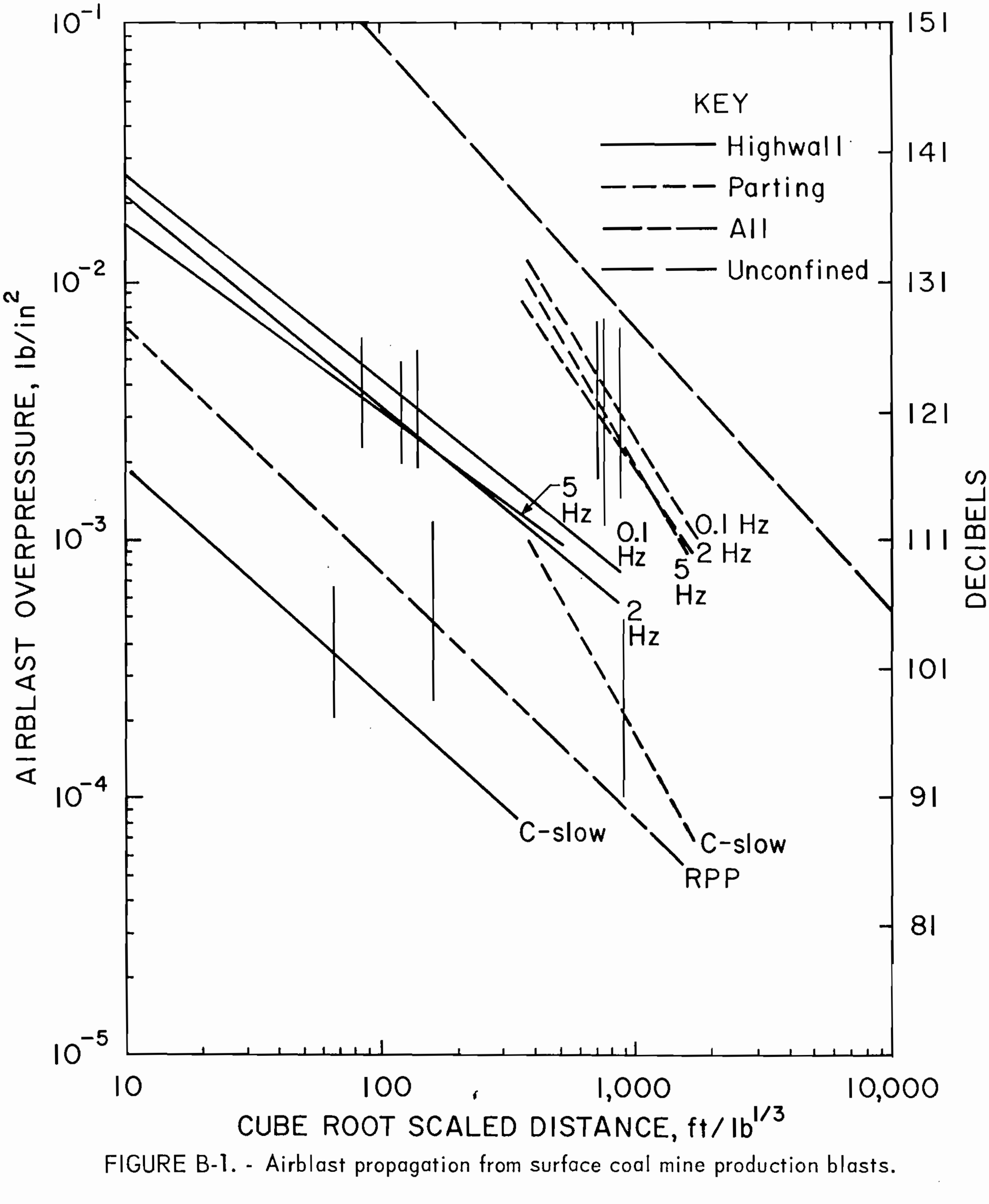

FIGURE B-1. - Airblast propagation from surface coal mine production blasts.

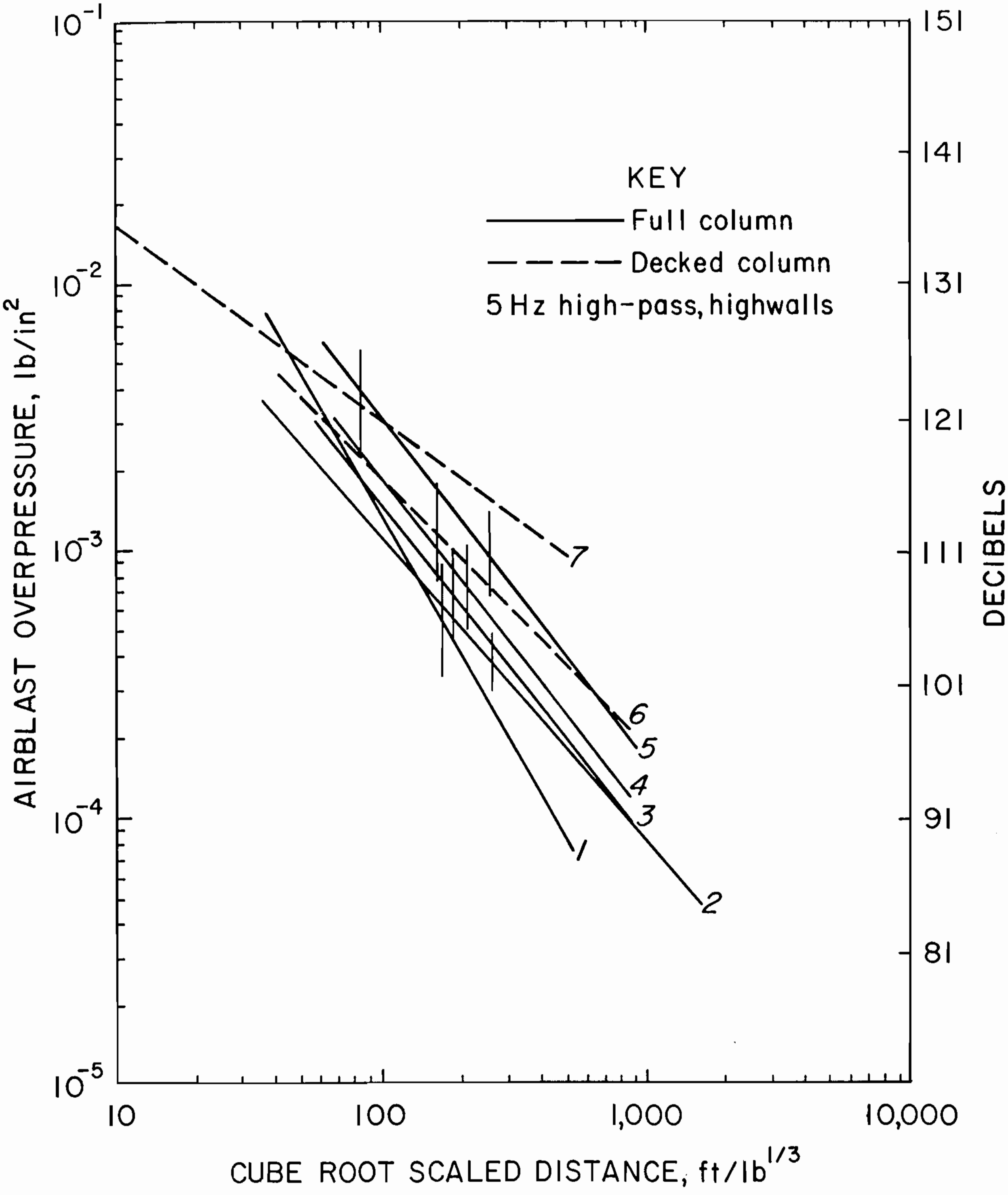

FIGURE B-2. - Airblasts from individual surface coal mines, highwalls with 5-Hz high-pass.

weight per delay, particularly at large distances. This is likely a confinement problem, with the generation of some GRP from the rock fracturing being produced by the earlier detonations within the blastholes. Examination of type 1 airblast records shows only one APP per hole, regardless of the number of decks. Undoubtly, the upper deck has a dominating influence on the airblast. The airblast levels from decked and undecked blasts are essentially the same at small distances.

BuMines Bulletin 656 (34) describes investigations of airblasts from quarry production shots and derives a design relationship of 2.6 ft of stemming per inch of blasthole diameter. This was developed for small-diameter holes (about 3 inches), but is presently considered unnecessarily restrictive, particularly for large holes. In some cases, the 2.6-ft/in value would require a hole full to the collar with only stemming.

Airblasts from a variety of sources are shown in figure B-3 (0.1-Hz highpass for BuMines, and 2-Hz for VME data). The quarry and metal mine data have much scatter; however, on the average they represent greater airblast levels than coal mine highwall shots, and less than parting shots for moderate scaled distances (less than 600 ft/lb$^{1/3}$). The VME study (24) found lower average levels, but also demonstrated that greater confinement and the lack of a requirement to displace the rock gave lower airblast levels in most coal highwall blasting.

Several investigators have noticed the different airblast levels and character in various directions from the free face. Both Kamperman (18) and Taylor (64) observed a 5- to 10-dB difference between levels at the front and back of the pit face. Figure B-4 shows airblast propagation curves for four directions, relative to both the free face and the direction of the blast initiation down the face. The horzontal hole values are from Wiss (83). Most mines are concerned with vertical holes and, as stated earlier, the front direction is potentially more serious because of both the higher levels and the tendency to produce high-frequency, type 1 airblasts. In all directions, constructive interference can occur, and this involves solving the geometric problems of the blast patterns and delay intervals (83). The directional airblast data for the Bureau measurements are from table 3, with 0° being the direction of blast initiation down the face, 180° opposite, 270° in front of the free face, and 90° behind.

Detonating cord poses a special problem, but one which is easily solved. Cord on the ground surface can be treated as any other unconfined explosive on a per weight basis. Wiss (83) and Viksne (69) describe airblasts from various amount and types of detonating cord, with and without cover. Wiss (83) found that 3 inches of sand reduces 50 grain cord by 20 dB (factor of 10), and 12 inches gives almost total confinement. Wiss measurements were made within 1,000 ft. At large distances, detonation cord becomes a less of a problem due to attenuation of high frequencies.

The Bureau's airblast measurements from all sources with linear frequency response down to 5 Hz or lower are summarized in figure B-5. The upper and lower limit predictions are shown by the free-air (unconfined) and RPP lines, respectively. The difference between total confinement and free-air blasts

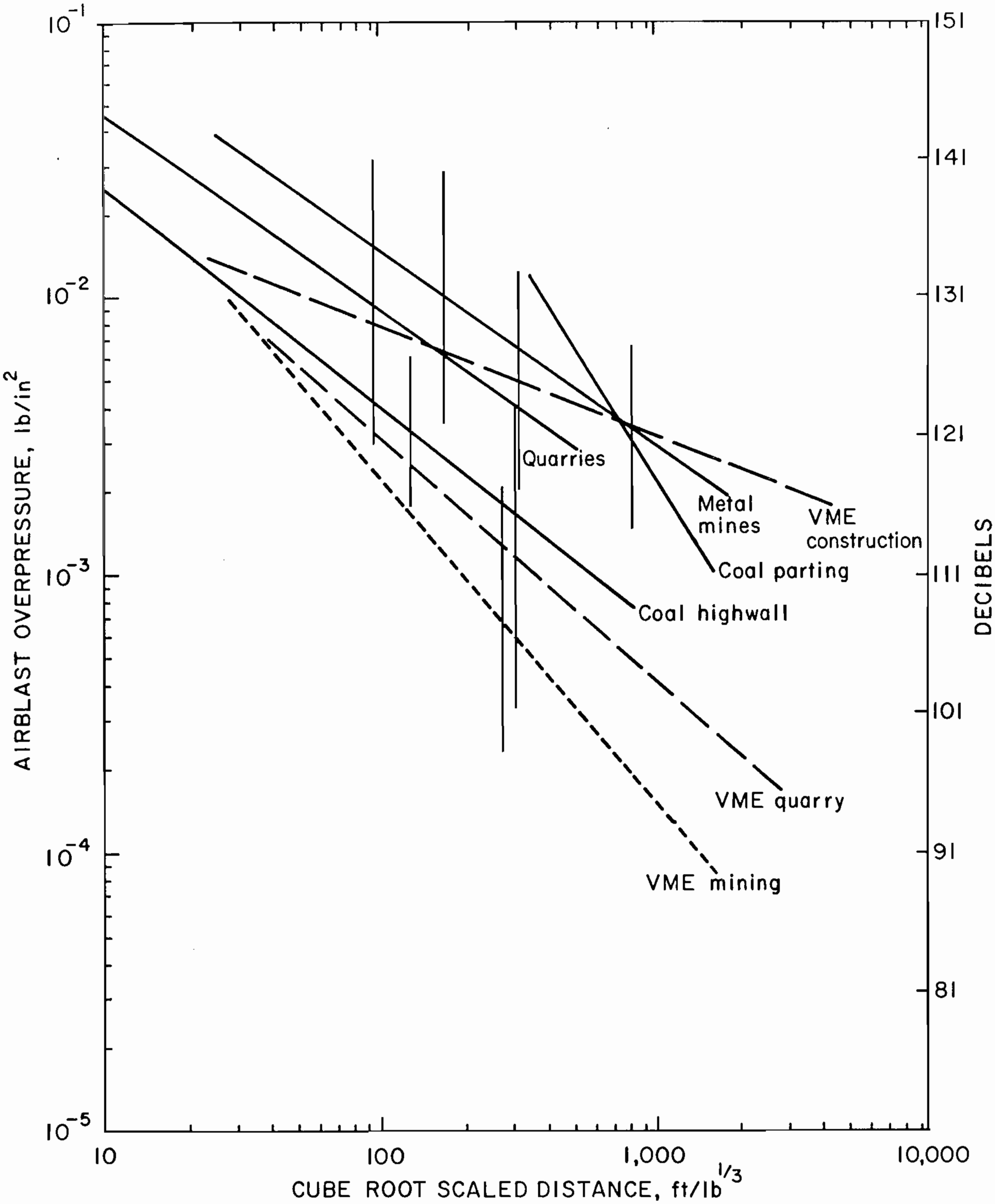

FIGURE B-3. - Airblasts from various types of mining, 0.1-Hz high-pass.

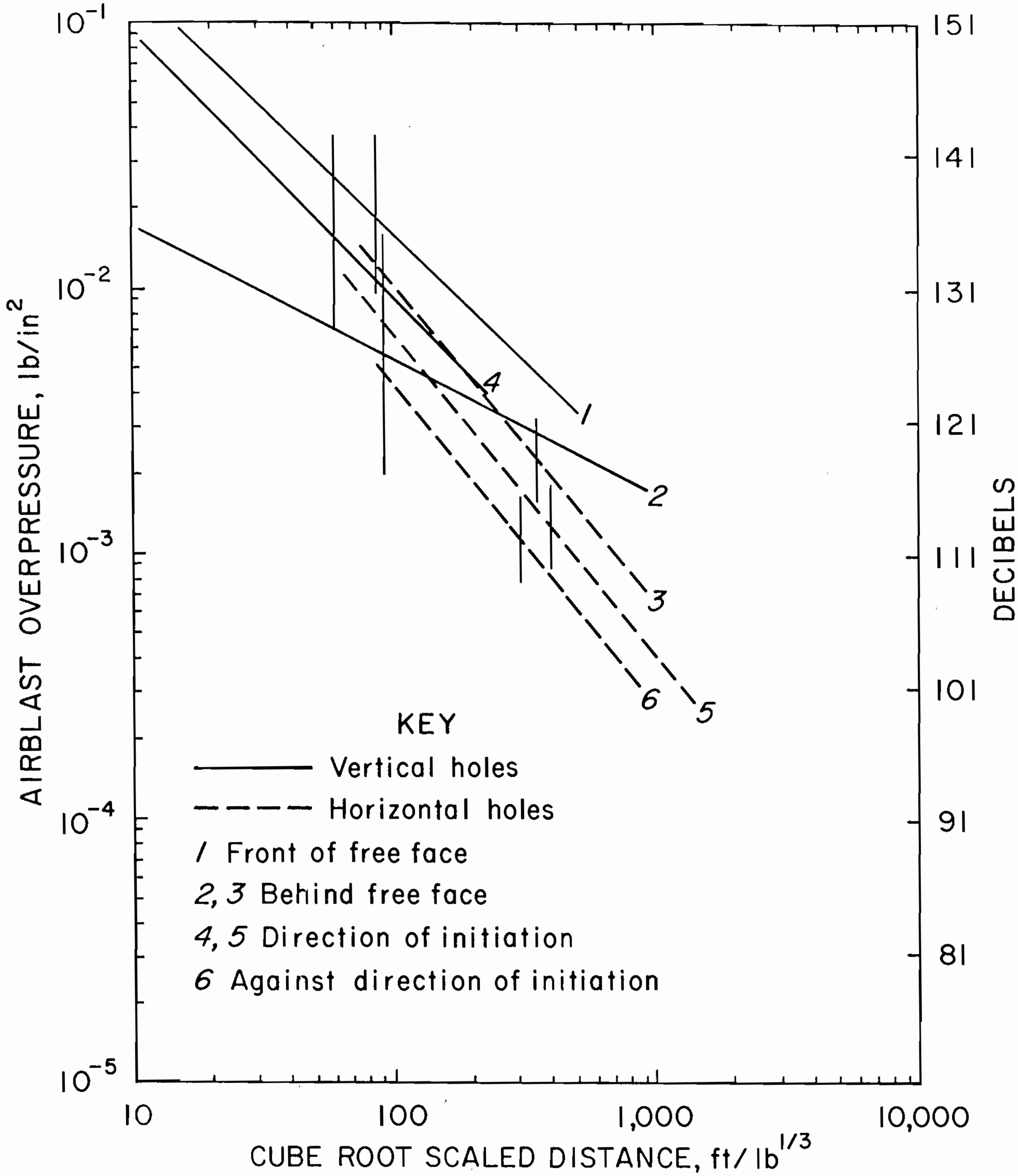

FIGURE B-4. - Airblast propagation from various face orientations.

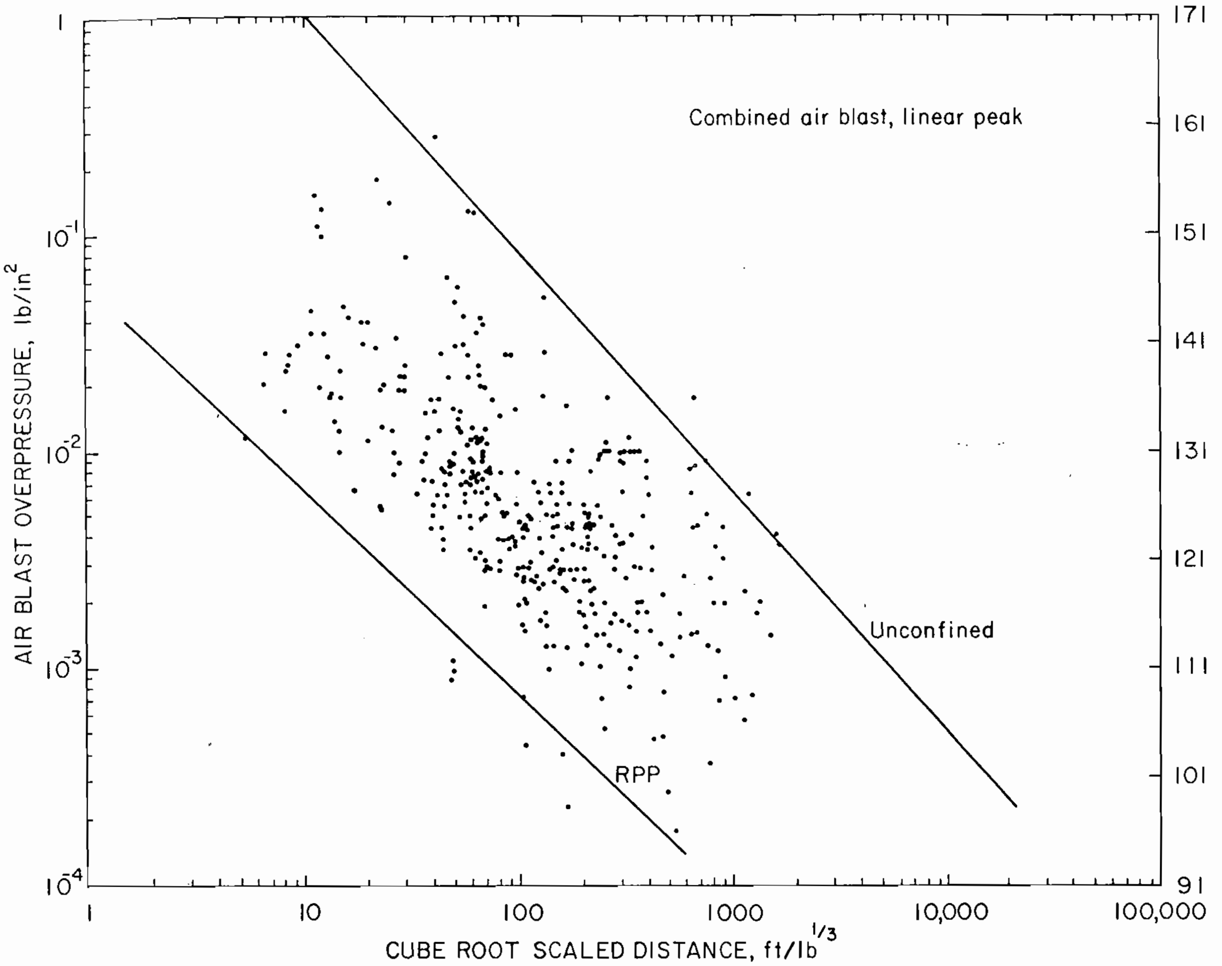

FIGURE B-5. - Combined airblast measurements, all sites.

is a remarkably constant 41 ± 5 dB. Most of the high values (> 145 dB) in this figure were obtained closer than the nearest house.

Table B-1 lists the airblast propagation equations and statistics. The effects of blast design on airblast generation are still not fully understood, and research is continuing on reinforcement between holes, delay intervals, and decking.

TABLE B-1. - Equations and statistics for airblast propagation

	Equation	Correlation coefficient	Standard error, pct	Transformed standard error, pct	Number of measurements
Coal highwall..0.1 Hz..	AB= 0.162 $(D/W^{1/3})^{-0.794}$	0.739	88.2	5.5	115
2 Hz..	AB= .146 $(D/W^{1/3})^{-.823}$	.774	75.0	4.9	83
5 Hz..	AB= .087 $(D/W^{1/3})^{-.725}$	.839	61.2	4.1	41
C-slow..	AB= .015 $(D/W^{1/3})^{-.885}$	.792	83.2	5.7	89
Coal parting...0.1 Hz..	AB=169 $(D/W^{1/3})^{-1.623}$	.587	120	6.8	19
2 Hz..	AB= 49.6 $(D/W^{1/3})^{-1.477}$	.500	159	8.3	16
5 Hz..	AB=194 $(D/W^{1/3})^{-1.666}$	.657	105	6.2	16
C-slow..	AB= 41.6 $(D/W^{1/3})^{-1.785}$	.603	122	6.9	22
Metal mine, highwall......0.1 Hz..	AB= .401 $(D/W^{1/3})^{-.713}$	.679	138	7.5	14
Quarry.........0.1 Hz..	AB= .246 $(D/W^{1/3})^{-.711}$	.580	165	8.4	73
Quarry[1]........0.1 Hz..	AB= .979 $(D/W^{1/3})^{-1.120}$	.757	120	6.9	10
Quarry[2]........0.1 Hz..	AB= .056 $(D/W^{1/3})^{-.515}$	.571	145	7.8	28
Quarry[3]........0.1 Hz..	AB= .028 $(D/W^{1/3})^{-.098}$	.050	193	9.3	11
Quarry[4]........0.1 Hz..	AB= 1.317 $(D/W^{1/3})^{-.966}$	.793	103	6.1	22

AB Airblast, lb/in^2.
D Distance, ft.
W Charge weight, lbs.
[1]Direction of initiation.
[2]Behind face.
[3]Opposite initiation.
[4]Front of face.

APPENDIX C.--WEATHER EFFECTS ON PROPAGATION

Reed has made several studies of long range airblast propagation from large surface blasts (1, 42, 44) and developed the IBM-M prediction scheme for free airblasts (43). Reed's airblast propagation is in the form--

$$\Delta P = K\, W^{0.4} D^{-1.2},$$

with ΔP being the airblast overpressure, W the charge weight, and D the distance (units arbitrary). This equation is identical to the following cube-root-scaled propagations used by the Bureau and others:

$$\Delta P = K\ (D/W^{1/3})^{-1.2}.$$

Nichols, Johnson, and Duval (34) include a summary of airblast propagation for stone quarry blasts, but do not plot an overall regression because of scatter between sites and tests. Vortman studies close-in propagation from row charges and found overpressures proportional to $R^{-1.1}$ (-6.6 dB per doubling of distance) (76). Schomer discusses airblast propagation and specifies -6.6 dB per doubling (50). Kamperman (18) studied propagation from quarry blasts and found a falloff of -20 dB per decade (also -6 dB doubling).

Oltmans (57) determined a decay of airblast level with distance proportional to $R^{-1.2}$ (-7.2 dB per doubling). Lucole (24) compiled airblast and ground vibration measurements gathered during 1 year by his firm, and plotted sound propagations for mining, quarrying, and construction (cube root scaled for airblast). As with many of the preceding studies and also the current Bureau of Mines research, meteorological factors were not specifically analyzed although they contribute to the scatter among measurements.

Sound propagation, particularly at large distances, depends on wind and temperature, both of which can bend the wavefronts and create anamolous sound levels. It is likely that the occasional complaints occurring at large distances are the result of weather-produced focusing of airblast. Studies have been made on weather effects on airblast; however, a practical prediction scheme has not been developed. Some mines use small pilot shots to assess propagation before the production blast. This is simple, but there may not be a good correlation between the pilot and production shots. The higher frequencies of the pilot shots do not propagate or undergo refraction the same way as the lower frequency energy from the full-scale blasts. Poulter (39) examined propagation as a function of temperature, humidity, and wind. He found that barometric pressure has no effect and humidity only a minor one. The factors of wind and temperature are critical to sound propagation. The wind changes the angle of the wavefront, and concentrates it near the ground when propagating downwind and up from the ground when propagating upwind. In the absence of inversions to refract it back down again, the upwind sound level will be far less than the downwind.

Schomer (50), Grant (11) and Kamperman (18) discuss wind effects on propagation, and Kamperman's analysis of close-in quarry measurements gave 10 to 15 dB greater sound level downwind than with cross or no wind conditions.

Wiss (83) analyzed wind effects from coal mine shots out to about 3 miles. He found that it changed the nominal -7.7 dB doubling to:

$$-(7.7 - 0.16\ V_{mph}\ \cos\theta\ \text{dB}),$$

where θ is the angle between the wind vector and direction vector of concern, and V is the wind speed in miles per hour. For example, a 15 mph wind blowing directly from the blast toward the area of concern (0°) would give -(7.7 - 2.4) dB per doubling, or -5.3 dB per doubling, and in the upwind direction (180°) would give -(7.7 + 2.4) or -10.1 dB per doubling. Wiss also gives corrections to the airblast propagation exponents for quantifying the wind effects. The magnitude of the slope correction was ±0.0265 U_v, where U_v is the vector wind velocity U cos θ, in miles per hour. As an example, the coal parting 5-Hz propagation equation from table B-1 was given as follows:

$$AB = 194\ (D/W^{1/3})^{-1.666}.$$

In a 20-mph wind blowing directly from the blast toward the point of concern, the exponent which describes the airblast overpressure decay will be reduced by an amount 0.530, determined from (0.0265 x 20 cos 0°), and the propagation equation becomes

$$AB = 194\ (D/W^{1/3})^{-1.136}.$$

Berning (2) also discusses wind and other unfavorable conditions for airblast propagation including a case of abnormal upwind propagation (skipping).

Air temperatures normally decrease with increasing altitude, with the reverse of this called a "temperature inversion," or warm air layer. The index of refraction of air changes with temperature, so that the normal condition of cooler air at higher altitudes refracts sound away from the ground. Conversely, temperature inversions refract sound downward, leading to higher than normal sound pressure levels at points of focus. Much work had been done on theoretical calculations of airblast focusing from temperature inversions (36-37, 39). Perkins (36) predicted that a single inversion could cause airblast to be 3 to 6 times more intense. Poulter (36) concluded that within a distance of two times the height of the inversion, no intensification would occur. Taylor (64) stated that up to a 10-dB increase can occur from inversion-produced refraction. Schomer (50) discussed both low-altitude inversions and jet stream focusing, for propagation distances of 2 to 40 miles and 30 to 300 miles, respectively. The short range case is applicable to mine blasts; a 3-times intensification was the maximum measured and the average was 1.8 times (5.1 dB).

APPENDIX D.--TERRAIN EFFECTS ON PROPAGATION

Terrain is another possibly critical factor for airblast propagation. The effect of the bench and blast face on levels and character was treated in the section on airblast characteristics. Wilton (81) discusses experiments of "air bursts" over valleys and the resulting 50-pct increase of intensity compared to flat terrain. He and Wiggins (80) both state that a 300-pct increase is possible. Topographic effects may be responsible for high airblast levels reported in the valleys of the Appalachian Mountain during strip mining.

APPENDIX E.--ADDITIONAL EQUATIONS AND STATISTICS

TABLE E-1. - Peak structure responses from airblasts

		Equation	Correlation coefficient	Standard error	Normalized standard error
ALL HOMES					
Peak SV (corner) versus	Peak AB (5 Hz)	SV=-0.0065 + 26.6 AB	0.725	0.092	0.556
	1/8-sec integrated AB (4-40 Hz)	SV= .0675 + 31.4 AB	.419	.112	.711
	1/4-sec integrated AB (4-40 Hz)	SV= .0059 + 68.4 AB	.626	.0963	.612
	1-sec integrated AB (4-40 Hz)	SV= .0424 + 95.0 AB	.491	.107	.686
	2-sec integrated AB (4-40 Hz)	SV= .0482 +118 AB	.437	.113	.705
	1/8-sec integrated AB (3.5-10 Hz)	SV= .0021 + 71.3 AB	.675	.0936	.579
	2-sec integrated AB (3.5-10 Hz)	SV= .0198 +181 AB	.541	.107	.661
	1/8-sec integrated AB (10-24 Hz)	SV= .0864 + 38.2 AB	.364	.118	.731
	1/4-sec integrated AB (10-24 Hz)	SV= .0515 + 69.5 AB	.498	.110	.680
	1-sec integrated AB (10-24 Hz)	SV= .0746 + 98.4 AB	.416	.115	.711
	2-sec integrated AB (10-24 Hz)	SV= .0939 +100 AB	.335	.119	.737
	1-sec C-weighted AB	SV= .0538 +223 AB	.557	.102	.654
	4-sec C-weighted AB	SV= .0464 +454 AB	.551	.104	.643
	Perceived level AB	SV= .08 +692 AB	.583	.105	.636
ONE-STORY HOMES					
Peak SV (corner) versus	Peak AB (5 Hz)	SV=-0.0106 + 27.2 AB	0.700	0.126	0.613
	1/8-sec integrated AB (4-40 Hz)	SV= .0875 + 26.5 AB	.313	.145	.772
	1/4-sec integrated AB (4-40 Hz)	SV=- .0213 + 74.6 AB	.593	.123	.612
	1-sec integrated AB (4-40 Hz)	SV= .0528 + 87.3 AB	.403	.139	.692
	2-sec integrated AB (4-40 Hz)	SV= .0593 +109 AB	.343	.150	.705
	1/8-sec integrated AB (3.5-10 Hz)	SV=- .0161 + 79.2 AB	.723	.110	.577
	2-sec integrated AB (3.5-10 Hz)	SV= .0018 +206 AB	.577	.131	.681
	1/8-sec integrated AB (10-24 Hz)	SV= .121 + 27.6 AB	.246	.155	.813
	1/4-sec integrated AB (10-24 Hz)	SV= .0690 + 60.9 AB	.388	.147	.769
	1-sec integrated AB (10-24 Hz)	SV= .112 + 68.8 AB	.266	.154	.807
	2-sec integrated AB (10-24 Hz)	SV= .137 + 58.6 AB	.182	.157	.824
	1-sec C-weighted AB	SV= .0660 +200 AB	.449	.136	.677
	4-sec C-weighted AB	SV= .0561 +421 AB	.458	.135	.672
	Perceived level AB	SV= .11 +622 AB	.521	.133	.692
TWO-STORY HOMES					
Peak SV (corner) versus	Peak AB (5 Hz)	SV= 0.0103 + 23.1 AB	0.707	0.049	0.365
	1/8-sec integrated AB (4-40 Hz)	SV= .00570+ 62.2 AB	.708	.0453	.364
	1/4-sec integrated AB (4-40 Hz)	SV=- .0123 + 89.1 AB	.726	.0441	.354
	1-sec integrated AB (4-40 Hz)	SV=- .0202 +170 AB	.762	.0415	.333
	2-sec integrated AB (4-40 Hz)	SV= .0242 +151 AB	.500	.0560	.450
	1/8-sec integrated AB (3.5-10 Hz)	SV= .103 + 12.3 AB	.118	.068	.511
	1/4-sec integrated AB (3.5-10 Hz)	SV= .055 + 47.5 AB	.395	.0630	.473
	1-sec integrated AB (3.5-10 Hz)	SV= .110 + 18.0 AB	.0817	.0683	.513
	2-sec integrated AB (3.5-10 Hz)	SV= .125 + 0.156 AB	.0005	.0686	.515
	1/8-sec integrated AB (10-24 Hz)	SV= .0335 + 66.0 AB	.707	.0485	.365
	2-sec integrated AB (10-24 Hz)	SV= .0119 +254 AB	.877	.0329	.247
	1-sec C-weighted AB	SV= .0196 +335 AB	.964	.0171	.137
	4-sec C-weighted AB	SV= .022 +585 AB	.941	.022	.177
	Perceived level AB	SV= .06 +809 AB	.680	.047	.403

TABLE E-2. - Integrated structure responses from airblasts

	Equation	Correlation coefficient	Standard error	standard error
ALL HOMES				
1/8-sec SV (corner) versus 1/8-sec AB (4-40 Hz)....	SV= 0.0375 + 17.1 AB	0.408	0.0628	0.736
1/4-sec SV (corner) versus 1/4-sec AB (4-40 Hz)....	SV= .0068 + 30.5 AB	.583	.0492	.689
1-sec SV (corner) versus 1-sec AB (4-40 Hz)........	SV= .0090 + 36.4 AB	.474	.0431	.811
2-sec SV (corner) versus 2-sec AB (4-40 Hz)........	SV= .0031 + 38.8 AB	.431	.0367	.909
1/8-sec SV (corner) versus 1/8-sec AB (3.5-10 Hz)..	SV= .0076 + 37.0 AB	.645	.0539	.616
1/4-sec SV (corner) versus 1/4-sec AB (3.5-10 Hz)..	SV= .0026 + 42.4 AB	.682	.0455	.622
1-sec SV (corner) versus 1-sec AB (3.5-10 Hz)......	SV= .0093 + 42.3 AB	.453	.0449	.822
2-sec SV (corner) versus 2-sec AB (3.5-10 Hz)......	SV= .0040 + 55.6 AB	.530	.0357	.857
1/8-sec SV (corner) versus 1/8-sec AB (10-24 Hz)...	SV= .0454 + 27.3 AB	.384	.0652	.745
1/4-sec SV (corner) versus 1/4-sec AB (10-24 Hz)...	SV= .0166 + 36.7 AB	.553	.0519	.708
1-sec SV (corner) versus 1-sec AB (10-24 Hz).......	SV= .0195 + 40.0 AB	.425	.0456	.836
2-sec SV (corner) versus 2-sec AB (10-24 Hz).......	SV= .0226 + 27.1 AB	.299	.0403	.964
1-sec SV (corner) versus 1-sec C-weighted..........	SV= .0103 + 92.0 AB	.580	.0399	.751
2-sec SV (corner) versus 4-sec C-weighted..........	SV= .0079 +134 AB	.550	.0340	.842
ONE-STORY HOMES				
1/8-sec SV (corner) versus 1/8-sec AB (4-40 Hz)....	SV= 0.0364 + 16.8 AB	0.352	0.081	0.839
1/4-sec SV (corner) versus 1/4-sec AB (4-40 Hz)....	SV=- .0250 + 38.8 AB	.630	.061	.762
1-sec SV (corner) versus 1-sec AB (4-40 Hz)........	SV= .00935+ 35.5 AB	.407	.056	.903
2-sec SV (corner) versus 2-sec AB (4-40 Hz)........	SV= .00520+ 36.8 AB	.364	.050	1.06
1/8-sec SV (corner) versus 1/8-sec AB (3.5-10 Hz)..	SV=- .0160 + 44.9 AB	.724	.0625	.618
1/4-sec SV (corner) versus 1/4-sec AB (3.5-10 Hz)..	SV=- .0273 + 51.3 AB	.746	.0549	.651
1-sec SV (corner) versus 1-sec AB (3.5-10 Hz)......	SV= .0091 + 44.0 AB	.434	.0582	.895
2-sec SV (corner) versus 2-sec AB (3.5-10 Hz)......	SV=- .0047 + 57.6 AB	.518	.0488	.963
1/8-sec SV (corner) versus 1/8-sec AB (10-24 Hz)...	SV= .0498 + 21.0 AB	.331	.0855	.845
1/4-sec SV (corner) versus 1/4-sec AB (10-24 Hz)...	SV=- .0039 + 43.7 AB	.555	.0685	.812
1-sec SV (corner) versus 1-sec AB (10-24 Hz).......	SV= .028 + 33.5 AB	.320	.0612	.940
2-sec SV (corner) versus 2-sec AB (10-24 Hz).......	SV= .0298 + 21.6 AB	.217	.0556	1.101
1-sec SV (corner) versus 1-sec C-weighted..........	SV= .00792+ 83.4 AB	.517	.053	.853
2-sec SV (corner) versus 2-sec C-weighted..........	SV= .00407+144 AB	.519	.046	.971
TWO-STORY HOMES				
1/8-sec SV (corner) versus 1/8-sec AB (4-40 Hz)....	SV= 0.0170 + 29.8 AB	0.563	0.034	0.472
1/4-sec SV (corner) versus 1/4-sec AB (4-40 Hz)....	SV= .0191 + 29.3 AB	.457	.031	.501
1-sec SV (corner) versus 1-sec AB (4-40 Hz)........	SV=- .00553+ 55.1 AB	.686	.017	.411
2-sec SV (corner) versus 2-sec AB (4-40 Hz)........	SV=- .0183 + 68.7 AB	.825	.0079	.251
1/8-sec SV (corner) versus 1/8-sec AB (3.5-10 Hz)..	SV= .0575 + 9.00 AB	.161	.0416	.544
1/4-sec SV (corner) versus 1/4-sec AB (3.5-10 Hz)..	SV= .0308 + 22.9 AB	.398	.0338	.464
1-sec SV (corner) versus 1-sec AB (3.5-10 Hz)......	SV= .0249 + 20.3 AB	.256	.0239	.234
2-sec SV (corner) versus 2-sec AB (3.5-10 Hz)......	SV= .0154 + 24.4 AB	.306	.0416	.426
1/8-sec SV (corner) versus 1/8-sec AB (10-24 Hz)...	SV= .0417 + 23.6 AB	.422	.0382	.500
1/4-sec SV (corner) versus 1/4-sec AB (10-24 Hz)...	SV= .0239 + 37.3 AB	.573	.0302	.460
1-sec SV (corner) versus 1-sec AB (10-24 Hz).......	SV= .0049 + 59.5 AB	.807	.0146	.293
2-sec SV (corner) versus 2-sec AB (10-24 Hz).......	SV= .0311 + 39.4 AB	.614	.0121	.353
1-sec SV (corner) versus 1-sec C-weighted..........	SV= .00865+104 AB	.833	.0128	.310
2-sec SV (corner) versus 2-sec C-weighted..........	SV= .0148 + 99.8 AB	.678	.010	.318

TABLE E-3. - Peak midwall responses from airblasts

		Equation	Correlation coefficient	Standard error	Normalized standard error
ALL HOMES					
Peak SV (midwall) versus	Peak AB (5 Hz).....................	SV= 0.181+126 AB	0.672	0.437	0.536
	1/8-sec integrated AB (4-40 Hz)....	SV= .286+217 AB	.560	.466	.590
	1/4-sec integrated AB (4-40 Hz)....	SV= .214+307 AB	.583	.457	.579
	1-sec integrated AB (4-40 Hz)......	SV= .241+519 AB	.562	.466	.590
	2-sec integrated AB (4-40 Hz)......	SV= .257+658 AB	.529	.481	.601
	1/8-sec integrated AB (3.5-10 Hz)..	SV= .364+238 AB	.447	.511	.638
	1/4-sec integrated AB (3.5-10 Hz)..	SV= .370+272 AB	.416	.519	.649
	1-sec integrated AB (3.5-10 Hz)....	SV= .423+415 AB	.376	.529	.661
	2-sec integrated AB (3.5-10 Hz)....	SV= .405+578 AB	.392	.525	.656
	1/8-sec integrated AB (10-24 Hz)...	SV= .241+369 AB	.709	.403	.504
	2-sec integrated AB (10-24 Hz).....	SV= .268+992 AB	.668	.425	.532
	1-sec C-weighted AB................	SV= .379+944 AB	.620	.442	.534
	4-sec C-weighted AB................	SV= .355+1862 AB	.607	.448	.558
	Perceived level AB.................	SV= .54 +2000 AB	.495	.494	.629
ONE-STORY HOMES					
Peak SV (midwall) versus	Peak AB (5 Hz).....................	SV= 0.277+104 AB	.706	.435	.461
	1/8-sec integrated AB (4-40 Hz)....	SV= .238+211 AB	.623	.445	.507
	1/4-sec integrated AB (4-40 Hz)....	SV= .113+317 AB	.626	.449	.510
	1-sec integrated AB (4-40 Hz)......	SV= .178+511 AB	.579	.465	.528
	2-sec integrated AB (4-40 Hz)......	SV= .194+660 AB	.539	.484	.532
	1/8-sec integrated AB (3.5-10 Hz)..	SV= .363+249 AB	.577	.480	.529
	1/4-sec integrated AB (3.5-10 Hz)..	SV= .420+259 AB	.482	.515	.568
	1-sec integrated AB (3.5-10 Hz)....	SV= .448+423 AB	.426	.532	.586
	2-sec integrated AB (3.5-10 Hz)....	SV= .356+700 AB	.500	.509	.561
	1/8-sec integrated AB (10-24 Hz)...	SV= .305+317 AB	.711	.413	.455
	2-sec integrated AB (10-24 Hz).....	SV= .299+889 AB	.678	.433	.477
	1-sec C-weighted AB................	SV= .352+997 AB	.649	.434	.493
	4-sec C-weighted AB................	SV= .351+1880 AB	.610	.452	.513
	Perceived level AB.................	SV= .51 +2768 AB	.600	.453	.529
TWO-STORY HOMES					
Peak SV (midwall) versus	Peak AB (5 Hz).....................	SV=-0.190+223 AB	0.711	0.414	0.558
	1/8-sec integrated AB (4-40 Hz)....	SV= .147+329 AB	.525	.477	.666
	1/4-sec integrated AB (4-40 Hz)....	SV= .147+400 AB	.564	.463	.647
	1-sec integrated AB (4-40 Hz)......	SV= .142+719 AB	.571	.460	.643
	2-sec integrated AB (4-40 Hz)......	SV= .180+858 AB	.514	.480	.671
	1/8-sec integrated AB (3.5-10 Hz)..	SV= .420+191 AB	.248	.556	.759
	1/4-sec integrated AB (3.5-10 Hz)..	SV= .339+279 AB	.306	.546	.745
	1-sec integrated AB (3.5-10 Hz)....	SV= .435+367 AB	.280	.551	.750
	2-sec integrated AB (3.5-10 Hz)....	SV= .474+405 AB	.257	.555	.756
	1/8-sec integrated AB (10-24 Hz)...	SV= .115+493 AB	.727	.394	.538
	2-sec integrated AB (10-24 Hz).....	SV= .186+1261 AB	.667	.428	.584
	1-sec C-weighted AB................	SV= .395+898 AB	.575	.458	.640
	4-sec C-weighted AB................	SV= .357+1844 AB	.589	.457	.639
	Perceived level AB.................	SV= .53 +1561 AB	.427	.518	.737

TABLE E-4. - Integrated midwall responses from airblasts

	Equation	Correlation coefficient	Standard error	Normalized standard error
ALL HOMES				
1/8-sec SV (midwall) versus 1/8-sec AB (4-40 Hz)......	SV= 0.175 +120 AB	0.504	0.303	0.666
1/4-sec SV (midwall) versus 1/4-sec AB (4-40 Hz)......	SV= .113 +141 AB	.561	.224	.596
1-sec SV (midwall) versus 1-sec AB (4-40 Hz)..........	SV= .0832+160 AB	.514	.165	.643
2-sec SV (midwall) versus 2-sec AB (4-40 Hz)..........	SV= .0675+174 AB	.538	.131	.999
1/8-sec SV (midwall) versus 1/8-sec AB (3.5-10 Hz)....	SV= .246 +117 AB	.355	.333	.724
1/4-sec SV (midwall) versus 1/4-sec AB (3.5-10 Hz)....	SV= .196 +161 AB	.374	.255	.666
1-sec SV (midwall) versus 1-sec AB (3.5-10 Hz)........	SV= .148 +112 AB	.305	.187	.729
2-sec SV (midwall) versus 2-sec AB (3.5-10 Hz)........	SV= .104 +155 AB	.364	.147	.706
1/8-sec SV (midwall) versus 1/8-sec AB (10-24 Hz).....	SV= .144 +209 AB	.651	.270	.600
1/4-sec SV (midwall) versus 1/4-sec AB (10-24 Hz).....	SV= .0976+230 AB	.702	.196	.513
1-sec SV (midwall) versus 1-sec AB (10-24 Hz).........	SV= .0885+239 AB	.620	.154	.618
2-sec SV (midwall) versus 2-sec AB (10-24 Hz).........	SV= .0642+258 AB	.697	.113	.544
1-sec SV (midwall) versus 1-sec C-weighted............	SV= .126 +297 AB	.560	.159	.647
2-sec SV (midwall) versus 4-sec C-weighted............	SV= .0382+753 AB	.711	.108	.520
ONE-STORY HOMES				
1/8-sec SV (midwall) versus 1/8-sec AB (4-40 Hz)......	SV= 0.116 +124 AB	0.597	0.287	0.689
1/4-sec SV (midwall) versus 1/4-sec AB (4-40 Hz)......	SV= .0335+157 AB	.640	.218	.523
1-sec SV (midwall) versus 1-sec AB (4-40 Hz)..........	SV= .0151+187 AB	.725	.124	.460
2-sec SV (midwall) versus 2-sec AB (4-40 Hz)..........	SV= .0348+178 AB	.633	.115	.488
1/8-sec SV (midwall) versus 1/8-sec AB (3.5-10 Hz)....	SV= .238 +124 AB	.472	.326	.631
1/4-sec SV (midwall) versus 1/4-sec AB (3.5-10 Hz)....	SV= .213 +113 AB	.435	.264	.612
1-sec SV (midwall) versus 1-sec AB (3.5-10 Hz)........	SV= .111 +154 AB	.534	.158	.562
2-sec SV (midwall) versus 2-sec AB (3.5-10 Hz)........	SV= .0898+177 AB	.581	.126	.535
1/8-sec SV (midwall) versus 1/8-sec AB (10-24 Hz).....	SV= .156 +186 AB	.684	.269	.523
1/4-sec SV (midwall) versus 1/4-sec AB (10-24 Hz).....	SV= .0625+228 AB	.780	.183	.427
2-sec SV (midwall) versus 2-sec AB (10-24 Hz).........	SV= .0575+227 AB	.782	.0963	.410
2-sec SV (midwall) versus 4-sec AB C-weighted.........	SV= .0452+640 AB	.759	.096	.407
TWO-STORY HOMES				
1/8-sec SV (midwall) versus 1/8-sec AB (4-40 Hz)......	SV= 0.111 +179 AB	0.456	0.313	0.744
1/4-sec SV (midwall) versus 1/4-sec AB (4-40 Hz)......	SV= .105 +168 AB	.503	.228	.662
1-sec SV (midwall) versus 1-sec AB (4-40 Hz)..........	SV= .0894+179 AB	.395	.188	.818
2-sec SV (midwall) versus 2-sec AB (4-40 Hz)..........	SV=- .0565+443 AB	.600	.131	.707
1/8-sec SV (midwall) versus 1/8-sec AB (3.5-10 Hz)....	SV= .282 + 89.6 AB	.185	.354	.820
1/4-sec SV (midwall) versus 1/4-sec AB (3.5-10 Hz)....	SV= .191 +131 AB	.264	.261	.747
1-sec SV (midwall) versus 1-sec AB (3.5-10 Hz)........	SV= .191 + 50.7 AB	.109	.209	.883
2-sec SV (midwall) versus 2-sec AB (3.5-10 Hz)........	SV= .217 - 58.6 AB	-.0573	.171	.885
1/8-sec SV (midwall) versus 1/8-sec AB (10-24 Hz).....	SV= .0863+275 AB	.645	.275	.632
1/4-sec SV (midwall) versus 1/4-sec AB (10-24 Hz).....	SV= .0725+288 AB	.651	.206	.583
1-sec SV (midwall) versus 1-sec AB (10-24 Hz).........	SV= .0869+283 AB	.493	.183	.774
1-sec SV (midwall) versus 1-sec C-weighted............	SV= .149 +234 AB	.417	.186	.809

APPENDIX F.--STRUCTURE RESPONSES FROM OTHER IMPULSIVE NOISE SOURCES

Some research has been done on response from transient air overpressures, primarily to assess sonic booms. Kamperman (18) investigated the transfer functions of airblasts from quarries into annoying floor motions. He used only standard deviation to rank the descriptors and did not measure 2-Hz, 5-Hz, and 6-Hz peak airblasts. As with the midwall response results from this study, Kamperman found that the best correlations were with various SEL values and that the difference among many of the techniques were not significant. Some of his results (tables 3.4-4) are comparable to the Bureau's midwall responses (for example, the C-slow, peak, and 4- to 200-Hz SEL airblasts versus peak floor vibrations). However, his values are 3 to 6 times lower indicating that airblasts are a poorer source of energy for floor excitation than for vertical walls.

Kryter (19) cites a White Sands study with worst-case displacements of 0.035 inches for the ceiling, 0.053 inches for the midwall, and 0.016 inches for racking from a 5-lb/ft^2 (0.0347-lb/in^2 or 142 dB) sonic boom;[1] assuming a midwall frequency of 16 Hz and a racking frequency of 8 Hz, these become 3.52, 5.33, and 0.80 in/sec particle velocities, respectively. These are higher than the extrapolation of the mean of the Bureau's blast responses (from figs. 30 and 32) by about 30 pct, but within the ranges measured.

Kryter also discusses the difference in spectra among sonic booms from different size planes and the greater damage risk from larger planes. The larger aircraft have increased low-frequency energy (2-6 Hz) so the energy spectra for the boom should better match that of the structure. As with blasting, increased response with high frequency has been observed and dominates the response plots ("high" this time refers to 4-16 Hz, as compared to type 2 airblast frequencies of 0.5-1.5 Hz).

Sutherland (63) described acoustic response tests on 8x10-foot wall panels, presumably from steady-state sources and found maximum responses at resonance frequencies of

5.57 g/psi for uninsulated wood-frame wall,

2.79 g/psi for insulated wood-frame wall,

and 0.10 g/psi for 8-inch concrete block wall.

Resonant frequencies were not given, but assuming 16 Hz for the wood-frame wall, 25 Hz for the block wall, and an airblast level of 0.01 psi (131 dB), the three responses become 0.21, 0.107, and 0.0024 in/sec, respectively. Unlike the wood-frame walls, the concrete block wall responded greater at other

[1]All sonic boom and long-range airblast measurements were made with wideband systems (at least 0.1-Hz low-frequency cut-off) unless specified otherwise. These overpressure values are based on a wide-enough bandwidth to measure all the acoustic energy present. For convenience, sound levels re 20 x 10^{-6} N/m^2 have been calculated for these overpressures.

than its resonant frequency, increasing to 1.0 g/psi (0.024 in/sec/psi) at 30 times that of its natural frequency. These values are lower than the Bureau's measured response by 5 to 10 times, either because of the steady-state sources or the modeling problems with wall sections.

Wiggins (80) extensively describes the response of structures to sonic booms and includes the analysis of the complicated response-spectrum technique and also the more practical use of peak response (e.g., peak particle velocity) and peak airblast overpressure. Wiggins computed racking responses from the effective load (front minus back pressure) for comparisons with measured responses and measured mean response data from both low- and high-frequency sonic booms (3-10 Hz). He noted 3.38 to 7.81 micro inch per inch per pound per square foot (μin/in/psf) strain in a vertical stud, racking displacements of 3.5 to 6.7 x 10^{-4} in/psf. Window strains ranged up to 23 μ in/in/psf and peak displacements up to 0.13 in/psf depending on window size and aircraft path. Wiggins discussed how various motion or sound descriptors can be used depending on the relative frequencies of the source and the object affected. For airblast analysis, this is complicated by the frequency variability among the different airblast types. It may be possible, although impractically complex, to develop a descriptor that simulates peak overpressures for $T_{AB} > T_S$ and impulse for $T_{AB} < T_S$ (where T is the period). Wiggins recommended peak pressure alone, since no better descriptor was then known.

Conversion of the Wiggins peak displacement data to peak particle velocities using 8 Hz for the racking and 16 Hz for the midwalls, gives 0.018 to 0.034 in/sec/psf and 0.21 to 0.44 in/sec/psf, respectively. Structure responses from airblasts (figs. 30 and 32), are significantly higher at 0.09 to 0.11 in/sec/psf and 0.39 to 0.71 in/sec/psf.

Newberry (33) measured sonic boom effects on house walls and roofs of 2.3 to 4.8 lb/ft^2. His displacement responses ranged from 0.00074 to 0.0080 in/psf, roughly corresponding to the highest of Wiggin's responses for racking and midwalls, respectively. Conversion to particle velocities gives maximum wall responses of up to 0.80 in/sec/psf which is within the range of the Bureau's findings for midwalls (fig. 32). His roof response was about one-third of the Bureau's whole house racking motion.

Leigh (22) describes sonic boom response measurements in a wood-frame house with a measured peak displacement of 0.034 inch at 16.7 Hz, and acceleration of 0.64 g at 20 Hz from a sonic boom of 2.29 lb/ft^2 (135 dB). These do not covert to the same particle velocity, suggesting that Leigh's midwall motions are not sinusoidal (unlike the Bureau's wall motion data). From displacement and acceleration, the responses compute to 1.55 and 0.86 in/sec/psf, respectively, somewhat higher than Newberry. Leigh also tested gypsum panels for sonic-boom-induced strain, and measured 31 to 47 μ in/in for a 10 lb/ft^2, and 0.069 lb/in^2, sonic boom N-wave of 100-msec duration.

Mayes (25) described sonic boom and blast-induced stresses in a wall stud and found values of 33 to 50 lb/in^2/psf for sonic booms and 14 to 16.3 lb/in^2/psf for single charge blasts.

Clarkson and Mayes (7) describe building responses from sonic booms including wall accelerations, displacements, and stresses. The stress results were previously reported by Mayes (25), and the shear displacements and the wall accelerations corresponding to a 2-lb/ft^2 sonic boom (0.0139 lb/in^2, 134 dB) were 0.0030 to 0.0065 inch and 0.1 to 0.4 g, respectively. Midwall displacements were different for the inside and outside walls; the maximum envelopes were 0.0063 inch and 0.0144 inch for the 2-lb/ft^2 sonic boom. Unlike most other results, the inside wall responses measurement did not increase linearly with increasing overpressure.

Blume (3) studied the responses of structure to sonic booms, providing much of the data for the comprehensive sonic boom summarizes (7, 19, 25, 63, 80). Roof line racking displacements of 0.0042 to 0.0050 inch were measured for overpressures of approximately 2.0 lb/ft^2, and maximum midwall displacements and accelerations were 0.023-0.034 inch and 0.46-0.74 g. (Mean values were typically lower by a factor or about one-half.)

The Langley Research Center studied Concorde-noise-induced building vibrations (29-31). Because the responses were from steady-state noise sources, and were processed as 1/2-sec integrated values, they are not comparable with the data from sonic boom and airblast response studies.

Seaman (51) describes a theoretical analysis of window breakage recognizing that the process is nonlinear and that a small chance for damage exists even at low airblast levels for large enough populations.

A summary of all structure responses from the various impulsive noise sources is given in tables 7 and 8 in the main text of this report.

APPENDIX G.--OTHER AIRBLAST DAMAGE RESEARCH

Early research by the Bureau of Mines (82) and Ballistics Research Laboratory (36) determined that the breakage of window glass in structures should occur at lower levels than other damage. Windes (82) evaluated glass breakage from small open-air shots consisting of one to two sticks of 1- by 8-inch dynamite at distances of 3 to 30 feet. Damage occurred at overpressures of 0.88 to 1.10 lb/in^2 (170 to 172 dB); none was observed at 0.62 to 0.72 lb/in^2 (167 to 168 dB). These levels apply to properly mounted glass; however, glass under strain could fail at overpressures as low as 0.10 lb/in^2 (151 dB). Perkins and Jackson (36) conducted extensive tests on glass panes mounted in frames with similar results. They defined damage threshold for properly mounted glass of 0.75 lb/in^2 (168 dB), and for poorly mounted glass under stress of 0.10 lb/in^2 (151 dB). They also noted that rattling of window sashes occurred at 0.03 to 0.05 lb/in^2 (141 to 145 dB). It has been recognized that these levels are too high for continuous use in urban areas and where there are large number of people or objects affected. They do not provide realistic guidelines for either blast design or environmental regulation (57). The likely reasons for their high damage thresholds are the small high-frequency shots and small panes studied.

Poulter (39) evaluated glass breakage and plaster damage produced by airblast from totally unconfined explosives. He found that glass damage could occur at cube-root-scaled distances as high as 260 ft/lb$^{1/3}$, and plaster cracking as high as 63 ft/lb$^{1/3}$. This agrees with the conclusions of other studies (36, 82) that plate glass is more damage-sensitive than plaster. Using the "unconfined" line in figure B-5, these minimum-scale distances correspond to approximately 0.0320 lb/in^2 (141 dB) and 0.290 lb/in^2 (160dB), respectively. Poulter's scaled-distance values are based on weather conditions which favor maximum damage.

Several studies of airblast propagation by Reed have been indirectly concerned with the problem of glass damage (1, 42-43, 45). Primarily interested in airblast at large distances (tens of miles) from large-scale surface blasts, Reed has also studied other related problems such as the accidental Medina blast in San Antonio, Tex., 1968, which resulted in claims for 3,644 windows (43, 45). Reed predicted the existence of strong focusing east of the blast produced by westward winds at a 6,000-ft altitude and correlated this with the many damage claims for the large population impacted (45). He noted that damage costs become very small below 3 mb (0.0435 lb/in^2, 144 dB), although they still exceed the laboratory tests conducted by Pittsburgh Plate Glass Co. by a factor of 10. Overall claims for window damage correspond to \$7.00 per 1,000 people for an overpressure of 1.12 mb (0.0162 lb/in^2, 135 dB), and can be computed for other pressures by the following relationship:

$$C = 4.75 \times 10^{-3} (\Delta p)^{2.78},$$

where C is the cost in dollars (1973) and Δp is the overpressure in millibars (1 mb = 0.0145 lb/in^2). From the Medina blast, Reed developed two equations for probabalities of single pane damage and number of panes broken based on a large population sample (43):

$$P = 3.71 \times 10^{-6} A^{1.22} (\Delta p)^{2.78},$$

where P is the breakage probability for a single pane, A is the pane area, in square feet, and Δp is the peak overpressure, in millibars. Reed also derived a predictor for the number of broken panes:

$$Q = 1.3 \times 10^{-4} N (\Delta p)^{2.78},$$

where Q is the number of panes broken, and N is the population impacted. Both equations give very small estimates of damage at typical airblast levels of 120 to 130 dB. At 130 dB, for a large window (64 ft^2), and significant population (100), the two values become $P = 1.67 \times 10^{-4}$ and $Q = 3.67 \times 10^{-3}$, still a small damage risk.

Reed also examined the log-normal damage model by combining the high and low level data for a new window damage equation:

$$\Delta p \ (50\%) = 75 \times (2.5)^{\pm 1}$$

where Δp (50%) is the overpressure, in millibars, corresponding to the 50-pct probability of damage (43). This gives a wide range of values, 30 to 187 mb (0.44 to 2.71 lb/in^2, 164 to 179 dB). However, this equation is not useful for the mining airblast problem since it is necessary to consider the probabilities at the extremes of the predictions (e.g., low levels). Reed's glass breakage probability and also a sonic boom risk analysis by Wiggins (79) are given in figure 40 (main text). Two other papers by Reed specified 2 mb (0.029 lb/in^2, 140 dB) as a general glass damage threshold for single point explosions in air (1).

Taylor described an analyses by Warren on glass breakage in 30 greenhouses from small line charges (64). For an airblast level of 4.2 lb/ft^2 (0.0292 lb/in^2, 140 dB), breakage was 0.7 pct, or 239 out of 35,000. This is approximately ten times what would be predicted by Reed's equation (43); however, the state of stress and other conditions in the greenhouse are not discussed.

An extensive review by Sutherland (63) described fatigue in wood-frame and concrete residential walls from steady-state sound. Damage was found for the following cases: 143 dB sound pressure level for 80 min (walls); 145 dB sound pressure level for 20 min (roof); and 153 dB sound pressure level for 10 min (8-inch concrete wall). No damage was observed in the concrete wall from a 139 dB level held for 170 minutes. Fatigue stress for the concrete at 5×10^6 cycles was 55 pct of the ultimate stress.

An analysis of airblast damage data for glass was included in general analysis of environmental impact of noise and vibration by von Gierke (70). He lists safe charge weights for a variety of conditions, corresponding to less than a 50-pct probability of the breakage of even a single pane. For clustered populations ($N \geq 4$) and surface explosions, the safe quantity of explosive is--

$$W < 328 R^3/N,$$

where N is the population impacted, R is the distance, in kilometers, and W the charge weight per delay, in kilograms. For a uniform population distribution, this reduces to $W < 40\ R^3$, where R is the distance to the nearest residence. Proper confinement allows an increase in explosive weights by a factor of about 80 times, assuming that the scale depth of burial exceeds 1.4 $m/kg^{1/3}$, a condition usually met in typical mine blasts (scale depths of burial can be computed by Wiss' formulas given in the section on blast design). The safe charge weights than become $W < 26{,}430\ R^3/N$ for a clustered population, and $W < 3{,}200\ R^3$ for a uniform distribution. These are probably stricter than necessary for many mining situations, (such as well confined blasts such as for highwalls). Von Gierke also gives a variation of Reed's broken glass estimation equation:

$$Q = 1.56 \times 10^{-16}\ N\ (PK)^{2.78},$$

where Q is the number of panes broken, N is the population impacted and PK is the peak-to-peak amplitude of the pressure variation in Pascals (N/m^2). Von Gierke assumes that PK is 2.7 times the peak free air pressure owing to both reflection at the ground and the use of peak-to-peak pressures. However, blasting at close ranges usually does not generate significant negative phases (figs. 3-5 and 28-29 in the main text), and ground reflection effects are already included in the measured overpressures. Therefore, the equation as given is a reasonable predictor for glass damage from airblast. A worst case from figure 3 corresponds to PK equalling two times the peak overpressure, giving a Q of 2.67×10^{-9} for N equalling 100 and peak overpressure of 200 N/m^2 (149 dB).

Redpath (41) combined several studies including Reed's on the Medina blast (43) and another accidental surface blast to derive a glass breakage predictor which he feels is more representative (and restrictive) in the overpressure range of 0.1 lb/in^2 to 1.0 lb/in^2 (151 to 171 dB). At an overpressure of about 0.060 lb/in^2 (146 dB), he predicts a breakage probability of 0.0012 (0.12 pct) which is close to Reed's estimate of 8.9×10^{-4} for a window pane area of 3.5 ft^2. Extrapolating beyond the limits of Redpath's data gives a glass damage probability of 0.00010 (0.010 pct) at 0.036 lb/in^2 (141 dB).

Implicit in the analyses of the damage probabilities are several statistical assumptions. The airblast events are considered independent; that is, the damage risk not influenced by past airblast history. This contrasts to the hypothesis that a window which was not broken by a given airblast would be less likely to be broken by another airblast at the same level. The damage risk is also assumed to be directly proportional to the number of exposures so that risk from all airblasts is the sum of all the individual risks. As an example, a 10^{-5} damage probability from one blast becomes 10^{-2} for 1,000 similar blasts.

APPENDIX H.--SONIC BOOM DAMAGE

Sutherland (63) summarized theoretical and experimental studies of sonic boom damage. He notes that a sonic boom overpressure of 2.5 lb/ft^2 (0.0174 lb/in^2, 136 dB) would preclude damage, based on the theoretical damage calculations of stresses in the structure. The results of experimental sonic boom tolerance tests at White Sands were--

Cracks in plaster on wood lath.............	6.5-10 lb/ft^2 (0.045-0.069 lb/in^2, 144-148 dB)
Nail popping--1/2-inch gypsum board........	10.3 lb/ft^2 (0.0715 lb/in^2, 148 dB)
Paint flaking on old gypsum board..........	4.0 lb/ft^2 (0.0625 lb/in^2, 147 dB)
Falling bric-a-brac and rattling dishes....	6-11 lb/ft^2 (0.0417-0.0764 lb/in^2, 143-148 dB).

The estimated peak stress in the wood frame at an overpressure of 6.5 lb/ft^2 (0.045 lb/in^2, 144 dB) is 180 lb/in^2, which corresponds to a strain of 150 x 10^{-6} μ in/in. Assuming the same amount of strain in the cement or mortar in plaster or gypsum board gives peak stresses of 290 to 810 lb/in^2 (depending on the board's formulation). These are close to the failure stresses observed in static tests.

Sutherland (63) also reviews window and other damage from sonic booms. In a study of 24 windows 3 ft x 3 ft x 1/8 in, no failures were observed below 20 lb/ft^2 (0.139 lb/in^2, 154 dB). However, precracked windows failed at levels as low as 7.6 lb/ft^2 (0.053 lb/in^2, 145 dB). A sonic boom criterion for no damage is given by--

$$p_o \left(\frac{a}{h}\right)^2 \geq 0.8 \times 10^6 \ lb/ft^2,$$

where p_o is sonic boom overpressure, in pounds per square foot, a is the side of an approximately square window, and h is the window thickness (same units as a). With a/h generally less than 330, the safe maximum overpressure is 7.3 lb/ft^2 (0.051 lb/in^2, 145 dB). Sutherland noted that for large population samples and sonic boom overpressures of 1.7 lb/ft^2 (0.0118 lb/in^2, 132 dB), it was typical to receive one claim per 300,000 homes. These involved mostly bric-a-brac with about 10 pct of the claims for plaster damage.

Wiggins analyzed the sonic boom tests in Oklahoma City and White Sands in detail, listing all the "damage events" and associated boom levels which occurred at White Sands (80). The lowest value for any event was 2.1 lb/ft^2 (0.0146 lb/in^2, 134 dB) which caused the fall of a fleck of loose paint. A plaster crack from structure racking was observed at approximately 4.2 lb/ft^2 (0.029 lb/in^2, 140 dB); however, plaster cracks typically required 7 to 14 lb/ft^2 (0.049 to 0.097 $lb.in^2$, 145 to 151 dB). A hairline settlement crack was extended about 2 inches after 20 booms of 5.2 lb/ft^2 (0.0361 lb/in^2, 142 dB); however, further extension was also caused by a person jumping on the floor near the wall. Wiggins lists cases of glass damage, which typically had thresholds of 8 to 16 lb/ft^2 (0.056 to 0.11 lb/in^2, 146 to 152 dB) and notes that a significant amount of breakage occurred at 38 lb/ft^2 (0.264 lb/in^2, 159 dB). Much of the glass damage was attributed to impact of the severely rattling window sashes, rather than direct pressure against the panes. Consequently, the mechanism of glass failure may be different for windows in loose frames and glass mounted to be immovable. The panes which failed at White Sands were two 8- x 10-foot store front windows (at 38 lb/ft^2). Wiggins evaluates the Oklahoma City data by recommending a 5-lb/ft^2 (0.035 lb/in^2, 142-dB) safe level for new plaster and 10 lb/ft^2 (0.069 lb/in^2, 148 dB) for cured plaster.

Clark (6) describes a sonic boom impact study in the St. Louis area which involved widespread pretest publicity and mechanisms for complaints. Out of 76 flights over the metropolitan area of 3 million people, a total of 84 complaints were received, all for damage or falling objects. Investigators judged 27 of these complaints to have likely validity (40 pct plaster, 30 pct glass, 10 pct both). Sonic boom overpressures were not measured, but estimated to be up to 3 lb/ft^2 (0.021 lb/in^2, 137 dB).

Kryter (19) calculated maximum "safe overpressures" for large panes subjected to booms from four different aircraft, based on Wiggins' (80) maximum failure rate of one crack per 100,000 (table H-1). A low damage threshold is evident for the largest windows, consistent with the matching of their 3-Hz natural frequency with long N-wave duration for the large aircraft (the 0.250- to 0.350-sec period is approximately equivalent to 3 Hz). Table H-1 shows that a relatively low sonic boom overpressure level will meet a 10^{-5} damage probability for a 100- x 200-inch window. However, this window is larger than the majority of windows residences, as is the next smaller size. Additionally, the 1/4-inch thickness appears substandard for the two largest window sizes, where 5/16 inch is normal for an 80-ft^2 pane and 3/8 or 1/2 inch is standard for a 139-ft^2 pane (51). Increasing the thickness of the 80-ft^2 and 139-ft^2 windows increases their safe levels by 2 and 5 dB, respectively.

TABLE H-1. - Maximum safe[1] sonic boom overpressures for large glass panes of 1/4-inch thickness (19)

Window size, in	Area, ft^2	Natural frequency, Hz	N-wave duration, sec	Typical aircraft	Maximum safe overpressure		
					Lb/ft^2	Lb/in^2	dB
100 x 200	139	3.0	0.250-0.350	SST, B-70.......	0.35	0.0024	119
			.170	B-58..........	.59	.0041	123
			.100	F-106.........	1.4	.0097	131
76 x 152	80.2	5.0	.250-.350	SST, B-70.......	1.57	.0109	132
			.170	B-58..........	1.57	.0109	132
			.100	F-106.........	2.6	.0181	136
53 x 106	39	10.0	.250-.350	SST, B-70.......	5	.035	142
			.170	B-58..........	5	.035	142
			.100	F-106.........	5	.035	142

[1]Safe as defined as less than one chance in 10^5 per pane per boom.

The safe values from table H-1, corrected for thickness are plotted in figure H-1. These are based on the probability of one minor crack in 100,000 window-exposures. The frequency notably affects the safe level, demonstrating

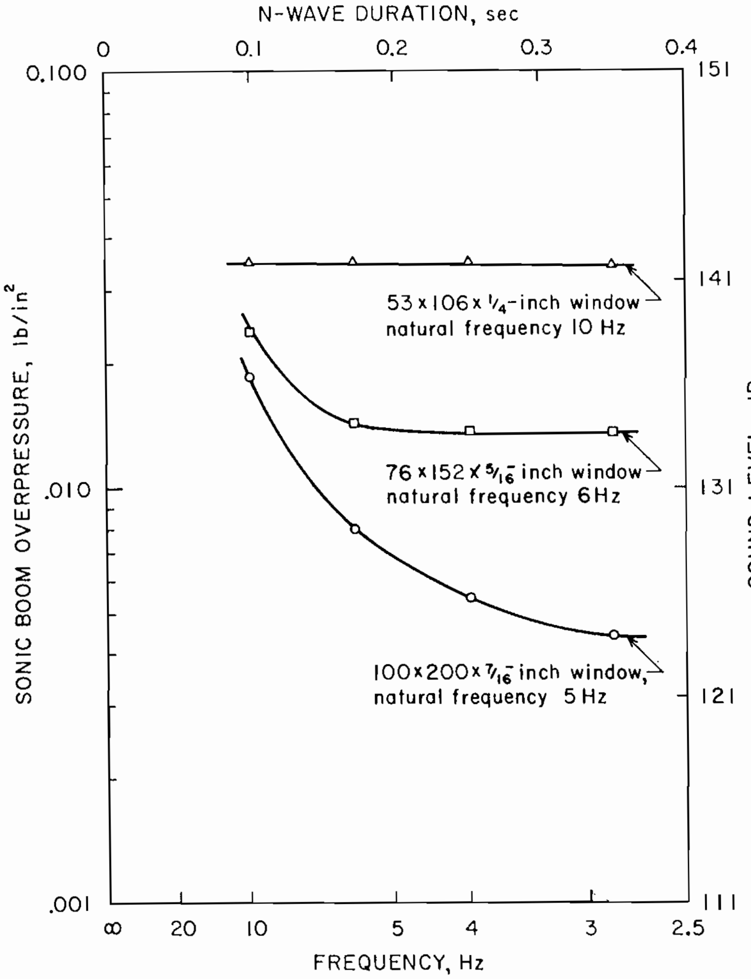

FIGURE H-1. - Maximum safe sonic boom overpressures based on a 10^{-5} glass breakage probability.

that failure probability decreases for sonic booms of frequency higher than that of the window resonance. For airblasts, the type 1 airblast theoretically should present a lower damage probability than the low-frequency type 2. Figure H-1 shows that it is prudent to apply a safety factor of 9 dB per doubling of window area for large panes. Consequently, the maximum recommend (0.1 Hz) airblast overpressure of 134 dB should then be reduced by 9 dB per doubling of window size above 80 ft^2, to maintain the same 10^{-5} damage probability. Where a higher damage probability is acceptable, this correction is not necessary. Reed's damage equation (43) gives 7.3 dB per doubling of area, which is in good agreement.

Leigh examined the failure and fatigue of plaster panels subjected to sonic-boom-type loading (22). He subjected 13 panels to 1,000 N-waves of 10-lb/ft^2 (0.0694-lb/in^2, 148-dB) overpressure, having a duration of 100 msec. Generated strains were 31 to 47 μin/in; the single failure was attributed to too much clamping pressure around the edges. Noting that the static failure strain for plaster panels (wallboard) is approximately 460 μin/in and resulting stress 300 lb/in^2, Leigh predicted that panels will fail at 10^4 sonic booms that produce 260 μin/in.

Taylor's analysis of the general airblast problem included relevant sonic boom data (64). The St. Louis sonic boom study, involving many millions of boom-person exposures (BPE), concluded that superficial damage such as glass cracks began at levels of 2.0 to 3.0 lb/ft^2 (0.0139 to 0.0208 lb/in^2, 134 to 138 dB), and a similar study at Oklahoma City found no damage at 6 lb/ft^2. (Smaller aircraft produce less damaging higher frequency sonic booms.) Taylor noted that 2 lb/ft^2 overall is a minimum damage threshold for general sonic boom exposure.

A summary review of the effects of sonic booms and similar impulsive noises on structures was also made by the National Bureau of Standards for the U.S. Environmental Protection Agency (32). They noted that 2,000 flights in Virginia, Missouri (St. Louis study), Oklahoma (Oklahoma City study), and California (Edwards Air Force Base) produced no significant damage at overpressures up to 6 lb/ft^2 (0.042 lb/in^2, 142 dB). Similarly, no significant damage was found in New Mexico (White Sands study) for 1,200 flights at up to 3.3 lb/ft^2 (0.023 lb/in^2, 139 dB). In unmonitored tests, it was normal to receive 12 to 25 claims per million BPE for glass, plaster, or bric-a-brac at levels of 1.8 lb/ft^2 (0.0125 lb/in^2, 133 dB).

Another review of sonic boom damage was made by Clarkson and Mayes (7). They summarized the damage claims from the St. Louis study (390 x 10^6 BPE), Oklahoma City (462 x 10^6 BPE), and Chicago (305 x 10^6 BPE). The boom overpressures were nominally 1.8 lb/ft^2 (0.0125 lb/in^2, 133 dB), except for Oklahoma City at 1.2 lb/ft^2 (0.0083 lb/in^2, 129 dB); payment for damage claims were \$151, \$192, and \$377 per million BPE, respectively, for the three areas. For normal blasting impact, claims of this magnitude would be essentially insignificant. Clarkson and Mayes describe an analysis of cumulative crack growth damage in plaster on wood lath in a two-story structure over a period of several weeks. Booms were kept at 5 lb/ft^2 (0.0347 lb/in^2, 142 dB) for 20 days, and then increased in increments of 2 lb/ft^2 until damage occurred. The change of slope at 11 lb/ft^2 (0.0764 lb/in^2, 148 dB) corresponded to the onset of damage.

Blume's study of sonic boom responses of two residences at Edwards Air Force Base found no damage from the approximately 2.2 lb/ft^2 (0.0153 lb/in^2, 134 dB) sonic booms (3). However, three cases of damage occurred within the community, out of 110,000 panes, with an estimated minimum overpressure of 3.75 lb/ft^2 (0.026 lb/in^2, 139 dB).

APPENDIX I.--ANNOYANCE FROM IMPULSIVE NOISE

Most studies of annoyance from impulsive noise have been done for predictions of sonic boom and artillery impact.

The CHABA noise guidelines include annoyance from impulsive sources based on C-weighted day-night average (L_{cdn}) (70). They generalize that the yearly C-weighted average should be kept below 55 dB for minimum complaints (for any type or duration of noise). Based mainly on Borsky's sonic boom survey (4), which involved a test program of eight events per day for 6 months, the CHABA team derived three specific annoyance relationships for impulsive noises. Two of these are survey curves from the Oklahoma City study representing impulses with differences between peak and L_{sc} (C-weighted sound-exposure level) of 26 and 20 dB. The 26 dB line in the CHABA report most closely represents blasting, and shows 2.5, 5, and 13 pct annoyed at 57, 58, and 60 dBL_{cdn}, respectively. The third CHABA annoyance criteria is a generalized annoyance relationship based on 19 surveys and shows approximately 5, 8, and 15 pct annoyed at 57, 60, and 65 dBL_{cdn}, respectively. The CHABA report also discusses the use of C-weighted sound exposure measurements, which are used to derive L_{cdn}, but does not recommend maximum L_{sc} levels. No mining-type blasts were used in these analyses.

Using the L_{cdn} curves from the CHABA report (70) or from Stachura's study (61), an airblast which has a constant 105 dBC level for 1 sec would give an L_{cdn} level of 55.6 dB. Consequently, the upper limit of the safe airblast level derived from analysis of response and damage is equal to the annoyance criterion of 56 dB (approximately 5 pct annoyed), where some complaints could be expected. This assumes that the CHABA guidelines do apply to blasting as evaluated by C-weighted sound-exposure levels. Shot 101 which was used as the type 1 example, was an almost constant 102 dBC-slow for 0.95 sec, or an L_{dn} level of 52.4 dB. No attempt was made to compute L_{cdn} for the many blasts in table 3 (in the main text of this report) since almost all have time-varying C-weighted levels. Presumably, L_{cdn} levels could be obtained from all the recordings for comparisons with other sound descriptors and measured responses. The Department of Housing and Urban Development (HUD) is using L_{cdn} contours to evaluate the suitability of land for development, based on the CHABA criteria. The proposed 65 dB L_{cdn} would allow nine events per day of 105 dBC-slow.

The Environmental Protection Agency (EPA) recommends an L_{dn} of 55 dB outdoors in residential areas to protect the public health and welfare and prevent annoyance based on the CHABA guidelines (68). No special provisions are specified with regard to impulse noise and annoyance.

Attempts to produce a single descriptor for all annoying noise are laudable; however, they tend to smooth over significant differences in characteristics and fail to represent the annoyance potential of infrequent, impulsive noises. The L_{cdn} technique averages the C-weighted airblast over periods of 1 day to 1 year, equating it to a lower level, steady-state source. However, it does not allow for the different annoyance factors that exist for the impulsive sources, which seldom exceed 1 second, and steady-state noises, which are typically perceived as interfering with everyday activities. Most airblast concern is with house rattling, startling, and fear of damage.

The L_{Cdn} measurement methodology has been developed to characterize the overall environmental impact of impulsive noise, and not specifically to regulate the sources of impulse noise. Being responsive to weighted levels, frequency of events, and the time of day, this is probably the best method available for assessing the general state of noise at a site. For a small number of events per unit time and those for which C-weighting is not consistently applicable, this descriptor becomes less reliable as opposed to Army base artillery practice and sonic booms near military airfields. Blasting represents a case where L_{Cdn} may be too coarse a descriptor. Airblast control requires a measure of a peak level or sound exposure level, which averages only over the duration of the event. This study has shown that C-weighted or special-filtered sound exposure levels are sometimes the best impulsive sound descriptors for structural response, although it is not necessary to use them exclusively.

Sonic booms were the subject of many studies in anticipation of the widespread use of supersonic transports. These impulsive noises are similar to blasting but have different spectra and shorter durations. They are of higher frequency than type 2 airblast and are in just the right range for strong structural response (3 to 10 Hz). The frequency spread of energy is typically wider than blasting, which makes excitation of residential structure more likely. Sonic boom impact is reduced because of their characteristic short duration and small amount of energy for their peak level. They are not much more than a single N-wave cycle, and so are potentially less annoying than the airblasts. Peak responses from sonic booms were discussed previously, and in many cases exceeded the levels of responses measured from production blasts (See table 7 and 8.)

Higgins and Carpenter examined perceived levels (PLdB) to evaluate sonic boom impact compared to aircraft flyovers (14). Table I-1 shows equivalences between the PLdB and the 0.1-Hz linear airblast using Higgins' PLdB equation (previously discussed under the section on Processing of Airblast Time Histories). The acceptability clearly varies for the different types of production shots and the 134-dB (0.1-Hz) maximum level is generally equivalent to the 93- to 97-pct acceptability range, or a PLdB of 100. All PLdB values in table I-1 were computed from production-blast time histories and were made by comparing least-square fits of PLdB levels from production blasts (table 3), broken down by the type of blast. Stachura (61) gives the equations and statistics for these comparisons.

TABLE I-1. - Annoyance versus perceived level and equivalent 0.1-Hz peak airblast

PLdB	Equivalent peak linear (0.1 Hz) airblast, dB				Acceptability, pct	
	Coal highwall	Coal parting	Quarry	All	Mean	Range
111	148	143	147	145	50	36-78
108	145	140	144	142	80	54-87
100	137	132	136	134	95	93-97
95	132	127	131	129	99	

Kryter compared reactions of people to both aircraft flyovers and sonic boom overpressures (19-20). The perceived noise levels (PNdB) (not the same as Higgins' perceived levels) were determined for equivalent severity to the peak sonic boom overpressures. At Edwards Air Force Base, where the population has long been subjected to sonic booms, a 1.69-lb/ft^2 (132-dB) boom was judged equivalent to 109 PNdB indoors and 105 PNdB outdoors, and rated between "just acceptable" and "unacceptable" by 27 to 33 pct of subjects interviewed. At nearby towns, the same sonic boom levels were rated noiser by 9 dB indoors and 3 to 6 dB outdoors, with 40 pct of the people rating them unacceptable. Since the great majority of sonic boom objections are based on house rattling and other inside noises, a direct comparison can be made between airblasts and sonic booms from the midwall responses in table 8 (main text of this report) and the observation by Kryter that a peak midwall displacement of 0.016 in is considered "just acceptable" (20). Table 8 shows that most studies of sonic booms, including Kryter's, found peak midwall responses were comparable to or greater than those resulting from blasting. Using Kryter's 1.53-in/psi sonic boom data and the Bureau's 0.74 to 1.04 in/psi for blasting, the "just acceptable" sonic boom is 0.0105 lb/in^2 (131 dB) and airblast is 0.015 to 0.0216 lb/in^2 (135 to 137 dB). Other measured sonic boom responses from table 8 (main text) would give similar values; however, the Wiggins (80) study would lead to lower airblasts for equivalent responses by at least 6 dB. Assuming that the C-slow wall responses would be the same for blasts and sonic booms, the 0.016 in displacement corresponds to a maximum of 112 dB C-slow.

Aside from the Higgins and Carpenter and the Kryter analyses, the only human response data applicable to blasting is the Borsky survey of human annoyance from sonic booms in Oklahoma City in 1964 (4). An average of eight booms per day for 6 months was generated at nominal levels of 1 to 2 lb/ft^2 (128 to 134 dB). Actual mean levels for the three series of tests were 1.13, 1.23, and 1.60 lb/ft^2 (table I-2). However, over 5 pct of all booms in the last two series over the closest two zones exceeded 2.2 lb/ft^2 (134 dB). Tests were preceded with extensive publicity to make the population aware that it was being subjected to a test involving SST flights. Borsky's survey involved three interviews at each of 3,000 households plus almost 400 control interviews and 441 partial studies (fewer than three interviews per household), for a total of 10,293 interviews. The survey determined annoyance, interference, complaints, acceptability, attitude, and damage claims.

TABLE I-2. - Overpressures from sonic boom annoyance survey by Borsky (4)

Zones, miles from central track	Sonic boom overpressures, lb/ft^2 (dB)								
	Mean			5 percent exceeded			Maximum		
	Series 1	Series 2	Series 3	Series 1	Series 2	Series 3	Series 1	Series 2	Series 3
0-8	1.1 (128)	1.2 (129)	1.6 (132)	1.7 (132)	2.2 (134)	2.6 (136)	2.7 (136)	3.2 (138)	3.8 (139)
8-12	.8 (126)	1.1 (128)	1.4 (130)	1.6 (132)	2.2 (134)	2.4 (135)	2.5 (135)	3.2 (138)	3.4 (138)
12-16	.7 (125)	.9 (126)	1.0 (128)	1.2 (129)	1.7 (132)	2.1 (134)	1.8 (133)	2.7 (136)	3.0 (137)

The metropolitan area was divided into three zones 0-8, 8-12, and 12-16 miles from center line. Variations between the overpressures from zone to zone were small compared with variations between series (table I-2). The most commonly reported reactions were to house rattles (86 to 89 pct) and from startling (15.2 to 21.3 pct). A significant number of people reported sleep or rest interference (6.9 to 10.9 pct) and radio, TV, or conversation interference (3.6 to 6.8 pct) (table I-3). Most sleep and rest complaints probably resulted from the first daily booms at 7 a.m. As the levels increased, more people reported that they felt like complaining, although fewer actually did (probably from resignation). Essentially all objections to the sonic booms were indoor-related interference. Table I-3 was based on Borsky's urban data (his table 11), because this more closely applies to the blasting environment.

Highly significant was the attitude of the people surveyed on acceptability. Among those who considered the SST and its boom necessary (favorable population), the acceptability to eight booms per day (series 1) was twenty times greater than among those who considered both unnecessary; however, this ratio decreased to seven times at higher levels (table I-3). This same effect occurs for mining communities and underscores the importance of good public relations and a visible and conscientious attempt to minimize blast effects. In general, a belief that the sonic booms were necessary and unavoidable decreased the number of people indicating "more than a little annoyed" from 74 pct to 29 pct.

TABLE I-3. - Reactions from sonic boom annoyance survey by Borsky (4), by series

Series	Interference, percent				Very annoyed, percent				Complained, percent		Acceptability, 8 boom/day, percent		
	House rattles	Startled	Rest or sleep	Radio, TV	House rattles	Startled	Rest or sleep	Radio, TV	Felt like	Did	General	Favorable population	Unfavorable population
1	86.3	15.2	6.9	3.6	11.8	7.1	4.0	2.0	11	2.7	4.8	0.8	16
2	85.8	17.0	8.3	5.1	18.7	9.0	5.3	2.5	13.9	2.3	13.5	3.8	35
3	89	21.3	10.9	6.8	25.8	11.7	7.5	3.9	14.2	2.0	18.4	5.3	40

Borsky also analyzed his data by zones of sonic booms as compared to other environmental intrusions (table I-4), from his table 102. The case of 1 to 2 events per day most closely represents mining or quarrying. Approximately 4 pct would object to one or two daily sonic booms averaging 125 to 132 dB (5 pct of booms exceeding 129 to 136 dB) and having maximum overpressures of 133 to 139 dB (tables I-2 and I-4). At about 12 miles from the aircraft's flight path, sonic booms became less than significant in terms of a neighborhood's pattern of life. This indicates that 125 to 128 dB would be acceptable as a mean value, and 133 to 137 dB as a maximum for sonic booms, based on a survey of the third zone (12-16 miles).

The sonic boom levels versus the percent "more than moderately annoyed," from both the Borsky (4) and Kryter (20) studies are shown in figure I-1. For linear-peak sonic boom overpressures, there is no significant difference between aircraft types. Kryter's data indicates an increasing rate of annoyance beginning at 133 dB, and both studies inticated that 5 pct would be annoyed at a mean sonic boom level of 124.5 dB. The maximum sonic boom levels, and those not exceeded 95 pct of the time in the Borsky study are also plotted, with tolerable sonic booms of 134 and 130 dB, respectively (5 pct annoyed). Schomer derives C-weighted sound exposure levels (L_{SC}) of the Borsky sonic booms (47) and found mean, 95 percentile, and maximum boom levels for 5 pct annoyed of 98.5, 105 and 108 dB C-slow.

TABLE I-4. - Reactions from sonic boom annoyance survey by Borsky (4), by zones

Zone, miles	Could not accept sonic booms, percent		General dislikes about neighborhood	
	10-12 per day	1-2 per day	Objecting to sonic boom, percent	Ranking of sonic boom
0-8	14.8	3.4	18.5	1st
8-12	17.0	4.3	16.8	2d
12-16	7.7	1.8	7.3	8th

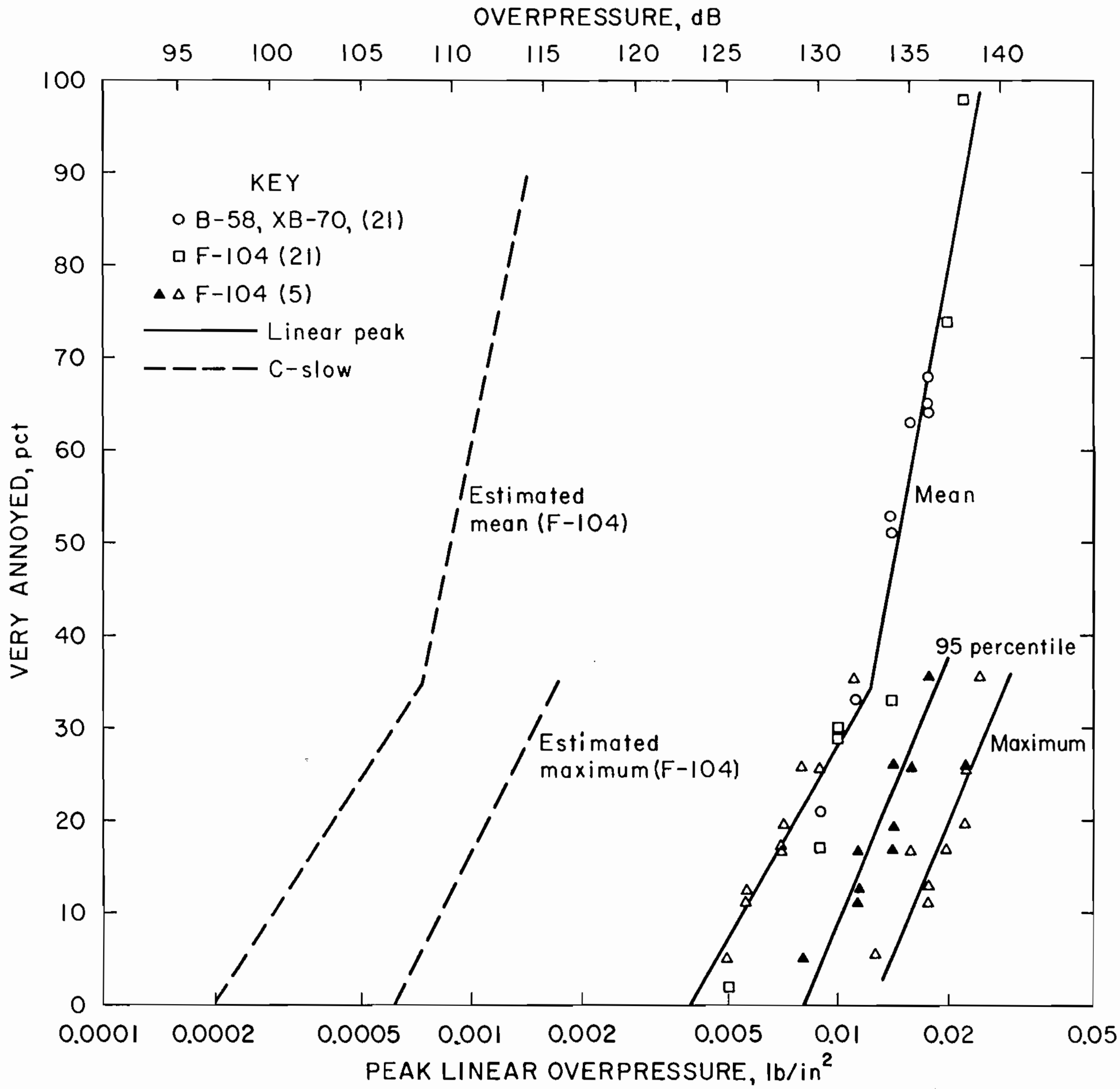

FIGURE I-1. - Population very annoyed by sonic boom-produced house rattles.

Application of the sonic boom data to blasting requires comparison of their relative midwall responses. As discussed previously, the midwall motions (plate response) can produce considerable motion of loose objects, and resulting secondary noise. Blume's (3) sonic boom response values from table 8 (in the main text) are similar to airblasts, although the booms are worse in terms of peak motions. The sonic booms produced approximately the same or slightly greater peak midwall motion, depending on which motion descriptor is used. For equivalent wall displacements, velocities, and accelerations, the airblast can be 0, 2.8, and 5.3 dB greater than the sonic booms, respectively. Since it is not known which motion descriptors best assess rattling potential, or the possibility of racking-produced rattling, it is reasonable to make a rough equivalence between blasting and sonic booms when both are measured as the linear peak levels. The C-slow (approximating C-weighted sound exposure level) does not correlate as well with midwall motions (table 5); however, within a wide band of uncertainty (± 6 dB), the C-slow annoyance values for sonic boom could be used to estimate such values for blasting.

Young examined the human tolerance to simulated artillery blasts on 30 subjects in a small room (85). Comparisons were made between the impulse, consisting of a cam-operated piston on the room wall, and a variety of steady-state noise sources including aircraft landings and takeoffs. At sound pressure levels in the range of 100 to 120 dB, the simulated artillery was judged equal in annoyance to

(1) Aircraft operations of 8 dB less (linear peak);
(2) Aircraft operations of 10 dB more (L_{SA}); and
(3) Aircraft operation (L_{SC}).

The test impulses were predominantly 75 to 100 Hz which may be appropriate for artillery but are far too high for confined blasting. The artillery was about as annoying as aircraft for L_{SC} but less so when measured using peak linear methods. Therefore, the steady-state sources must have more low-frequency energy than the simulated artillery. Since confined blasting has relatively more infra-sonic energy than some steady-state sources, the artillery appears more potentially annoying to people than mining airblast for the descriptors above. Without knowing the human reaction to both, or at least quantifying their spectral differences, the impact of blasting cannot be directly compared to other sources.

Schomer has made several evaluations of impulsive noise to assess the environmental impact of artillery and demolition airblasts around Army bases (46, 50). The Army's concern is both to minimize adverse environmental effects on its neighbors and define land use criteria for development around bases. Schomer's approach to the impact surveying and assignment of noise-contour building criteria are applicable to blasting; however, his quantitive analyses may not be applicable since the sources and resulting responses have not been shown to represent effects from confined production blasts.

In an analysis of the Young study, Schomer corrected the L_{SA} for the losses in transmission through building walls (46). An analysis for outdoor comparison was made by shifting the artillery noise 5 to 10 dB downward (for an equivalent reaction), and showing that the A-weighted sound exposure (L_{SA}) greatly underestimates the annoyance. Schomer found that L_{SC} was better than L_{SA}; however, for blasting, the L_{SC} will also underestimate the annoyance potential, as the predominant frequencies of production mining airblasts are far below those of Young's simulation. Schomer does not examine the annoyance characteristics which result from secondary effects of the wall vibrations. It is significant that outdoor and indoor tolerances to the levels of impulsive noise are different because of transmission loss; however, Borsky (4) showed that the annoyances stem from indoor-related interferences. Consequently, it is through analyses of structure responses (wall motions) that annoyance comparisons between different sources should be made. A summary of airblast annoyance is given in table 13, based mainly on the Borsky study (4).

Schomer summarizes sonic boom and Reed's airblast analyses to predict community response to blast noise (49). Although Schomer had no quantitive data on mining-type airblasts or its response effects, some of his observations are relevant. In reviewing sonic boom studies, Schomer noted that fear of property damage correlated with complaints, and that spectral differences strongly influence a signal's annoyance value. Consequently, sonic boom data should not directly applied to the blasting situation unless relative responses are determined.

Schomer describes the use of Effective Perceived Noise Levels (EPNL) and Composite Noise Ratings (CNR), which are rather too complex for the mining industry and regulatory agencies, and have not been shown to be superior to a simple peak or event-duration time average for evaluating impulsive noise impact. For nonimpulsive sources, a day time EPNL of 92 to 110 dB is the rough threshold of complaints, corresponding to peak levels (at close distances of about 2,000 ft) of 116 to 130 dB. Schomer does not currently recommend using EPNL methods, but rather the L_{dn} methodology discussed previously.

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Bureau of Mines
Report of Investigations 8485

STRUCTURE RESPONSE AND DAMAGE PRODUCED BY AIRBLAST FROM SURFACE MINING

by

David E. Siskind, Virgil J. Stachura,
Mark S. Stagg, and John W. Kopp

ERRATA

Page 13 (table 1): Insert under Notes for both Bruel and Kjaer 2209 and GenRad 1933 "Recording device is optional."

Page 51 (figure 38): Caption should include "(Numbers in parentheses correspond to regression lines in table 9.)"

Page 52 (figure 39): Caption should refer to "table 9" instead of "table 5."

Page 55, Title for fourth paragraph should read "Criteria."

Page 61 (figure 40): Caption should read "Numbers in parentheses correspond to references."

Page 76, Line 8 from bottom should read "...function of depth as given..."

Page 76, APP equation should have "D_{cg}" as part of exponent.

Page 76, following the APP equation, it should read "for small-scale blasts in limestone, where D_{cg} is the distance..."

Page 76, last sentence should read "Wiss quantified the confinement effect from full-scale coal mine blasts:"

Page 77, equation at top of page should be $APP + SRP = K_2 e^{-1.0} B_s$.

Christensen, Lindsay

From: David Tirman [dtirman@jmaventuresllc.com]
Sent: Monday, November 23, 2009 11:00 AM
To: Christensen, Lindsay
Cc: Rob Brueck; David Landry; Allen Breuch
Subject: RE: Homewood
Attachments: Homewood Master Plan Illustrative February 2009.pdf; HwdAmphitheaterRGB.jpg

Lindsay,

The amphitheatre is located adjacent to the base gondola terminal to the north west. Attached is a copy of the master plan and a rendering of where the amphitheatre sits. The plan does not specifically call out the amphitheatre but you'll be able to locate it between the two attachments.

At this point we're not 100% sure that there'd be pile driving as we are still awaiting a detailed geotechnical report that will let us know more about soils conditions and the potential need for piles. I don't believe that the current schematic design drawings indicate piles but rather perimeter and spread footing foundations. It is probably safe to assume some percentage of piles would be needed however (suggest 10%). There may be some degree of blasting due to boulders below grade, however, there's also another technique for breaking up boulders that does not require blasting…which is the more likely way we'd opt to go. I would think that any potential blasting would be fairly limited if required.

I hope this helps.

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F: (530) 582-1851
E: dtirman@jmaventuresllc.com

From: Christensen, Lindsay [mailto:lchristensen@jsanet.com]
Sent: Monday, November 23, 2009 9:23 AM
To: David Tirman
Subject: RE: Homewood

Hi David,
I have a couple of last questions for you.
1. Where was the Hillside Ampitheatre located?
2. Will there be any pile driving or blasting?
Thank you!
Lindsay

Regional Plan for the Lake Tahoe Basin

GOALS AND POLICIES

TAHOE
REGIONAL
PLANNING
AGENCY

CUMULATIVE NOISE EVENTS[§]	
Land Use Category	**Average Noise Level Or CNEL range (dBA)**
NUMERICAL STANDARDS: Background noise levels shall not exceed the following levels:	
High Density Residential Areas	55
Low Density Residential Areas	50
Hotel/Motel Areas	60
Commercial Areas	60
Industrial Areas	65
Urban Outdoor Recreation Areas	55
Rural Outdoor Recreation Areas	50
Wilderness and Roadless Areas	45
Critical Wildlife Habitat Areas	45
POLICY STATEMENT: It shall be a policy of the TRPA Governing Board in the development of the Regional Plan to define, locate, and establish CNEL levels for transportation corridors.	
TRANSPORTATION CORRIDORS[1]	
Highway 50	65[2]
Highways 89, 207, 28, 267 and 431	55[2]
South Lake Tahoe Airport	60[3]

1. Recommended CNEL levels for transportation corridors.
2. This recommended threshold overrides the land use CNEL thresholds and is limited to an area within 300 feet from the edge of the road.
3. This recommended threshold applies to those areas impacted by the approved flight paths

<u>GOAL #1</u>

SINGLE EVENT NOISE STANDARDS SHALL BE ATTAINED AND MAINTAINED.

People can be annoyed by a specific noise source. Thresholds were adopted that apply to aircraft, boats, motor vehicles, off-road vehicles, and snowmobiles to reduce impacts associated with single noise events.

POLICIES

1. **AN ORDINANCE AND ENFORCEMENT PROGRAM SHALL BE DEVELOPED TO PERMIT ONLY AIRCRAFT THAT MEET THE SINGLE EVENT NOISE THRESHOLDS TO USE THE AIRPORT.**

§ Amended 05/28/97

Hochschule, Zurich

)LOGY

ALITY CONTROL

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ENT
Editors

OUR ACOUSTIC ENVIRONMENT

FREDERICK A. WHITE

Professor of Nuclear Engineering
Professor of Environmental Engineering
and Industrial Liaison Scientist
Rensselaer Polytechnic Institute

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Table 4

Change in Sound Level	Change in Perceived "Loudness"
3 dB	Just perceptible
5 dB	Noticeable difference
10 dB	Twice (or $\frac{1}{2}$) as loud
15 dB	Large change
20 dB	Four times (or $\frac{1}{4}$) as loud

Table 5 permits the addition of decibel readings. Thus, suppose the first machine produced a reading of 90 dB, and the second machine yielded a reading of 85 dB. What would be the reading with both machines running simultaneously? From Table 5 we note that for a difference between the two of 5 dB we should add 1.2 to 90 dB, giving us a resultant of 91.2 dB. If we had three sound sources in a common enclosure, we could use the table to obtain the sum of the first two, and then use again the table for getting the resultant of the first two plus the third.

Table 5 Addition of Decibel Readings for Two Sound Sources

Difference between Two dB Readings	Add to Larger dB Value
0.0 dB	3.0 dB
0.5	2.8
1.0	2.6
1.5	2.2
2.0	2.1
2.5	2.0
3.0	1.8
4.0	1.5
5.0	1.2
6.0	1.0
7.0	0.8
8.0	0.6
10.0	0.4
13.0	0.2
15.0	—