Transportation systems, vital to the U.S. economy, are the predominant source of sounds outdoors. How detrimental these sounds are to human health and well-being is a subject of continuing debate. When loud enough and frequent enough, however, the sounds diminish the quality of life (see box, page 6).

Transportation Sound Levels

Estimates of the maximum sound levels produced by common transportation sources are shown in Table 1; waterway sources are not included. Sound levels should be associated with a location on the ground or with a distance from the source; the levels in Table 1 are associated with specific distances and operating conditions.

The aircraft sound levels are for distances of 1,000 feet, and the ground transportation sources are for 50 feet—the distances at which the source sound levels can be measured reliably. The derivation of sound levels at other distances requires information about factors that affect the propagation of sound—such as the terrain, the location of buildings or other shield-
ing structures, the meteorological conditions, the aircraft engine mounting, the aircraft elevation, and the direction of flight in relation to the listener. The maximum levels at a distance of 50 feet would be at least 25 decibels (dB) lower if heard at 1,000 feet.

The levels for the surface transportation sources are from federal agency models. The aircraft levels derive from the Federal Aviation Administration’s (FAA’s) aircraft noise model data and from field measurements. The sound levels should be considered typical or average; actual levels will vary above and below those indicated in the table.

**No Escape**

Stand outside almost anywhere in the continental United States, and within a short time—probably less than 1 hour—the sound of a truck, automobile, airplane, or train will be audible. The percentage of land in each county in which the various transportation sources are likely to be heard during the daytime can be estimated from standard transportation sound levels, the routes followed by each mode, and estimates of the background sound levels throughout the continental United States.

Figures 1, 2, and 3 show the percentages of land in each county in which the sounds of roadway traffic, rail traffic, and high-altitude jets may be heard (1).

The roadway results represent the network of limited access, primary, and secondary roads; local roads are not included. The rail results are for freight lines only, and the aircraft results are for high-altitude intercity jet traffic only—general aviation operations or departures and arrivals in the vicinity of airports are not included. The road and jet results, therefore, are likely to be underestimates, particularly for densely populated areas and for the vicinity of major airports.

**Aircraft Noise**

Aircraft noise is an issue for people who live near airports. Noise is the reason most often cited for public resistance to increases in runway capacity or to alterations in the use of airspace.

Aircraft-produced sound can reach levels that interfere with speech outdoors in communities some distance from an airport. For example, a modern commercial jet can produce sound levels of 70 dB(A)\(^1\) to 80 dB(A) up to 3 miles from a runway, loud enough to interfere with speech outdoors for about 20 to 35 seconds. A moderately busy commercial airport with 200 to 300 daily departures could interfere with speech 10 to 20 times per hour.

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### TABLE 1 Approximate Maximum Sound Levels for Transportation Sources

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Estimated Speed/ Operating Condition</th>
<th>Approximate Maximum A-Weighted Sound Level, dB(A)</th>
<th>Distance, feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commercial jet</td>
<td>Takeoff</td>
<td>85</td>
<td>1,000</td>
</tr>
<tr>
<td>Commercial jet</td>
<td>High Altitude Cruise</td>
<td>85</td>
<td>1,000</td>
</tr>
<tr>
<td>Corporate jet</td>
<td>Takeoff</td>
<td>85</td>
<td>1,000</td>
</tr>
<tr>
<td>Propeller aircraft</td>
<td>Takeoff</td>
<td>70–80</td>
<td>1,000</td>
</tr>
<tr>
<td>Helicopter</td>
<td>Cruise</td>
<td>70</td>
<td>1,000</td>
</tr>
<tr>
<td>Roadway Vehicles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy truck</td>
<td>50 mph</td>
<td>83</td>
<td>50</td>
</tr>
<tr>
<td>Medium truck</td>
<td>50 mph</td>
<td>79</td>
<td>50</td>
</tr>
<tr>
<td>Automobile</td>
<td>50 mph</td>
<td>72</td>
<td>50</td>
</tr>
<tr>
<td>Rail Vehicles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel locomotive</td>
<td>50 mph</td>
<td>88</td>
<td>50</td>
</tr>
<tr>
<td>Rail cars</td>
<td>50 mph</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td>Locomotive horns</td>
<td>-</td>
<td>96–110</td>
<td>50</td>
</tr>
</tbody>
</table>

\(^{1}\) dB(A) = A-weighted decibels, a summation of sound levels across frequencies.

**Aircraft Sound Metric**

FAA has identified a day–night average sound level (DNL) of 65 dB from aircraft operations as the limit of acceptability for residential housing (see Figure A, page 6). Federal funding is available to assist with sound insulation and property acquisition in areas with noise above the acceptable level. The federal government, however, does not set land use policies; local authorities determine the relationship between land use and sound levels.

DNL is a measure of total sound energy in 24 hours and therefore may include many combinations of aircraft sound levels and events. Three dB(A) = A-weighted decibels. See box, page 6.
Sound is quantified either as a total accumulation of sound energy for a period of time or as a measure of a single event. Almost all environmental sound is measured in A-weighted decibels [dB(A) or dBA]. A-weighting is a summation of the sound levels across frequencies; this summation de-emphasizes the levels at different frequencies and corresponds to the way people hear.

The total accumulation metrics are called equivalent levels and represent the sound levels for either 1 hour, symbolized as $L_{eq;1h}$, $Leq(H)$, or $L_{eq}$—if the time period is defined—or a 24-hour period, called the day-night average sound level (DNL or $L_{dn}$). DNL includes a weighting or penalty of 10 dB for sound that occurs between 10 p.m. and 7 a.m.

Single events are quantified as an accumulation of sound energy over the duration of the event, termed the sound exposure level (SEL); or as a maximum level, $L_{max}$; or as the length of time that the sound was above a specified threshold, known as time above (TA).

According to the U.S. Environmental Protection Agency (EPA), cumulative sound exposure below 55 dB DNL poses minimal risk of adverse effects on human health, as well as minimal annoyance. Figure A shows typical values of DNL for various locations and identifies the levels established by EPA, the Department of Housing and Urban Development, and the Federal Aviation Administration in making decisions about funding assistance.
source of noise exposure and, if frequent or at night, a likely cause of complaints. A few loud corporate jets a week, for example, can raise public concern, regardless of DNL values. In areas with no loud jet operations, the sound of propeller aircraft flying over quiet neighborhoods, if frequent enough—particularly on weekends—may raise concern.

Helicopters are not usually louder than other aircraft (see Table 1) but can be identified easily by sound, especially when “blade slap” occurs, and can cause complaints. Helicopters also travel slower than fixed-wing aircraft and can be heard for a longer time.

Other aviation-related sources of sound include engine testing for maintenance or before a flight; auxiliary power units that provide electricity while the aircraft is at a gate; taxiing aircraft; and the low-frequency rumble from jets at takeoff. This last source is difficult to assess and control because the A-weighted sound level does not represent low-frequency

Figure C charts the sound level of a single event, showing the maximum level and the TA. Figure D compares several typical maximum sound levels.

As the summation of all the sound energy in a single event, the SEL is generally 5 to 10 dB higher than the maximum. The SEL reflects the duration of a sound and provides a more complete estimate of the disruptive or annoying quality of an event.
Everyone is familiar with aircraft noise—the deep rumble of a jet taking off or the whistling whoosh of an airplane approaching the runway. The causes of these noises, however, are less familiar.

Aircraft noise has two main sources: the propeller-driven or jet engines and the airframe. Engine noise is wasted or lost energy. Only a minute portion of the engine's power radiates as noise but is sufficient to create problems for the neighborhoods around airports.

The noise generated by a propeller is a buzzing, caused by the propellers slicing through the air. The pitch or frequency of the noise is directly related to the speed of the propeller. If the propeller spins faster, the pitch goes up; if slower, the pitch goes down.

Reducing propeller noise is almost impossible—producing the thrust for flight is what causes the noise. Advanced aerodynamic modeling techniques have developed lower-noise propeller designs, but the decrease is limited.

In contrast, jet engines have two major noise-producing sources. The first is called compressor whine, the high-pitched whistling from the front of the engine. The spinning machinery inside the engine is the cause, most noticeably when an aircraft is approaching a runway. Sound-absorbing liners along the inlet of the jet engine can reduce compressor whine.

The other source of noise from a jet engine is the hot, high-speed jet of air that streams out the back. This is commonly called jet noise—the deep rumbling when a jet aircraft takes off. The mixing of the hot, high-speed jet of air from the engine with the cold, slow air moving around the engine causes jet noise. The faster and hotter the jet exiting the engine, the stronger the mixing and the louder the rumbling behind the engine.

A high-bypass engine design reduces jet noise by creating a second, cooler, and slower flow of air around the hot central core jet. The second stream is still much faster than the air around the engine but acts as a sheath effectively reducing the speed of the air exiting the engine. The second stream holds down the magnitude of the mixing and the resultant noise. The design also improves fuel efficiency, an added bonus.

As the engine noise becomes quieter, the noise generated by the airframe becomes more predominant. Like jet noise, airframe noise is caused by the mixing of air, but from aerodynamic inefficiencies.

For example, the lowered landing gear on an aircraft causes noise as the air forcibly flows around the gear and mixes with the relatively undisturbed air. Similarly, the flaps that are lowered for landings and takeoffs cause mixing and create more noise. Even structural details like recessed windows can create noise. Airframe designers try to eliminate as many of these potential noise sources as possible, to hold down the total noise from the aircraft.

A variety of advances have reduced aircraft noise, and in the past 25 years the number of people with significant exposure to aircraft noise has decreased from approximately 7.5 million to 0.5 million. Nevertheless, reducing aircraft noise emissions remains a necessity.

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sounds—low-frequency sound propagates farther, with less attenuation, than high-frequency sound; and low-frequency sound penetrates into houses more readily than does high-frequency sound.\(^2\)

**Controlling Aircraft Noise**

FAA has an ongoing program to reduce the number of noise-sensitive areas exposed to high levels of aircraft noise (2). Airports can conduct a federally funded Part 150 Study to identify actions to reduce aircraft noise in sensitive areas—a federally funded project is not necessary to initiate a study.

Several methods can limit residential exposure to aircraft noise, including the acquisition by an airport of properties in the highest noise areas—for example, with a DNL greater than 70 or 75 dB from aircraft; houses, schools, and churches can be insulated for sound; preferred runways can be used, if wind conditions permit; flight corridors also can be altered; and cockpit procedures can be developed for the best use of thrust, speed, and climb, to limit departure and arrival noise.

The success of any of these methods, however, depends on trust and good communication with the communities and with the aircraft operators. Residents often do not understand how an airport operates, how airspace is managed, and the degree of flexibility that airports, air traffic controllers, and pilots have in managing flight operations. Aviation professionals are realizing the importance of developing clear, forthright communication and dialog with residents.

The distribution of responsibilities complicates attempts to limit the conflicts between noise-sensitive land use and aviation noise. FAA controls the airspace, the pilot is responsible for flying the plane, local jurisdictions determine land use, and the airport meets aviation needs and provides convenient passenger service. These stakeholders must work together to minimize the noise exposure for noise-sensitive lands.

**Noise from Roadways**

At high volumes and speeds, roadway traffic can produce an almost constant sound level, punctuated by increases from noisy vehicles or loud trucks—although noticeable, the increases are not dramatic and are not likely to exceed the general level by more than 5 to 10 dB. In contrast, the sound of sparse nighttime traffic primarily of heavy trucks is a series of single events.

Noise from roadway traffic became a significant issue in the early 1970s, when the Interstate system was extending through cities, towns, and residential areas. In response to legislation requiring documentation of the environmental effects of federally funded projects, the Federal Highway Administration (FHWA) developed methods to measure, predict, and control highway traffic noise (3, 4).

**Roadway Traffic Sound Metric**

FHWA has determined that traffic noise impacts occur when predicted levels of traffic noise approach or exceed the Noise Abatement Criteria (5). Impacts also can occur when predicted noise levels substantially exceed existing sound levels.

Roadway traffic noise is evaluated with an hourly A-weighted equivalent sound level, Leq\(\text{h}\). When the predicted traffic noise for the loudest hour in a residential location regularly approaches or exceeds 67 dB(A) Leq\(\text{h}\), noise abatement must be considered.

To gain funding, an abatement measure must reduce noise substantially and affordably. FHWA permits states to determine the approach-or-exceed level, the amount of reduction a measure would provide, and whether the costs are reasonable.

Table 3 provides 1-hour equivalent sound levels measured at 150 feet from the center of a roadway for

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\(^2\) A-weighting is a summation of the sound levels across frequencies. See sidebar, page 6.
The Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) was established in September 2003 to serve as the Center of Excellence for Aircraft Noise and Aviation Emissions Mitigation. PARTNER fosters breakthrough technical, operational, and workforce capabilities for quieter and cleaner aircraft and works to enhance understanding of aerospace environmental issues. The Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and Transport Canada cosponsor the center.

Nine universities have developed an integrated plan for research, dissemination of research results, education, and center operations and financing, with Massachusetts Institute of Technology as the lead: Boise State University, Florida International University, Pennsylvania State University, Purdue University, Stanford University, University of Central Florida, University of Missouri–Rolla, and York University. PARTNER’s research agenda was developed in collaboration with 32 industrial, government, community, and professional organizations involved in aviation.

PARTNER research will provide critical information to government decision makers and industry executives for addressing the environmental impacts that challenge the growth of civil aerospace. The center also will train the next-generation workforce to meet the continuing challenges of aviation environmental issues.

Following are some of the projects under way:

- Low-Frequency Noise Study, involving experimentation and analysis; findings could lead to regulatory action and the development of technology to mitigate the impacts of low-frequency noise.
- Measurements, Metrics, and Health Effects of Noise, developing metrics to evaluate the impact of airport noise on a community, including noise annoyance, physiological responses, cognitive performance, and sleep quality.
- Continuous Descent Approach, devising procedures to decrease aircraft noise and reduce emissions and fuel burn.
- Land Use and Airport Controls, studying the effects of aviation noise and how to apply the information to improve land use in and around airports.
- Supersonic Transport, investigating the acceptability of shaped sonic booms from a new class of supersonic business aircraft.
- NoiseQuest, assembling a website resource of educational information about aviation noise for airports and communities.
- Measurements, Metrics, and Health Effects of Emissions, characterizing aircraft and airport emissions to determine the health effects.
- Aircraft and Climate, modeling the effects of aircraft on the atmosphere to understand how aviation may contribute to climate change.
- Valuations and Trade-Offs of Policy Options, developing tools and metrics to quantify the environmental impacts of aviation and to evaluate interactions between technology, operations, policy, and the environment.
- Report to the U.S. Congress: Aviation and the Environment, outlining a national vision statement, a framework for goals, and recommended actions.
- Lateral Alignment in Complex Systems, working interactively through NASA’s Joint Planning and Development Office with stakeholders in aviation and the environment to forge policies and processes for enhanced communication and collective action.
- Environmental Design Space, developing tools to evaluate the trade-offs at the aircraft system level between noise, emissions, and performance, to support policy decision making.

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different traffic mixes and speeds. During any of the scenarios, the sound would interfere with speech almost continuously. A 13-foot-high noise barrier 25 feet from the edge of the roadway would reduce levels by 8 to 9 dB—a noticeable difference that would improve the audibility of speech communication.

Roadway Noise Issues
The federal government does not have an ongoing program to reduce the number of homes exposed to high sound levels from street traffic. Some states independently provide Type II—that is, retrofitted—noise barriers for roadways. The examination of noise and the design of abatement measures usually occur as a requirement of the environmental process for proposed highway construction or for capacity improvement projects.

Several approaches are used to control the noise produced by roadway traffic. Most common is the construction of noise barriers or berms—high, continuous walls or earthen hills—that shield noise-sensitive areas along a right-of-way. To be effective, the barriers or berms must be long—often several thousand feet long—and unbroken.

As a result, berms are feasible only along limited-access highways or long sections of arterials that have few curb-cuts. Most roadway noise analysis and abatement therefore focuses on these types of roads and does not address many of the other types of highly traveled urban or suburban arterials or feeder roads.

### TABLE 3 One-hour Equivalent Sound Level at 150 feet from Roadway

<table>
<thead>
<tr>
<th>Vehicles per Hour</th>
<th>Speed, mph</th>
<th>Leq(h) dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,500</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>1,500</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>1,500</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>1,500</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Research Projects Target Highway Noise

Several National Cooperative Highway Research Program (NCHRP) projects are under way to develop products that will help highway agencies measure highway noise, enhance computer analysis of traffic noise impacts, and identify and implement effective means for reducing noise impacts on nearby communities:

- **Measuring Tire–Pavement Noise at the Source** (NCHRP Project 1-44) is developing rational procedures for measuring tire–pavement noise from light and heavy vehicles operating at highway speeds and on all types of paved surfaces.

- **Truck Noise Source Mapping** (NCHRP Project 8-56) is applying acoustic measurement and noise source mapping techniques to identify, locate, and quantify noise sources on the typical commercial truck and tractor-semitrailer combinations that operate on U.S. roadways.

- **Texturing of Concrete Pavements** (NCHRP Project 10-67) will recommend texturing methods to improve the frictional characteristics of concrete pavement surfaces, with consideration of the effects on noise.

- **Highway Research and Technology: International Information Sharing** (NCHRP Project 20-36) supported the participation of professionals from state departments of transportation in a 2004 scanning tour that reviewed how other countries are using quiet pavements to mitigate highway noise (see article, page 16). The tour was part of the International Scanning Program of the American Association of State Highway and Transportation Officials, NCHRP, and the Federal Highway Administration.

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The Federal Highway Administration (FHWA) published the *FHWA Highway Noise Barrier Design Handbook* with accompanying CD-ROM and video in February 2000 and is preparing to release the *FHWA Highway Construction Noise Handbook* with accompanying CD-ROM in early 2006. Both titles were developed by the Acoustics Facility at the John A. Volpe National Transportation Systems Center in support of the FHWA Office of Natural Environment.

The *FHWA Highway Noise Barrier Design Handbook* package reflects improvements and changes in noise barrier design since the original 1976 publication, addressing acoustical and nonacoustical issues associated with highway noise barrier design. Handbook topics include:

- Overview, historical perspective, and terminology;
- Acoustical considerations of noise barrier design, including a brief discussion of performance;
- Noise barrier types, descriptions, and special features;
- Noise barrier materials, including surface textures;
- Aesthetics;
- Utility, structural, and safety considerations;
- Product evaluation;
- Installation, maintenance, and cost considerations;
- Typical design processes;
- Assessments of effectiveness, including performance, costs, and community acceptance; and
- Tools and information resources to aid in design.

The handbook and the associated material do not represent FHWA policy on noise abatement but are intended as an aid to agencies, organizations, and individuals involved in noise barrier design. The materials present a variety of considerations in the design of noise abatement features but do not promote or recommend any particular type of barrier feature.

The *FHWA Highway Construction Noise Handbook* package also reflects advances since the original 1976 publication, covering acoustical and nonacoustical issues associated with highway-related construction noise. Topics include:

- Introduction, background, and terminology;
- Effects of construction noise on humans and wildlife;
- Construction noise criteria and metrics;
- Operations and equipment for measuring construction noise, including the processing and interpretation of data;
- Prediction of construction noise, including methodology and impact evaluation;
- Mitigation of construction noise at the source, along the path, and at the receptor, including consideration of the time period, the duration of operations, and enforcement-related issues, as well as contract specifications and provisions;
- Data for construction equipment noise levels and ranges for both stationary and mobile equipment;
- A compendium of construction noise experiences, including a searchable database and contacts;
- Related training materials, including manuals, training programs, and references;
- Public involvement during the project phase, using a variety of techniques; and
- Interagency, intra-agency, and other coordination.

Under development with the handbook is a simplified prediction model for noise levels on typical construction projects.

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Because barriers can cost up to $20 per square foot—or more than $1 million per mile—a significant number of homes must benefit to justify the expenditure. Low-density residential areas—such as rural areas or large-lot suburban locations—are less likely to qualify for barrier construction than are high-density areas.

Moreover, most states will not build a noise barrier without the residents’ concurrence. Sometimes a few residents pressure a highway agency, money is allocated, and a study is conducted, but public meetings reveal that a majority of the residents would prefer traffic noise to a long, high wall.

Several state agencies have conducted studies to set priorities for barrier construction; this approach minimizes the number of disputes about which neighborhoods along a highway will have barriers. The method involves measuring sound levels; computing the loudest hours throughout the corridor; determining the barrier locations, heights, and costs; and identifying the number of homes that will benefit in each neighborhood according to the number of decibels reduced.

The policy ranks the neighborhoods by the cost per home benefited. The barriers are built in order of priority, with the timing determined by the availability of funds.

**Controlling Roadway Noise**

The usual methods for limiting roadway noise include building barriers or berms, establishing traffic controls such as speed limits, altering vertical or horizontal alignment for new roadways, establishing buffer zones along a right-of-way, and using quiet pavement—a recent innovation.

Barriers are the most common solution for protecting outdoor areas, when justified by the cost–benefit. Sound insulation sometimes is chosen, particularly for schools, and quiet pavement is gaining interest, as indicated by many research projects in the United States and abroad (see related articles on pages 16 and 18).

**Rail Noise**

Rail transportation generates sound and vibration levels that can be significant. Although low-frequency sound from aircraft can produce vibration in structures, and elevated highways or roads on certain kinds of geological formations also can produce vibrations that travel through the ground and affect structures, these circumstances are too rare or too isolated to be included in any routine analysis.

In contrast, rail generates ground-borne vibrations throughout the right-of-way. In densely populated areas, buildings often are located close to the right-of-way or even above the right-of-way for underground transit, so that vibration of structures is likely. Along surface rail lines, the proximity of residences makes the sound levels and the vibrations an issue.

In response to environmental legislation, the Federal Railroad Administration (FRA) and the Federal Transit Administration (FTA) have developed methods to measure, predict, and control noise and vibration from rail and rapid transit. The methods are applied as part of the environmental documentation required for federally funded projects.

**Rail Sound Metrics**

FRA and FTA have published guidance manuals with step-by-step directions for preparing assessments of
rail noise and vibration (6–7). Like FAA, both agencies use DNL as the metric to determine the impacts of rail noise; like FHWA, both also use Leq(h).

DNL is used to measure the effects on residences. The Leq(h) for the loudest hour of the day applies to other noise- and vibration-sensitive uses. FRA and FTA identify two levels of noise impact—impact and severe impact—based on the sound levels from the proposed rail project and the sound levels before the project (Figure 4). Table 4 shows some relationships between DNL values and types of trains at different speeds.

Figure 4 shows how rail noise impacts are determined. Category 1 lands require quiet but are used mainly during the day; therefore the sound is measured in Leq(h). Category 2 lands include residences; DNL is the metric. Category 3 lands have institutional uses with daytime and evening activities, which are deemed to be 5 dB less sensitive to project noise than lands in Categories 1 and 2.

Rail vibration impact thresholds are determined from an absolute level. The thresholds of impact depend on the number of events—more than 70 events per day is considered frequent, and fewer than 70, infrequent.

The lowest threshold is for buildings that require a low ambient vibration for operation—for example, buildings with equipment such as electron microscopes or with sensitive manufacturing processes. This lowest threshold is roughly equivalent to the threshold for human perception. Higher thresholds are used for residences and yet higher for institutions with daytime-only uses.

### Rail Noise and Vibration Issues

Rail systems include a variety of noise sources—some are associated with the operation of rolling stock, such as locomotives and rail cars, horns and whistles, and wheel squeal on tight curves, but many ancillary sound sources also may contribute. Some are related to rail operations, such as crossing signals, crossovers and switches, substations, and locomotive idling, but others are from the transportation modes that tie into the rail system, such as buses and automobiles at stations and in park-and-ride lots.

Horns for grade crossings can be a problem for nearby residents (see box, page 24). The air horns on freight and some commuter rail locomotives vary in sound levels. Although engineers signal the same “two longs, a short, and a long,” the duration depends on the operator and can affect different numbers of homes along a right-of-way. Current research is examining the use of horns that are permanently mounted at crossings and that sound automatically as a train approaches.

Locomotives often idle for long periods or overnight at termini in suburban areas. Sometimes these idling locations must be moved to accommodate changes in operations or schedules, and residential areas with no previous rail noise exposure are subjected to the sound of an idling locomotive for hours or overnight.

Older engines could not always be restarted and had to idle, but modern locomotives are designed to shut down, sometimes automatically after a period of

### TABLE 4  DNL for Different Types of Trains, 50 feet from Track

<table>
<thead>
<tr>
<th>Type of Train</th>
<th>Speed</th>
<th>Number of Trains per hour</th>
<th>DNL at 50 feet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Day</td>
<td>Night</td>
</tr>
<tr>
<td>4-car rapid transit</td>
<td>50 mph</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>4-car rapid transit</td>
<td>20 mph</td>
<td>20</td>
<td>2</td>
</tr>
<tr>
<td>8-car, 1-locomotive commuter</td>
<td>60 mph</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>8-car, 1-locomotive commuter</td>
<td>20 mph</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
idling, and are quieter as well. Idling not only produces noise but consumes fuel and releases air pollution, adding to the reasons to reduce the idling times.

**Controlling Rail Noise and Vibration**

If an analysis indicates an impact or a severe impact from rail noise or vibration, mitigation alternatives must be evaluated. On projects that include the purchase of new vehicles, an effective measure may be to develop vehicle design specifications. Other methods to reduce impacts include the design or retrofitting of track support systems, the maintenance of wheels and rails, the construction of noise barriers, and the use of sound insulation for buildings.

When vibration levels are the source of the impact, changing the track support system can be effective—a “floating slab,” a resiliently supported concrete slab to which the tracks are fastened; resilient rail fasteners; and resilient mats under the ballast or concrete ties supported by rubber pads are methods to reduce ground vibrations. Subway projects frequently use these techniques. Vibration problems are less common for at-grade and elevated track.

Sound levels and vibration levels can be reduced by grinding the wheel and rail surfaces. Irregular surfaces, flats produced when wheels lock in stopping, and rough wheels or rails can increase a train’s sound and vibration levels. Wheel truing—eliminating flat spots and assuring the roundness of the wheels—and proper grinding of rail profiles can be costly. Rail grinding may require extensive analysis to ensure that the final contours of the surfaces will be durable.

Noise barriers can be effective for at-grade and elevated rail lines. The barriers can be located close to the rail line and need not be high if the wheel–rail interaction is the primary source of noise. On elevated rail lines, barriers 4 feet high can be effective. In addition, if barriers are not feasible—for example, near grade crossings—installing sound insulation in nearby houses may be a solution.

**References**

Representatives of the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) participated in an International Scan of Quiet Pavement Technologies, April 30–May 16, 2004, visiting Denmark, the Netherlands, France, Italy, and the United Kingdom. The tour was conducted as part of the International Scanning Program of AASHTO, FHWA, and the National Cooperative Highway Research Program. The 14 participants had experience in noise and pavement issues and included members from FHWA, state departments of transportation, private industry, academia, and the Acoustics Facility at the Volpe National Transportation Systems Center.

The tour documented the state of the practice in design, construction, maintenance, and monitoring of quiet pavement systems and identified innovative practices. In addition, the team gathered information on noise measurement methodologies and monitoring systems. The group examined sections of single-layer and double-layer porous asphalt on high-speed facilities. On low-speed facilities, thin textured surfaces were found to be successful. Exposed aggregate concrete and diamond-ground concrete sections served well in countries that selected concrete pavement because of climate or other considerations.

Several issues noted during the scan demonstrated the need for further research:

- Which measurement methodology was most effective: close-proximity or sound-intensity measurements at the tire–pavement interaction or measurements from the receptor at the wayside?
- What are the correlations between the close-proximity or sound-intensity methods and the wayside methods of measurement?
- Does the cleaning of porous pavements renew the noise reduction capabilities or does it damage the pavement?
- What are the effects of quiet pavement on light vehicles compared with heavy vehicles?
- How durable are the pavements? Although noise reductions over time were noted for some pavements, many experimental types have not yet demonstrated longevity. Several countries did not have the funds to monitor pavements over time.
- What is the best way to account for noise reduction—as an absolute adjustment or in terms of frequency?
- How can all the many factors that affect noise reduction on a quiet pavement be considered? For example, variations in construction, aggregate selection, climate, vehicle types, binder, pavement temperature, measurement technique, pavement thickness, and typical reference pavement can affect the noise reduction. Moreover, the pavement must satisfy safety and durability requirements before noise reduction capabilities are considered.

The scan showed that although quieter pavements can be implemented with success, more research is needed. Each country had different experiences and different conclusions from research, as well as differing environmental and economic considerations.

The scan underscored the need for communication and coordination in the United States, where each state has the flexibility to run its own program. Because quiet pavement research involves many stakeholders, includes many variables, and is in the beginning stages, communication among stakeholders is important. Coordination is essential to avoid errors, assess progress, and guide the research to produce practical results.

FHWA has drafted a memorandum on the research requirements for demonstrating that a pavement qualifies as quiet. By adhering to these requirements, stakeholders will facilitate the accurate comparison of data and trends.

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