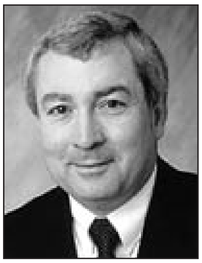
*Noise is a major driver in the design and operation of transportation systems.*

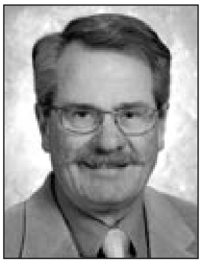
# Challenges and Promises in Mitigating Transportation Noise

Ian A. Waitz, Robert J. Bernhard, and Carl E. Hanson

Ian A. Waitz



Robert J. Bernhard



Carl E. Hanson

There are only a few places in the United States where transportation noise is not noticeable.[1] Figure 1 shows the results of an analysis estimating the percentage of each county in the United States where highway, rail, and aircraft noise are noticeable during the day (Miller, 2003). In 1981, the Environmental Protection Agency (EPA) estimated that 19.3 million people in the United States were exposed to a day-night average sound level ($L_{dn}$) greater than 65 dB from highway traffic. The corresponding numbers

[1] "Noticeability" is a function of the difference between the sound level of a specific transportation source and the background sound level in a community.

Ian A. Waitz is director of PARTNER (Partnership for AiR Transportation Noise & Emissions Reduction) and the Jerome C. Hunsaker Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology. Robert J. Bernhard is vice president for research, Notre Dame University. Carl E. Hanson is supervisory consultant, Harris Miller Miller & Hanson Inc.

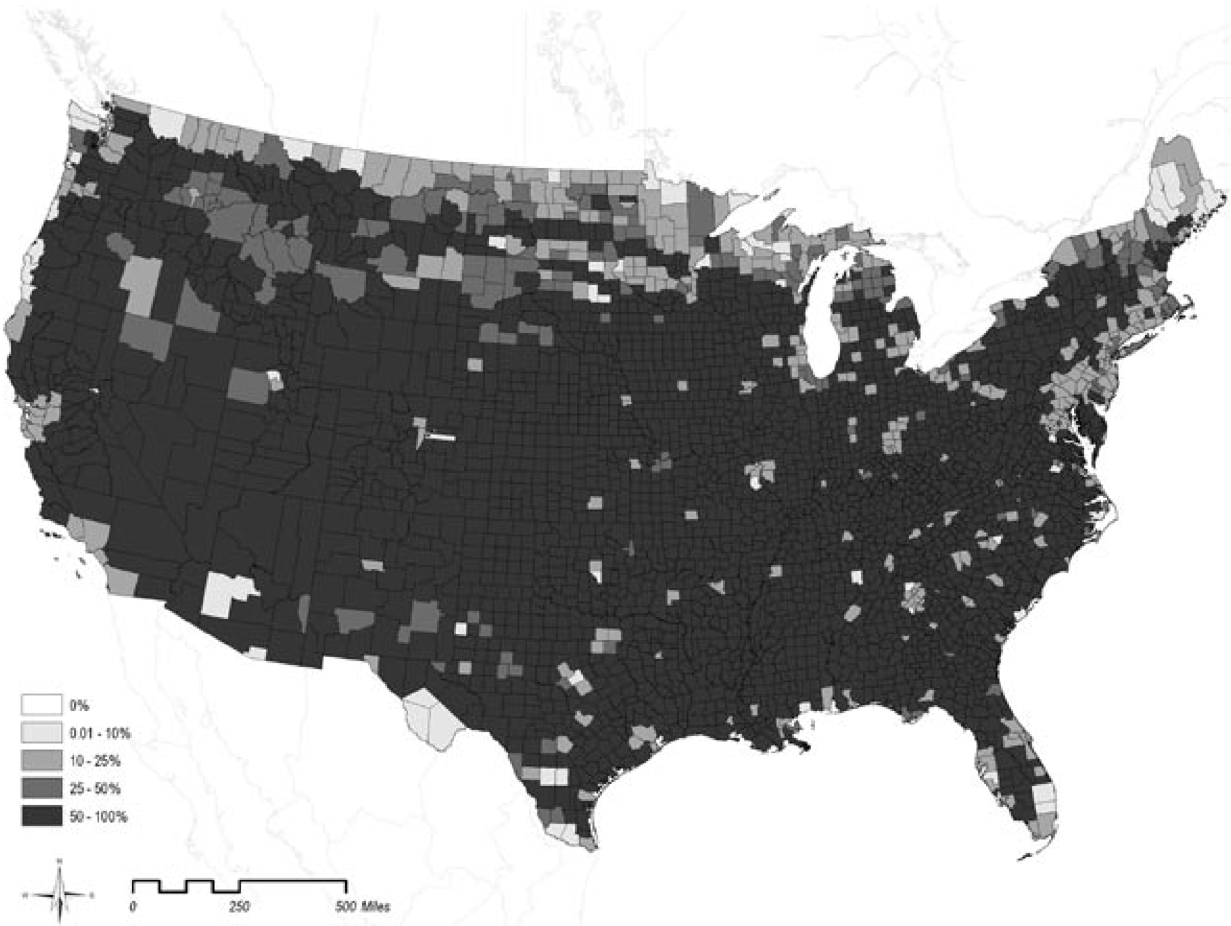



FIGURE 1 Percentage of each county that has noticeable noise from high-altitude aircraft, interstate rail traffic, or primary and secondary road traffic (whichever is highest). Local street traffic, considered background noise, can make the other sources less noticeable in densely populated areas (hence lower percentages may result for some of these areas). Source: Adapted from Miller, 2003.

for aircraft and rail were 4.7 million and 2.5 million, respectively.

Since the introduction of quieter aircraft, the number of people exposed to high levels of aircraft noise has dropped dramatically, to about 500,000. Updated figures for highway and rail noise are not available, but they may have increased with population growth and higher volumes of traffic.

Transportation noise can be annoying, disrupt sleep, interfere with communication, reduce property values, adversely impact health, and adversely affect academic performance. A comparison of noise annoyance from aircraft, road traffic, and rail noise based on exposure-response studies (Figure 2) showed that annoyance levels differed significantly for different modes of transportation (Miedema and Vos, 1998). When noise levels were less than 45 dB, the annoyance for all modes was negligible, but they increased monotonically as a function of $L_{dn}$.

The rate of increase was found to be higher for aircraft noise than for either highway or rail noise. Factors believed to contribute to the differences include façade-exposure differences (noise on one side of a house from highway and rail noise as compared to all sides from aircraft), differences in onset rates, and differences in attitude.

Because large numbers of people are impacted by transportation noise, and because the impacts are significant, noise levels are important concerns in the design and operation of all modes of transportation. Transportation noise is frequently the dominant environmental concern voiced by the public about the development and expansion of transportation systems. In this article, we review some unique aspects of road, railway, and aviation noise and describe some efforts to reduce the effects of noise to accommodate anticipated increases in demand for transportation.

## Issues Specific to Different Modes of Transportation

*Highway Noise*

Highways are the most pervasive source of transportation noise. Effects range from disturbances of the natural soundscape in wilderness areas to sound levels near occupational safety limits for the exterior of residences close to high-capacity freeways.

Highway noise comes from several sources. Noise from engines, exhaust systems, and power trains tend to dominate for low-speed or accelerating conditions. Tire/pavement noise tends to be most important at typical freeway speed. Aerodynamic noise tends to dominate only in very high-speed situations that are not common in the United States.

Tire noise may be dominant for automobiles, even under cruising conditions on urban streets. For trucks, power-train noise is a major source of noise on arterial roadways, but tire/pavement noise tends to dominate at freeway speeds, where a heavy truck makes approximately as much noise as 10 cars. Thus, even when there are relatively few trucks on the road, truck noise tends to be more noticeable than automobile noise.

Highway noise policy is implemented through approval (or denial) of federal matching funds for highway projects. Federal policy states that matching funds may only be used for noise mitigation where (1) there is frequent human "use"; (2) where predicted noise levels approach the noise-abatement criterion (NAC), which is typically 67 dBA (A = A-weighted) for the worst single hour of the year for receptor locations near residences; and (3) where mitigation is feasible and reasonable.

Because noise at a level of 67 dB interferes with speech, mitigation is a consideration only where it would be difficult to hold a conversation and where there is a fairly continuous stream of traffic. However, when sound-propagation effects and background noise are considered, only residences within 200 to 400 feet of a heavily trafficked highway are usually eligible for noise mitigation. In addition, the neighborhood must be fairly densely populated for mitigation to meet the reasonableness requirement.

Although speed limits and changes in vertical (e.g., raising or lowering elevation of the highway) or horizontal alignment (e.g., moving a highway farther away from a neighborhood) are allowable mitigation methods, the most common approach is sound-wall barriers, which create an acoustical shadow. The performance of barriers is limited, however, by diffraction effects at the barrier edges. Barriers must be constructed to break the line of sight between the source and the receiver and must be as close to either the receiver or source as possible to maximize noise attenuation. Typical sound-wall barriers cost $1.3 to $2 million per mile. Thus barriers are expensive and have limited benefits. Nevertheless, they are one of the few options currently available.

The level of tire/pavement noise depends on the combination of type of tire and type of pavement. For any given pavement type (e.g., Portland cement concrete,

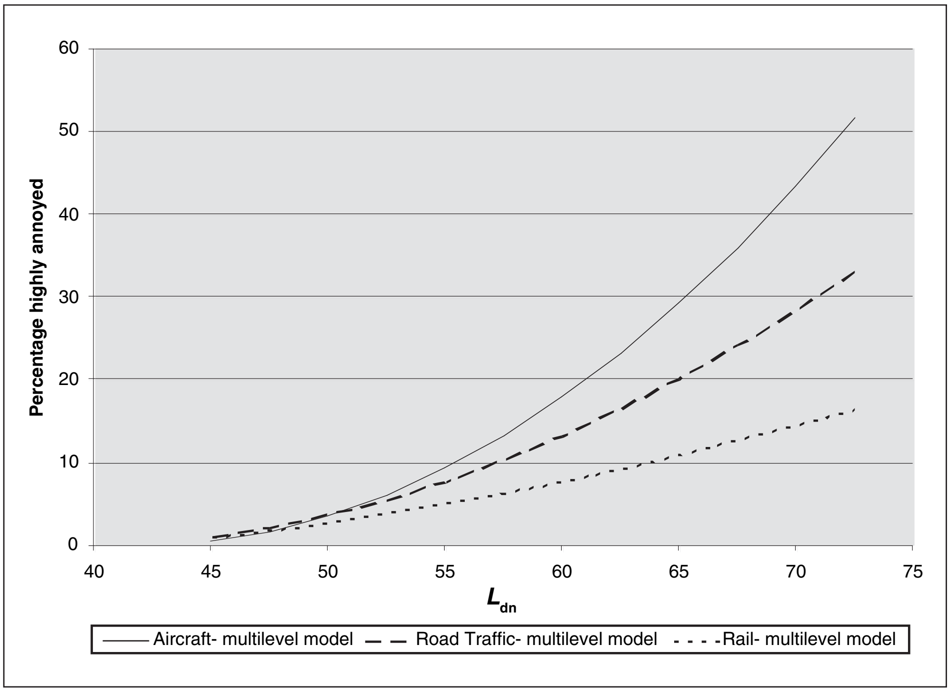



FIGURE 2 Percentage of highly annoyed people correlated with day-night average sound level ($L_{dn}$) for three modes of transportation. Source: Miedema and Vos, 1998. Reprinted with permission of the Acoustical Society of America.

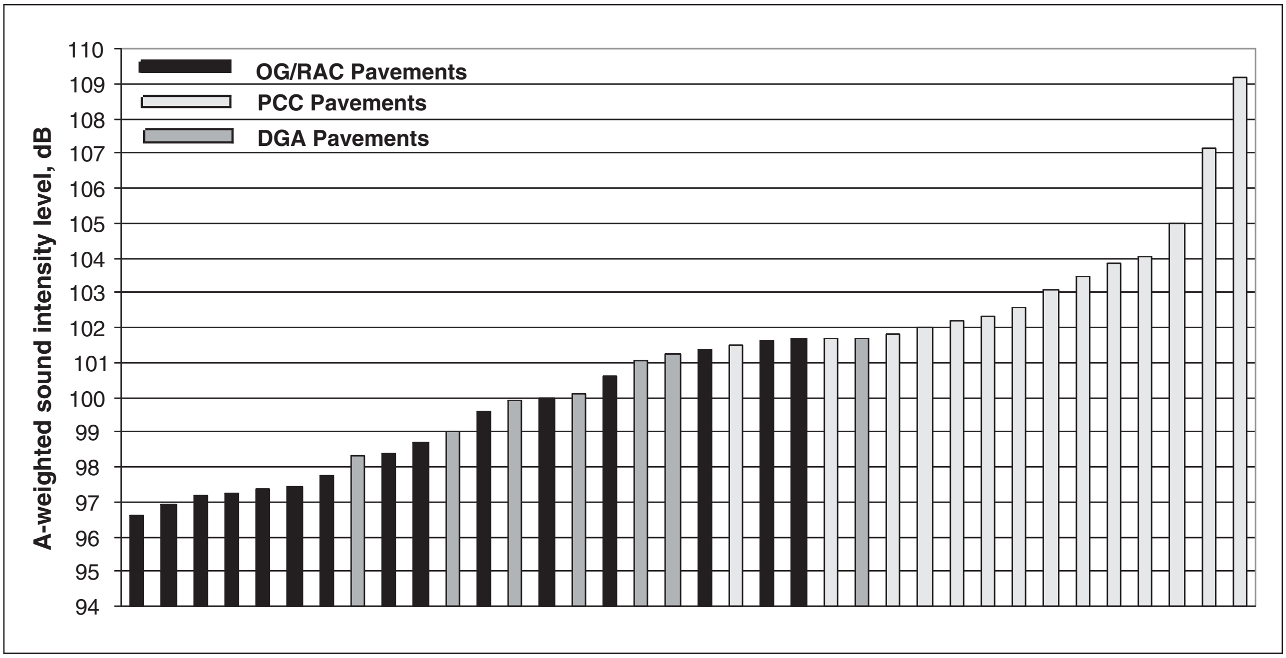



FIGURE 3 Sound-intensity levels on California highways measured by the onboard sound-intensity method. PCC = Portland cement concrete. DGA = dense graded asphalt. OG/RAC = open-graded/rubber asphalt concrete. Source: Donavan, 2005. Reprinted with permission of the Institute of Noise Control Engineering/USA.

asphalt) noise produced by different sections of roadway vary significantly, even with the same tires. Figure 3 is a compilation of tire/pavement noise generation measured on various California highways by microphone sensors near the tire. As the figure shows, there is a substantial difference between the loudest and quietest pavements. There is also significant variation for the same type of pavement caused by differences in construction and the condition of the pavement.

### *Aviation Noise*

Of the noise from the three transportation modes under discussion, aircraft noise is typically the most localized. Annoying levels of aircraft noise are limited largely to areas within several miles of airports, although concerns about noise from aircraft at cruising altitudes have arisen in National Parks and other quiet areas.

As noted above, on a per dB basis, people consider aircraft noise more annoying than noise from surface modes of transportation. We do not know how much this difference is related to physical and physiological factors as compared to public perceptions and other factors.

Aviation noise results from a combination of acoustic energy generated by unsteady fluid-mechanical processes in aircraft engines, noise generated from the unsteady interaction of exhaust jets and/or propellers with the surrounding air, and noise related to unsteady flow produced by the airframe. Takeoff and approach noise are the primary sources of community complaints. The former is dominated by engine noise, whereas the latter is dominated by a combination of airframe and engine noise.

The most dramatic reductions in transportation noise have been in aviation. As shown in Figure 4, in the last 35 years, the number of people in the United States impacted by aviation noise has been reduced by 95 percent, even though there has been a six-fold growth in air-transportation mobility (as measured by the number of people-miles traveled) (Waitz et al., 2004). Today, fewer than 0.5 million people in the United States are impacted by aircraft noise of greater than 65 dB $L_{dn}$ (and fewer than 5 million at greater than 55 dB $L_{dn}$), even though there were 750 million enplanements this year alone.

This dramatic improvement in noise performance is the result of technological advances, the most significant of which was the introduction of high-bypass-ratio turbofan engines (introduced because of their superior fuel efficiency). The technological improvements were promoted by new certification standards included in the Airport Noise and Capacity Act of 1990, which mandated a phase-out of 55 percent of the older, noisier, fleet. The phase-out is estimated to have cost the U.S. airline industry $5 billion (GAO, 2004).

Most projections suggest that continuing technological and operational advances in noise reduction will not keep pace with the growing consumer demand for air travel. Thus modest increases in the number of people impacted by aviation noise are anticipated.

Despite the reductions in noise described above, noise is still the environmental issue of most concern for airports (GAO, 2000), and a growing number of noise-related operating restrictions and fees are being imposed on airlines (Boeing Commercial Aircraft, 2006). Communities surrounding some airports have taken steps to delay or cancel airport-expansion plans or impose operating restrictions, such as flight-path restrictions and curfew hours during which operations are not permitted. One example of a delay is the runway expansion at Logan International Airport in Boston. In the early 1970s, construction of a half-built runway was halted by a court injunction that remained in place for 30 years.

In the United States, we also spend approximately $300 million a year, collected from fees and taxes on airline tickets, to insulate homes and purchase land around airports in areas where aircraft noise levels exceed 65 dB $L_{dn}$ (NRC, 2002). However, most of the population exposed to aviation noise lives outside these areas.

*Railroad and Urban-Transit Noise*

In 1981, it was estimated that 2.5 million people were exposed to railroad and urban-rail noise. Considering the explosive growth in railroad operations in recent years and the increase in track miles of urban-transit systems, that number is probably greater today. In addition, a recent study by the Federal Railroad Administration (FRA) estimated that more than 9 million people are impacted by noise from train horns at the 154,000 grade and highway crossings in the United States (DOT, 2002).

The impact of rail noise from operations is confined to relatively narrow corridors, but, because urban-transit systems are located in densely populated cities, they expose large numbers of people to significant noise levels. Within a few hundred feet of surface or elevated tracks, noise levels can exceed 85 dBA, which is high even in the context of a typical urban-noise environment. Despite the potential effects of rail-transit noise on people in cities, EPA estimates that noise exposure from rail transportation is mostly from railroad freight operations and freight yards, which, together, accounted for 80 percent of the total rail-noise exposure in 1981.

Noise generation from rail systems can be divided into two categories: moving sources and stationary sources. Noise generated by moving sources, such as trains traveling on tracks, include propulsion noise from diesel engines or electric motors; mechanical noise from fans, compressors, and auxiliary units; wheel/rail noise from rolling, impact, and squealing; and aerodynamic noise from turbulent boundary layers, vortex shedding, and wakes.

Stationary sources in fixed locations include noise at road crossings from horns and bells; noise from layover tracks from idling diesel engines; and yard noise from retarders, car couplers, and idling locomotives. Poorly

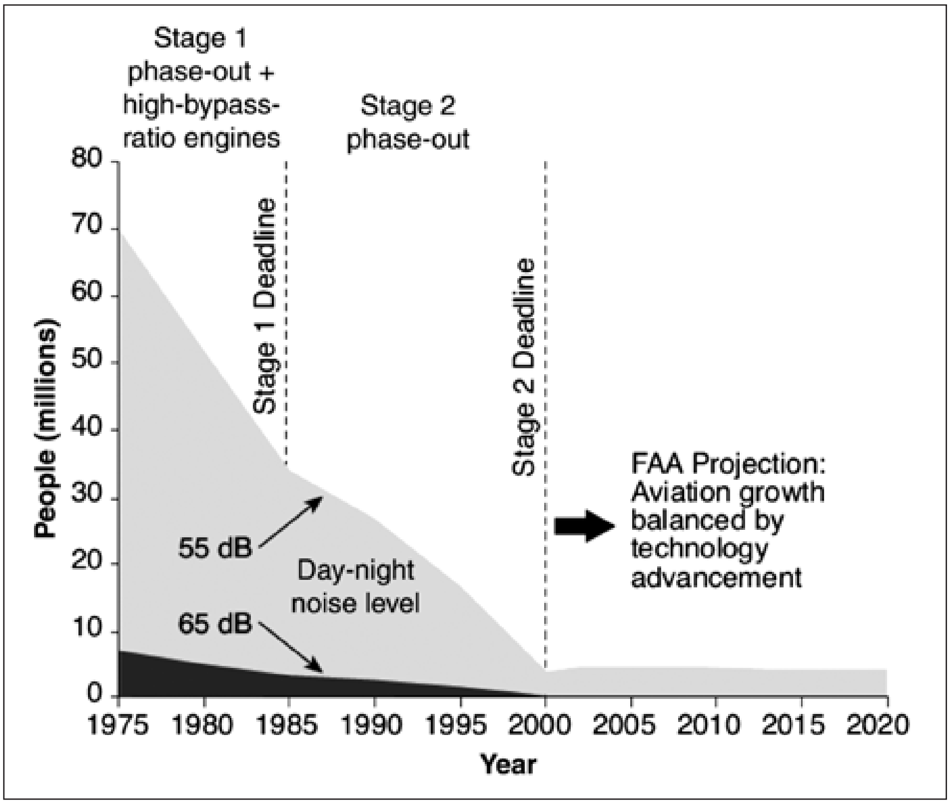



FIGURE 4 Estimated number of people affected by aircraft noise in the United States. Source: Waitz et al., 2004.

maintained vehicles and facilities are the root cause of excessive noise from both railroads and urban-rail systems. Flat spots on steel wheels, rough rail-running surfaces, and misaligned rail joints can increase noise levels by 10 dBA compared to well maintained systems. Deferred maintenance is often the result of budget shortfalls, especially in urban transit systems.

Unlike highway vehicles and aircraft, rail transportation generates significant ground-borne vibrations that are often associated with noise. The pass-by of a heavily loaded train causes ground vibrations that are transmitted to nearby buildings where they can be felt as physical shaking or heard as a rumbling sound. People often misinterpret ground vibration as noise. Vibration is generally a problem only a short distance from the tracks, but it can interfere significantly with activities that require low-vibration environments.

In 1987, the Federal Transit Administration (FTA) issued a joint regulation with the Federal Highway Administration for mitigating adverse noise impacts from rail transportation. The regulation states that mitigation measures are eligible for funding when FTA determines that ". . . the proposed mitigation represents a reasonable public expenditure after considering the impacts of the action and benefits of the proposed mitigation measures" (DOT, 1987). Noise from freight railroad operations and yards is regulated by standards developed by EPA and enforced by FRA (EPA, 2003).

*Quieter pavements can have the same safety, durability, and cost as current pavements.*

Several local transit agencies have developed their own policies for mitigating noise and vibration impacts. Chicago Metra has adopted a general policy statement on mitigating noise and vibration with criteria consistent with FTA criteria and a strategy for implementation of cost-effective mitigation measures. The Metropolitan Boston Transit Authority (MBTA) and other transit agencies have adopted similar policies on a project-by-project basis.

## Mitigating Noise in the Future

### *Highway Noise*

As shown in Figure 3, pavements can be made significantly quieter. Based on data collected to date, substantial improvements in pavement types can be made by improving how they are built and maintained. In addition, novel quiet-pavement concepts have been demonstrated that are several decibels quieter than the quietest sections of pavement shown in Figure 3 (Sandberg and Ejsmont, 2002). The general strategy for quieter pavements is to make them porous and somewhat elastic with as little positive texture as possible. These pavements can be constructed to have the same safety, durability, and cost characteristics as pavements constructed with current technology.

Tires are not typically designed to minimize radiated noise. Although automobile tires can be made quieter, the improvement would generally mean lower durability and/or higher cost.

Sound-wall barrier design is fairly mature. However, the performance of barriers could be improved by building them taller and closer to the noise source, which might entail building a partial tunnel for the highway.

Studies on understanding the causes of "annoyance" are ongoing. For highway noise, outlier events, such as air-compression braking by trucks and poorly maintained exhaust systems, increase annoyance. Tonal sounds from the periodic texturing of pavement or uniform tread-block sizes also increase annoyance. Spectral and temporal engineering of the radiated sound could reduce annoyance levels without necessarily reducing sound-pressure levels.

### *Aviation Noise*

We will need a balanced approach to make further reductions in community noise from aircraft. This approach must include technological advances, operational advances, and better land-use planning around airports. The latter presents many challenges, and there are many examples where federal guidelines for land use have not been followed, exacerbating community noise problems. Even when airports are located in sparsely populated areas (e.g., Dallas/Fort Worth International Airport and Denver International Airport), local decisions often lead to increased land use in areas with high aircraft noise. It is not clear how these issues will be addressed in the future, but several airport communities have developed effective forums for addressing these issues proactively (e.g., San Francisco

Community Roundtable and O'Hare Noise Compatibility Commission).

Near-term improvements are most likely to come from operational advances. The Federal Aviation Administration is working with airports and airlines to implement continuous-descent arrivals, which require aircraft to approach airports on steeper descents with lower, less variable throttle settings. This type of descent has been shown to reduce noise, burn less fuel, and reduce emissions (Clarke et al., 2006). However, noise reductions from operational measures are likely to be limited.

Technological improvements will be necessary for more significant reductions in noise. Evolutionary improvements in technology are likely to continue to reduce noise from aircraft engines and airframes at a rate of 2 to 3 dB per decade. Step-change technologies (e.g., aircraft with noise signatures quieter than typical background urban and suburban noise levels) are also being investigated by academia, industry, and government (e.g., Hileman et al., 2007), but many economic and technological risks are still unresolved. Such technologies are not expected to be introduced for at least 15 to 20 years. Despite the significant technological opportunities for reducing aviation noise, federal funding for basic research in this area has decreased markedly in the last 10 years (NRC, 2002).

Low-noise technology and operational measures must be considered in the context of trade-offs with fuel efficiency and emissions, because other environmental concerns, such as climate change and local air quality, must also be addressed.

### *Railroad and Urban-Rail Transit Noise*

Noise control for conventional rail systems is often a matter of good, timely maintenance. Wheel/rail noise can be minimized by ensuring that running surfaces are smooth. In urban transit systems, wheel truing and rail grinding are key elements in controlling noise. Special treatments for controlling squealing noise on curves have resulted as a side benefit of friction-management programs. Research on optimum shapes for very-high-speed trains has contributed to our understanding, and eventual control, of aerodynamic noise sources that dominate noise from trains moving at speeds of more than 150 mph.

Because noise has been identified as a key issue associated with environmental assessments for new rail systems, both FTA and FRA have made guidelines available for assessing noise and vibration. FTA's guidance manual, *Transit Noise and Vibration Impact Assessment*, includes criteria and procedures for determining impacts and mitigation measures for excessive noise and vibration in projects funded by FTA under its policy for implementing environmental-mitigation measures (DOT, 2006a).

*Trade-offs are necessary to address noise-reduction, environmental, and safety concerns.*

FRA's manual, *High-Speed Ground Transportation Noise and Vibration Impact Assessment*, provides similar information for high-speed rail projects (DOT, 2005). Both manuals have been instrumental in encouraging planners of new rail systems to take noise control into account.

Another policy development in controlling noise from rail systems is a recently enacted rule for using locomotive horns at grade crossings (DOT, 2006b). The rule protects public safety by requiring the use of horns but also establishes maximum horn-noise levels, limits on the duration of horn use, and guidelines for implementing quiet zones. Many communities have taken steps to reduce or eliminate horn noise by following these guidelines.

Sound insulation for homes impacted by rail noise has not been developed to the same extent as it has for homes near airports. The MBTA commuter railroad conducted pilot studies on houses near grade crossings where horns are blown but where noise barriers are impractical because of sight-line requirements. These studies have resulted in recommendations for treating homes where mitigation would be practical. Another example is Chicago Metra, which has included sound insulation in its noise policy. Nevertheless, these agencies are exceptions to the general rule.

## Summary

Transportation sources dominate the noise environment in many regions of the United States. The greatest number of people is exposed to impact levels of highway noise, followed by rail noise, and then by aviation noise. However, on a per dB basis, aircraft noise is estimated to be most annoying. Thus aircraft noise is a severe problem in areas near airports, whereas highway and rail noise are more widespread problems.

A positive trend in reducing transportation noise is that aircraft have become dramatically quieter as the result of technological improvements, and noise contours around airports have shrunk commensurately. However, with aviation operations projected to triple by 2020 and sometimes-conflicting requirements for aircraft fuel efficiency and emissions, it remains to be seen if this trend will continue.

Another positive trend is tire-pavement research to reduce highway noise at the source instead of installing noise barriers, which shield only localized areas. For rail noise, agency guidelines developed for identifying problems early in the project development stage are being used throughout the United States to reduce the impact of noise. Many federal, state, and local transportation agencies are adopting and implementing noise-mitigation policies, and noise is a major consideration in the design and operation of all transportation systems.

## References

Boeing Commercial Aircraft. 2006. Timeline of Aircraft Noise Certification and Phaseout Rules. Available online at *http://www.boeing.com/commercial/noise/timeline.pdf*. Accessed June 2006.

Clarke, J.-P., D. Bennett, K. Elmer, J. Firth, R. Hilb, N. Ho, S. Johnson, S. Lau, L. Ren, D. Senechal, N. Sizov, R. Slattery, K.-O. Tong, J. Walton, A. Willgruber, and D. Williams. 2006. Development, Design, and Flight Test Evaluation of a Continuous Descent Approach Procedure for Nighttime Operation at Louisville International Airport. Report of the PARTNER Continuous Descent Approach Development Team, Report No. PARTNER-COE-2006-02, January 9, 2006. Available online at *http://www.mit.edu/people/liling/files/cda_rpt.pdf*.

Donavan, P. 2005. Reducing Traffic Noise with Quieter Pavements. Proceedings of Noise-Con 2005, Minneapolis, Minn., October 2005. CD ROM only.

DOT (U.S. Department of Transportation). 1987. Environmental Impact and Related Procedures, Final Rule, 52 FR 32646-32669. Federal Transit Administration and Federal Highway Administration. Washington, D.C.: DOT.

DOT. 2002. Final Rule for the Use of Locomotive Horns at Highway-Rail Grade Crossings, Final Environmental Impact Statement, Office of Railroad Development. Washington, D.C.: DOT.

DOT. 2005. Final Report: High-Speed Ground Transportation Noise and Vibration Impact Assessment. HMMH Report No. 293630-4. Office of Railroad Development, October 2005. Available online at *http://www.fra.dot.gov/us/content/253*.

DOT. 2006a. Transit Noise and Vibration Impact Assessment. FTA-VA-90-1003-06, May 2006. Available online at *http://www.fta.dot.gov/documents/FTA_Noise_and_Vibration_Manual.pdf*.

DOT. 2006b. Use of Locomotive Horns at Highway-Rail Grade Crossings: Final Rule. 49 Code of Federal Regulations Parts 222 and 229, (FR 71, 159, August 17, 2006).

EPA (Environmental Protection Agency). 2003. Noise Emission Standards for Transportation Equipment: Interstate Rail Carriers. 40 Code of Federal Regulations Part 201.

GAO (U.S. General Accounting Office). 2000. Aviation and the Environment: Results from a Survey of the Nation's 50 Busiest Commercial Service Airports. Report to the Ranking Democratic Member, Committee on Transportation and Infrastructure, House of Representatives, GAO/RCED-00-222, Washington, D.C. Available online at *http://www.gao.gov/archive/2000/rc00222.pdf*.

GAO. 2001. Aviation and the Environment: Transition to Quieter Aircraft Occurred as Planned, but Concerns about Noise Persist. Report to the Ranking Democratic Member, Committee on Transportation and Infrastructure, House of Representatives, GAO-01-1053, Washington, D.C. Available online at *http://www.gao.gov/new.items/d011053.pdf*.

Hileman, J., Z. Spakovszky, M. Drela, and M. Sargeant. 2007. Airframe Design for "Silent Aircraft." AIAA 2007-0453, 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nev.

Miedema, M.E., and H. Vos. 1998. Exposure–response relationships for transportation noise. Journal of the Acoustical Society of America 104(6): 3432–3445.

Miller, N.P. 2003. Transportation noise and recreational lands. Noise/News International 11(1): 9–20.

NRC (National Research Council). 2002. For Greener Skies: Reducing Environmental Impacts of Aviation. Washington, D.C.: National Academies Press. Available online at *http://books.nap.edu/catalog/10353.html*.

Sandberg, U., and J.A. Ejsmont. 2002. Tyre/Road Noise Reference Book. Kisa, Sweden: INFORMEX.

Waitz, I.A., J. Townsend, J. Cutcher-Gershenfeld, E.M. Greitzer, and J.L. Kerrebrock. 2004. Aviation and the Environment: A National Vision Statement, Framework for Goals and Recommended Actions. Report to the United States Congress on behalf of the U.S. DOT, FAA, and NASA. Available online at *http://mit.edu/aeroastro/partner/reports/congrept_aviation_envirn.pdf*.