Noise pollution—what can be done?

"An old riddle asked, 'What comes with a carriage and goes with a carriage, is of no use to the carriage and yet the carriage cannot move without it?' The answer: 'A noise.'

And yet noise is of great use to us and to all animals. Many events of nature, whether the meeting of two objects or the turbulent flow of air, radiate a tiny part of their energy as pressure waves in the air. A small fraction of the energy that is scattered enters our ears, and we hear it and thus we know of the event. Hearing is a late development in evolution but it has become the sentinel of our senses, always on the alert.

But hearing does more. The ear and the brain analyze these sound waves and their patterns in time, and thus we know that it was a carriage, not footsteps that we heard. What is more, we can locate the position of the carriage, and tell the direction in which it is moving. . .

Many birds and animals have also learned to signal one another by their voices, both for warning and for recognition. But we humans, with good ears and also mobile tongues and throats, and above all, our large complex brains, have learned to talk. We attach arbitrary and abstract meanings to sounds, and we have language. We communicate our experiences of the past and also our ideas and plans for future action. For human beings, then, the loss of hearing brings special problems and a special tragedy. But human society creates a special problem even for those with perfect hearing—the problem of unwanted sound, of noise, which is as much a hazard of our environment as disease germs or air pollution."

These eloquent words by Hallowell Davis, recently quoted,[1] were written as the introduction to a popular book on *Sound and Hearing.*[2] They show us clearly where we must lay the foundations for a strategy of noise abatement. But we shall not progress far unless we recognize that the problems we face are, in fact, peculiar to the age in which we live in at least one respect. For the noise that saturates the workshop, pervades the modern city, invades the home and even penetrates the wilderness is associated with a vast increase in the use of energy during the past few decades, particularly for transportation and labor-saving machinery. We are no longer dealing with a single carriage but with a collective enterprise of unprecedented magnitude. So, the control of noise at the source, in the design of buildings and in the planning of cities is likely to be of major concern to all levels of government in many countries for years to come.[3]

With noise as with other pollutants, we are beginning to see clearly the dimensions of the problem and the adjustments that are needed to bring about a solution. Whether we shall, in fact, succeed is part of a larger question, concerning the ultimate destiny of our twentieth-century civilization, which remains to be answered.

Sound power and mechanical power

How large is the fraction of energy inadvertently converted into sound by the machinery that is so much a part of our way of life? Figure 1 answers this question for a selection of noise sources.

The horizontal scale shows the mechanical power of a few widely used transportation vehicles, recreational machines and power tools, and the vertical scale the "A-weighted" sound power that each produces. A-weighted measurements are made with an instrument having the response specified in Table 1. This particular frequency response, which is widely used in sound level meters and noise dose-meters, is somewhat like that of the human hearing system. In particular, it de-emphasizes low-frequency sounds and provides maximum sensitivity around 3 kHz. So, A-weighted sound level and sound power are appropriate measures of noise.

The values of sound power in figure 1 have been calculated from published values of A-weighted sound level measured at various distances from the sources of sound.[3,4] There are, of course, other more sophisticated measures, such as the perceived noise level, which have been developed with the purpose of making more refined comparisons between complex sounds, especially those that have strong tonal components. Some of these measures are shown in the box on page 50. All of the data in this article are presented in terms of A-weighted measurements.

The values of mechanical power output in figure 1 have been estimated for operating conditions that are pertinent to the problem of noise. For example, the power of a turbo-fan aircraft has been estimated for typical values of thrust and air speed when the aircraft is climbing at an altitude of 300 meters after takeoff. The motor vehicles are assumed to be cruising at freeway speeds.

The mechanical power ranges from 200 watts for the typical dishwasher to 55 000 kW for the Douglas DC 10 and Lockheed L 1011: a factor of more than 10^5. The acoustic power ranges from 30 microwatts for the dishwasher

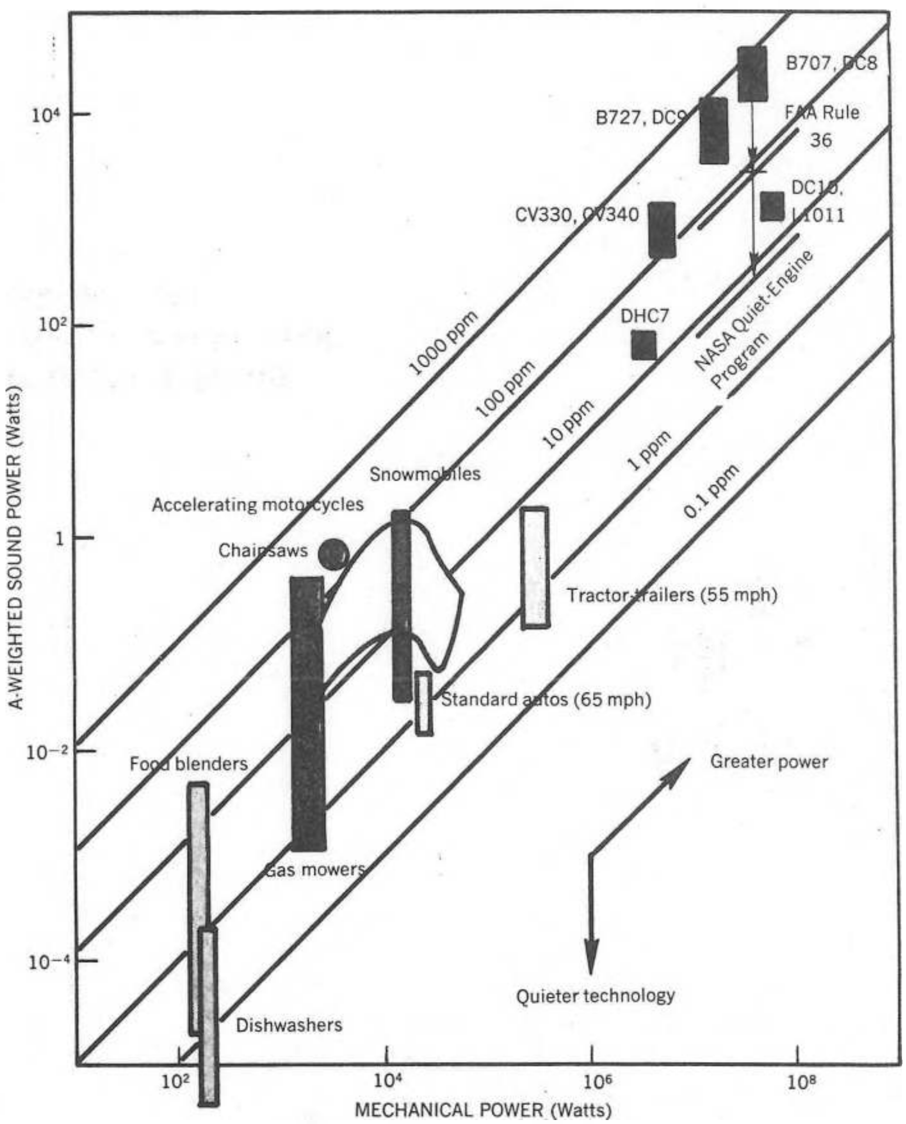
Edgar A. G. Shaw is a principal research officer in the Physics Division of the National Research Council of Canada and is past president of the Acoustical Society of America.

As the noise level of the environment rises and community reactions increase, new approaches in "hardware" and "software" become necessary.

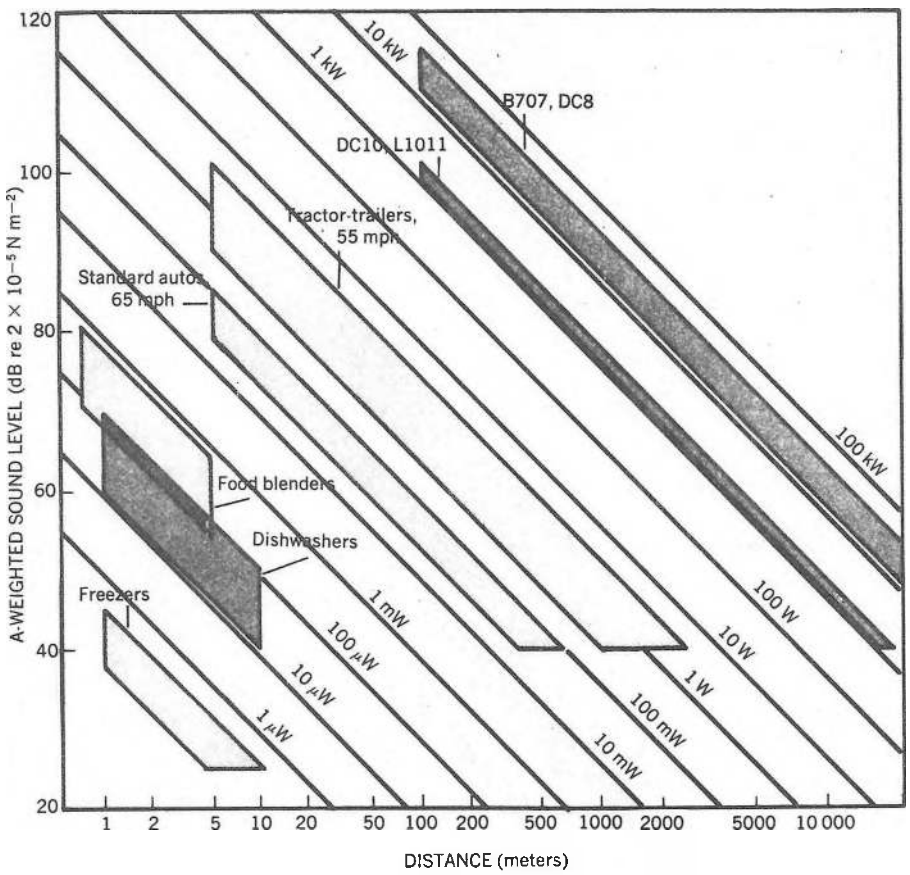
Edgar A. G. Shaw

to 30 000 watts for some of the large aircraft: a factor of 10^9. The general trend that is obvious in figure 1 is the clustering of data about the diagonal from bottom left to top right: The acoustical power output tends to increase with the mechanical power. It should not, of course, be inferred that the noise output of a machine is a reliable indicator of its mechanical power though some owners of sports cars, motorcycles and vacuum cleaners are, perhaps, of that opinion! The fraction of mechanical power converted into acoustical power expressed in parts per million is indicated by the five diagonal lines. It is indeed very small in every case, barely reaching 1000 ppm for the noisier aerodynamic noise sources and dropping below 1 ppm for some of the electrically powered machinery.

The relationship between technological change and the problem of noise in recent years is particularly clear in the case of aircraft noise. The bar marked "CV330, CV340" represents the last of the turbo-propeller planes in large-scale use on this continent. This aircraft developed about 4500 kW of mechanical power when climbing, and produced as a byproduct about 900 watts of A-weighted sound power. Higher up is a symbol representing the Boeing B 727 and Douglas DC 9 turbo-fan intercity aircraft now in widespread use. These produce a total thrust roughly equivalent to 15 000 kW of mechanical power when climbing and, as a byproduct, 8000 watts of sound power. So we have three to four times as much mechanical power and ten times as much sound power. For the transcontinental B 707 and DC 8 aircraft, the figures are even more impressive: roughly 33 000 kW of mechanical power when climbing and 30 000 watts of A-weighted sound power. Later, we shall see that there is



Estimated values of A-weighted sound power versus mechanical power for various machines. The colored diagonals are lines of constant mechano-acoustical efficiency (sound power/mechanical power) in parts per million. The "FAA Rule 36" line approximately indicates current noise levels for new aircraft designs, while the goal of a research program is labeled "NASA Quiet Engine Program." The DHC is a De Havilland commercial plane. Figure 1



A-weighted sound level as a function of distance from various sources. Both inverse-square-law spreading and atmospheric absorption have been taken into account, assuming a "standard" day (temperature 15 °C, relative humidity 70%, atmospheric pressure 760 mm Hg) and sources that emit "red" noise (Table 2). Diagonals show A-weighted sound power. Figure 2

Table 1. Frequency response of A-weighting network used in sound-level meters

Frequency (Hz)	Relative response (dB)	Energy-weighting factor
32	−39.2	1.2×10^{-4}
63	−26.1	2.45×10^{-3}
125	−16.1	2.45×10^{-2}
250	−8.6	0.138
500	−3.2	0.48
1000	0.0	1.00
2000	+1.2	1.32
4000	+1.0	1.26
8000	−1.1	0.78

Table 2. "Red" noise: Energy per unit bandwidth proportional to (frequency)$^{-2}$

Center frequency of octave bands (Hz)	Relative levels of octave bands (dB)	Relative energy per octave band	Relative energy per unit bandwidth
63	12	16	256
125	9	8	64
250	6	4	16
500	3	2	4
1000	0	1	1
2000	−3	0.5	0.25
4000	−6	0.25	0.0625

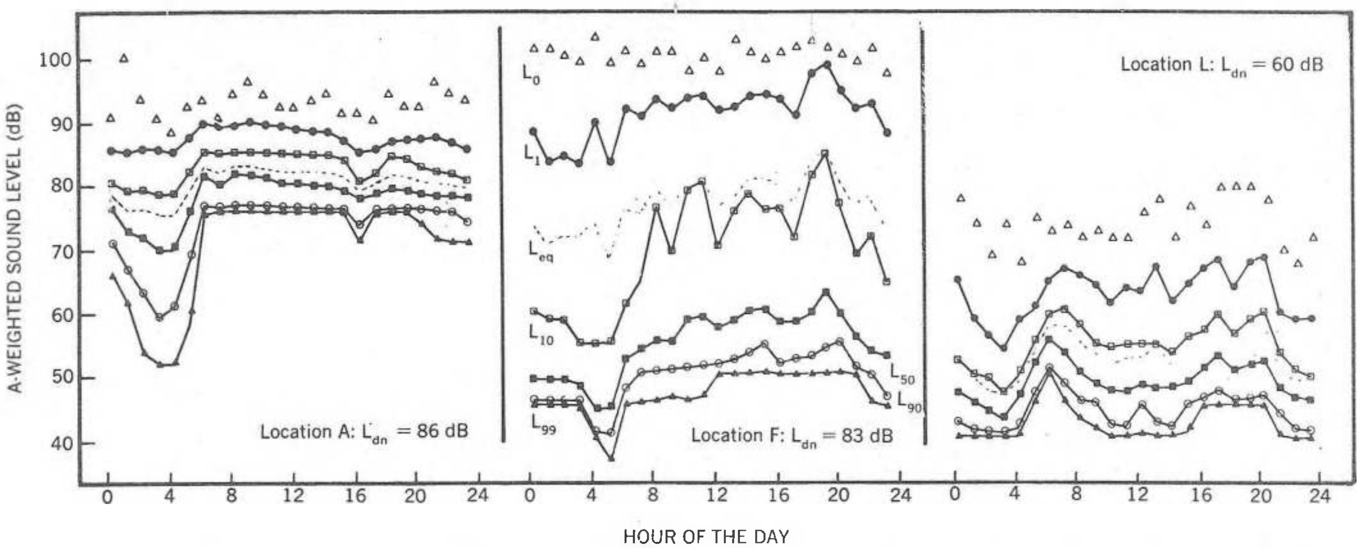
another side to this story that offers hope for the future. For the moment, let us follow the development of the noise problem.

If technology has carried us up the energy scale with respect to the magnitude of the individual noise sources, it has also provided increasing numbers of sources. According to a report by the US Environmental Protection Agency Administrator,[4] the number of automobiles in the US increased from 40 million in 1950 to 87 million in 1970, and the number of trucks from 9 million to 18 million in the same period. The number of commercial turbo-fan planes increased by a factor of 10 in a ten-year period: from 200 in 1960 to 2000 in 1970,[4] replacing an approximately equal number of smaller, quieter and slower propeller-driven planes. The report also records a tremendous proliferation of gasoline-powered tools and recreation vehicles. For example, gasoline-powered lawnmowers, which were very rare in 1950, numbered 10 million in the US by 1960 and 17 million by 1970, while snowmobiles, which were nonexistent in 1960, numbered nearly one million in 1970.

Noise levels

It is not the acoustic power of a source but the amount of sound we actually receive that affects us, and this depends on distance as well as on the power of the source. The sound level (or noise level) expressed in decibels is a convenient way of describing the strength of sound at any particular location and time. It can be measured with a simple hand-held sound level meter, or else it can be recorded for later analysis and processing.

Figure 2 shows the sound levels produced by some of the noise sources included in figure 1 over distances pertinent to the noise problem. It is assumed that aircraft radiate spherically, while sources situated on or near a reflecting surface, such as a highway, radiate into a single hemisphere only. (The diagonal lines show the attenuation of spherical radiators of the sound power shown.) Most of the fall in noise level with increasing distance is simply due to the spreading of energy according to the inverse square law. Beyond a few hundred meters, however, atmospheric absorption becomes a significant factor.[5] The scale of distance in figure 2 has been stretched to take into account the loss of energy due to absorption and the resultant changes of spectrum with distance for sources producing "red" noise of limited total bandwidth as indicated in Table 2. Aircraft exhaust noise and motor-vehicle noise fit this specification reasonably well. It must however be remembered that atmospheric absorption is strongly dependent on frequency. So



Patterns of outdoor-noise level at three Los Angeles residential locations. Each value L_x shows the level exceeded x percent of the time in a one-hour period, with L_0 showing the maximum recorded; the dotted lines show the hourly equivalent levels L_{eq}. At A, a third-floor apartment overlooking the San Diego Freeway, the median level is 80 dB, with 90-dB peaks. At F, 3/4 miles from the Los Angeles Airport, the median is lower but some peaks exceed 100 dB. Location L is in an old residential area. Figure 3

figure 2 cannot be applied to intense narrow-band, particularly high-frequency, sources. Levels appreciably lower than those shown in figure 2 are likely when the source of sound and the receiver are close to the ground or where there are obstacles such as buildings along the transmission path. Reductions in sound level of 10 dB from these effects are typical for motor vehicles at distances[6] of the order of 300 m.

To place these sound levels in proper perspective it must be remembered that the decibel scale is logarithmic to accommodate the enormous dynamic range of the human hearing system. The zero on this scale is defined to correspond approximately to the normal threshold of hearing. The highest level shown in figure 2, 120 dB, implies a sound intensity 10^{12} times as great as the threshold intensity of 0 dB, since a 10-dB increase in level corresponds to a ten-fold increase in intensity. The smallest change in sound level that can be readily detected is about 1 dB, while a 10-dB increase in sound level (more properly, loudness level) is perceived as a doubling of "loudness." In passing we note that the A-weighted levels that are hazardous to hearing start at about 80 dB or a little less, while the levels that may be disturbing or annoying lie between 40 and 80 dB.

The individual sources of urban noise are not heard in isolation. Many sources, operating simultaneously in and around a city, combine to produce a complex pattern of sound at each location. A 24-hour recording of A-weighted sound level, suitably processed, provides an excellent measure of the pattern. Such recordings have been made at many locations in several countries during the past few years. The three sets of data presented in figure 3 are from a study by Kenneth Eldred[7] of the noise levels at 18 representative locations in the United States. Each value L_x shows the level exceeded x percent of the time during a one-hour period. Thus L_{99} serves to define the background noise level while L_{50} shows the median level. L_{10} and L_1 indicate the "peakiness" of the pattern.

Values of L_{99}, L_{90}, L_{50}, L_{10} and L_1 for the daytime period at all eighteen locations covered by the study are brought together in figure 4. Notice that the median level, L_{50}, ranges from 20 dB at the north rim of the Grand Canyon to 80 dB outside the window of a third-floor apartment next to a freeway, referred to as "location A." Notice also that the spread of levels varies greatly. At an urban residential area near a major airport, for example, the difference between L_1 and L_{99} is 44 decibels, whereas at an urban shopping center the difference is only 12 dB. It is worth noting that, in many cases, the median level, L_{50}, can be explained very well in terms of motor-vehicle traffic. Knowing the number of moving vehicles per square kilometer at each hour of the day and the sound power produced by the average vehicle, one can calculate the median noise level in the community throughout the day and night quite accurately.[6] So it is the motor vehicles that are responsible for much of the steady background of noise in modern cities.

One month at 80 dB—enough

The patterns of noise level in figure 3 bring out rather clearly some of the important characteristics of urban noise. The first pattern (A), recorded with a microphone outside a window of a third-floor apartment overlooking the eight-lane San Diego Freeway in Los Angeles, shows a median level at the steady value of 80 dB from early morning to late evening with peak levels, indicated by the colored triangles, of roughly 90 dB. It is said that the average tenancy in that apartment block is only one month. Location F is in a neighborhood of single-family dwellings only three-fourths of a mile from the Los Angeles International Airport. The median noise level during the day is only 55 to 60 dB, but there are broad peaks at levels which, because of aircraft overflights, sometimes exceed 100 dB. These peaks account for the high value (approximately 95 dB) of L_1. Even at 3 a.m. these intense peaks occur every ten minutes. It is hardly surprising to learn that the residents at that location are very dissatisfied with the pattern of noise in their neighborhood. The third of these locations, L, lies in an old residential area near the center of Los Angeles a half mile from the Santa Monica Freeway. The background noise level is around 45 dB most of the day except during the morning rush hour, when the level rises to a very steady 65 dB. The noise peaks (L_0), which never exceed 80 dB, are mostly due to local automobiles and neighborhood activities, such as children playing. The residents of that neighborhood are said to find this pattern of noise very acceptable.

Is it feasible to define a single numerical index that sums up the overall impact of a given pattern of noise on the people who live in a community? This is a very important question. Such an index could provide the key to the specification of environmental-quality standards for noise and hence a measure of

Some measures of noise widely used in contemporary literature

. . . a simple guide through the dense jungle of acoustical terminology.

A-weighted sound level

$$L_A = 10 \log_{10} (p_A^2/p_0^2) \qquad \text{(dB)}$$

where p_A^2 is the mean square A-weighted sound pressure (see Table 1) and p_0 is the reference sound pressure; $p_0 = 2 \times 10^{-5}$ N/m^2. A-weighted levels are frequently identified by the letter A following the decibel symbol: dB(A) or dBA.

Equivalent level

$$L_{eq} = 10 \log_{10} \left\{ \int_{t_1}^{t_2} p_A^2 \, dt / [p_0^2 (t_2 - t_1)] \right\} \qquad \text{(dB)}$$

where t_1 and t_2 define the time period of integration.

Day–night average level

$$L_{dn} = 10 \log_{10} \left\{ \left[\int_{0700}^{2200} p_A^2 \, dt + 10 \int_{2200}^{0700} p_A^2 \, dt \right] \Big/ [24 \, p_0^2] \right\} \qquad \text{(dB)}$$

where time is measured in hours and the limits specify day and night.

Community Noise Equivalent Level
CNEL is similar to L_{dn} but evening energy (1900 to 2200 hours) is given a weight of 3 instead of 1.

Loudness level
The loudness level of a sound is numerically equal to the sound-pressure level in decibels of the 1000-cycle pure tone judged by listeners to be equivalent in loudness. It is calculated by complex but standard procedures (see PNL). The unit is the phon.

Perceived Noise Level
A measure of the "noisiness" of a complex sound is given by the PNL which, for its calculation from physical data, is based on several standardized properties of the human hearing system, such as the equal-noisiness contours and a band-summation formula, determined by psycho-acoustic methods. PNL is expressed in PNdB. It is closely related to the loudness level. PNL_{max} is the highest level of a transient noise attained during any 0.5-second time period. For typical noise spectra, PNL $\simeq L_A + 13$.

Composite Noise Rating for aircraft noise

$$\text{CNR} = \text{PNL}_{max} + 10 \log_{10} (N_d + 16.7 \, N_n) - 12 \qquad \text{(dB)}$$

progress towards noise abatement. The patterns of noise at locations A and F, though very different, are almost equally objectionable to the residents. The steady roar of noise at location A seriously interferes with speech communication outside and inside the apartment block. On the other hand, the frequent intense peaks of noise rising far above the background level at location F are exceedingly disturbing, despite the comparatively low median noise level. So, any system for rating noise patterns in residential areas must certainly take both of these factors into account.

A number of rating schemes are based on the concept of average energy (see the box on this page). Let us suppose we have some means of collecting all of the A-weighted sound energy that arrives at a particular location over a certain period of time (which might be one hour or a whole day). We then calculate the decibel level of steady noise that would give the same total energy over the same time period. This level L_{eq} is variously described as the energy-equivalent level, the equivalent level or the average sound level. For example, a single peak lasting only 3.6 seconds at a level of 90 dB is equivalent in energy content to a whole hour of steady noise at a level of 60 dB. The usefulness of L_{eq} as a single number index is associated with its sensitivity to high peak levels, as figure 3 shows.

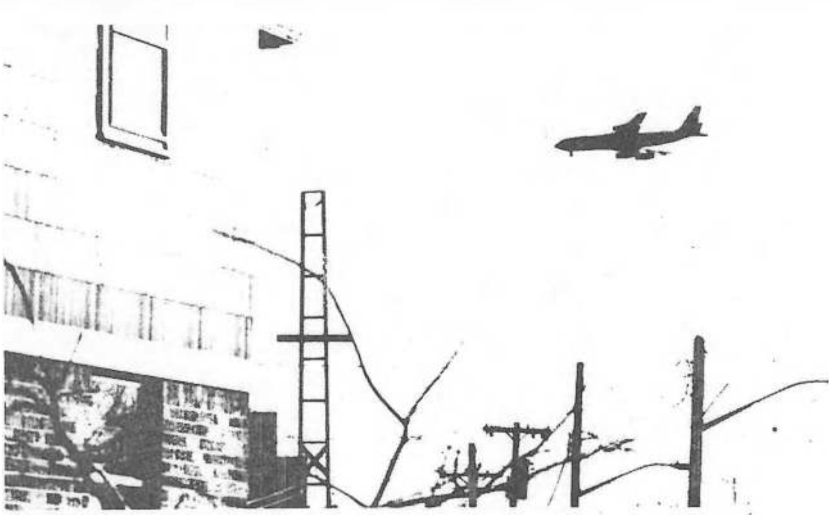
Experience shows that people are less tolerant of noise at night than during the day. It may therefore be appropriate to give extra weight to the sound energy that arrives during the night. This concept is, in fact, incorporated in the Composite Noise Rating (CNR) and the Noise Exposure Forecast (NEF), both of which have been widely used to evaluate noise patterns around airports. In the scheme recently adopted by the US Environmental Protection Agency,[8] the sound energy arriving during the night (10 p.m. to 7 a.m.) is multiplied by ten before the summation. The decibel level that results from this temporal weighting procedure is known as the "day–night average sound level" (L_{dn}). (This measure is very similar to the Community Noise Equivalent Level (CNEL) developed and used in California.) Note that the values of L_{dn} at the three locations discussed above, A, F and L, are shown in figure 3 to be 86, 83 and 60 dB respectively.

The effects of noise on people

The World Health Organization has defined health as "a state of complete physical, mental and social well-being and not merely an absence of disease and infirmity." This widely quoted definition accurately reflects what most of us feel about health, but it requires refinement before it can provide a proper basis for public policy. It is significant that the US Noise Control Act of 1972 imposed on the Administrator of the Environmental Protection Agency the duty of developing and publishing "criteria with respect to noise . . ." and "information on the levels of environmental noise the attainment of which . . . are requisite to protect the public health and welfare with an adequate margin of safety."[8] It is therefore necessary to identify clearly the adverse effects of noise, to devise measures of noise that are well correlated with them and to establish quantitative relationships between these effects and the measured values of noise exposure.

Hearing loss due to noise is obviously important. It is known that a single intense sound, such as the explosion of a firecracker at the ear, can cause permanent hearing loss in one brief moment.[1] Such injury, known as "acoustic trauma," is fortunately rare. Much more common is the repeated exposure to steady noise at excessive levels. Consider, for example, a person who is exposed to broad-band steady noise at an A-weighted level of 100 dB at his place of work. Such a person is likely to incur a steady increase in the level of his or her hearing threshold throughout the eight-hour working day. This is known as "temporary threshold shift" (TTS). Let us suppose that the next sixteen hours are spent at home in comparative quiet. During this period of rest the hearing-threshold level is likely to return to normal or near normal. If, however, the noise exposure is repeated day after day and year after year, the hearing loss, which was initially temporary, may gradually become permanent.

Figure 5 shows the maximum amounts of noise-induced permanent threshold shift (NIPTS) to be expected when a working population is exposed to various levels of steady noise each working day during a 40-year period.[8,9,10] The lower pair of curves show the predicted values of NIPTS averaged over the three audiometric frequencies (0.5, 1 and 2 kHz) traditionally associated with speech perception. The



where N_d is the number of noisy events during the day (7 a.m. to 10 p.m.) and N_n the number during the night.

Noise and Number Index
NNI is similar to CNR apart from the coefficient of the second term, which is 15 instead of 10. Hence NNI is more strongly dependent on the number of events than is required by energy averaging.

Effective Perceived Noise Level
EPNL is the maximum value of PNL during a noisy event weighted to take account of the event's duration and, where necessary, the presence of a prominent pure tone. It is expressed in EPNdB.

Noise Exposure Forecast

$$\mathrm{NEF} = \mathrm{EPNL} + 10 \log_{10} (N_d + 16.7\ N_n) - 88 \qquad \text{(dB)}$$

Since L_{dn}, CNEL, NEF, CNR and NNI all vary at least approximately as log(energy) and incorporate broadly similar day–night weighting, the following approximations can be used for comparison purposes:

$$L_{dn} \simeq \mathrm{CNEL} \simeq \mathrm{NEF} + 35 \simeq \mathrm{CNR} - 35 \simeq \mathrm{NNI} + 25$$

upper pair are considered important since it is at 4 kHz that the largest noise-induced threshold shift usually occurs. Moreover, there is evidence to suggest that the role of high-frequency hearing in everyday speech communication has been underestimated.[8] It is necessary to add that NIPTS is not in general a linear function of years of exposure. In fact the larger values of hearing loss tend to develop rapidly during the first few years. To a first approximation, figure 5 can be extended to cover intermittent noise exposure by applying the equal-energy principle, according to which a halving of daily duration is equivalent to a 3-dB decrease in level. European noise dosemeters operate on this principle. (In North America, according to present rules, a halving of daily duration is considered equivalent to a 5-dB decrease in level.[11])

Not included in figure 5 is the progressive loss of hearing with age known as presbycusis; this, like noise-induced hearing loss, varies greatly from individual to individual. It is usually significant at 4 kHz by the age of 60. Estimates of presbycusis vary substantially from one study to another; this in turn affects estimates of noise-induced hearing loss.

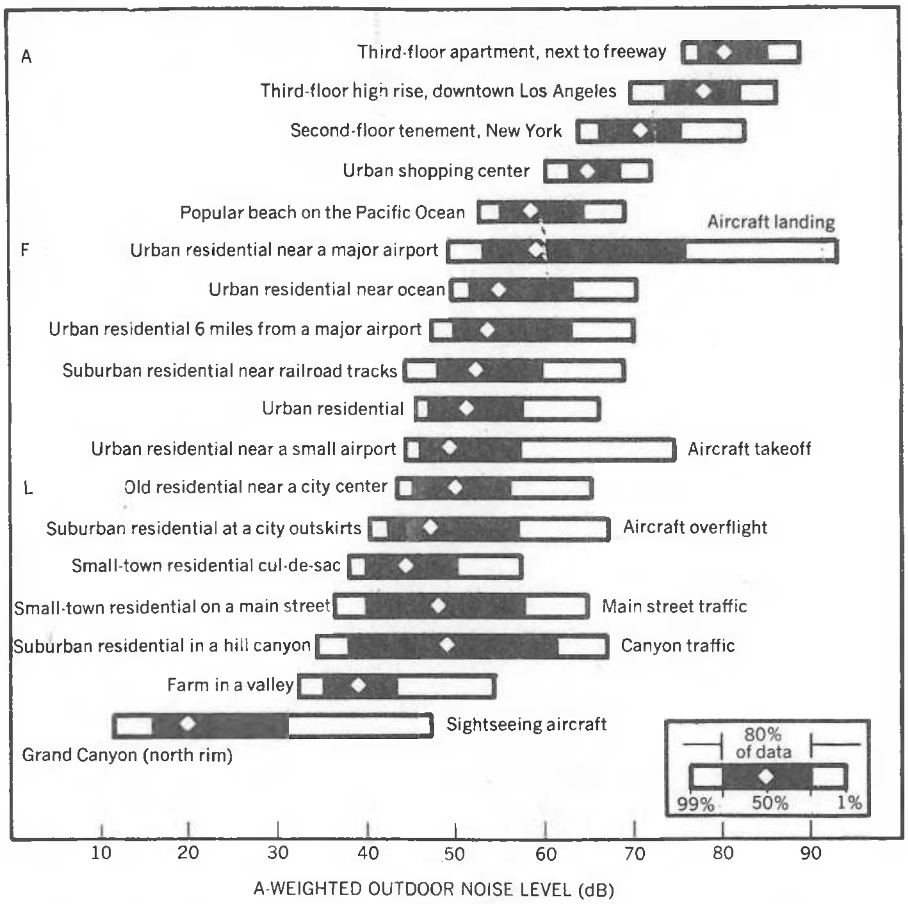
Information of the kind presented in figure 5 provides a rational basis for setting limits of noise exposure, which are the subject of much discussion at the present time.[8,12] Before such limits can be set, it is necessary to decide what is a significant noise-induced hearing loss. For example, should we be concerned only with the loss of hearing at 0.5, 1 and 2 kHz, as in current definitions of hearing handicap for speech? And if so, what percentage of the population should be protected against how much loss? To put the question in another and extreme form, what level of noise exposure is permissible if the entire population is to be fully protected against permanent noise-induced threshold shift? Figure 5 suggests that virtually complete protection of 90% of the population would require an A-weighted limit of no higher than 75 dB for an eight-hour day. In many jurisdictions, occupational noise exposure for the standard day is now limited to 90 dB.[11]

Human welfare is clearly dependent on the maintenance of adequate speech communication. Figure 6 shows how the quality of communication is affected by the masking due to various levels of background noise. For satisfactory communication with a "normal" voice at a distance of 3 meters (on a residential patio, for example), a background level no greater than 55 dB is required. Relaxed conversation at the same distance would be possible at a level no greater than 45 dB, a condition met at only three of the locations included in figure 4. Within residences and educational institutions, a level no greater than 45 dB is considered necessary for satisfactory communication, and a level of 40 dB is desirable.[1,8,13]

It is the community response to noise as expressed in complaints and other overt actions that often seems most persuasive to those who have to make policy decisions concerning noise abatement. Given a suitable measure of community noise level such as the day–night average level it is, in fact, possible to predict community response with moderate accuracy provided that various empirical allowances are made for community lifestyle and attitudes.[7,14] But underlying a complaint about noise there is annoyance—and the connection between the two is by no means simple. Moreover, annoyance does not stand alone but is related to the disruption of human activities by noise, particularly activities occurring inside the home.[15] The interference with relaxation and sleep, the loss of privacy, and the masking of speech and music are all known to be important.[16,17] To these may be added reports of persistent physiological responses to noise,[1] which have not yet been brought together in a satisfactory way.

Some of these effects, particularly sleep interference, are amenable to direct study. For example, laboratory measurements indicate that the probability of an awakening or a significant shift in sleep level increases from 0.2 to 0.8 when the level of noise from a passing truck is raised from 40 to 80 dB.[18] The relationship between such changes in sleep level and the overall quality of a night's sleep is not yet known, but the intense annoyance engendered by sleep interference due to aircraft noise is well established.[17]

In recent years annoyance has been studied in a number of countries by means of carefully designed social surveys. It has been found that individuals, equally exposed to noise, express degrees of annoyance that depend strongly on individual attitudes toward



Noise levels recorded at 18 outdoor locations in the United States by K. M. Eldred.[7] Values of L_{99} (the level exceeded 99% of the time in one hour), L_{90}, L_{50}, L_{10} and L_1 are indicated for the period 7 a.m. to 10 p.m. Figure 3 gives the hourly distribution of sound levels for the three locations A, L and F, which are described in greater detail in the text. Figure 4

the source of noise and the operator ("fear of aircraft," "misfeasance"). Figure 7 indicates that there is a well defined relationship between the percentage of people "highly annoyed" and an appropriate measure of outdoor noise level such as L_{dn}. The British data published in 1963[15] are in excellent agreement with the data obtained ten years later in Britain and the United States.[17,19] Furthermore, a social survey concerned with motor-vehicle noise[8] provides an additional point that lies on the same line. This and other information from social surveys will doubtless prove very useful to policy makers until sleep interference and other specific effects of noise are better understood.[20]

Hardware: source, path and receiver

The most satisfactory place to deal with noise is of course at the *source*, particularly by quieter design. In the case of motor vehicles, for example, we require quieter engines, better air-intake and exhaust mufflers, quieter cooling fans and quieter tires. Similar changes are needed in a wide variety of tools and equipment powered by internal combustion engines. We can also achieve quieter motor vehicle operation by reducing the vehicle acceleration and speed. We can reduce the number of noise sources in a city by increasing the number of passengers per car, or by building a quiet rapid-transit system. Confining the operation of noisy vehicles or machinery to the daytime can also be very helpful. Vibration dampers and soundproof enclosures can be used to reduce the radiation of sound from industrial machinery.

There are many ways of modifying the transmission *path* to reduce the level of noise at the receiver. We can, for example, increase the distance between source and receiver by rerouting traffic and by setting aside large areas of land around new airports for nonresidential use. The receiver can be screened from the source by building depressed highways, by erecting noise barriers and by designing buildings and clusters of buildings which serve as barriers. We can take full advantage of interference between the direct and ground-reflected waves at near-grazing incidence by keeping the source and receiver close to the ground and by controlling the acoustic properties of the reflecting surface. The level of reverberant sound inside a workshop can be reduced by treating its walls and ceiling with sound-absorbent materials.

Finally sound insulation can be provided at the *receiver*. For example, we can insulate people from aircraft and freeway noise by enclosing them in soundproof buildings with forced ventilation and heavy glazing. We can conserve hearing by providing hearing protectors, and seeing that they are worn, or by strictly limiting the exposure time wherever the noise levels are hazardous.

These are but a few examples of the acoustical techniques that are already available in a rapidly developing field. There is hope—but no certainty—that they will vigorously be used in the immediate future.

Software: economics and legislation

Occasionally, market forces create a dramatic demand for noise abatement at the source. For example, the comparatively quiet outboard motor of recent years has proved highly attractive to power-boat users. In many cases, however, the listener is merely a neglected third party in the transaction. Nowhere is this more evident than in the case of a refrigeration unit, installed near the boundary line between two houses, which provides the owner with central air conditioning but imposes a new burden of noise on the neighbor who relies on natural ventilation. In the language of the economist.[21]:

> "Noise is a classic example of an "externality"—the side effect of a private action, imposing an unwanted cost upon third parties who are not partners to the action and who receive no benefit from it. Because market forces alone do not provide the producers of externalities with sufficient incentive to avoid their undesirable effects, control over such activities becomes a matter of public policy."

In recent years, new laws have appeared on the statute books of many countries recognizing noise as an undesirable by-product of modern technology, and seeking to regulate it in quantitative ways. Moreover, it has become increasingly clear that there are specific tasks that are appropriate to each level of government.[3] For example, a municipality may quite properly establish suitable maximum levels of noise from stationary noise sources at all property boundaries for various categories of land use, and taking into account local factors, such as climate and lifestyle. On the other hand, the designer of an air-conditioning system may not find it easy to meet the local ordinance unless he can identify and obtain component parts manufactured to the required standard. This information is best conveyed by "noise labelling," which should for simplicity be national or international. A standard system of noise labeling could be applied to a wide range of products including, for example, kitchen equipment.

Many jurisdictions are attempting to

regulate noise by setting maximum levels for individual motor vehicles in operation, but few would claim more than minor successes. The numbers of vehicles and the distances travelled are so great that it is clearly beyond the capacity of most cities, states and provinces to deal with any but the most blatant offenders; this leaves the collective problem of urban noise almost untouched. The prevailing quality of technology is determined at the production line, and it is here that motor-vehicle noise must be firmly grasped. National standards are clearly desirable, if not essential. In Europe, in fact, the problem is seen to require concerted action by the Economic Community.[21]

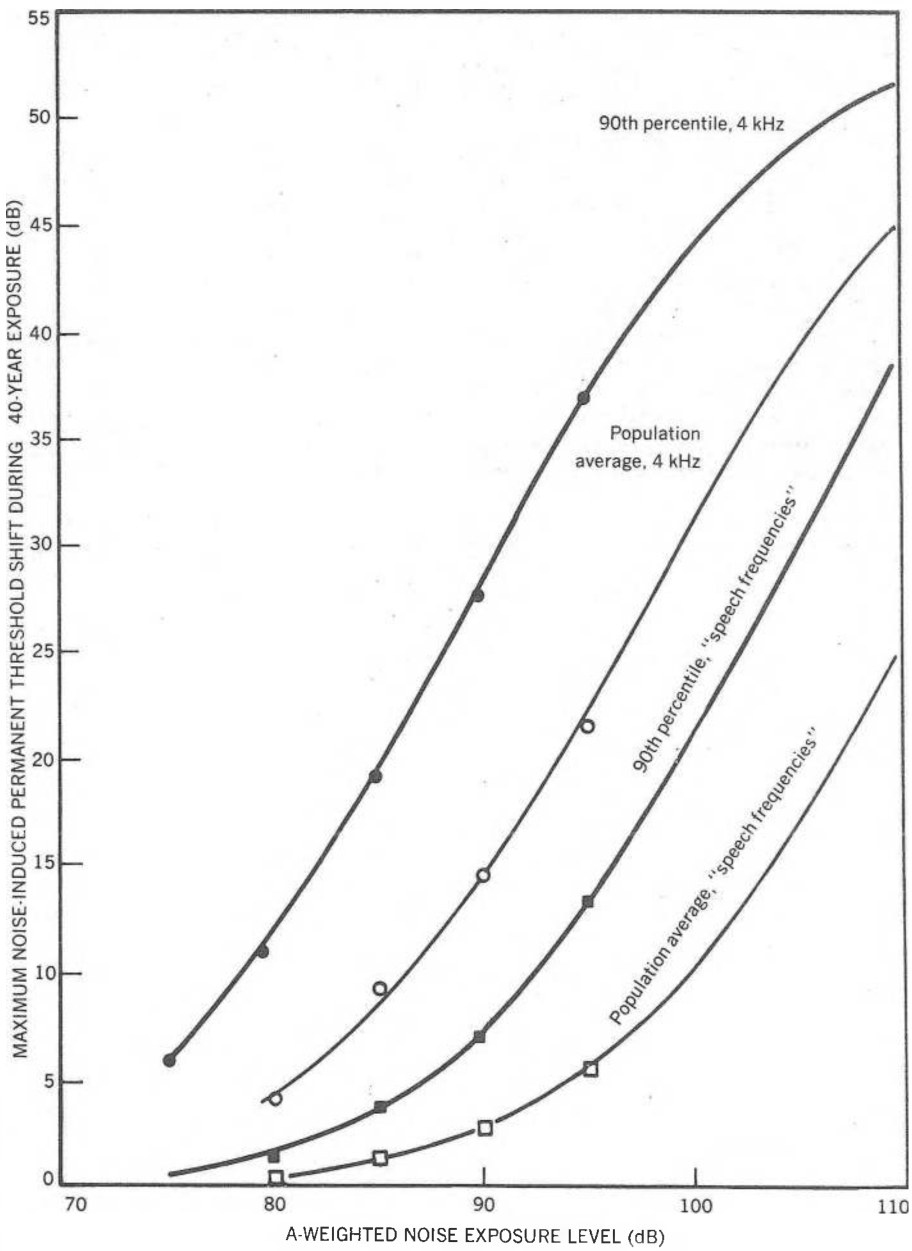
Noise abatement is rarely obtained cost-free and few adequate measures of the corresponding benefits are yet available. A partial exception is hearing conservation, which has acquired substantial monetary value during the past twenty years by virtue of numerous court judgments on occupational hearing loss. In a similar fashion, judgments and claims pending against airport operators for the illegal "taking" of property have provided a strong incentive for aircraft noise abatement.[22] A few attempts have been made to establish correlations between the market prices of property and community noise levels but the results cannot be considered reliable due to the lack of control over some of the pertinent variables.[22,23] The lack of adequate measures of the cost–benefit ratio is a major problem to those who must decide the extent and timing of noise-abatement measures. At present it is hardly possible to do more than estimate the costs of alternative strategies designed to meet a given goal.

The art of the possible

If we consider the limits of current technology, the laws and rules that are already in existence or in the process of formulation and the constraints imposed by the nature of urban noise itself, it is not difficult to see how much progress can reasonably be expected in the next decade or two.

Over a period of years a large body of information on urban noise levels has been gathered from many parts of the world, but it is only quite recently that attempts have been made to estimate the distribution of levels over an entire population. Figure 8 is a very free interpretation of a recent report on the day–night average sound levels in residential areas covering approximately two-thirds of the population of the United States.[24] The people omitted from the study are those living in unincorporated settlements in predominantly rural areas. The portion of curve below 55 dB brings the missing segment of population into the distribution—on the speculative and untested hypothesis that noise pollution as measured by the day–night level has barely penetrated the rural areas. If this should prove to be wrong, the secondary peak at 46 dB would disappear. We can note at once that more than half of the people of the US live in areas where the outdoor day–night average noise level exceeds the value of 55 dB identified by the US Environmental Protection Agency[8] as necessary to protect the public health and welfare against interference with activity at residences that depend on natural ventilation or have useable outside space.

As has been noted earlier, much of the urban noise is due to motor vehicles; so it is here that we must focus attention in developing a strategy for noise abatement. Recently, a statistical study[25] was made of the distribution of peak noise levels to be expected at a distance of 15 meters from a single lane of traffic at freeway speeds in North America. For simplicity it was assumed that 90% of the vehicles are automobiles, and 10%, tractor-trailers. This is the mixture of light and heavy vehicles commonly observed. The distribution is bimodal, with a large group of vehicles peaking around 73 dB and a much smaller group peaking around 86 dB. However, when the number of vehicles at each level is weighted according to the sound power, the distribution shifts massively toward the high



Maximum expected permanent hearing-threshold shift induced by exposure to steady noise of a given level 8 hours each working day for 40 years. The data for 75–95 dB are new estimates[8,9] based on three major studies of occupational hearing loss in several countries; the portions of curves above 95 dB are standard functions.[10] The colored lines show 90th percentiles and the black lines, population averages. The lower pair of curves shows the average threshold shifts over the traditional "speech frequencies," 0.5, 1 and 2 kHz. Figure 5 levels. It becomes apparent that the heavy vehicles, which represent only 10% of the traffic stream, produce 69% of the A-weighted sound power. (At lower speeds the noise levels for all vehicles are of course lower, but the disparity between classes is much the same.) If each tractor-trailer emitted no more sound power than an automobile the level of the highest peaks would drop by 13 dB, and the corresponding energy-equivalent level by 4.6 dB. In figure 1, the tractor-trailers would then move to the 0.1-ppm line.

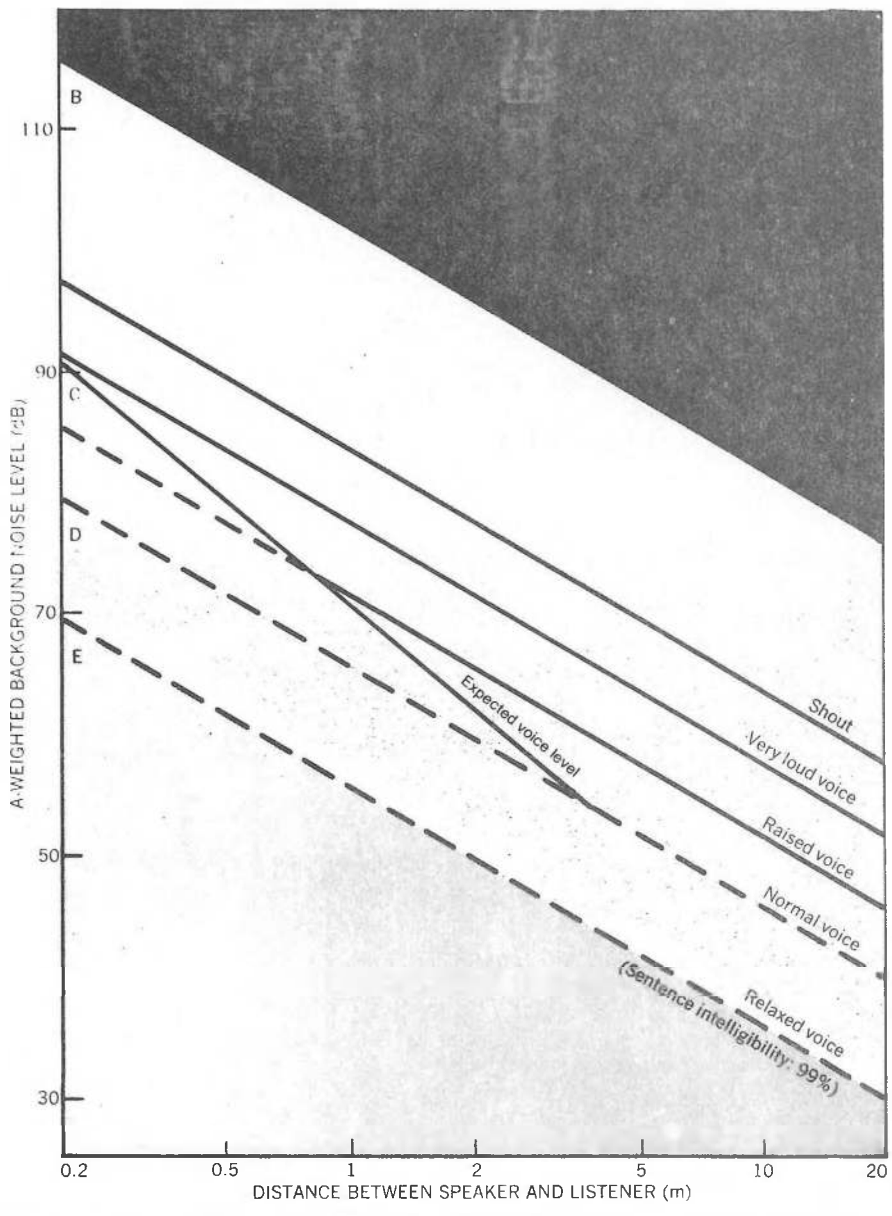
The technology required to bring about this improvement, with the possible exception of quiet tires, is readily available—as has already been demonstrated.[26] It is, in fact, partly foreshadowed in some of the quieter urban buses in use today.[25] At current prices, the required design changes (engine-transmission enclosure, improved exhaust muffler, enlarged cooling system, etc) might add $1200 to the retail price of a heavy diesel truck. The US Environmental Protection Agency has recently issued a notice of rule-making to limit the A-weighted noise levels of newly manufactured medium- and heavy-duty trucks, measured at a distance of 15 meters, to 83 dB in 1977, 80 dB in 1980 and 75 dB in 1983 for speeds below 35 mph.[27] Separate rules are expected to limit tire noise, which is important at high speeds.

So, during the next decade or so it should be possible to improve the "texture" of urban noise considerably by reducing the noise-emission levels of all urban vehicles including motorcycles and equipment such as construction machinery, to the level of present-day automobiles. These reductions should also bring the general level of urban noise down by 5 dB, provided the density of sources remains unchanged. It would probably be unwise to seek any general decrease in *automobile* emission levels until all vehicles that use the same roads can move down the scale together.

Commercial Aircraft

The new generation of commercial aircraft represented by the DC 10 and the L 1011 provides tangible evidence of the progress being made in the abatement of aircraft noise. As shown in figure 1, these new planes produce only about 1500 watts of A-weighted sound power on takeoff, compared with the 30 000 watts produced by the smaller and less powerful B 707 and DC 8 aircraft.[4] This remarkable improvement is largely due to the introduction of high bypass ratio turbo-fan engines. Not only are the new engines much quieter than their predecessors but they are also mechanically more efficient. This is acoustical design at its best. The shaded square representing the DC 10 and the L 1011 lies well below the line marked "FAA Rule 36," which indicates in an approximate way the current noise limit set by the US Federal Aviation Authority for new aircraft designs.

Should existing commercial aircraft be required to conform with FAA Rule 36? This is a crucial question, since the existing fleets of aircraft are likely to remain in service for many years. A notice of proposed rule-making published by the US Federal Aviation Authority[28] and discussions within the US Congress and elsewhere indicate a firm intention to proceed with measures that could bring most of the aircraft operating in the United States into compliance with FAA Rule 36 by 1979. The principal measure under discussion is the treatment of the engine nacelles with sound absorbing material, which would cost approximately $200K for aircraft such as the DC 9 that are powered by the Pratt and Whitney JT8D engine, and approximately $800K for aircraft such as the DC 8, powered by the JT3D engine. This measure might be supplemented by operational procedures such as a two-segment approach path with an upper segment of 5.5 deg or 6 deg, depending on the aircraft type. Substantial amounts of thrust cutback following takeoff are also under consideration. It is also possible, at relatively high cost, to re-fan existing engines to obtain more substantial noise reductions. These proposals have been the subject of much discussion in the Inter-



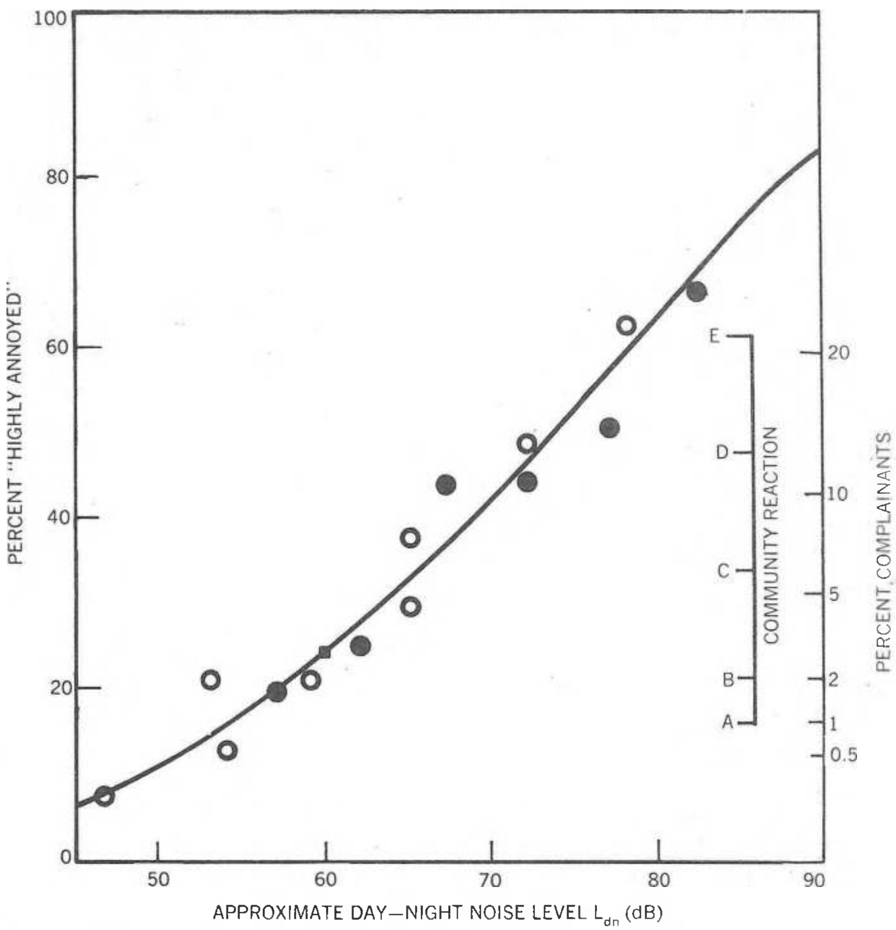
Maximum noise levels at which speech communication is possible at 95% intelligibility are here given as a function of speaker–listener distance, at various voice levels. Speech is impossible in area **A**, possible only with a maximum vocal effort in **B**, difficult in **C** and practical at normal voice level in **D**. In **E**, speech intelligibility becomes 99% for relaxed conversation. The "expected voice level" line refers to the normal reaction to background noise. Figure 6 national Civil Aviation Organization since their ramifications are obviously worldwide.

The Quiet Engine Program of the National Aeronautics and Space Administration, now nearing completion, shows that aircraft 5 to 10 decibels quieter than the DC 10 and L 1011 could be built with existing technology[29]; see figure 1. Such aircraft are likely to come into service within a decade. Further progress will probably require aircraft bodies specially tailored to reduce aerodynamic noise as well as new concepts in engine design—these can hardly be expected before 1990.

Residential areas where the day-night average noise level exceeds 65 dB have been described as "impacted" by noise, in the sense that the noise problem is clearly substantial.[4] Referring to figure 8, we can see that approximately 35 million people in the United States, or 17.5% of the total population, live in areas fitting this description. There is no reason to doubt that the figures are comparable to those in many other technologically advanced countries. Of the 35 million, approximately 7.5 million are exposed primarily to aircraft noise, 2.5 million to freeway noise and the remainder to urban traffic noise. As we have seen, the technology likely to be widely used within the next decade should reduce aircraft noise by 5 to 10 decibels and heavy-motor-vehicle noise by roughly 10 to 12 decibels. These improvements could therefore shift the tail of the distribution, which represents nearly 4 million people exposed to levels in excess of 75 dB, from point B to B′ by 1985. By that time, the day-night level of urban noise would be largely determined by the automobiles, so it would be unreasonable to expect the mode of the distribution to shift by more than 5 dB—perhaps from A to A′.

These reductions in level are by no means negligible when measured against figures 6 and 7. But they carry us less than halfway towards the goal and could easily be offset by increases in the numbers of sources: more automobiles and more aircraft. Moreover, the early gains will come, as we have seen, without radical changes in technology. The second phase will therefore make greater demands on scientists and engineers. For example, to reduce the noise emission of a *heavy truck* to a value 10 decibels lower than the median value for a present-day *automobile* would call for entirely new concepts in tire design.

It is possible that the quietest tires made today are approaching a fundamental limit that cannot be breached without losing the uniquely high traction of pneumatic tires rolling on the traditional road surfaces. And it is clear that a better understanding of

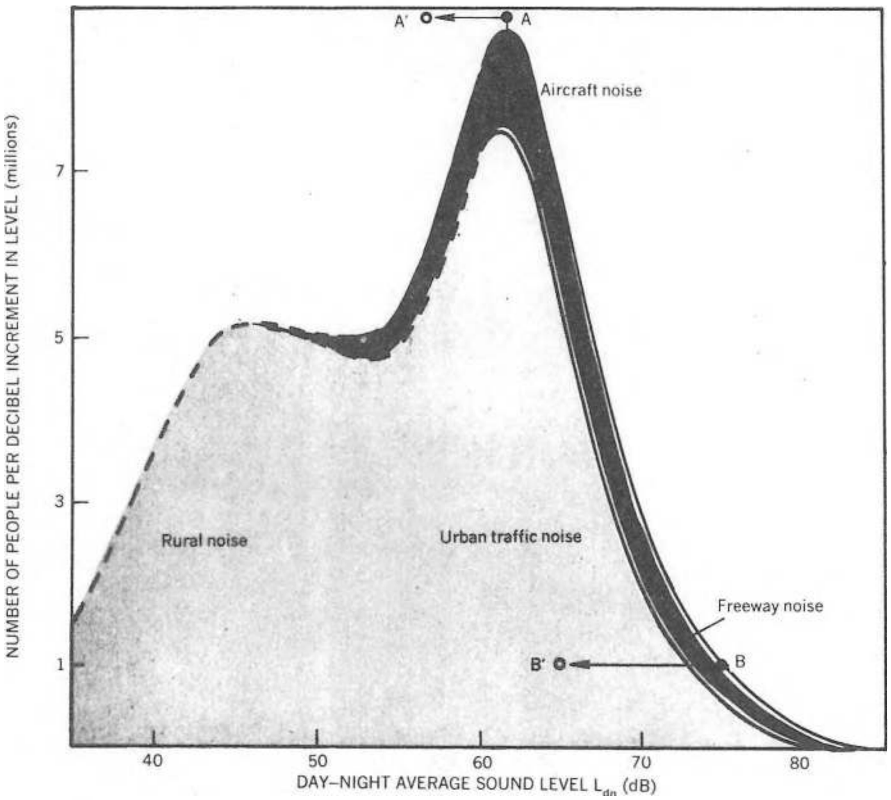


Annoyance, complaints and community reaction resulting from intrusive noise rise sharply as the noise level increases. The curve shows the average percentages of people found to be highly annoyed as a function of day-night sound level. Data from a 1961 London Airport survey are indicated by solid colored circles, while the open circles represent combined data from surveys at London Airport in 1967 and in eight US cities in 1971. The solid black square shows the average percentage of people highly annoyed by motor-vehicle noise at 20 locations in three US cities. The levels of community reaction indicated represent: **A**, none; **B**, sporadic complaints; **C**, widespread complaints or a single threat of legal action; **D**, several threats of legal action or strong appeals to local officials, and **E**, vigorous community action. Figure 7

sound propagation through city streets[31] and in the atmosphere above the city[32] is badly needed if the cumulative effects of many noise sources are to be mitigated. Indeed it is probable that radical changes will be needed in the design of cities as entities. The creation of "quiet islands" within cities is an ancient concept likely to prove valid and necessary once again. So it is quite likely that the second phase of noise abatement will prove very costly and even unattainable unless adequate preparations are made by architects and urban planners without delay. For example, it would be short-sighted indeed to make costly investments in an urban transit system or in a city-center airport for STOL aircraft, intended to provide service for several decades, without first setting environmental standards that look equally far into the future.

Individual responsibility

Finally, what can be said about permanent noise-induced hearing loss? As the average life span increases, it would be sad if we failed to take all reasonable measures to conserve the acuity of the sense organs in old age. At the tail of the distribution in figure 8, where the day-night level exceeds 75 dB, there may be a marginal hazard for those who spend many hours outdoors each day (see figure 5 and reference 8). The total number of people involved must, however, be very small compared with the number exposed to hazardous levels of noise in industry. In West Germany, for example, it has been estimated that 15% of the working population are employed in places where the A-weighted noise level is equivalent to a daily exposure in excess of 90 dB.[33] (Because of differences in definition this figure is not strictly comparable with the limit of 90 dB that is current practice in North America.) A trend towards lower limits of occupational noise exposure is clearly evident, and it seems likely that an A-weighted equivalent level no higher than 80 dB will eventually be accepted in most countries. It may, however, be



The population of the US distributed by the day–night sound level to which they are exposed. The estimates for urban traffic noise are based on recent measurements[24] at residential sites and original study. The 66-million rural population not included in the study is covered by a hypothetical extension. The dark-colored and white areas represent population exposed primarily to aircraft and freeway noise.[8,30] The shifts in the peak, **A–A'**, and high-level tail **B–B'**, of the distribution represent reasonable goals for the year 1985. Figure 8

many years before this level is reached, since the potential costs of the necessary machinery modifications are causing much consternation.[12] It is perhaps ironical that the accumulation of permanent noise-induced hearing loss could be brought to an end overnight were it possible to ensure that earplugs or earmuffs were worn wherever necessary.

We have seen that scientists, engineers, architects and planners, working together where necessary, can devise technically feasible solutions to the problem of noise. Whether these solutions are in fact adopted will depend on the decisions made by a host of people acting jointly through political systems and singly in their daily lives. And this brings us face to face with the ultimate question of individual responsibility. Can a society as complex and energetic as ours truly flourish unless its members are individually willing to participate in solving its collective problems?

References

1. J. D. Miller, J. Acoust. Soc. Am. **56,** 729 (1974).
2. H. Davis, *Introduction to Sound and Hearing*, LIFE Science Library, New York (1965), © 1965 Time Inc.
3. "Legislative Control of Noise," National Research Council of Canada Report APS-500, Ottawa (1972).
4. "Report of the Administrator of the Environmental Protection Agency to the President and Congress on Noise," Senate Document 92-63, US GPO, Washington (1972).
5. J. E. Piercy, abstract in J. Acoust. Soc. Am. **52,** 1310 (1972).
6. E. A. G. Shaw, N. Olson, J. Acoust. Soc. Am. **51,** 1781 (1972).
7. K. M. Eldred, "Community Noise," Document NTID 300-3 prepared by Wyle Laboratories for the US Environmental Protection Agency, Washington (1971).
8. "Information on Levels of Environmental Noise Requisite to Protect the Public Health and Welfare," US Environmental Protection Agency, Washington (1974).
9. D. L. Johnson, "Prediction of NIPTS due to Continuous Noise," Aerospace Medical Research Laboratory document TR-73-91, Wright-Patterson Air Force Base, Ohio (1973). See also reference 8.
10. W. Burns, D. W. Robinson, "Hearing and Noise in Industry," HMSO, London (1970).
11. "NIOSH Recommended Standard for Occupational Noise Exposure," Sound and Vibration, Nov. 1972, page 35.
12. "Proposed Requirements and Procedures for Occupational Noise Exposure," Occupational Safety and Health Administration, US Federal Register **39,** 37773, 24 October 1974.
13. J. C. Webster, in *Proceedings* of the Conference on Noise as a Public Health Hazard, ASHA, Washington (1969), page 49.
14. K. N. Stevens, W. A. Rosenblith, R. H. Bolt, Noise Control **1,** 63 (1955).
15. "Final Report of the Committee on the Problem of Noise," Alan Wilson, Chairman, HMSO, London (1963).
16. "Community Reaction to Noise," TRACOR Document T-70-AU-7454-U, Austin (1970). See also references 8 and 17.
17. P. N. Borsky, "A New Field-Laboratory Methodology for Assessing Human Response to Noise," National Aeronautics and Space Administration Contractor Report CR-2221, Washington (1973).
18. G. J. Thiessen, abstract in J. Acoust. Soc. Am. **53,** 366 (1973).
19. W. K. Connor, H. P. Patterson, quoted in reference 8.
20. "Social and Economic Impact of Aircraft Noise," Sector Group on the Urban Environment, Organization for Economic Cooperation and Development, Paris (1973).
21. "Urban Traffic Noise: Strategy for an Improved Environment," Organization for Economic Cooperation and Development, Paris (1971).
22. "The Economic Impact of Noise," Document NTID 300.14 prepared by the National Bureau of Standards for the US Environmental Protection Agency (1971).
23. *Report* on the Conference on Acoustics and Societal Problems, Acoustical Society of America, New York (1972).
24. W. D. Galloway, K. M. Eldred, M. A. Simpson, "Population Distribution of the US as a Function of Outdoor Noise Level," Document 550/9-74-009, prepared by Bolt Beranek and Newman for the US Environmental Protection Agency, Washington (1974). See also reference 8.
25. N. Olson, J. Acoust. Soc. Am. **52,** 1291 (1972). See also reference 3.
26. W. H. Close, "DOT Quiet Truck Program," in *Proceedings* of the International Conference on Noise Control Engineering, Washington (1974).
27. US Environmental Protection Agency, "Proposed Noise Emission Standards for New Medium and Heavy Duty Trucks," US Federal Register, Part II, 30 October 1974.
28. US Federal Aviation Administration, "Civil Aircraft Fleet Noise Requirements" (Notice of Proposed Rule Making) US Federal Register **39,** 11302 (27 March 1974).
29. C. C. Ciepluch, Noise Control Engineering **1,** No. 2, 68 (1973).
30. H. von Gierke, *Report* of Task Group 3, Aircraft/Airport Noise Study, US Environmental Protection Agency, Washington (1973).
31. R. H. Lyon, J. Acoust. Soc. Am. **55,** 493 (1974).
32. T. F. W. Embleton, J. E. Piercy, abstract in J. Acoust. Soc. Am. **56,** S35 (1974).
33. G. Hubner, "Enforcement of Occupational Noise Standards in the Federal Republic of Germany," *Proceedings* of the International Conference on Noise Control Engineering, Washington (1974), page 15. □