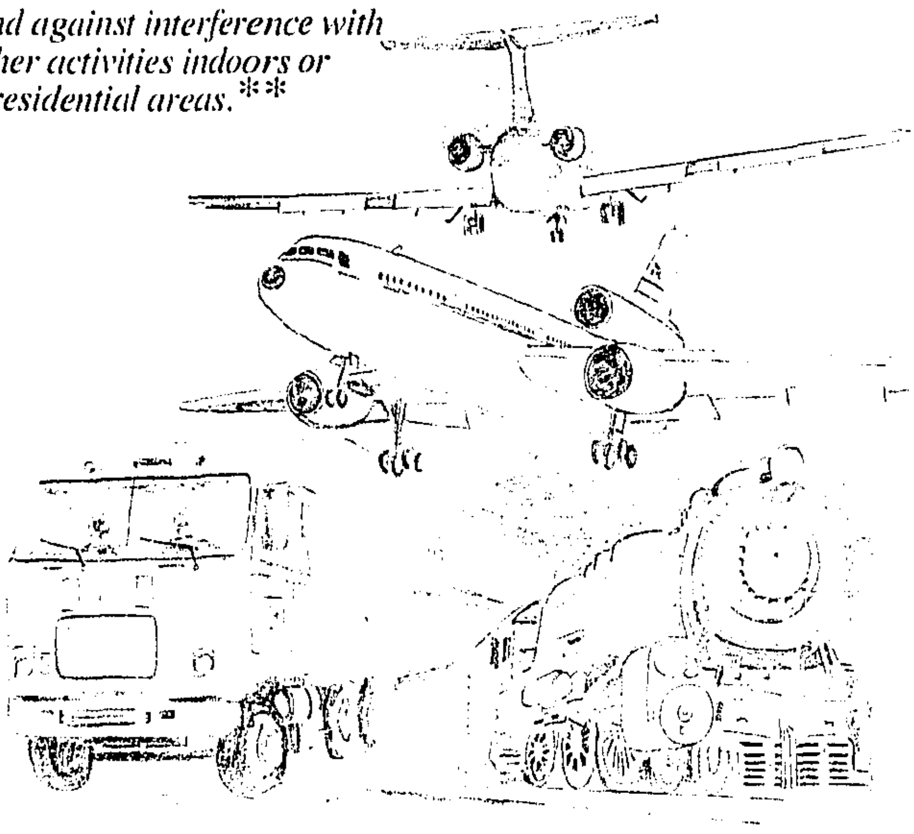
Noise — How Much Is Too Much?*

Henning E. von Gierke† *contends that enough is known about the effects of noise on people to produce guidelines for maximum noise levels. Adopted by the Environmental Protection Agency, these guidelines are designed to protect the public with an adequate margin of safety against hearing loss from occupational and environmental noise exposures and against interference with speech or other activities indoors or outdoors in residential areas.***



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Everybody is in favor of controlling undesired noises — noises which might interfere with human activities at home or on the job, or noises so loud or disturbing that they might be harmful or injurious to a person's temporary well being or long-term health. There is evidence that civilized people have tried for thousands of years to control such noises through social customs and rules, the planning of houses and cities, and through city ordinances.[1] The Industrial Revolution brought about a steady rise in noise levels in cities and factories, increasing from year to year through most of this century. This, combined with the growing population density, resulted in higher and more frequent exposure of most individuals to noise.

It will soon be a hundred years since industrial noise exposures were clearly recognized as the cause of occupational deafness. Knowledge regarding this subject has increased rapidly in the last twenty years. Nonauditory physiological and psychological manifestations of noise exposure have been extensively studied. In spite of a few potentially positive findings and many speculations based on experiments on animals or humans at extremely high levels, however, it was not possible to prove any other disease to be caused or aggravated by exposure to moderate noise levels — levels which would not yet cause concern about direct effects on the ear.[2]

It might well be that careful future epidemiological research will discover such direct nonauditory effects on physiological or mental health. At this moment, their existence has not yet been clearly established; however, the fact remains undisputed that people are annoyed, awakened, disturbed, and frustrated by noise intrusion, that the communication with others and individual thoughts are disrupted, and performance capability is decreased. Noise is one of the stressors of modern life; hardly anyone doubts that it can have an effect on a person's general well being. These effects have been studied in great detail and are documented quantitatively.[2,3] Furthermore, all these individual manifestations of living in noise combine and make people aware that the quality of the environment is not optimal, that each individual pays a price for living in noise even if this price cannot be quantitated. Health, according to the definition of the World Health Organization, is not the mere absence of disease, but the total physiological and psychological well being. In this context there is no doubt — noise affects our health.

The last twenty years have produced an increasing concern with the quality of the environment, and noise was rightfully included among the pollutants to be controlled. Although it was probably aircraft noise which focused public and political attention on the noise problem and resulted in active programs in many countries and at the international level with organizations

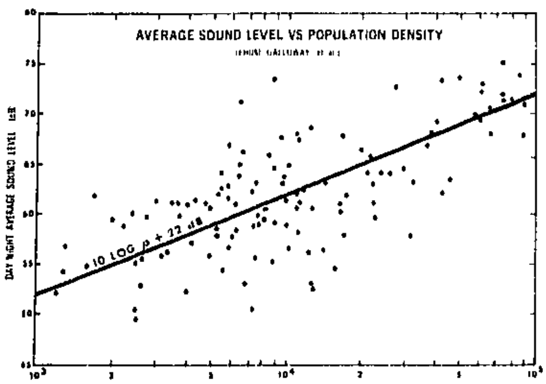

Figure 1 —Day-night sound level as a function of population density ρ. (Based on survey of 100 sites in US)[5]

> "The problem of increasing exposure. . . to increasing environmental noise levels is of such dimension and global magnitude that only long range, continuous planning at the national and international levels can produce the desired results."

such as the International Civil Aviation Organization (ICAO), Organization for Economic Cooperation and Development (OECD), and World Health Organization (WHO), an unbiased, unemotional analysis of the problem clearly shows that no single noise source is to blame for the situation.[4] Truck noise, traffic noise, railroad noise, industrial noise, and people noise are all large-scale potential offenders. Only lack of foresight and planning with regard to some of these offenders and the varying density of the transportation systems and the different emphasis on rail versus highway or air transportation determines which of the problems prevails at the moment or will prevail in the future. The point has been made that the average noise level is primarily a function of the overall population density alone, regardless of the specific origin of the noise (Fig. 1).[5] It is justified and imperative, therefore, not to concentrate unduly on one noise source, but to consider the total spectrum of noise environments that people can be exposed to by their movements through time and space. This includes all types of noises from all sources; the term environmental noise emerged for it. People are exposed to environmental noise from various sources around them, including those they generate as well as those to which they might personally object.

The problem of increasing exposure of people to increasing environmental noise levels is of such dimension and global magnitude that only long-range, continuous planning at the national and international levels can produce the desired results. To be worthwhile, the goals must be unambiguous, just, and clear in order to obtain the widest public support. Worthwhile results will have their price, and the price will be paid only if the public, not the expert, is convinced that the result is worth the price. To assist the public in making as informed a decision as possible is the responsibility of the acoustic community. Finding the answer to the question, "How much noise is too much?" is not a scientific problem; people at large must decide in what environments they want to live. Science can only tell and predict the consequences of living in different environments.

To discuss the consequences of various environmental noise exposures and to weigh the merits of different goals, a measure of environmental noise is needed. It is not enough to have measures which show how one type of noise interferes with one type of human activity, how another type of noise affects another human function, and then to produce different yardsticks for each type of noise for each human function. What is needed is one yardstick to measure the integrated effect of environmental noise on human health and well being, a yardstick for environmental quality with respect to noise. It is unfortunate that in this area acoustic science has not been as responsive to the public needs as it could have been. More new yardsticks have been created and tried every year than the acoustic community, let alone the public, could digest and evaluate.

At the 1973 International Congress on Noise as a Public Health Problem,[6] a review of methods for the evaluation of noise included six possible ways for the direct measurement of noise, two graphical measures, nine measures to calculate the noise of individual events, and thirteen measures to evaluate the severity of the exposure of communities to multiple events which constitute the real world of environmental noise. Most of the latter thirteen cannot be measured and monitored in the field with standardized equipment or without unreasonable expenditures. A correction of this trend is mandatory if reasonable goals for environmental noise which can guide noise control efforts and planning at all societal, technical, and economic levels are to be discussed and established.

In the US, an important step was initiated by the Noise Control Act of 1972,[7] through which Congress directed, among other measures, the Environmental Protection Agency (EPA) to publish:

(a) "...the scientific knowledge most useful in indicating the kind and extent of all identifiable effects on the public health or welfare which may be expected from differing quantities and qualities of noise..."

(b) "...information on the levels of environmental noise the attainment and maintenance of which in defined areas under various conditions are requisite to protect the public health and welfare with adequate margin of safety..."

(c) "...implications of identifying and achieving levels of cumulative noise exposure around airports..."

In response to these charges, which become clearer in context of the whole Noise Control Act of 1972 and its legislative history, EPA produced several reports with the collaboration of federal interagency task forces, the National Academy of Sciences Committee on Hearing, Bioacoustics and Biomechanics (CHABA), scientific and industrial organizations, citizens' representatives, and public meetings. The International Congress on Noise as a Public Health Problem at Dubrovnik, Yugoslavia was another step in collecting the most up-to-date information available and in formulating the best solution available, supported by the overwhelming majority of the various experts and interest groups involved.[6] The result had to be a compromise based on the best interpretations and extrapolations of the available knowledge; but, first of all, it had to be a practical compromise, which, according to the law, had to be published not later than twelve months after enactment of the act so that it could form the basis for further action toward an effective environmental noise control program. This paper reports the results of these studies, presents the method designed for measuring and assessing environmental noise, and identifies the levels of environmental noise required to protect public health and welfare.[8,9] By necessity, this paper gives a summary of only the important approaches, reasoning, and results; for details, supporting data, and the wording of EPA's official position, the references must be consulted.[9]

The basic philosophy behind the approach can be summarized in the following statements.

(1) The effects of environmental noise on public health can be discussed only if the total noise exposure of the public, regardless of the individual noise source, is considered. With respect to most health effects, it makes no difference whether the noise exposure is self-generated or created by others and passively endured.

(2) Identification of long-range goals regarding environmental noise must be in terms of this total noise exposure which must be unambiguously measurable and predictable, as far as possible.

(3) Desirable or permissible noise levels and exposure durations for each individual noise source must be derived from the desirable total noise exposure from any source to which the public may be exposed without undue effects on health. Emission standards for individual noise sources must be justified in terms of their effectiveness in reducing the total environmental noise exposure from all sources.

(4) The requirement for a practical measure for environmental noise presently prohibits accounting for individual characteristics of each noise source. In the interest of simplicity and uniformity, it is not realistic to require measurement of these individual source characteristics. This constitutes no drawback as long as the common measure for environmental noise can be easily translated into more detailed and, hence, more complicated measures which will retain their usefulness in connection with emission standards and certification procedures for specific noise sources.

(5) The levels identified, in response to (b) above, to be protective of public health and welfare are levels below which, with a reasonable margin of safety, no identifiable permanent health effects have been observed. These levels might be considered long-term goals for any public noise control program. They are not to be considered as limit values or even proposed standard values since in their establishment, technical and economic feasibility and the weighting of potential benefits from the noisy operation versus small potential health impairment have not been considered.

Descriptor of Environmental Noise Exposure

There is no doubt that to account for all human reactions to noise — the short-range, instantaneous responses as well as any integrated, long-term effects — a complete physical description of the noise, its magnitude, frequency spectrum, and the variation of both these parameters in time probably should be obtained. To reduce such a complex function to a single indicator for the environmental quality with regard to noise, based on an integrated measure of its effects over months, years, or a lifetime, would be a difficult task even in the unlikely case that one might be able to find agreement on a single indicator for health and well being. In the definition of health and well being of an individual, two potential conflicts arise between (1) the individual's own short-term enjoyment and his objective long-term health interest and (2) the consideration of an individual's health interests and society's collective evaluations and goals. This complexity in the definition of health effects must be kept in mind when the complexity of the noise environment and its simplification to a single descriptor are discussed. Simplification of both variables of the health-to-noise relationship is a *must* if any meaningful and useful correlation within a reasonable period of time is desired.

With this philosophy, EPA's choice of a descriptor for environmental noise is based on the following considerations:[8]

1. The measure should be applicable to the evaluation of pervasive noise in all possible exposure conditions and locations over long periods of time.
2. The measure should correlate well with known effects of the noise on the individual and the public.
3. The measure should be simple, practical, accurate, and unambiguous. In principle, it should be useful for planning and monitoring, as well as for enforcement purposes.
4. The required measurement equipment with standardized characteristics should be commercially available.
5. The single measure of noise at a given location should be predictable, within an acceptable tolerance, from knowledge of the physical events producing the noise.
6. The measure should be closely related to existing methods currently in use.

As well-proven effects of noise exposure on health, functional capacity, and well being, these facts were considered: (a) the effects of noise on hearing (Temporary and Permanent Threshold Shift); (b) the direct effects of noise on speech communication; (c) the effects of noise on general well being as a result of the various interference effects of noise whether with sleep, with relaxation, with speech communication, or with others.

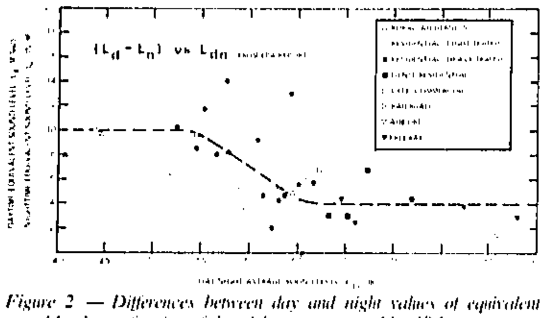

Figure 2 — Differences between day and night values of equivalent sound level as a function of day-night average sound level.[9] L_{dn}

Manifestations of the latter interference effects resulting in various degrees of discontent with noise are individual annoyance and complaint behavior and group or community reactions. For annoyance, only the integrated long-term annoyance response to living in a certain noise environment shall be considered, not the immediate direct response to an individual noise event. The long-term integrated annoyance response can be assumed to result from the individual noise events and the short-term reaction to them, but the severity of this response might be strongly weighted by other environmental factors.

By singling out the above three categories of health effects, the possible occurrence of other effects producing direct physical or mental illnesses in small segments of the overall population shall not be completely disregarded. Present epidemiological evidence as well as hypotheses based on animal experiments, however, is not strong enough to assume such relationships to be proven. On the contrary, all available evidence points to the conclusion that "if noise control sufficient to protect persons from ear damage and hearing loss were instituted, then it is highly unlikely that the noises of lower level and duration resulting from this effort would directly induce nonauditory disease."

Trying to correlate the three types of cumulative long-term effects cited earlier (a, b, c above) with a single descriptor fulfilling the conditions 1 through 6 led to the selection of the long-term average sound level called equivalent sound level (L_{eq}), as the best descriptor for the magnitude of the environmental noise. This equivalent sound level is the constant sound level which, in a given situation and over the considered time period, would expose the ear to the same amount of energy as the actual time-varying noise pattern. This concept has been used broadly before to relate individual and community reaction to aircraft and other noises.[10] It can be used to estimate the severity and likelihood of the noise's interference with speech. The same equal energy concept has also been invoked widely — also not undisputed, but considered conservative — in correlating hearing loss with noise exposure.[8]

To account for the dependence of human reactions to the frequency content of the noise, the A-weighted sound level was selected. Despite many attempts to improve its weighting characteristics to correlate individual effects such as speech interference, noisiness, or hearing loss, it appeared within the current state-of-the-art as the best common denominator to describe the stimulus for all three effects. [Even for the evaluation of human annoyance alone, the evidence that another weighting function (for example, a D-type weighting) might be preferable to A-weighting was not considered as conclusive; the fact that no such network has yet been standardized excluded it from consideration at this time.]

Consequently, the basic descriptor for environmental noise is

$$L_{eq} = 10 \log_{10} [1/(t_2 - t_1)] \int_{t_1}^{t_2} 10^{L_A(t)/10} dt, \qquad (1)$$

where $t_2 - t_1$ is the time interval over which the levels are evaluated. For description of the noise environment at various locations, the time interval is usually the 24-hour day; the equivalent sound level for this period has been designated as $L_{eq(24)}$. For consideration of the long-term health effects under consideration here, the $L_{eq(24)}$ for an individual day is not of interest, but rather the average $L_{eq(24)}$ over a year period is selected. For some environments, such as typical workplaces in factories, offices, or schools, the 24-hour equivalent sound level is replaced by the average over the 8-hour work period, $L_{eq(8)}$.

This simple concept of the equivalent sound level had to be refined somewhat to account for most community response and public opinion surveys which revealed that the same noise environment is considered more disturbing or annoying during nighttime than daytime. Not only do the requirements for undisturbed sleep and relaxation make a lower noise level desirable, but the exterior background noise levels drop during the night in most communities by 10 dB or more. In addition, the reduced activity inside homes contributes to the general lowering of noise levels there. As a result of all three factors, intrusive noise events are more disturbing during the night. To penalize nighttime noise events commensurate with their disturbing severity, a weighting factor of 10 dB is applied to all nighttime noises; i.e., nighttime noises are treated as if they were 10 dB noisier than they actually are. A similar weighting is applied in many of the more complicated noise rating schemes in use during the last twenty years.[11]

In various procedures and/or countries, three time periods are assumed during the day with different weightings — day, evening, night. Although such fine differentiation might be of interest for the scheduling of individual noise events, it has been shown that for the normal distribution of environmental noise, the overall outcome, i.e., the weighted 24-hour equivalent sound level, is essentially identical for the two-period and three-period day.[9] Consequently, for the characterization of the noise environment with respect to long-term health effects, the simpler two-period day was selected. (Daytime, 7 to 22 hrs; nighttime, 22 to 7 hrs.) The day-night weighted $L_{eq(24)}$ is being called the day-night sound level or L_{dn}

$$L_{dn} = 10 \log_{10} (1/24) [15 (10^{L_d/10}) + 9 (10^{(L_n + 10)/10})], \qquad (2)$$

with L_d and L_n representing the daytime and nighttime sound levels, respectively. Justification for the 10 dB penalty on nighttime noises is derived from data[9] such as those in Fig. 2; in quiet environments ($L_{dn} < 55$), L_d is the controlling factor determining L_{dn}; whereas, in noisy environments ($L_{dn} > 65$), L_n is only 3 to 4 dB below L_d. Therefore, the 10 dB nighttime penalty is effective in characterizing the need for day and nighttime noise reduction.

Although L_{dn} is the descriptor of choice for the overall round-the-clock noise climate of the environment to be correlated with the integrated long-term response to the environment, to evaluate hearing loss and communication disturbance, a nighttime penalty does not seem appropriate and $L_{eq(8)}$ or $L_{eq(24)}$ is used instead. The argument which has been made, however, that optimum conversation of hearing needs an absolute quiet environment[12] for recovery during the night and the fact that long-term annoyance by intruding noises is closely related to the speech interference effects during daytime and evening hours, make L_{dn} the best candidate presently available for describing the overall quality of the environment with regard to noise.

The advantages of L_{eq} and L_{dn} are best verified by showing that these measures satisfy all six requirements listed earlier. Values for both measures can be calculated theoretically from known pressure-time patterns. For specific noises with normal distributions, L_{dn} can be easily correlated to statistical descriptions of the noise such as L_{10} or L_{50}. (L_{10} and L_{50} are the levels exceeded 10% or 50% of the time, respectively.) An example is

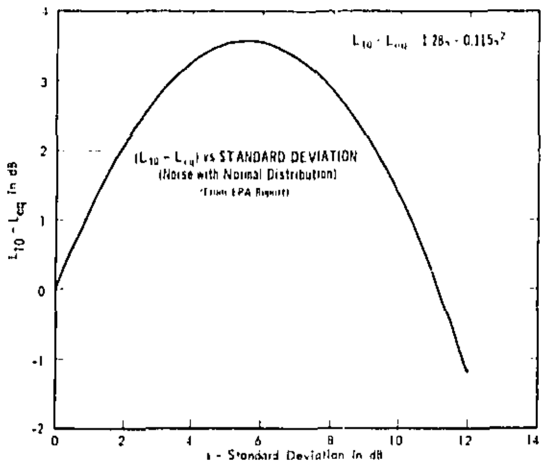

Figure 3 — Difference between L_{10} and L_{eq} as a function of the standard deviation of a noise with normal distribution[9]

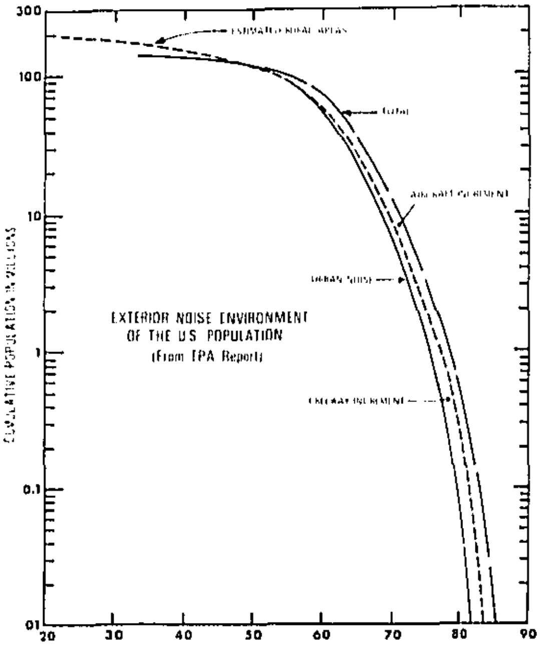

Figure 4 — Population of US exposed to residential day-night sound levels in excess of specified values[3,4,8]

shown in Fig. 3.[8] The L_{dn} descriptor can be used to approximate most of the more complicated evaluation schemes, such as Noise Exposure Forecast (NEF), Composite Noise Rating (CNR), Noise Pollution Level (NPL), etc. An approximate rule of thumb is:[8]

$$L_{dn} \simeq \text{CNEL (Community Noise Equivalent Level)}$$
$$\simeq \text{NEF} + 35 \simeq \text{CNR} - 35. \quad (3)$$

The big advantage of L_{eq} and L_{dn} over most of these other measures is that they can be easily measured and monitored over long time periods. Commercial equipment to read out L_{eq} is available. It might be argued that these advantages are achieved as a result of several disadvantages — the most severe of which is undoubtedly the deletion of any pure-tone correction or penalty in the L_{eq} and L_{dn} scheme, a correction used widely in the prediction and evaluation of the human response to aircraft noise, e.g., NEF procedure, and incorporated in the noise certification procedures for aircraft. This shortcoming has to be accepted at the present time since it is this feature which would make it impossible to verify exposure predictions with pure-tone correction through measurements with simple, standardized and relatively inexpensive equipment. In addition, it did not appear that the pure-tone penalties currently used for aircraft noise have been validated for all types of noises and for all intensity levels. Actually, there are indications that they are not the same for all levels. For the effectiveness of an overall noise abatement program, this shortcoming is minor — objectionable pure-tone components produced by some noise sources contributing to the overall environmental noise can and should be controlled by more elaborate source emission standards (such as the aircraft certification procedure). They do not have to be reflected in the descriptor for the long-term noise climate.

Another possible objection to the use of L_{eq} and/or L_{dn} might be that the long-term average is not appropriate to control the harmful or annoying effects of short duration, high-level noises. This argument is only partly valid. For example, limiting L_{eq} to 60 dB, a level that will be shown later as representative of the range desirable in communities, restricts a 110-dB noise to a duration of 1 sec per day! Therefore, L_{eq} can be trusted to reflect even a few high noise level episodes per day in the overall descriptor, perhaps with not much less weight than such isolated episodes deserve on the overall biological/psychological weighting scale. Moreover, the control of extremely short, high-level noises and impulse noises must be managed by source emission standards.*

With a basic descriptor to characterize environmental noise with respect to health and well being, it is now possible to describe the noise environments of various places, their changes with time, and the noise exposure of individuals and populations as they move through various noise environments during their daily lives and throughout their whole lifetimes. The daily predicted noise doses received by individuals can be verified by measurements with personal noise exposure meters carried by the person, assuming that self-induced and desired sound exposure is discounted. All these measurements can be made in terms of the descriptors L_{eq} and L_{dn}.

In the practical application of this concept and for most of the reasoning that will follow, it is helpful to be able to estimate noise levels in residential dwellings from the outdoor environmental noise. For the US, the difference in noise reduction provided by houses in warm and cold climates was not found to be significant enough to warrant separate treatment to determine exposure forecasts. An approximate national average of 15 dB noise reduction with open windows and 25 dB reduction with closed windows was established and used in arriving at desirable outdoor L_{dn} levels.[13] It is important to note at this point, however, that even in relatively noisy areas, inside noise levels, particularly during the daytime, correlate poorly with simultaneously recorded outside levels; the inside noise sources in residential sites as well as in offices and similar spaces are appreciable and easily overlooked.[14]

Outdoor day-night sound levels in the US are presented as examples in Fig. 4.[4,5] Exposure patterns of individuals during

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*The effect of short-duration noise events on the value of L_{eq} is discussed by T. J. Schultz in the March-April 1975 issue of NOISE CONTROL ENGINEERING (Volume 4, Number 2), p. 52.

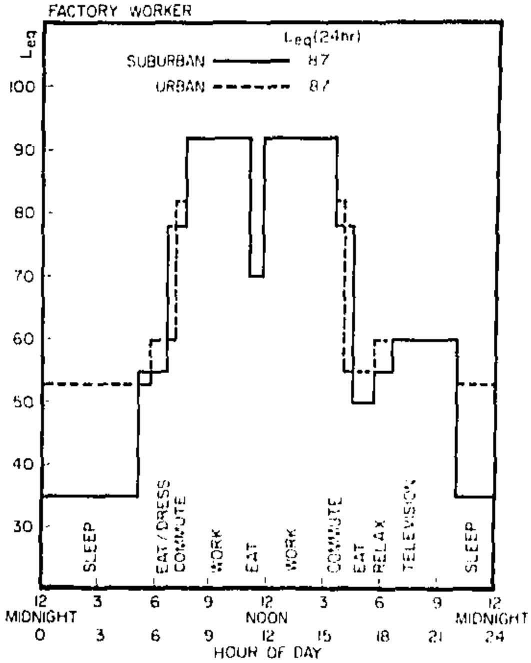

Figure 5 — Typical individual noise exposure patterns[8]

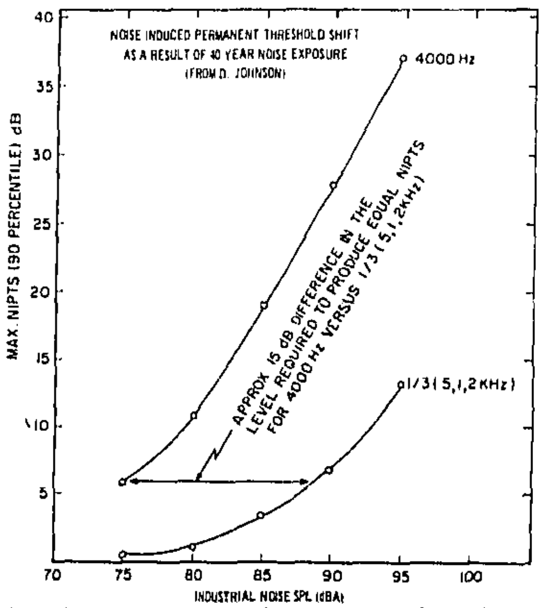

Figure 6 — Maximum NIPTS (90th percentile) over 0.5, 1, and 2 kHz occurring during a 40-yr industrial exposure to various noise levels at 4 kHz and averaged[16]

their daily routines are shown in Fig. 5. These are just examples taken from the larger series of life-styles discussed in the EPA report.[8] Table I summarizes the $L_{eq(24)}$ values for these typical cases.

TABLE I

TYPICAL AVERAGE DAILY EXPOSURES FOR VARIOUS US LIFE STYLES, ESTIMATED FROM ASSUMED LIFE-STYLE PATTERNS AS SHOWN IN FIG. 5 (FROM REF. 8)

	$L_{eq(24)} = L_{dn}$ Suburban	Urban
Preschool child	60	69
School child	77	77
Housewife	64	67
Office worker	72	70
Factory worker	87	87

Identifying Safe Levels for Hearing Conservation

In spite of some uncertainties and everybody's desire for the perfect study, there is adequate information available to predict with reasonable confidence the hearing impairment that continuous noise exposure produces in the general population after a lifetime exposure. When attempting to identify safe levels to be established by EPA, the existing evidence on noise-induced hearing loss was reviewed in detail.[15,16] The combination of the results by Passchier Vermeer,[17] Robinson,[18] and Baughn[19] produced average relationships between noise-induced hearing loss (noise-induced permanent threshold shift, NIPTS) and the continuous noise exposure, which caused each author's individual prediction to deviate less than 5 dB from the average. If, based on these data, noise that has no significant effect on the hearing of a population is to be identified, three questions should be decided: What is meant by hearing? What are significant effects? What population is considered? These decisions are always somewhat arbitrary and must be answered differently if population averages and an application to preventive medicine purposes or individual cases and an application to compensation purposes are discussed.

Although it is well known that NIPTS from continuous exposure can first be detected and becomes most severe in the 3 to 5 kHz frequency range, up to now most hearing conservation programs have been based on the NIPTS produced in the traditional speech frequency range 0.5, 1, and 2 kHz and the goal to avoid any serious speech communication handicap through hearing loss in this area. As seen in Fig. 6, the maximum NIPTS produced in a population after forty years of noise exposure (after the age of twenty) is much more severe for 4 kHz than for the average of 0.5, 1, and 2 kHz.[16] It is obvious that hearing at 4 kHz is an earlier and more sensitive indicator of NIPTS than hearing at the lower frequencies; therefore, the derivation of safe levels with respect to hearing was based on the avoidance of any substantial effects at 4 kHz.[8,9]

As a significant effect on hearing, a 5 dB NIPTS was selected somewhat arbitrarily as the smallest change which can be reliably measured and verified in individuals. This definition appeared to be a more sensitive indicator than the traditional hearing risk concept which is defined as the difference between the percentage of people with a specified handicap in a noise-exposed and in a non-noise exposed (but otherwise equivalent) group. As a handicap, a 25 dB fence* regarding hearing level for

*A hearing impairment is usually not considered a handicap unless the average hearing loss in the speech frequency range (0.5, 1, 2 kHz) exceeds 25 dB with reference to the I.S.O. audiometric zero.

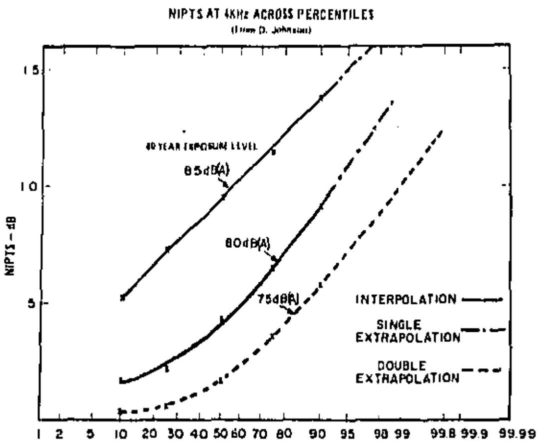

Figure 7 — NIPTS at 4 kHz across percentiles for various 40-yr exposure levels[16]

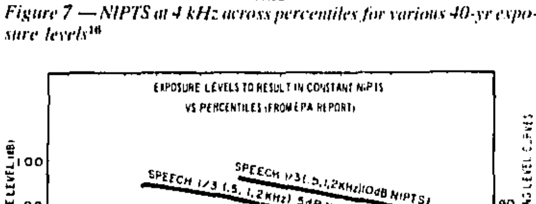

Figure 8 — Solid lines are curves of constant NIPTS as a function of 40-yr exposure level (lefthand scale) and population percentile; dashed lines represent hearing levels (righthand scale) by percentiles of a non-noise-exposed 60-yr old population. NIPTS curves must stay above and will merge with normal hearing level curves (dotted lines).[8]

the speech frequencies usually was assumed. Taking NIPTS for a high percentile point of the population (> 80th percentile) gives a more sensitive and significant indicator than taking hearing risk, the value of which is changing with the height of the fence used and its location with respect to the distribution curve. The final question — what percentage of the population should be protected against a 5 dB NIPTS at 4000 Hz after forty years of noise exposure was answered by the assumption that ears cannot be damaged by sounds which cannot be heard. When a certain percentile of the population would obtain a 5 dB NIPTS at such a low environmental noise exposure that this noise could not be perceived any more by the same percentile of a normal, non-noise exposed population due to presbycusis, then lower noise levels are unlikely to produce a 5 dB NIPTS in any part of this population.

Following the reasoning outlined requires some extrapolation of available NIPTS data to high percentiles and lower levels of noise exposure as indicated in Fig. 7.[8] No matter how the data are extrapolated, however, the potential quantitative effects on the outcome of these considerations are small. From data such as those in Fig. 7, the relationships in Fig. 8 for the exposure level

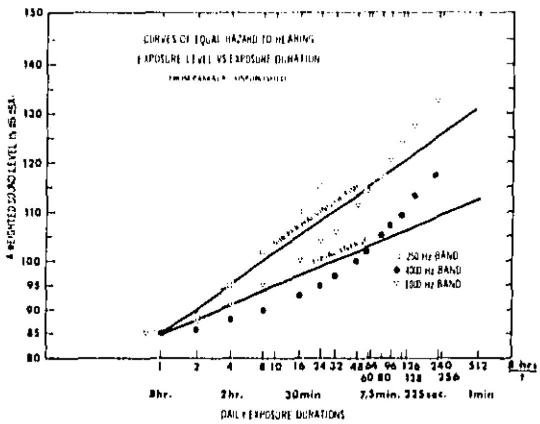

Figure 9 — Curves of equal hazard to hearing at 0.25, 1, and 4 kHz: sound level as a function of daily exposure duration. (Based on temporary threshold shift data). Straight lines indicate tradeoff relationships of 3 dB and 5 dB increase per halving of exposure time. (From unpublished data of H. O. Parrack.[18]*)*

to produce a 5 dB NIPTS as a function of population percentile are derived.[8] Extrapolation of the 4000 Hz, 5 dB NIPTS curve would indicate that a noise of 70 dB(A) would be required to produce this loss in 1% (the most sensitive percentile) of the general population.

Due to presbycusis, however, 5% of the non-noise exposed population (from the Public Health Service data) cannot hear a sound any more at a level below 70 dB re 20 micropascals (righthand scale of Fig. 8). To produce a 5 dB NIPTS in this part of the population (which, for safety's sake, is assumed to be the same as the one most sensitive to noise-induced hearing loss), certainly noise levels higher than their hearing level are required. As a consequence, the extrapolated 5 dB NIPTS curve cannot cross the hearing level curve for a normal population at age sixty but must stay above it as indicated. It may be concluded that a forty-year noise exposure below an $L_{eq(8)}$ of approximately 73 dB(A) is satisfactory to prevent the NIPTS at 4 kHz from exceeding 5 dB for the entire statistical distribution. [If this argument is unsatisfactory, then protecting the 99th percentile at 71 dB(A), a level only 1.5 dB different, may be preferred.]

To prevent the same loss from occurring at 3 kHz after a lifetime's exposure requires levels below 78 dB(A). Exposure levels below 83 dB(A) are required for the same average loss at frequencies of 0.5, 1, and 2 kHz. This difference in level highlights the conservatism adopted by protecting against a loss at 4 kHz instead of in the conventional speech range. Allowing a 10 dB NIPTS for the average of 0.5, 1, and 2 kHz, the 99th percentile can be protected by keeping exposure levels below 90 dB(A). This is the range of statistical risk allowed currently by most industrial hearing conservation criteria!

After establishing a safe level for a nominal lifetime, 8 hr/day exposure, levels for shorter and longer daily exposure time are derived according to the equal energy rule — for each halving of daily exposure time, the admissible levels are increased by 3 dB. It is well known that this relationship is a very crude approximation and that probably no simple relationship fits the data perfectly. Fig. 9 shows that the temporary threshold shift data for 4 kHz are fitted better by the equal energy rule than by the 5 dB increase of level per halving of time relationship.[18] The latter might fit the data in the conventional speech frequency range better. Nevertheless, with the only reliable data point at 8 hrs daily exposure and with the emphasis on protecting hearing up

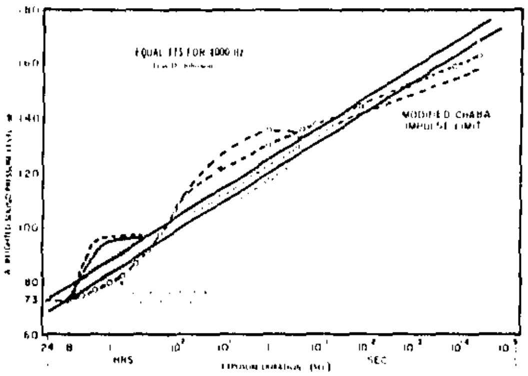

Figure 10 — Curves of equal hazard to hearing based on equal temporary threshold shift at 4 kHz: sound level as a function of daily exposure duration. Upper equal energy line has a 5 dB correction added for intermittency.[8]

to at least 4000 Hz, the equal energy rule appears as the better and more conservative approximation.

Since most environmental noise patterns are fluctuating and intermittent, an intermittency correction is proposed whenever $L_{80} < 65$ dB(A). With this correction, the curve for safe exposure level versus time is shown in Fig. 10 and divides the 8 hrs to 1.5 minutes range in the middle of the shaded area, identifying the range of uncertainty suggested by equal temporary threshold shift data depending on the intermittency and frequency range considered.[9]

In summary, adjusting by the equal energy rule for the facts that the voluntary and involuntary exposures to environmental noise are going on for 24 hr/day and 365 day/year (instead of the 8 hr exposures on 250 workday/year in the industrial situation) produces the following corrections:

8 hr/day industrial situation	Safe Level 73 dB(A)
24 hr/day (−5 dB) 365 day/year (−1.6 dB)	Safe Level 66.4 dB(A)
Intermittent noise, 24 hr/day, 365 day/year	Safe Level 71.4 dB(A)

Keeping the yearly average of $L_{eq(24)} < 70$ dB should protect the general population against any significant NIPTS, i.e., health effects with respect to hearing, with an adequate margin of safety.

It shall be mentioned here only briefly that the same basic philosophy, to protect NIPTS from exceeding 5 dB at 4 kHz in more than 10% of the population, was also adopted for evaluating exposure to impulse noise. The equal energy rule was invoked to arrive at exposure limits as a function of impulse duration and to account for more than one repetitive impulse per day. Under certain assumptions not to be discussed here (for an individual impulse $L_{eq} \simeq L_{peak} - 9$ dB), exposure limits for continuous noise as well as for single impulses can then be drawn as a continuous line as a function of exposure time and/or impulse duration (Fig. 10). The data points in Fig. 10 indicate points of equal risk of NIPTS at 4 kHz based on the relationship between NIPTS and noise-induced temporary threshold shift (NITTS).[8]

Identification of Environmental Noise Levels with Respect to Activity Interference/Annoyance

Environmental noise can interfere with a broad spectrum of human activities, such as speech communication in conversation and teaching; telephone conversation; listening to TV, radio, music; concentration during mental activity; relaxation; and sleep. From the combination of all these individual interferences, the overall judgment of the individual is formed as to the degree of interference, disturbance, and annoyance caused by the noise environment. The amount of interference with speech communication can be well quantified, is dependent almost entirely on the physical characteristics of the noise, and conclusions can be supported by much research data. The degree of interference with activities other than speech communication is often dependent on other parameters, such as attitude towards the noise source, familiarity with the noise, general psychological state, etc. These parameters are not constants; they can change for each individual from day-to-day and undergo changes during a lifetime; they can change from individual to individual, from country to country; and they might change with time as the value systems of societies, their environmental awareness, their appreciation of privacy, and their economic situations change. Regardless of these potential influences, it appears possible to specify for today's population levels of environmental noise which do not interfere significantly with their activities and do not degrade their overall well being.

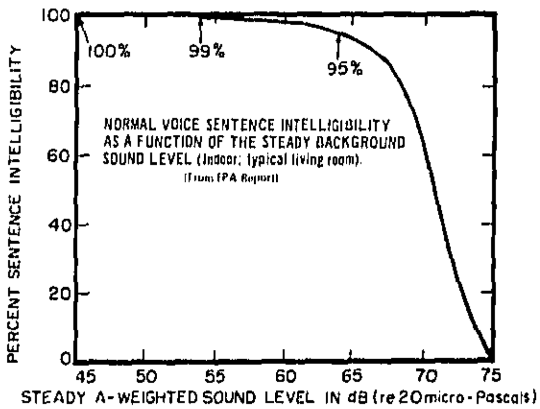

Figure 11 — Normal voice sentence intelligibility as a function of steady background sound level in indoor situation (assumes 300 sabins absorption typical of living rooms and bedrooms; valid for distances greater than 1 m). (From Ref. 8 based on Refs. 2, 20, 21)

Interference with speech. As for speech communication, the following approach was taken to quantify the noninterference of environmental noise with speech: indoors, in private homes, 100% sentence intelligibility is required for relaxed conversation in typical living rooms for all talker-to-listener separation distances. As Fig. 11 indicates, this is achieved for $L_{eq} \leq 45$ dB (reverberant field in a typical living room with 300 sabins of interior absorption).[1,2,20,21] Outdoors, there are usually free-field conditions, and speech intelligibility is described by Fig. 12.[20] 95% sentence intelligibility appears to allow for adequate, reliable speech communication for people who are walking or standing close together, approximately 1 to 2 meters apart. Such conversation is possible in noise levels up to approximately 60 dB steady A-weighted sound pressure level. Noise levels at this magnitude are also consistent with the desire for speech privacy, an attribute easily lost in the urban environment should background noise levels be too low. This sound level of 60 dB outside (with the average noise reduction of houses with partially opened windows assumed to be 15 dB) results in indoor levels of 45 dB, the same levels identified for satisfactory indoor conditions. Therefore, the same outdoor level satisfies both the outdoor and indoor speech communication criteria.

Before accepting these levels, one additional fact had to be analyzed. The laboratory investigations on which Figs. 11 and 12 are based were all conducted in steady noise environments and not in fluctuating noise environments such as normal urban

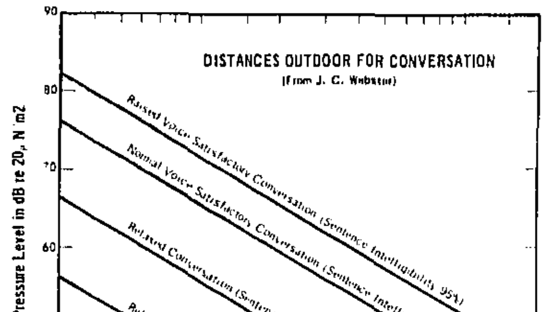

Figure 12 — Maximum distances outdoors over which conversation is considered satisfactorily intelligible[20]

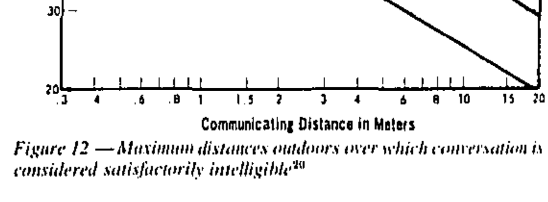

Figure 13 — Maximum percentage of interference with sentence intelligibility as a function of day-night average noise level. (L_{dn} is based on L_d + 3) (from Figs. 11, 12)

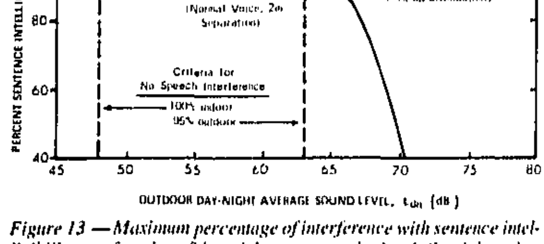

Figure 14 — Percentage of people with particular reasons for wanting to move[22]

noise or urban noise with aircraft flyovers. In a special analysis, it was assured that for constant L_{eq}, the percentage of noise interference with speech is greater for steady noise than for almost all types of environmental noise in which the magnitude varies with time.[8] Consequently, the limit levels in steady A-weighted sound pressure levels derived from Figs. 11 and 12 can be replaced directly by L_{eq} levels since the steady case is the most interfering one. (An additional analysis for steady intruding noise cycled on and off periodically also indicated satisfactory results for the indoor as well as outdoor case, if the steady noise is replaced by the L_{eq} of the cycled noise.)

Although noise levels guaranteeing no interference with speech communication are directly meaningful only in terms of L_{eq}, for comparison with other interference effects it is useful to express them also in approximate, corresponding L_{dn}. Based on the typical relationship between daytime and nighttime noises in the L_{dn} range of interest, L_{dn} can be assumed to be approximately 3 dB higher than the L_{eq} during the daytime. Using this assumption, the relationship between the interference effects of speech indoor and outdoor as a function of L_{dn} is seen in Fig. 13.

Interference with other activities. Noise can interfere with many other activities besides speech communication, and extensive studies over many years in Europe as well as in the US tried to correlate the frequency and severity of these interferences with the noise environment. Unfortunately, the severity can be measured here only in terms of the individual's subjective response. Even for the cases of sleep interruption or sleep interference, for which objective data are forthcoming and available, their translation from the laboratory to real-life is difficult; and their interpretation in terms of potential long-term effects on health and well being is equally problematic. Consolidated evidence from all noise surveys and public opinion studies, however, is consistent enough to draw this type of conclusive question: At what levels does noise start to interfere with the public's well being when compared to other environmental and socio-economic problems of present-day society?

One answer is obtained from data such as those obtained in the 1963 and 1967 London-Heathrow Airport noise surveys.[22,23] When the attitude of people toward their living area was studied and their reasons for desiring to move away were explored, noise did not represent a significant factor until environmental noise levels exceeded $L_{dn} \simeq 55$ dB (Fig. 14). These data are extremely important since they put noise into the proper perspective with regard to other environmental factors.

A second type of relationship emerged from all the public opinion/noise surveys conducted around larger airports in the US and Europe — the relationship between the environmental noise levels and the percentage of the population reporting to be highly annoyed by the noise. Actually, the results of the US and British surveys are remarkably consistent in this respect (Fig. 15).[24] (This relationship was used in studies by various US government agencies[25] and ICAO for several years and was recently verified by OECD in analyzing British, French, and Dutch survey results.[26]) Even the percentage of highly annoyed people who actively complain about the noise can be fairly well predicted.[27] Unfortunately, there are hardly any data for $L_{dn} <$ 55 dB, where the percentage of people highly annoyed is less than 20% and should rapidly diminish. It must be remembered here that the results showing 20% of all people as annoyed can be interpreted to mean that each individual of the total population is feeling annoyed 20% of the time. It is hardly possible for any human being to integrate annoyance over a very long time. To feel annoyed by noise a small percentage of the time is probably never avoidable even in the quietest surroundings; in other words, the percentage reporting to be annoyed in Fig. 15 will probably never reach zero.

Community response. The final set of data contributing to the overall question of noise interference with human activity and well being is the noise levels resulting in human group activity

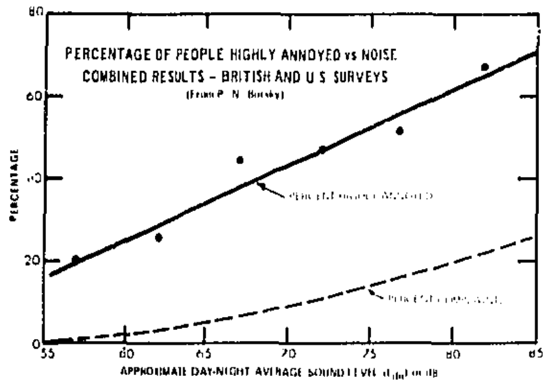

Figure 15 — Percentage of population reporting to be highly annoyed as a function of day-night average sound level. Combined results of British and US surveys[24]

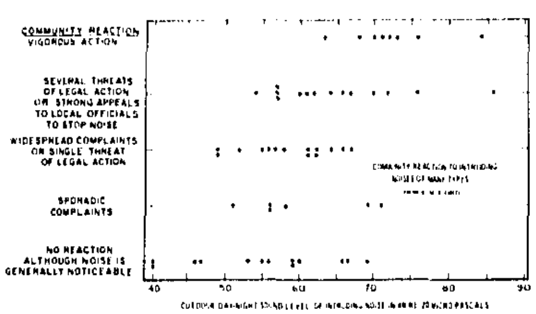

Figure 16 — Community reaction as a function of intruding outdoor day-night average sound level[28]

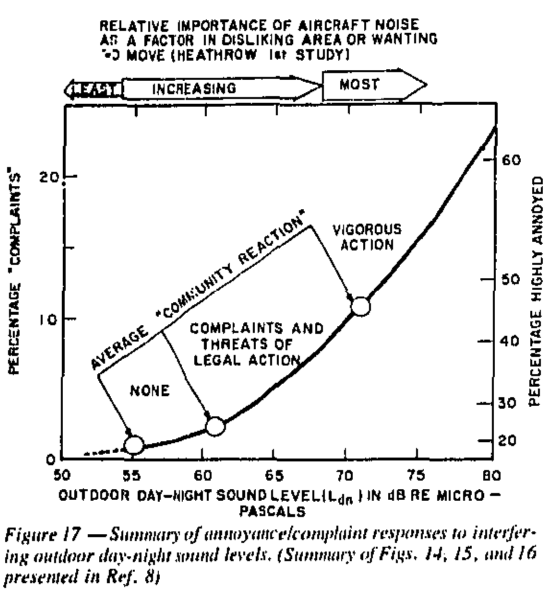

Figure 17 — Summary of annoyance/complaint responses to interfering outdoor day-night sound levels. (Summary of Figs. 14, 15, and 16 presented in Ref. 8)

and community action. Although these data are still more dependent on the socio-economic background and the legal-political system, data such as presented in Fig. 16 may be used to estimate noise environments that are considered as not interfering with normal community life.[28] It must be mentioned that the 55 case points of Fig. 16 are plotted without any corrections such as previous exposure history of community; type of environment such as urban, suburban, rural; misfeasance toward the noise; or others. If such corrections are included, the spread of the data points is smaller, and the average community response under the existing conditions can be predicted with satisfactory accuracy. In the present context, however, the basic noise interference was of interest, not the reaction modified by past history or present economic/political considerations.

Since the relationships of Figs. 14, 15, and 16 are all describing the long-term environmental noise effects regarding interference/annoyance, they can be combined into one figure.[8] The result, presented in Fig. 17, leads to the conclusion that an outdoor day-night sound level of 55 dB might be a reasonable limit, below which noise does not interfere significantly with human activities. The effects starting at this level are described as follows:

The average expected community reaction is none, even though 1% of the population might complain, and 17% might indicate that they are highly annoyed by the noise when asked in social surveys.

Noise is the least important factor governing attitude toward the area.

Outdoor conversations are easily possible with normal voice over distances up to 3.5 meters.

These outdoor levels result in indoor levels of approximately 40 dB, a level 5 dB below the level derived for no interference with indoor communication with an open window.

An indoor L_{dn} of 40 dB is usually coupled with a nighttime level L_n = 32 dB (open window), a level that is consistent with the limited data on sleep interference.

It was this combined reasoning which helped EPA to conclude that an outdoor $L_{dn} \leq 55$ dB in residential areas could be identified as the limit compatible with the protection of public health and welfare.

Conclusions

The analyses and assumptions summarized in this paper led the EPA to adopt L_{eq} and L_{dn} as the descriptors of environmental noise. An examination of all available data on noise-induced hearing loss prompted the conclusion that in environments with $L_{eq} \leq 70$ dB, the public is protected against noise-induced hearing impairment with an adequate margin of safety. Noise will have no effect on public health and well being due to interference with speech or other activities and will not result in undue, long-term annoyance as long as the yearly average L_{dn} is below 55 dB. Based on these results, EPA published Table II, identifying for most spaces the yearly average L_{eq} or L_{dn} compatible with public health and welfare.[8]

The limits of Table II are not rigid standards to be enforced, but rather goals and guidelines for a coordinated overall noise abatement program. The limits were derived with the total individual noise exposure in mind, occupational as well as nonoccupational. These limits can be monitored with relatively simple standard equipment; they can be monitored for spaces and for individuals moving through many environments during each day. An important feature for an overall noise control program is that the contribution of individual noise sources to the total L_{eq} or L_{dn} can be calculated or estimated for individual places as well as for an entire country. The cost effectiveness of various alternatives pertaining to source emission or aircraft certification standards and to highway or city planning can be evaluated.

The method and the limit levels identified cannot be applied to all types of noises or answer all problems. As for impulse

TABLE II
SUMMARY OF MAXIMUM NOISE LEVELS IDENTIFIED REQUISITE TO PROTECT PUBLIC HEALTH AND WELFARE[8]

Effect	Level	Area
Hearing loss	$L_{eq(8)} \leq 75$ dB	Occupational and educational settings
	$L_{eq(24)} \leq 70$ dB	All other areas
Outdoor activity interference and annoyance	$L_{dn} \leq 55$ dB	Outdoors — residential areas, farms, other outdoor areas where widely varying amounts of time are spent; other places in which quiet is a basis for use.
	$L_{eq(8)} \leq 55$ dB	Outdoors — school yards, playgrounds, etc. where limited time is spent.
Indoor activity interference and annoyance	$L_{dn} \leq 45$ dB	Indoor residential areas
	$L_{eq(24)} \leq 45$ dB	Other indoor areas — schools, etc., with human activities.

noise, sonic boom, infrasound, and ultrasound, the document cited discusses separately the limits compatible with public health and welfare.[8] It is also admitted that the limit for the outside environmental noise level of $L_{dn} \leq 55$ dB may be higher than some conditions; attitudes and situations make it desirable at some places. No one should be discouraged from striving for lower noise levels, which might be desirable for reasons other than public health.

Settling on the presented method for quantifying environmental noise and identifying uniform exposure limits does not mean that the search for a better descriptor for correlating noise to its health effects on people should stop. On the contrary, it is hoped that the extensive use of such a common descriptor will lead step-by-step to its improvement. A pure-tone correction and a weighting of the suddenness of the noise onset might be desirable refinements as soon as their general importance to human health effects is proven. They can be incorporated into the descriptor methodology without violating any of the requirements used for selection of the descriptor.

The importance of agreeing on such a common descriptor of environmental noise and of setting general goals for noise abatement programs cannot be overemphasized. After all, in the US the total number of people exposed to an L_{dn} of 60 dB and over is probably more than 30% of the total population. It is estimated that more than 15% are exposed to levels higher than an L_{dn} of 65 dB; 1.5% or 3 million people to an L_{dn} of 75 dB, and 600 000 people to levels above 80 dB — not from occupational exposure but from outdoor noise alone! In view of these estimates, the goal of $L_{dn} \leq 55$ dB appears to be very ambitious and remote; the debate, if the goal should be 3 dB lower or higher, does not appear to warrant the top priority. The goal and the descriptor — the common yardstick — however, are very important. They alone allow an appreciation of the task at hand and a quantitative evaluation of the progress of a balanced noise abatement program.

In summary, the question posed in the title can be answered! Perhaps, it is not yet known how quiet an environment is desired; but, certainly, it is known how much noise is too much and how much will interfere with the health and well being of a large percentage of those exposed. Acousticians all too often concentrate on advancing their knowledge instead of applying the knowledge they already have. Personally, the author believes that there is no excuse for withholding from the public the fact that it is already known how much noise is too much!!

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