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White Paper: The long-term cost of noise exposure

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Note: This White Paper supersedes the report published April 2009 in conjunction with NASA's "Buy-Quiet Process Roadmap" website. Costs for disability awards and hearing aids have been adjusted for inflation. Calculations of Net Present Value have been corrected to be inflation-neutral and to properly reflect the impairment and claims calculations using AAO-79.

A more detailed discussion of this topic will be presented at Internoise 2012.

Introduction

Noise control options on new and/or retrofitted equipment are often viewed as expensive, even luxury items. This is only possible because the cost of noise exposure is unknown. In practice the cost of noise exposure is often essentially assumed to be low, either zero or at most the cost of earplugs. But in fact the cost of noise exposure is considerable, even when reckoned on cash-flow considerations alone.

This report combines several sources of information to facilitate a comparison between actual cost of noise control and that of noise exposure.

Potential disability claims, purchase of hearing aids and batteries, purchase of hearing protective devices, and the cost of the hearing conservation program itself are taken into account. The following economic factors are NOT included in this estimate:

- the personal "human cost" of hearing loss.
- borrowing and lost opportunity costs if claims etc. cannot be paid out of current account surpluses.
- improved communication between personnel by slowing or halting the accumulation of hearing loss
- improved communication between personnel by reducing the isolation brought about by earplugs or earmuffs
- improved compliance with PPE policies by increasing the number of plug/muff options available in lower noise environments.
- reduced personnel turnover and the associated cost of training new workers

- reduced likelihood of community noise complaints.
- reduced energy consumption through greater energy efficiency.

This approach justifies noise control project costs based on cash-flow considerations alone. It is hoped that ethical and corporate responsibility considerations would cause these to be viewed as the *minimum* that should be invested.

Cost of noise exposure

The cost of exposing a person to noise for a career is estimated from:

- the TWA noise exposure (presumed to be constant over time and based on $L_{EX,8h}$)
- the net present value of potential disability claims at the end of 30 years.
- the net present value of hearing aids and batteries that might be needed after retirement.
- the net present value of the hearing conservation program and personal protective equipment during the career.

The economic benefit of noise control is estimated by comparing the reduction of the net present value (*NPV*) of noise exposure to the cost of the corresponding noise control effort.

For the purposes of this paper, the discount rate for the *NPV* calculation is assumed to be 0% (inflation neutral). The *NPV* is then just the sum of the expected expenditures in today's dollars. This assumption translates in practice to the expectation that all inflated future costs will be paid with equally-inflated future dollars out of available cash accounts.

Hearing Loss and Impairment

For the purposes of this study, we've adopted a common definition of the onset of hearing impairment (AAO-79, 25 dB average). This state is achieved when the average threshold across the audiometric frequencies 500, 1000, 2000 and 3000 reaches 25 dB [1].

The rate at which noise-induced hearing loss accumulates varies primarily with exposure level and frequency. ISO 1999-1990 [2] provides a method for estimating the statistical distribution of Hearing Threshold (HL) in each frequency band given $L_{EX,8h}$.

The analysis assumes no previous significant noise exposure, followed by unprotected noise exposure beginning at age 25 and continuing for 30 years.

Results for selected levels spanning the range 80 to 115 dBA are displayed in Figure 1 below. A surprisingly broad range of HLs is possible across the population for a given exposure. The value HL_{nn} will be used to represent the HL of the nn-th percentile of the population. In other words, nn% of the population can be expected to have an HL of HL_{nn} or less. One individual will have an nn% chance of having HL_{nn} or less.

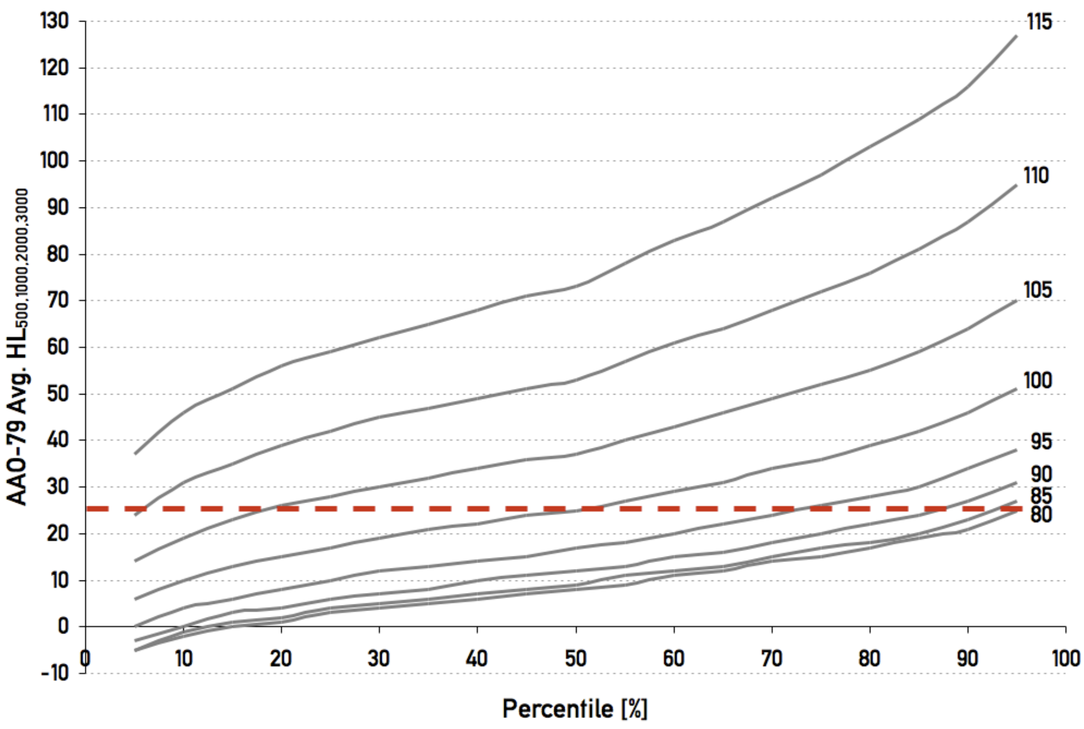

Figure 1: Cumulative Distribution of HL by Exposure Level

Percent Impairment

The percentage impairment *I(L)* is estimated in accordance with AAO-79 as

$$I_{nn}(L) = .015\left(HL_{nn}(L) - 25\right)$$

for values of HL between 25 and 91.6 (corresponding to 0 to 100% impairment). AAO-79 accounts for differences in the impairment of each ear, but for the purposes of this study we've assumed that the ears are equally exposed and equally impaired.

The percent impairment for a given noise exposure varies widely across the population along with HL. Thus we use $I(L)_{nn}$ to represent the nn-th percentile Impairment across the population. In other words, nn% of the population will have Impairment less than $I(L)_{nn}$. One individual will have an nn% chance of having $I(L)_{nn}$ or less.

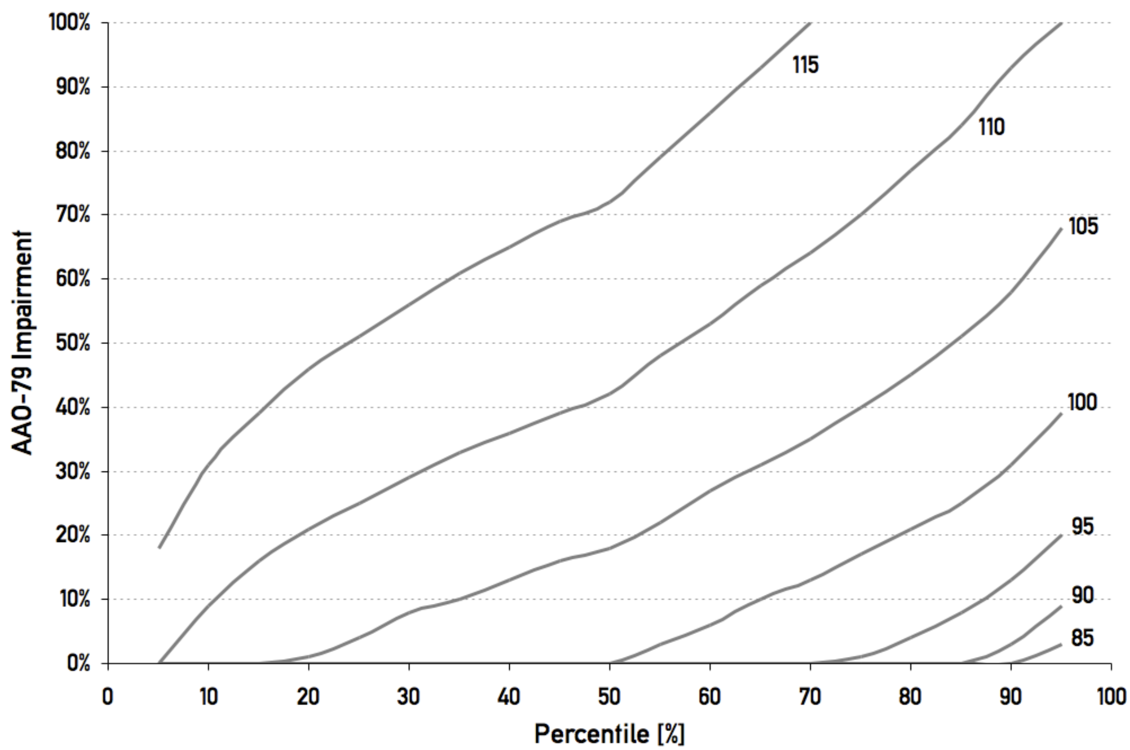

Figure 2: Cumulative Distribution of Percent Impairment vs. Noise Exposure Level

Probability of Impairment

The probability of HL 25 is represented in Figure 1 by the intersections of the dashed red line with the cumulative probabilities associated with each exposure level. For example, at 95 dB, HL 25 is reached near the 70-th percentile. Thus the probability of HL 25 or greater is approximately 30%, which means that 30% of the population so exposed will be considered "hearing impaired" according to this definition.

A polynomial function estimating the probability of HL 25 between 82 and 113 dBA exposure level has been developed:

$$P_I(L) = .057 - 4.45\times10^{-3}\left(L-80\right) + 5.94\times10^{-4}\left(L-80\right)^2 + 7.99\times10^{-5}\left(L-80\right)^3 - 2.05\times10^{-6}\left(L-80\right)^4$$

Below 82 dBA the probability approaches *0.057* and above 113 dBA the probability approaches *1.000*. Note that the probability never goes to zero, probably because of aging, work-related exposures not captured by dosimetry, and non-occupational noise exposures.

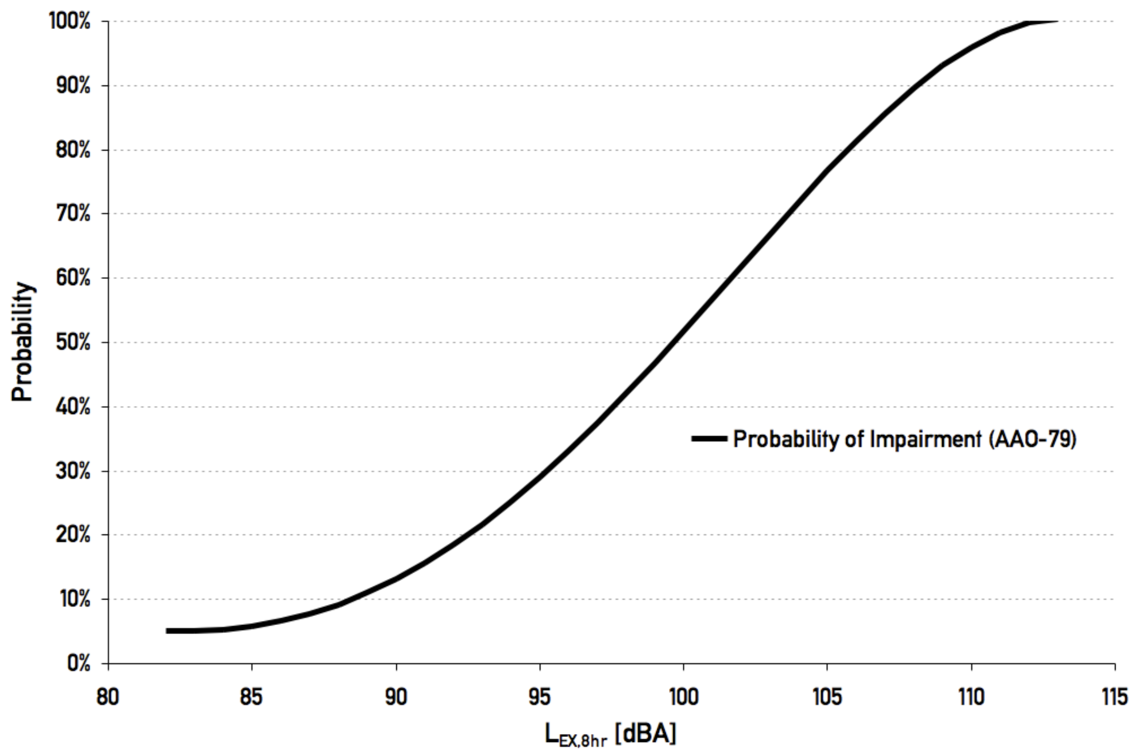

Figure 3: Probability of Impairment (*HL 25*) vs. Noise Exposure Level

Cost of Disability Claim

The cost of disability claims for hearing loss varies considerably by US State and will presumably vary over time. The cost of a dual-ear full disability claim across US States reported in *The Noise Manual*, Fifth Edition, ed. Berger et. al., Chapter 18, p. 696, averages approximately $66,000 in 2011 dollars (assuming a long-term average of 4.2% inflation).

The average claim may be multiplied by a "sensitivity" factor *S* that adopts the values 1 (less sensitive, bottom 10% of claim amounts) through 5 (very sensitive, top 10% of claim amounts), with the value 3 representing the average. Selection of the sensitivity factor implies some knowledge regarding the US State in which the claims might be generated and/or a degree of tolerable risk adopted for the project.

To find the cost of a partial disability claim according to AAO-79, the value of a full disability claim is multiplied by the percent impairment.

$$DC(L)_{nn} = -I(L)_{nn} \times \frac{S}{3} \times \$66,000$$

The mean value of DC(L) for a population cannot be precisely calculated, it can only be estimated to fall within a range with given probability, the so-called "confidence interval" based on a one-tailed t-test. This concept and tabulations of t factors are covered in most elementary statistics texts, such as [3].

For a normally-distributed population with mean μ and standard deviation σ, the mean <*x*> of a sample of size *N* can be expected to fall with probability q% in the range

$$\langle x \rangle < \mu + t_q \frac{\sigma}{\sqrt{N}}$$

For a sample size approaching the complete population, t_q goes to 0 and the sample mean equals the population mean. For smaller samples however, t_q becomes more and more significant until, with a sample size of one, it collapses to the simple statement

$$\langle x \rangle < x_q$$

which just means that, to q% confidence, the (average) value of a single sample will fall below the q-th percentile. This simply restates the original probability distribution.

The sample mean <H(L)> for N exposed persons can be expected to fall below

$$\langle HL(L,N,q) \rangle = HL_{50}(L) + t_q(N)\frac{\sigma(L)}{\sqrt{N}}.$$

q percent of the time (i.e., with q% confidence). With <*I(L,N,q)*> calculated from <*HL(L,N,q)*>, the equation becomes:

$$DC(L,S,N,q) = -\langle I(L,N,q)\rangle \times \frac{S}{3} \times \$66{,}000 \times N$$

The most commonly used confidence intervals are 95% and 99%.

Cost of Hearing Aids and Batteries

The National Institute of Occupational Safety and Health (NIOSH, "General information on the cost of noise") estimates the cost of a hearing aid at $1625, and the cost of batteries at $325 per year (adjusted for inflation to 2011 dollars). It is assumed for the purposes of this study that persons with HL $\geq$ 25 require hearing aids, and that two hearings aids are purchased every five years beginning at retirement and continuing for 30 years, with batteries provided throughout.

The *NPV* of hearing aids and batteries is approximately $39,000. Hence

$$HAB(L,N) = -P(L) \times N \times \$39{,}000$$

Cost of Hearing Conservation Program (HCP) and Personal Protective Equipment (PPE)

In a 2006 study by the US Navy entitled "Long-term cost benefit of noise control on ships", the cost of reducing the impact of noise on Navy personnel was $12,741.49 per person over 12 years at sea. This includes the cost both of the hearing conservation program and PPE issued to the personnel. Extrapolating this cost per year and allowing adjusting for inflation the net present value of the HCP and PPE is approximately $1,300 per year or $39,000 for 30 years.

The cost of the hearing conservation program and PPE is

$$HCP(N) = -N \times \$39{,}000$$

NASA policy requires that a HCP and hearing protection must be provided for personnel with TWAs of 82 or higher. The net present value of the HCP and PPE may be set to $0 for TWAs below 82.

Net Present Value of Noise Exposure and Noise Control

The sum of these equations provides an initial estimate of the Net Present Value of noise exposure *NPV_NX:*

$$NPV\_NX = DC\left(L,S,N,q\right) + HAB\left(L,S\right) + HCP\left(N\right)$$

if $L_{EX,8h}$ is 82 dBA or more.

The net benefit of a noise reduction strategy *NR* that costs NCC and reduces $L_{EX,8h}$ from L_1 to L_2 with *q*% confidence is therefore

$$NPV\_NR = N\left[\frac{S}{3}\left(\left\langle I(L_1,N,q)\right\rangle - \left\langle I(L_2,N,q)\right\rangle\right)\times \$66,000 + \left(P(L_1)-P(L_2)\right)\times \$39,000\right] - NCC$$

Economic analysis suggests that if the Net Present Value is positive, the project should be undertaken. Thus, the amount of noise control cost that can be justified is

$$NCC = N\left[\frac{S}{3}\left(\left\langle I(L_1,N,q)\right\rangle - \left\langle I(L_2,N,q)\right\rangle\right)\times \$66,000 + \left(P(L_1)-P(L_2)\right)\times \$39,000\right]$$

A conservative approach would be to prepare with 95% confidence for any single exposed individual, for which

$$NCC = N\left[\frac{S}{3}\left(I(L_1)_{95} - I(L_2)_{95}\right)\times \$66,000 + \left(P(L_1)-P(L_2)\right)\times \$39,000\right]$$

Parametric Study

The previous version of this computation incorrectly used *P(L)* instead of <*I(L)*> in the calculation of *DC*. Figure 4 below shows that the 95-th percentile impairment results are similar to results obtained using *P(L)*.

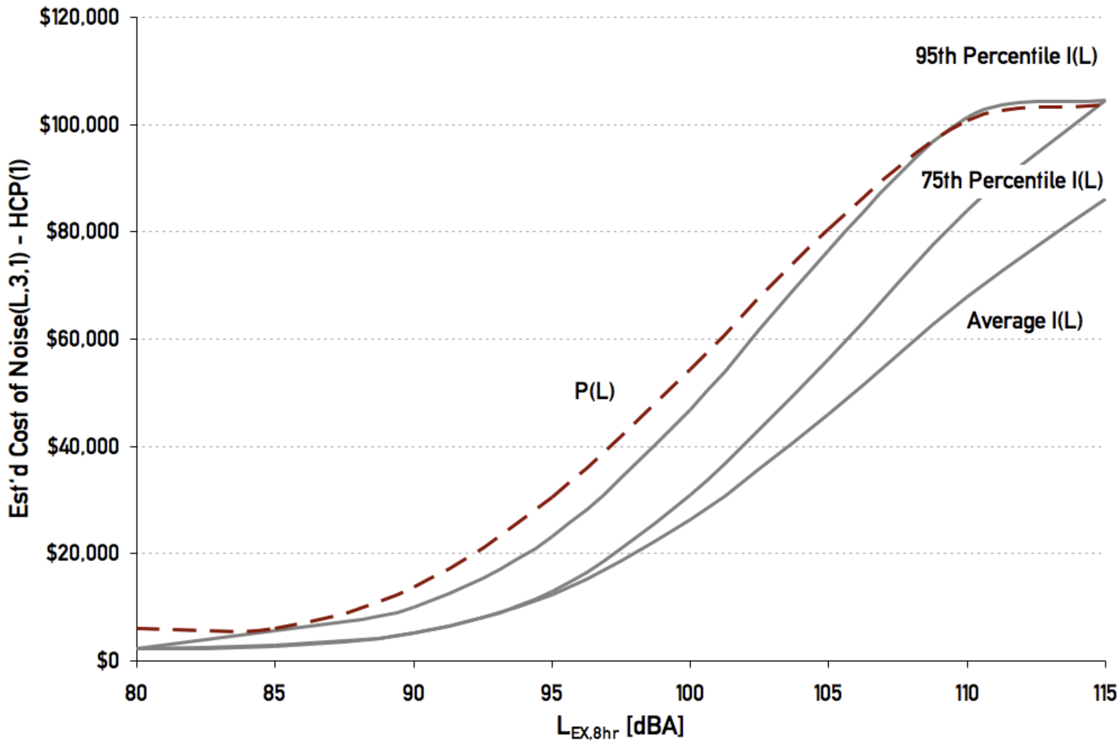

Figure 4: Estimated Cost of Noise (excluding HCP)

Conclusion

This white paper demonstrates a rather straightforward approach to obtaining estimates of the long-term cost of noise exposure. Reducing these long-term costs by mitigating noise exposure justifies, on cash-flow considerations alone, a *minimum* level of noise control expenditure.

The overall total justified costs have fallen considerably relative to the original analysis because of the removal of inflation from the *NPV* discount rate. The cost was incorrectly reckoned in *future inflated dollars*, essentially modeling a situation in which the exclusive source of cash for those far-off expenses was today's cash frozen, as if sitting in a vault.

The paper also presents a method for anticipating variability in results over various sample sizes. It can be argued however that each exposed person is a sample of one, for which the use of the 95-th percentile Impairment curve is appropriate. Whereas the previous white paper incorrectly used the probability of onset of impairment in claim calculations, the current paper uses the correct Impairment calculations per AAO-79. The 95-th percentile Impairment percentage tracks P(L) very well, so that the impact of this change is relatively minor.

This white paper represents the best information as of the day of its publication. It carefully lays the mathematical groundwork for the analysis or probabilities associated with the method. With respect to damage amounts and other costs, research is ongoing as information is culled from various sources.

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References

[1] *The Noise Manual*, Fifth Edition, ed. Berger et. al., Chapter 18, p. 696, American Industrial Hygiene Association, Fairfax, VA, 2003

[2] ISO 1999-1990 "Acoustics - Determination of occupational noise exposure and estimation of noise-induced hearing impairment"

[3] *Elementary Statistics,* Fourth Edition, Janet T. Spence et. al., Chapter 9, p. 154, Prentice Hall, Englewood Cliffs, NJ, 1983