CRM D0014732.A2/Final
September 2006

Computing the Return on Noise Reduction Investments in Navy Ships: A Life-Cycle Cost Approach

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Approved for distribution: September 2006

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Summary

Department of Navy (DoN) hearing loss costs continue to escalate. In FY 2005, the Veterans Administration (VA) paid $137M to more than 18,000 DoN veterans with hearing loss. Close to half of sailors who complete a career have some measurable hearing loss.[1] In addition, noise on ships may have a detrimental impact on morale, with consequent impact on reenlistment rates. The Deputy Assistant Secretary of the Navy (Safety) asked CNA to analyze the factors that influence hearing loss rates among sailors, evaluate the long-term costs, and help identify strategies to reduce these rates.

This study will help the DoN address the escalating costs of noise and hearing loss by developing a life cycle cost model of noise on a Navy Platform, and show how to apply the technique to the LHD Navy ship platform. The model we develop allows the Navy to compute the return on investment of noise reduction methods for either an entire platform or individual hazardous noise spaces on the ship. A user-friendly prototype calculator Excel "tool" is included as a deliverable from the study.

We point out that as impressive as the 15:1 to 17:1 return on investment from noise abatement engineering methods estimated in this report are, there are many benefits that are not accounted for in our model, such as the impact on personnel morale, life quality, and mission capability. Moreover, we know theoretically that costs of noise mitigation methods should be sub-additive because of economies of scale and benefits may be super-additive if methods applied to adjacent sites complement each other.[2] Therefore, more than likely the actual rates of returns for the whole platform are even higher than the ones estimated in this report.

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1. http://www-nehc.med.navy.mil/occmed/HCToolbox.htm
2. As in the common adage: "The whole is greater than the sum of the parts".

Based on results from the Excel calculator tool developed in this report, we recommend the following:

- The Navy should adopt a tool such as the one developed in this paper to evaluate all hazardous sites on Navy ships (not just the hazards for noise).
- The program managers of Navy ships should provide the necessary data to evaluate and prioritize noise abatement methods on their platforms.
- The Navy should allocate resources to improve and update the prototype calculator tool developed in this paper. Data can be used to further refine the parameter specification and functional forms outlined in this report and built into the Excel calculator tool.

These recommendations of applying, refining, and further developing user-friendly calculator tools for noise and other hazardous situations should help the both U.S. Navy and the U. S. Government save money by reducing the life-cycle cost of various Navy platforms.

Introduction

Hearing loss costs to the Veterans Administration (VA) continue to escalate and in FY 2005 VA payments were $137M per year to over 18,000 Department of Navy (DoN) veterans with hearing loss. See figures 1 and 2.

Figure 1. Veterans hearing loss disability costs, 1996-2005

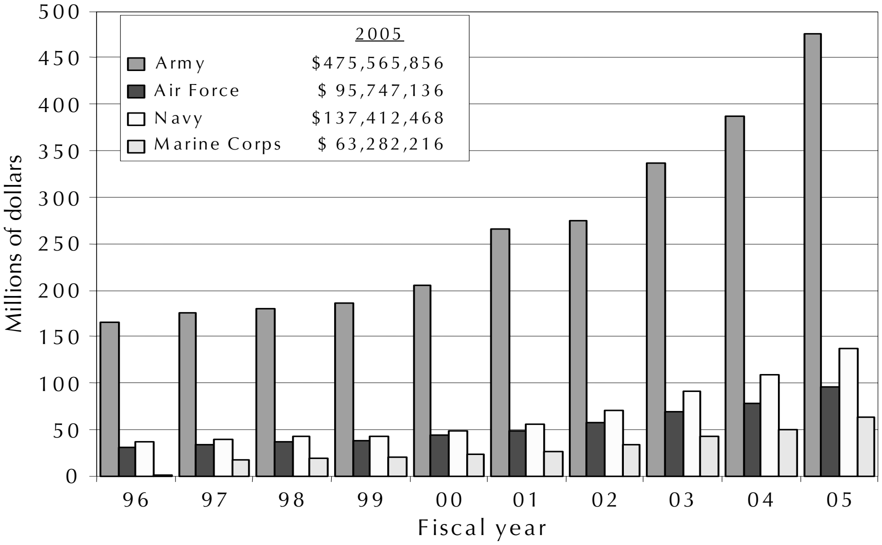
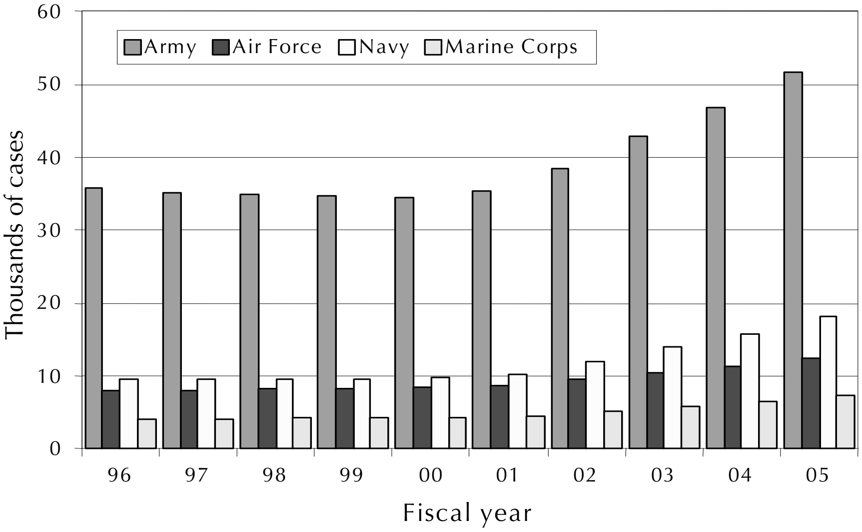


Figure 2. Veterans hearing loss disability cases, 1996-2005



This study develops a model to estimate the life-cycle costs[3] of hearing loss for a Navy ship, and then shows how to apply the technique to a Navy platform such as the LHD. The model we develop allows the Navy to compute the return on investment of noise reduction methods for a whole platform in general, and for individual hazardous noise spaces on the ship in particular. A user-friendly prototype calculator Excel "tool" is included as a deliverable from the study.

The rest of the report is broken into the following chapters. The next two chapters develop the specification of the life cycle cost model and how it can be used to compute the rate of return on noise abatement methods. The following chapter gives a numerical example for one site on a ship, and then discusses how the calculator tool can be used to evaluate an entire platform and prioritize noise abatement methods. The final chapter gives the conclusions from the study and makes recommendations to the Navy concerning the evaluation of hazardous sites in general, and hazardous noise sites in particular.

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[3] See Bratt, Evenden, and Spencer (1997 and 1998) for a discussion of how to estimate the life cycle cost of material health hazards in the Army.

Model

Consider a platform where personnel are exposed to various noise sources that are potentially harmful to hearing. We have three general types of methods that can be employed to reduce the personnel's exposure to the noise hazard at each noise site. These three types of methods are: engineering methods, the Hearing Conservation Program (HCP) along with personnel protective devices (PPD), and administrative methods that can reduce personnel's exposure time.

The engineering methods include methods that either reduce the noise at the source or reduce the noise via airborne path or structure-borne path. Appendices B and C in Chapter B4 of OPNAVINST 5100.19D (2000) give specific suggestions for engineering methods and personnel protective devices. Various engineering methods can achieve different levels of noise reduction with given frequencies at the source at various costs. These engineering costs may include a one time initial fixed cost, maintenance costs, and replacement cost over a ship's service lifetime. Reduction of noise at the source is a permanent solution, but largely untried due to perceptions of high cost.

Exposure to sound pressure can be dampened by wearing various types of personnel protective devices, with each of them subject to a probability distribution that the device is worn correctly.[4] The Hearing Conservation Program along with personnel protective devices [henceforth simply (HCP/PPD)] include various earplug, earmuffs, and Active Noise Reduction (ANR)[5] devices, as well as the cranial. Costs associated with the HCP/PPD include: (1) education, training, and enforcement to ensure personnel protective devices are worn and worn correctly; (2) audiograms, follow-up audiograms, and having an audiologist consult on proper wear and fitting, (3) checking for and reporting on a Significant Threshold Shift (STS),[6] (4) a

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[4] See Bjorn, et. al. (2006) for a discussion of these probabilities.

[5] ANR is not yet available in the current study.

[6] For a definition of STS, see Trost and Shaw (2005).

sailor's time involved, and (5) replacement cost of the PPD over a sailor's career. See Sachs, et. al. (2006) for a complete breakdown of these costs.

Finally, administrative methods may alter a sailor's exposure pattern to noise on the ship. This may include profiling a sailor out of the exposure area early in their careers and various on/off schedules where the sailor spends less time during deployment in the exposed area.[7] In the current study, we assume administrative methods are not a viable option[8] for decision makers to reduce hearing loss since personnel staffing decisions are dominated by the needs of the mission.

Five different pieces of information are assumed available for each noise source.[9] First, at each hazardous noise site, sound pressure, denoted L_A, its frequency, denoted Hz, and number of sailors needed to work on the site, denoted m, are needed.

Second, the sailor's exposure profile in terms of the sailor's age when first exposed to the hazardous noise site, denoted A, effective hours of exposure, denoted T_e, working hours in a shift, denoted T, working days in a week, denoted k, years of exposure, denoted θ, and other patterns related to exposure.

Third, for the ship's profile we need the years of deployment, denoted y, out of its life expectancy, denoted Y.

Fourth, we need cost information on noise reduction methods, including parameter values related to expected HCP/PPD cost per sailor, denoted C_1, parameter values related to expected engineering cost per noise source, denoted C_2, and parameter values related to expected administrative overhead cost, denoted C_3.

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[7] It may also be possible to reduce noise induced hearing loss by creating a quiet space in berthing where the sailor can recover, although measuring the impact of this method is beyond the scope of this study.

[8] However, we do account for administrative overhead costs to operate and implement the engineering and HCP/PPD methods.

[9] We try, as much as possible, to use the same notation contained in the ANSI's 1996 document.

Finally, information needed to calculate the benefit from reduced noise measured as avoidable cost includes parameter values related to the expected benefit, denoted B_1, derived from the HCP/PPD methods over the ship's lifetime, parameter values related to expected benefit, denoted B_2, derived from the engineering methods on this noise source over the ship's lifetime, and parameter values related to expected benefit, denoted B_3, derived from reducing additional recruiting cost incurred by this noise source over the ship's lifetime.

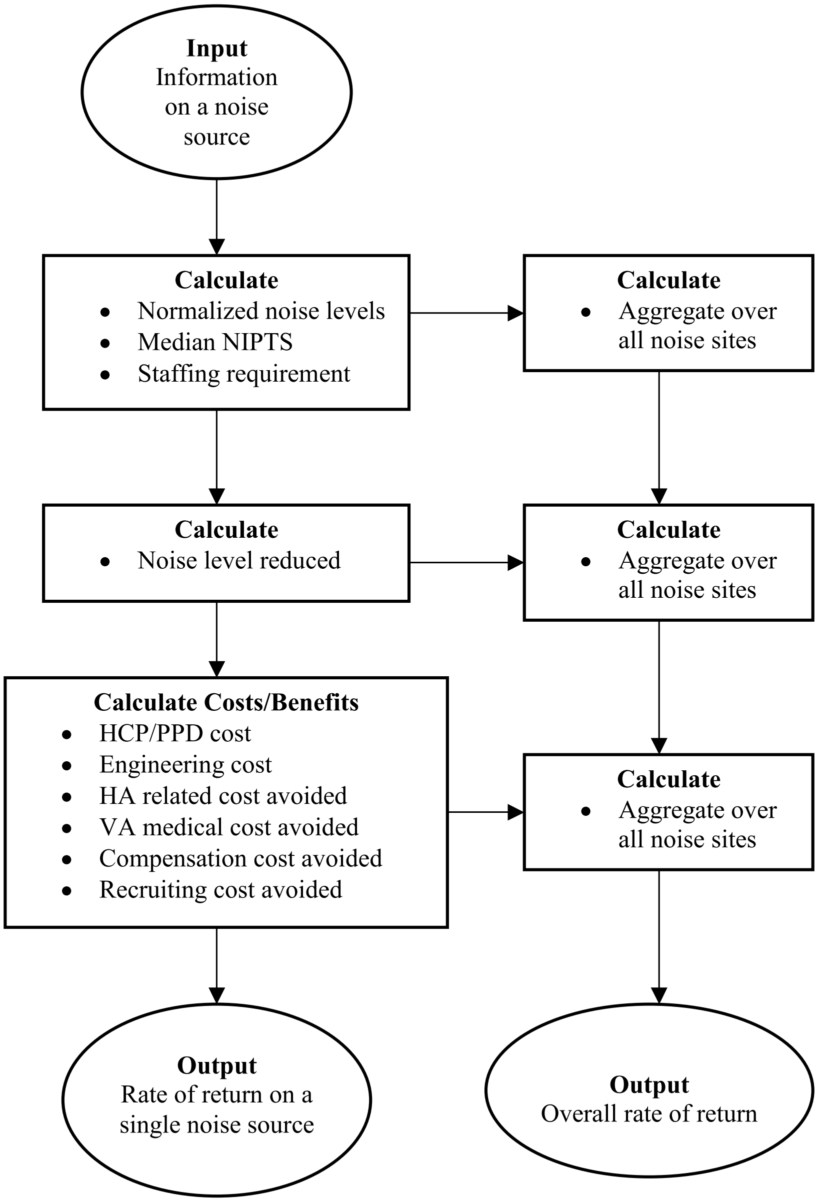
Since benefits are spread over several organizations over a ship's service lifetime, total benefit are further imputed to three categories: medical costs avoided, hearing aid related cost avoided, and disability compensation reduced. More specifically, VA medical costs include various costs associated with audiological procedures. Hearing aid (HA) related costs that include hearing aid examinations and select, electro-acoustic evaluation, the cost of issuing a hearing aid, hearing aid check, binaural HA check, binaural, Years 2, 3, 4, 5 repeat hearing aid set and check, and a five years supply of batteries. Disability compensation payments depend on degree of disability, and percent of offset.

Moreover, there are avoidable costs that may not be directly measurable in monetary terms, and are therefore **not included** in our model. For example, there are non-monetary losses in performance and readiness, efficiency, effectiveness (e.g. miss-communications due to poor hearing that leads to less combat efficiency), morale at various organizational levels, quality of life after military service, quality of the career, and morale at the individual level, just to name a few. There may also be the loss of life and serious accidents (CAT I Severity Code) caused by noise, although they are fairly rare in the Navy.

The flow chart in figure 3 depicts the basic logic of the model. Using the basic input information described above, sound pressure is normalized to eight hours per day and 5 days per work, and the median of Noise Induced Permanent Threshold Shift

(NIPTS), denoted $N_{0.50}$ is calculated using the formula given in the ANSI paper (1996).[10]

Figure 3. A flow chart for the model



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[10] The distribution of NIPTS can be also be derived but is not used in this model.

To compute the avoided cost (benefits) and the return on investment from noise reduction methods, our model uses information on the ship's lifetime staffing requirement at each noise site, the noise level at those sites, and the costs associated with implementing the HCP/PPD and engineering methods, including additional administrative overhead costs incurred by the noise reduction methods. Finally, rates of return on investment for both the HCP/PPD and the engineering noise reduction methods are calculated at each noise site as well as for the whole platform.

We define the expected rate of returns, denoted R, as the ratio of total expected benefit to total expected cost ratio,

(1) $R = (B_1 + B_2 + B_3)/(C_1 + C_2 + C_3)$

It is also possible to define partial rates of returns on investments made on HCP/PPD and engineering methods, respectively denoted R_1 and R_2 and defined as

(2) $R_1 = (B_1 + \lambda B_3)/(C_1 + \rho C_1)$

and

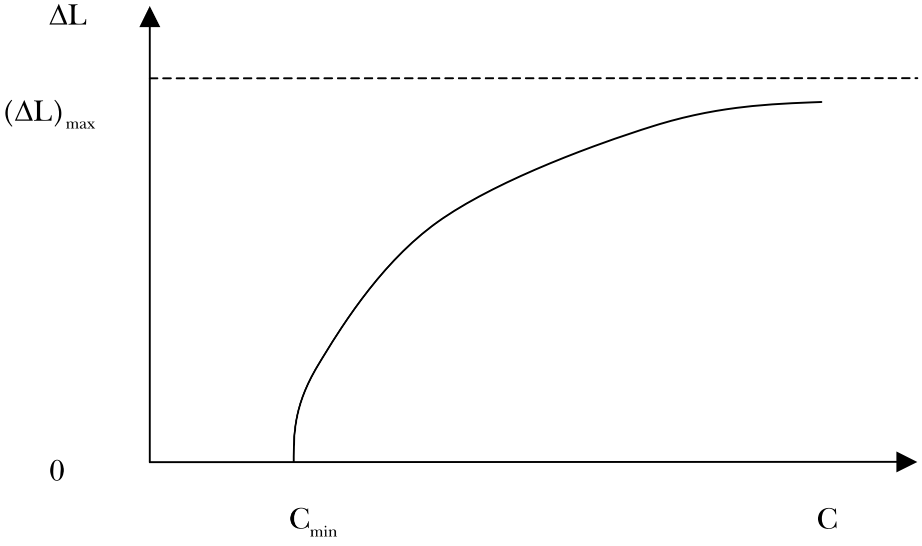
(3) $R_2 = (B_2 + (1 - \lambda)B_3)/(C_2 + \rho C_2)$

where λ is the percentage of benefit derived from reduced additional recruiting cost imputed to HCP/PPD methods and ρ is the administrative overhead rate.

In order to calculate these rates of return, we need all the input information as described earlier in this section and the following mathematical relationships to compute the costs and benefits of noise reduction. The specifications of the functional forms of these relationships are guided by fundamental economic theory. Parameters in these functions can be determined econometrically if there are sufficient numbers of observations. Alternatively, fitting data to the reasonable economic mathematical relationships that are assumed in this paper can derive parameter estimates. This later approach was the one taken in this study.

First, HCP/PPD and engineering methods can reduce noise, but each has an associated cost. Let ΔL be the noise level reduced. We must have $\Delta L = F(C)$, where $F' \geq 0$ and $F'' \leq 0$; i.e., noise reduction is increasing at a decreasing rate with money spent on reducing it. Moreover, it is realistic to assume that there is a limit as how much can be reduced by a measure. Hence, all noise cannot be eliminated even at a very high cost, and $\Delta L \to (\Delta L)_{max}$ as $C \to \infty$. Finally, there is a minimum amount of money needed to see any reduction in noise level. That is, if the cost, C, is below some value C_{min}, the reduction in noise, $\Delta L = 0$. We depict this cost function for the HCP/PPD and engineering methods in figure 4.

Figure 4. Relationship between noise reduction and engineering cost



The following specification of $\Delta L = F(C)$ satisfies all the requirements listed above and is the one we use in this study.

$$(4) \qquad \Delta L = \alpha(1 - \exp(-\beta(C - C_{min})) \text{ for } C \geq C_{min}$$

$$= 0 \text{ for } C < C_{min}$$

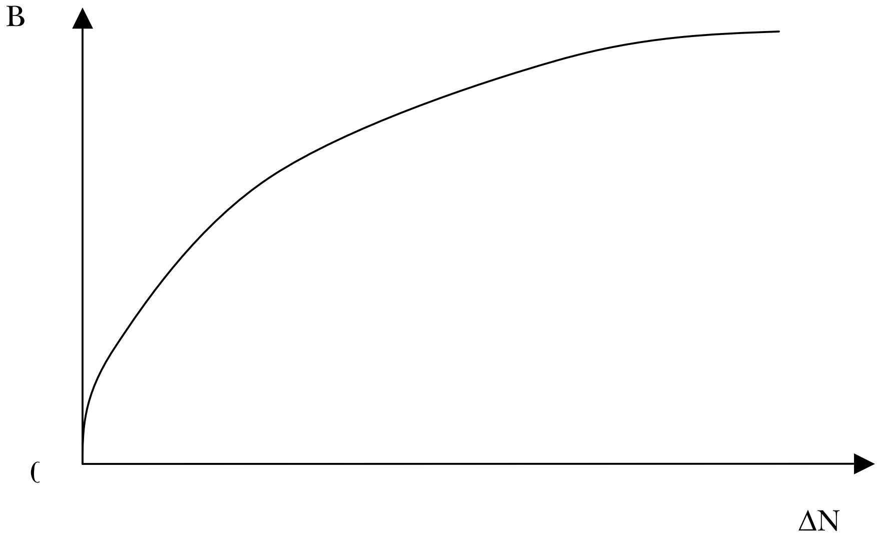
where C_{min} is predetermined and α and β are to be estimated. One can check that $d(\Delta L)/dC > 0$ and $d^2(\Delta L)/dC^2 < 0$ for α and $\beta > 0$. Equation (4) is applied to both C_1 and C_2. The corresponding noises reduced are denoted respectively ΔL_1 and ΔL_2.

Next, turning to the specification of the equation that relates benefits (avoided cost) to noise reduction, we consider two types of avoided cost from noise reduction. The first benefit is the sum of additional medical costs avoided, hearing aid associated costs avoided, and disability compensations avoided. The second benefit is the additional recruiting and training cost avoided from noise reduction.

Consider the first type of benefit, the avoided medical cost and hearing aid related costs. Let the avoidable cost (K) be a function of noise level, L, or K = G(L), where we must have $G' > 0$ and $G'' < 0$. Note that if the noise level is below 85 dB, it is assumed a constant minimum cost, denoted K_{min}.

Moreover, note that benefit is the saved cost, or change in K, ΔK when there is a noise reduction, ΔL. Thus, differentiating K = G(L), we have, defining expected $B = B_1 + B_2$, $B = \Delta K = G'(L)\Delta L$. We depict this benefit function in figure 5.

Figure 5. Relationship between avoided medical cost, hearing aid related cost, VA disability payments and noise reduction



The following specification K = G(L) satisfies all the requirements listed above and is the one we use in this study,

(5) $K = K_{min}(L - 85)^{\gamma}$ for $L \geq 85$

$= K_{min}$ for $L < 85$,

where K_{min} is given and γ is to be estimated. One can check that $dK/dL > 0$ and $d^2K/dL^2 < 0$ for $K_{min} > 0$ and $\gamma > 1$. Differentiating equation (5) and taking the natural logarithm of both sides of the equation, we get the linear function,

$$(6) \qquad \ln(B) = \ln(\gamma K_{min}) + (\gamma - 1)\ln(L - 85) + \ln(\Delta L)$$

Similarly, for the second type of benefit, the benefit from reduced recruiting and training cost, let the probability of additional recruiting activities, denoted as P, be a function of noise level, $P = H(L)$, where we must have $H' > 0$, $H'' < 0$ and $P \in [0, 1]$. Note that if the noise level is below 85 dB, we assume the probability of reenlistment remains constant at $1 - P_0$. Moreover, note that the benefits from noise reduction are a higher probability of reenlistment, or change in P, that results from a noise reduction, ΔL. The following specification $P = H(L)$ satisfies all the requirements listed above and is the one we use in this study,

$$(7) \qquad P = (1 - P_0 e^{-\mu(L - 85)}) \text{ for } L \geq 85$$

$$= 1 - P_0 \text{ for } L < 85,$$

where P_0 is given and μ is estimated. One can check that $dP/dL > 0$ and $d^2P/dL^2 < 0$ for $\mu > 0$ and $P_0 \in [0, 1]$.

We may also want to separately impute the total benefit derived from HCP/PPD and engineering methods to the three aspects of avoidable costs: additional medical costs avoided, denoted b_1, hearing aid associated costs avoided, denoted b_2, and disability compensations avoided, denoted b_3. We have

$$(8) \qquad b_1 = \mu_1(B_1 + B_2),$$

$$(9) \qquad b_2 = \mu_2(B_1 + B_2),$$

and

$$(10) \qquad b_3 = \mu_3(B_1 + B_2),$$

where $\mu_1 + \mu_2 + \mu_3 = 1$ and values of μ_1, μ_2, and μ_3 can be empirically determined.

Let M_j be the total number of sailors needed to staff the j^{th} noise source for the ship's deployed lifetime (y). We have

$$(11) \qquad M_j = m_j*(24/T_j)*(7/k_j)*(y/\theta_j),$$

where m_j is the number of personnel needed for each shift at the j^{th} noise source, T_j is the number of working hours in a shift at the j^{th} noise source, k_j is the number of days per week the personnel work at the j^{th} noise source and θ_j is the number of years a typical sailor will work at the j^{th} site in their Navy career.

To aggregate the costs and benefits over all noise sites on the ship's whole platform, we assume for simplicity, that they are straight additive, knowing that costs may well be sub-additive[11] and benefit super-additive[12]; and consequently the derived rates of return defined as the ratio of summed benefits to summed costs will be biased on the low side.

Let x be one of the following variables defined over all J noise sources:

- Total staffing requirement involved at all noise sites
- Total ship's life time staffing requirement
- Grand total cost, including total HCP/PPD cost, total engineering cost, and total administrative cost
- Grand total benefit, including total benefit derived from HCP/PPD methods, and total benefit derived from engineering methods
- Total benefits derived from both HCP/PPD and engineering methods, including the total imputed to additional medical cost avoided, the total imputed to hearing aid related cost avoided, and the total imputed to disability compensation avoided
- Total additional recruiting cost avoided, including the total imputed to all HCP/PPD methods and the total imputed to all engineering Methods

We have, denoting the total across all noise sources on the platform by X,

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[11] Meaning there are "economies of scale" if the whole ship has its noisy compartments reduced at the same time.

[12] Meaning that there are complementary noise reduction effects across various the sites, or "the whole is greater than the sum of the parts".

(12) $X = \sum_{j=1}^{j=J} x_j$.

However, many aggregated variables are only meaningful if they are weighted by the total number of sailors needed at each site. With J noise sources, let j be the j^{th} noise source, j = 1, 2,…, J. Let the weight for the j^{th} noise source be w_j, we have

(13) $w_j = M_j/\sum_{j=1}^{j=J} M_j$

Let z be one of the following variables defined over all J noise sources:

- L_{A8hrn}, (dB)
- Weekly Average (dB)
- Median NIPTS (dB)
- Noise reduction due to HCP/PPD methods (dB)
- Noise level achieved by HCP/PPD methods (dB)
- Noise reduction due to engineering methods (dB)
- Noise level achieved by engineering methods (dB)
- Change in probability of additional recruiting (dB)

We have, denoting the weighted average of z across all noise sources on the platform by Z,

(14) $Z = \sum_{j=1}^{j=J} w_j z_j$.

Finally, the rate of return on investments made on reducing noise level over all noise sources is defined as the ratio of total benefit over total cost. The rate of return on all investments made on the HCP/PPD measure to reducing noise level is defined as the ratio of total benefit derived from HCP/PPD over the total cost incurred by the HCP/PPD methods; and the rate of return on investment made on all the engineering methods to reduce noise level is defined as the ratio of total benefit derived from all the engineering methods over the total cost incurred by the engineering methods.

Populating the parameters of the model

Since we only have a few observations on some of the variables involved, unknown parameters in equations (4) to (10) cannot be estimated in the usual statistical sense. Fortunately, each of the equations (4) to (10) involve only one or two unknown parameters, which can be solved for with a pair of observations. By asserting a reasonable limiting case, we can derive all the needed parameters. In cases where the values we chose are not widely accepted by subject matter experts (SME), the calculator we develop easily allows for sensitivity analysis to investigate various possible values of unknown parameters on their impact on the final result.

Our source of information about the values of impacts of HCP/PPD and Engineering methods on noise reduction and their costs and benefits come from nine sources: (1) ANSI S3.44-1996 (1996) provides the formulae and associated parameter values to calculate normalized daily and weekly exposures and the median NIPTS; (2) the Naval Submarine Medical Research Lab (NSMRL) (2006) listed estimated costs of HCP/PPD methods and various avoidable costs in the three aspects of medical cost, hearing aid related costs, and disability compensations; (3) communications with Mark Lattner and Kurt Yankaskas at NAVSEA gave us data on noise levels for various Navy ships; (4) communications with Jim Janousek at NAVAIR gave us ranges of noise levels reduced by wearing earplugs, muffs, a cranial; and associated costs; (5) Noise Control Engineering (NCE) gave us possible engineering methods and costs to reduce noise at a noise source; (6) communications with Valerie Bjorn of NAVAIR gave us the effective noise reduction impacts of hearing PPD's, taking account of miss use and miss-fitting PPD's, (7) Trost and Shaw (2005 and 2006) estimated the hearing loss hazard ratios in various job ratings;, (8)Hansen, et. al. (2003) computed the reenlistment rates in different job ratings as well as the cost of recruiting and training a news sailor, and, (9) estimated LHD staffing requirements were obtained from Mr. Jack Keenan, CNA.

First, the following formulae and parameter values from ANSI (1996) are applied in the calculator directly.[13] For the median NIPTS, denoted $N_{0.50}$, we have

(15) $N_{0.50,\ \theta>10} = [u + v*\log(\theta/\theta_0)]*(L - L_0)^2$, for $\theta \in [10, 40]$,

and

$N_{0.50,\ \theta<10} = N_{\theta=10}*\log(\theta + 1)/\log(11)$ for $\theta \in [1, 10]$,

Table 1. Parameter values to compute NIPTS, from ANSI

Hz	u	v	L_0
500	-0.033	0.110	93
1000	-0.020	0.070	89
2000	-0.045	0.066	80
3000	+0.012	0.037	77
4000	+0.025	0.025	75
6000	+0.019	0.024	77

where "log" is the 10 based logarithm operator; u, v and L_0 depend on Hz, given by table 1 (Note that u and L_0 are not monotonic); θ is the total years of exposure to noise and θ_0 is set to one; and the calculation of L is given by equation (16) below; and

(16) $L = 10*\log[(\sum_{j=1}^{n} 10^{0.1*j*LA8hn})/k]$,

where

(17) $L_{A8hn} = L_{A8hn}$ if $L_{A8hn} \geq L_0$, and

$= L_0$ if $L_{A8hn} < L_0$

where

(18) $L_{A8hn} = L_{Aeq,T} + 10*\log(T_e/T_n)$

where T_e is the effective working hours, and T_n = 8 hours; $L_{Aeq,T}$ is the equivalent continuous A-weighted sound pressure level to be calculated below,

(19) $L_{Aeq,T} = 10*\log\{\int_{t1}^{t2} [P_A^2(t)/P_0^2]dt/(t_2 - t_1)\}$

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[13] According to Tufts, et. al. (2006) and NIOSH (1998), some adjustments are needed to fit the Navy's case.

where $T = t_2 - t_1$ is the duration of exposure, $P_0 = 20\mu P_a$, and P_A the sound pressure measured at the site in the unit of μP_a.

Note that equation (19) deals with the most general case where the sound pressure P_A varies with time. In this study we assume $P_A(t)$ is constant over time, and equation (19) is simplified by replacing $P_A(t)$ with its average value denoted P_A and equation (19) becomes $L_A = 10*\log(P_A/P_0)^2$.

Age issues are not crucial to our study since beginning sailors working on noise sites are expected to be at a similar young age and noise levels exposed with ear personnel protective devices (PPD's) are not exceedingly high. Should these assumptions not be valid in a follow up study, the simple formula of HTLAN = HTLA + NPTS – HTLA*NPTS/120 where HTLAN stands for "Hearing Threshold Level associated with both Age and Noise" and HTLA stands for "Hearing Threshold Level associated with Age", can be applied to decompose the observed hearing loss into the component due to aging and the component due to exposure to hazardous noises. Note that HTLA*NPTS/120 is negligible when HTLA + NPTS < 40.

Second, Sachs, et. al. (2006) did an extensive study on the cost of noise reduction through HCP/PPD Methods and estimated various avoidable costs in the area of medical treatment, hearing aid related costs, and VA disability compensations. It would be misleading if numbers were quoted directly from their study due to the detailed nature of their study. Table 2 summarizes the estimated total cost of combined HCP/PPD methods and those avoidable costs per sailor given the sailor's service years at sea. From their paper, it seems reasonable to assume that the medical cost and hearing aid related cost are equal.

Table 2. Estimated cost of the HCP/PPD program to reduce the impact of noise on Navy personnel

Years at sea	Total cost ($)
12	12,741.49
6	10,929.86
3	8,663.41
0	1,755.46

Third, according to email communications Jim Janousek of NAVIAR and the paper by Bjorn, Albery and McKinley (2006), the double protection from ear plugs and medically fitted earmuffs, in combination with the crewman sound attenuating helmet (the cranial), can produce 30 dB to 35 dB noise attenuation in theory.[14] In practice, as stated in Bjorn, Albery and McKinley (2006), the earmuffs and cranial are not always fitted properly. In addition, almost half of those surveyed by Bjorn, et. al. (2006) never wore the earplugs, and only 14 percent reported always wearing earplugs with their cranial. So the noise attenuation, in use, will be far less than 30 dB to 35 dB when averaged over all personnel, and could be as low as 10 dB noise attenuation when averaged over all users.

The cost of the earplugs and earmuffs are about $25, excluding the cost of fitting them properly to each individual. The assumption here is approximately $20.00 - $22.00 for the standard A9N Sound Attenuators used by the Navy and approximately $1.00 to $1.50 for the single foamy earplug or the rubber flange type plug. A custom made solid earplug may drive the total cost up to anywhere from $75.00 to $150.00 depending upon a lot of factors. A solid custom earplug, which provides repeatable proper fitting, when worn under the standard A9N sound attenuator which has been upgraded with a noise attenuation kit, NSN 4240-01-524-3339 (cost approximately $65.00) will provide 43 dB of passive sound protection.[15] The cost of the cranial is $125 to

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[14] The Active Noise Reduction (ANR) plug is not considered in this study. ANR acoustic noise canceling high tech "hearing aids" are capable of at least 35 dB noise attenuation, and probably more. The cost of ANR hearing protective devices is in the range of $4K to $7K. With ANR, one can reasonably assume the low end on the range of effectiveness will be much higher than the 10 dB (based on Bjorn survey) for the double protection earplug and earmuff when averaged over all the individuals issued the devices. There still is, of course, the problem of individuals who work "near" the noisy environment, but not in it, and are not issued the ANR equipment. The current contract requirement is to meet a 50 dB ANR requirement, with high hopes that technology will be able to soon exceed that number.

[15] Test reports are available from Wright-Patterson Air Force Base (WPAFB) verifying this data.

$250. So the total cost is roughly $300 for properly fitted earplugs, earmuffs, and cranial helmets.[16]

Fourth, Noise Control Engineering, Inc. (NCE) provided two examples of noise reduction, one of which reduced noise level from an engine diesel room from 98dB to 85dB via several engineering methods and the other to reduce the noise in a receiver room. See appendix C for the details of these two cost estimates. Table 3 summarizes the costs and noise levels involved for a receiver room in a typical Navy ship. Costs are calculated from estimated area treated in square feet and per square feet cost in dollars. The total cost of this noise reduction for a given site was just over $27K.

Table 3. Engineering cost ($27,763) from NCE to reduce the noise levels in a receiver room

	Cost ($)		Noise Level (dB)	
Receiver room treatment	Engineering	Installment	Reduction	Resulting
AC insulation		788	4	94
HTLM[a] (source side)		945	8	90
Floating deck	1,500	6,225	15	83
Cladding HTLM (receiver side)		945	12	86
Distributed isolation material (DIM)	800	1,860	7	91
Low frequency mach isolation	1,500	10,100	15	83
Damping	500	6,900	5	93

a. HTLM: High transmission loss material

Finally, using the hearing loss data collected and analyzed in Shaw and Trost (2005, 2006) and the reenlistment and recruiting and training cost documented in Hansen, Wenger, Monroe and Griffis (2003), we found that individuals in noisy jobs are more likely to leave the Navy and not reenlist. To see if that is true, In appendix A we estimate a linear regression of reenlistment rates for jobs as a function of the hearing loss hazard ratio in that job. This regression shows that an increase from a

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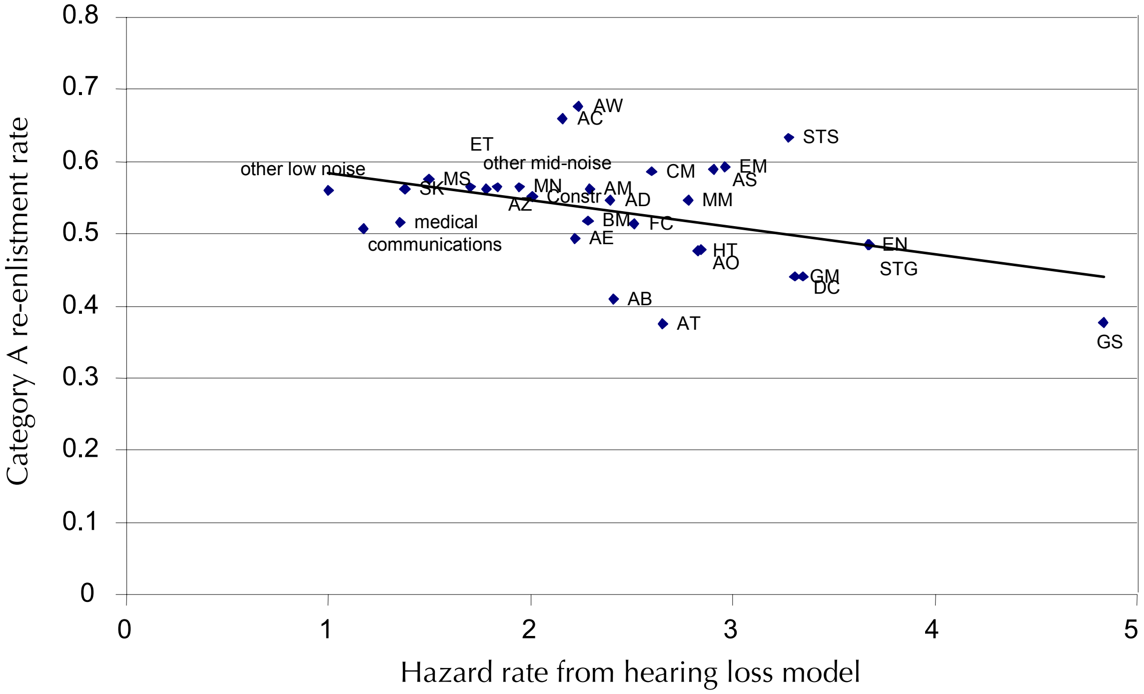
[16] Note that the helmet is to be a head protection system which is capable of incorporating a suite of hearing protection devices of various costs, both active and passive, to be communications and non-communications capable.

hazard ratio of 1 to a hazard ratio of 4, would predict an 11-percentage point decrease in the percent of reenlistments. This regression and fit is given below in figure 6.

Figure 6. Reenlistment rates as a function of hearing loss hazard ratios



Based on the information delineated above and assuming that no administrative methods are taken to reduce a sailor's exposure to noise there are four key equations that need to be specified. These are: (1) noise reductions due to HCP/PPD methods, (2) noise reductions due to engineering methods, (3) benefits (avoided cost) achieved by the HCP/PPD and engineering methods, and (4) the avoided cost of additional recruiting and training cost due to noise reduction.

First, for equation (4) applied to noise level reduced by HCP/PPD methods, we have, from Janousek (2006) and Felix, Tufts, Weathersby, and Marshall (2006), with $C = \$0.8K$ and $C_{min} = \$0.1K$, $\Delta L \approx 19$ dB; and a maximum of 45 dB can be reduced by these Methods, therefore $\alpha = 45$. Plugging all of these numbers into equation (4) and solving for β, we have $\beta \approx 0.77$. Thus, equation (4) for the HCP/PPD measure becomes

(20) $\Delta L = 45*(1 - e^{(-0.77*(C - 0.1)})$, for all $C > 0.1$.

Second, applying equation (4) to noise level reduced by engineering methods, we have, from NEC (2006) and Tufts, et al. (2006), with C = \$30K and C_{min} = \$0K, $\Delta L \approx 35$ dB; and a maximum of 50 dB can be reduced by these methods, therefore α = 50. Plugging all these numbers in equation (4) and solving for β, we have $\beta \approx 0.04$. Thus, equation (4) for engineering methods becomes:

(21) $\Delta L = 50*(1 - e^{-0.04*C})$, for all $C > 0$.

Third, to get an estimate of the two unknown parameter values in the benefit equation (6), consider two points. From Tufts et. al. (2006) and the results we have just derived above, noise level is first reduced from an equivalent weekly 138.9 dB per day to 120.1 dB, a 19 dB reduction by HCP/PPD methods. Then, the noise level is further reduced by engineering Methods from 120.1 to 85.2 dB, a 35 dB reduction. Plugging these numbers into equation (6) and solving for γ and K_{min}, we have $K_{min} = 0.179/M_j$ and $\gamma = 2.017$, where M_j is given by equation (11) and is the total number of sailors needed to staff the j^{th} noise source for the ship's deployed lifetime (y). Thus, the first order difference of equation (5) given by equation (6) becomes

(22) $B = \Delta K = 2.017*(0.179/M_j)*\Delta L*(L - 85)^{(2.017 - 1)}$, for all $L > 85$,

for the benefit derived by the noise reduction from engineering methods per sailor exposed to the noise source and,

(23) $B = \Delta K = 2.017*(0.179/M_j)*\Delta L*(L - 85)^{(2.017 - 1)}$, for all $L > 85$,

for the benefit derived by the noise reduction from HCP/PPD methods per sailor exposed to the noise source.

Finally, for equation (7), the probability function to reduce additional recruiting cost, we can infer from appendix A that $P \approx$ 45 percent when L = 85 dB and $P \approx$ 55 percent when L = 100 dB (i.e., (i.e., normalized weekly average at about 140 dB). Solving for P_0 and μ, we have $P_0 = 0.45$ and $\mu \approx 0.0037$. Thus, equation (7) becomes,

(24) $P = 1 - 0.45e^{-0.0037*(L - 85)}$, for all $L > 85$.

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Applying the "calculator tool" to a ship platform

In the previous two chapters we developed and then built a prototype "calculator tool" to compute the return on investment of various noise reduction methods on Navy ships, with particular emphasis on the HCP/PPD and engineering methods. To be a useful tool for program managers of ships, this calculator tool needs to be sophisticated enough to be believable, and yet simple enough so that is can be easily applied by ship program managers. This is the case with the tool developed and built in this report. First, our model predicts hearing loss from noise exposure over the career of a typical sailor on well-accepted ANSI scientific equations. Second, we base our estimate of avoided medical and hearing loss related costs on the paper by Sachs, et. al. (2006), who use Navy medical cost and VA disability payments outlined in the Department of Veterans Affairs Handbook (2004) to make their avoided cost estimate. Third, the additional recruiting and training cost for a new sailor are given in Hansen, et. al. (2003). And finally, from the User's Guide in appendix B of this report, it is clear the calculator tool only requires very few inputs for each noise source, and it will compute the return on investment for each noise reduction method at all individual noise sources and for the platform as a whole. So the calculator is easy to use.

Let us demonstrate the calculator with a numerical example. We then show how the calculator can be used to investigate the possibility of retrofitting noise reduction methods to a specific ship currently in the Fleet, the LHD.[17] The calculator tool, which is included as a separate attachment to this document, also contains two other numerical examples.

Assume twenty typical sailors are needed at a noise site with a noise level of 100 dB at 2000 Hz, working for 12 hours in a shift

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[17] It may be of even greater interest to apply the calculator to the LHD replacement ships, the LHA(R), which are still in the design stage.

during which only 10 hours of the shift are exposed to the hazardous noise, working seven days a week, and with six years total time at sea in the course of a 20 year Navy career. Further assume the ship is deployed for 24 years in its lifetime. Therefore, 160 total sailors will be needed at this site during the ship's lifetime, applying equation (11). The normalized daily exposure to noise is 101 dB, the normal weekly exposure is at 141.4 dB per day, and the median NIPTS is 64.2 dB, applying equations (15) to (19).

The noise reduction due to HCP/PPD methods that cost $800 per sailor is estimated at 18.8 dB, which reduces the normal weekly exposure to 122.6 dB. Engineering methods that cost $35,000 will further reduce the noise level by 37.7 dB, which reduces the normal weekly exposure to 84.9 dB, according to equations (20) and (21).

The total cost to achieve the noise level of 84.9 dB is estimated at $326,000 with $128,000 to carry out the HCP/PPD methods, $35, 000 to implement engineering methods, and $163,000 in additional administrative overhead costs.

Total benefit is estimated at $1,782,000 with $409,000 in avoided medical and related VA costs coming from HCP/PPD methods, $544,000 in avoided medical and VA costs from engineering methods, according to equations (22) and (23), and $829,000 from avoided additional recruiting cost. Out of the $829,000 avoided additional recruiting cost, $276,000 is imputed to those HCP/PPD preventive measures and $554,000 to engineering methods.

Consequently, the rate of return is 2.7 on investment made from HCP/PPD methods and is an impressive 15.7 from engineering methods. The overall rate of return is 5.5.

Finally, in order to apply the calculator to a whole platform, one would need all the hazardous noise sites listed, along with the engineering cost to reduce the noise at each site. In appendix C (table 8) we list some of the loudest sites on the LHD[18], along

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[18] These dB levels and locations are listed in the appendix B of the "Total Ship Review of Airborne Noise Issues for the LHA(R)", August 2003 draft.

with our estimates of their required staffing. In tables 4 and 5 we give two tables from NCE on the cost of reducing noise levels on ships. These three tables should be updated with information provided by the program manager of the LHA(R) program before using the Excel calculator tool to evaluate and rank the return on investment of engineering methods to either retrofit the LHD, or include noise reduction methods in the design of the still un-built replacement LHA(R) ships.

Table 4. NCE cost estimate ($23,030) of noise abatement for a typical diesel engine room on a Navy ship

Source Room Level Engine Room **110** dB(A)

Airborne Path Only

	Treated surface	Treated Area, sq ft	material $/sq ft	Installation cost/sq ft	Engineering Cost	Installed Cost, $	Noise Reduction, dB
Ac Insulation	overhead ER	900	$2.00	$1.50		$3,150	3
High Trans Loss Material	Fwd Bhd	360	$5.00	$2.00		$2,520	12
Std Bhd TL							30
Ac Ceiling	Overhead Receiver Compartment	150	$3.00	$2.00		$750	4

Resulting noise over A/B path only $6,420 **61** dB(A)

Structureborne Path Only

	Treated surface	#	material $/sq ft	Installation cost	engineering cost	Installed Cost, $	Noise Reduction, dB
Isolators	(2) gensets	16	$350	$3,000	$1,500	$10,100	15
DIM	(2) prop engines	2	$30.00	$1,000	$800	$1,860	7

minimum of isolation approaches listed above assuming prop engine and genset of equal strength 7

"standard" losses along S/B path 15

Resulting S/B noise from propulsion equipment **84** dB(A)

		Treated Area, sq ft	material $/sq ft	Installation cost/sq ft	Engineering Cost	Installed Cost, $	Noise Reduction, dB
Floating deck	Receiver Rm Deck	150	$6	$15	$1,500	$4,650	15

Resulting Noise over all paths $23,030 **70** dB(A)

Table 5. NCE cost estimate ($27,763) of noise abatement in a receiver room on a Navy ship

Receiver Room Level Work Space 15' x 15' x 9' **98** dB(A)

Receiver Treatment	Treated surface	Treated Area, sq ft	material $/sq ft	Installation cost/sq ft	Engineering cost	Installed Cost, $	Noise Reduction, dB	dB/$	Resulting Noise Level dB(A)
Ac Insulation	Overhead	225	$2	$2		$788	4	0.005	94
High Transmission Loss Material (HTL) [Source Side]	Aft Bhd	135	$5	$2		$945	8	0.008	90
Floating deck	Receiver Rm Deck	225	$6	$15	$1,500	$6,225	15	0.002	83
Cladding HTL Material [Receiver Side]	Aft Bhd	135	$5	$2		$945	12	0.013	86
Distributed Isolation Material (DIM)	(2) units	2	$30	$1,000	$800	$1,860	7	0.004	91
Low Frequency Machy Isolation	(2) units	16	$350	$3,000	$1,500	$10,100	15	0.001	83
Damping	various	400	$12	$4	$500	$6,900	5	0.001	93

Conclusions and recommendations

A few concluding remarks are needed before we give our recommendations. With very limited observations, functional forms and parameter values were specified that generate reasonable results. As more data becomes available from ship program managers, parameter values can be re-estimated to give more accurate results for specific ship platforms. Also, the calculator we have developed in this report enables users to conveniently explore impacts on results from any plausible parameter values.

Finally, we point out that as impressive as the 15:1 to 17:1 return on investment from noise abatement engineering methods estimated in this report and shown in the attached Excel calculator tool may be, there are many benefits that are not accounted for in our model, such as the impact on personnel morale, life quality, and mission capability. Moreover, we know theoretically that costs of noise mitigation methods should be sub-additive because of economies of scale while benefits derived from these methods should be super-additive because actions taken at adjacent sites may complement each other.[19] Therefore, more than likely actual rates of returns for a whole platform are even higher than the ones estimated in this report.

Based on results from the Excel calculator tool developed in this report, we recommend the following:

- The Navy should adopt a tool such as the one developed in this paper to evaluate all hazardous sites on Navy ships (not just the hazards for noise).
- The program managers of Navy ships should provide the necessary data to evaluate and prioritize noise abatement methods on their platforms.

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[19] Commonly referred to as the adage: “The whole is greater than the sum of the parts”.

- The Navy should allocate resources to improve and update the prototype calculator tool developed in this paper. Data can be used to further refine the parameter specification and functional forms outlined in this report and built into the Excel calculator tool.

These recommendations of applying, refining, and further developing user-friendly calculator tools for noise and other hazardous situations should help save money for the Navy in particular, and for the U. S. Government as a whole, by reducing the life-cycle cost of various Navy platforms.

Appendix A: Measuring the impact of noise on recruiting and training cost

Hazard rate models

We use hazard rate models to conduct our statistical analyses of factors associated with a Significant Threshold Shift (STS) in hearing ability among Navy personnel. See Shaw and Trost (2005 and 2006) for a discussion of the data used in this analysis and for a definition of STS. In this appendix, we describe the approach and explain why it is an appropriate technique for our analysis.

Background

Here we describe how to measure the determinants of the length of time before a STS will occur in active Navy personnel. Using typical regression methods to explain duration (time-to-hearing loss) data of this type presents a number of practical problems [references 1, 2 and 3]. One difficulty is that the events and characteristics that might explain individual risk may be changing over time.

There are, however, techniques designed explicitly to deal with duration data. As outlined in [1], these techniques are used in the industrial engineering fields, where there is interest in explaining the time-to-failure of equipment. They are used in the medical fields where the interest may be in explaining survival time following treatment or diagnosis. Economists use these techniques to explain duration of unemployment. The technique is often referred to as survival analysis. In the current context, the approach is to model the probability that a particular individual will get an STS, given that others at potential risk have remained (survived).

Modeling assumptions and techniques[20]

The model asserts that the risk of a STS occurring at time t (t in our model is time in months since entering the service) for an individual j is a function of time and personal characteristics:

$$h(t) = h_0(t)\exp(x_{t,j}\beta)$$

$$h_0(t) = pt^{p-1}$$

This is called the hazard function. The function $h_0(t)$ describes how the baseline risk varies over time. Since we wanted to allow for either constant, positive or negative duration dependence, we the baseline risk took on the Weibull distribution shown above. When the parameter $p = 1$, the hazard rate is constant over time, when $p > 1$, it is increasing over time and when $p < 1$ it is decreasing over time. The expression $\exp(x_{t,j}\beta)$ expresses how that risk increases or decreases with changes in a set of $x_{t,j}$ variables that describe the characteristics of the sailor at that point in time. This particular specification means that the proportional effect of an increase in $x_{t,j}$ does not depend on time in the Navy. It is called a *proportional hazard model.*

The purpose of the model is to determine how the characteristics x are associated with risk. This is done using maximum likelihood estimation of the hazard functions. We estimate coefficients (β) for the variables in the model to best fit the observed data. Specifically, we select coefficients on the characteristics of reservists to maximize the probability of observing the losses that actually occurred at each particular time in the Navy. To do this, we maximize the likelihood function given in [3].

In dealing with duration data, hazard rate models are preferred to alternative statistical techniques because they address the various problems that arise in the standard regression techniques. In particular:

- Hazard rate models can explicitly represent the complex stochastic process underlying survival times. The assumptions be-

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[20] References [2] and [3] provide introductions to survival analysis.

hind standard ordinary least squares, probit, and censored regression models are usually not as well suited to explaining time-to-loss.

- The hazard models specifically address data-censoring (or truncation) problems. Data available will usually cover a narrow window of time. The hazard rate models can account for observations that were at risk before we observed them or are still at risk when we stop observing them. By addressing these concerns, hazard rate models avoid biased estimates.
- The approach can deal with time-varying characteristics. Time-to-death is likely to depend on personal characteristics and events that change over time. Designing a regression approach that would explain survival time would present a real challenge. In the hazard model, the individual's characteristics are re-evaluated at each point in time that a STS occurs.
- The hazard rate models use data effectively in determining relative risks. Some means of distinguishing between propensity for loss and simple population demographics is required. For example, the number of STS for male sailors will exceed female the number of female STS occurrences. This must be due in part to the fact that there are more males than females in the Navy. It may also be that males are more likely than females to get an STS. To separate these two effects, the method uses data on losses and comparable survivors.
- More generally, the method allows us to look systematically at complex combinations of risk factors.

Interpreting results

The model of interest estimates the risk of an STS with a set of demographic and career variables such as type of job and gender. Results can be expressed either as *hazard rates* or as *coefficients*. The hazard rate compares the risk for two people who are the same except for a unit difference in one particular characteristic. A hazard rate of 1 (or close to 1) indicates that the risk is not appreciably different for sailor with that characteristic than for those without. A value of less than 1 indicates lower risk. For example, a value of 0.5 means that an individual has only half the risk of someone without the characteristic. Similarly, values above 1 indicate higher risk. The estimation actually determines the coefficient β_i and each hazard rate is calculated as $\exp(\beta_i x_i)$. We only present the hazard rates in this study, but can also provide the coefficients if needed.

When interpreting the results, it is also important to note the *p-value* of the variable. The p-value indicates how sure we can be that the hazard rate differs from 1. Typically, researchers consider coefficients with p-values of less than 0.1 to indicate a variable that is significantly associated with a different risk.

Estimating risks of hearing loss for different job ratings

Our model evaluates the risk of any hearing loss. The regression results are listed in table 6. We present the results in two ways. The first column is the *hazard rate*, which represents the relative risk associated with the variable. The second column presents the estimated coefficients (which are simply the logarithms of the hazard rates). We provide the coefficients to enable readers to calculate total risk. We then describe the noteworthy results. Several of the results match intuitive expectations for individuals more likely to suffer from hearing loss, but others do not.

Table 6. Estimation results for the risk of hearing loss[a]

	(1) Hazard ratio[b]	(2) Coefficient	(3) p-value
female	0.7835368	-0.2439372	<0.001 ***
black	0.759344	-0.2753004	<0.001 ***
Hispanic	1.099512	0.0948665	0.017 **
Asian	0.788507	-0.237614	<0.001 ***
Other Race (including Native American)	1.680155	0.5188863	<0.001 ***
civilian	0.0031921	-5.747092	<0.001 ***
Air Traffic Controlman (AC)	2.158599	0.7694593	<0.001 ***
Aviation Machinist Mate (AD)	2.391015	0.8717178	<0.001 ***
Aviation Electrician's Mate (AE)	2.221056	0.7979829	<0.001 ***
Airman (AN)	3.070887	1.121966	<0.001 ***
Aviation Ordnanceman (AO)	2.843117	1.044901	<0.001 ***
Aviation Support Equipment Technician (AS,ASM,ASE)	2.902415	1.065543	<0.001 ***
Aviation Warfare Systems Operator (AW,AX)	2.238378	0.8057513	<0.001 ***
Construction Mechanic (CM,CMD)	2.600485	0.955698	<0.001 ***

	(1) Hazard ratio[b]	(2) Coefficient	(3) p-value
Aviation Maintenance Administration (AZ)	1.835399	0.6072619	<0.001 ***
Boatswain's Mate (BM)	2.283758	0.8258224	<0.001 ***
Medical Rating (HM,DT)	1.356052	0.3045778	<0.001 ***
Hull Technician (HT)	2.826099	1.038897	<0.001 ***
Machinist Mate (MM)	2.781517	1.022997	<0.001 ***
Mineman (MN,TM)	1.948446	0.667032	<0.001 ***
Culinary Specialist (MS,CS)	1.495424	0.4024097	<0.001 ***
Seaman (SN)	2.932156	1.075738	<0.001 ***
Damage Controlman (DC)	3.350239	1.209032	<0.001 ***
Electricians Mate (EM)	2.960255	1.085275	<0.001 ***
Sonar Technician - Surface (STG)	3.675314	1.301639	<0.001 ***
Sonar Technician - Submarine (STS)	3.277204	1.186991	<0.001 ***
Aviation Boatswain's Mate (AB,ABE,ABF,ABH)	2.408627	0.8790568	<0.001 ***
Storekeeper (SK,AK,DK,PC)	1.374955	0.3184211	<0.001 ***
Aviation Electronics Technician (AT,AV)	2.651715	0.9752066	<0.001 ***
Construction (BU,CE,CN,EO,SW,EA,CU)	2.005035	0.6956616	<0.001 ***
Engineman (EN,FN)	3.671014	1.300468	<0.001 ***
Electronics Technician (ET,EW)	1.779082	0.5760972	<0.001 ***
Fire Controlman (FC,FT,FTB,FTG,FTM,AQ)	2.510435	0.9204561	<0.001 ***
Gunner's Mate (GM,GMG,GMM,GMT)	3.308766	1.196575	<0.001 ***
Gas Turbine Systems Tech (GS,GSE,GSM)	4.835191	1.575921	<0.001 ***
Communications Rating (RM,IT,DP)	1.173502	0.1599928	0.06 *
Aviation Structural Mech (AM,AME,AMH, AMS,AF)	2.288671	0.8279714	<0.001 ***
Other noisy ratings	1.703087	0.5324427	<0.001 ***
Years assigned to carriers[c]	1.069659	0.0673398	<0.001 ***
Years assigned to surface combatants	1.075582	0.0728624	<0.001 ***
Years assigned to submarines	1.076649	0.0738531	<0.001 ***
Years assigned to amphibs	1.066333	0.0642261	<0.001 ***
Years assigned to support ships	1.029326	0.0289046	0.006 ***
Years assigned to fighter/attack squadrons	1.098427	0.0938793	<0.001 ***
Years assigned to helicopter squadrons	1.110778	0.1050606	<0.001 ***
Years with fixed-wing squadrons (not fighter/attack)	1.105359	0.1001706	<0.001 ***
Years assigned to shore (most of career on shore)[d]	1.078414	0.075491	<0.001 ***
Years assigned to shore (with non-shore career)	1.057775	0.056168	<0.001 ***

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a. * significant at 10%; ** significant at 5%; ***significant at 1%.

b. For categorical variables, hazard ratios are interpreted relative to an excluded category. For example, the black values are relative to whites and rating values are relative to individuals in a quiet rating group (not listed).

c. For the variables that are number of years, and not just zero or one, the hazard ratio must be raised to the power of the number of years. For example, for someone who spent five years on a carrier, the hazard ratio is 1.069659 to the 5th power.

d. Two separate variables are used for time spent in shore assignments because those who are in the hearing conservation program and mostly on shore tend to have noisy jobs, while those who are not mostly on shore have quieter shore assignments.

Individual factors and risk

Males have a higher risk

This is consistent with previously published medical reports.

Blacks, Asians, and Hispanics have different risks

This is also consistent with what is already known. This study found a higher risk for Asians, and a lower risk for blacks and Hispanics.

Certain job ratings have higher risks

Jobs involving aircraft, sonar, and engines were among those most at risk for hearing loss. The ten ratings with the most risk are, beginning with those most at risk:

- Gas Turbine Systems Tech (GS, GSE, GSM)
- Sonar Technician - Surface (STG)
- Engineman (EN, FN)
- Damage Controlman (DC)
- Gunner's Mate (GM, GMG, GMM, GMT)
- Sonar Technician - Submarine (STS)
- Airman (AN)
- Electricians Mate (EM)
- Seaman (SN)
- Aviation Support Equipment Technician (AS, ASM, ASE)

Because the analysis controls for other factors, it shows that these people are much more at risk even than people who are doing different work in the same units.

Time spent in certain types of units increases risk

Spending time in squadrons greatly increases the risk. Spending a year in a squadron gives 10 percent more risk than spending the year in training, for the same rating. Time spent on combat ships also increases the risk, but not as much as being in a squadron. Those who spend time on ships but are rotated onto shore are harmed less by their time on shore than by their time on ships.

Combining risk factors

The above hazard rates provide information about how risk varies with a single characteristic. However, there might be interest in determining how risk changes with multiple characteristics. To estimate the relative risk between two people who differ by multiple characteristics, we can use the coefficients in the second column of table 2. Specifically, the value of each variable that differs between the individuals is multiplied by the corresponding coefficient, the result is summed, and the exponential function is applied to that result.

As an example, suppose we wanted to estimate the risk for a black male aviation structural mechanic as compared with a white male in one of the quiet ratings. (All other characteristics are assumed to be the same for the two individuals.) We can calculate the relative risk as

$$=\exp(b_{black}black + b_{ratingAM}ratingAM)$$

$$=\exp(-0.2759344 + 0.8279794)$$

$$=1.74$$

The coefficients are drawn from table 6 (for convenience, pertinent lines from table 1 are repeated here in table 7). The variables black and rating AM are both 1, because they are indicator variables (i.e., equal to 1 if the individual has the characteristic and equal to 0 otherwise). Notice that we did not have to include a variable for female because the comparison is between two males. We did not include other variables, because they too are assumed to be the same for both individuals. Once the relevant values are specified, we can calculate the hazard rate. In this case, the combined risk is 1.74 times that of the reference individual.

Table 7. Selected estimation results from table 6

	(1) Hazard ratio	(2) Coefficient	(3) p-value
black	0.759344	-.2753004	<0.001 ***
Aviation Structural Mechanic	2.288671	0.8279714	<0.001 ***

Noisy jobs and re-enlistment

It is plausible that people in noisy jobs are more likely to want to leave the Navy. There is also anecdotal evidence that some people who experience hearing loss must either switch jobs or leave the Navy. To see if that is true, we did a simple linear regression of re-enlistment rates for jobs on the hazard ratios from the above equation. Category A re-enlistment rates were taken from Hansen, Wenger, Monroe, and Griffis (2003). GENDETS were not included in this regression because those who are still GENDETS when they make a re-enlistment decision are more likely to leave for reasons that have nothing to do with the noisy work environment. This regression showed that an increase of 1 in the hazard ratio gives a 3.7 percentage point decrease in the reenlistment rate. See figure 6 presented above.

Appendix B: User guide for Excel calculator that computes the return on noise reduction investments in Navy ships

Introduction

A user-friendly prototype calculator is built to calculate the rates of return on investment from reducing ship noise, using an Excel spreadsheet program. In addition to obtaining the rates of returns on investment for noise reducing measures, users can explore outcomes for various budget environments and maximum noise level requirements, and carry out sensitivity analysis on alternative values of input variables and parameters as well as functional form specifications.

The calculator consists of four sheets, one for each of three general noise sources and another one for the whole platform. On each sheet for a noise source, there are two columns: an input column on the left and an output column on the right. The input and output columns are explained below.

All sheets are password protected to avoid accidental alternations of the program. The password is "fea" for all sheets. Cells whose values are to be input by users are unlocked.

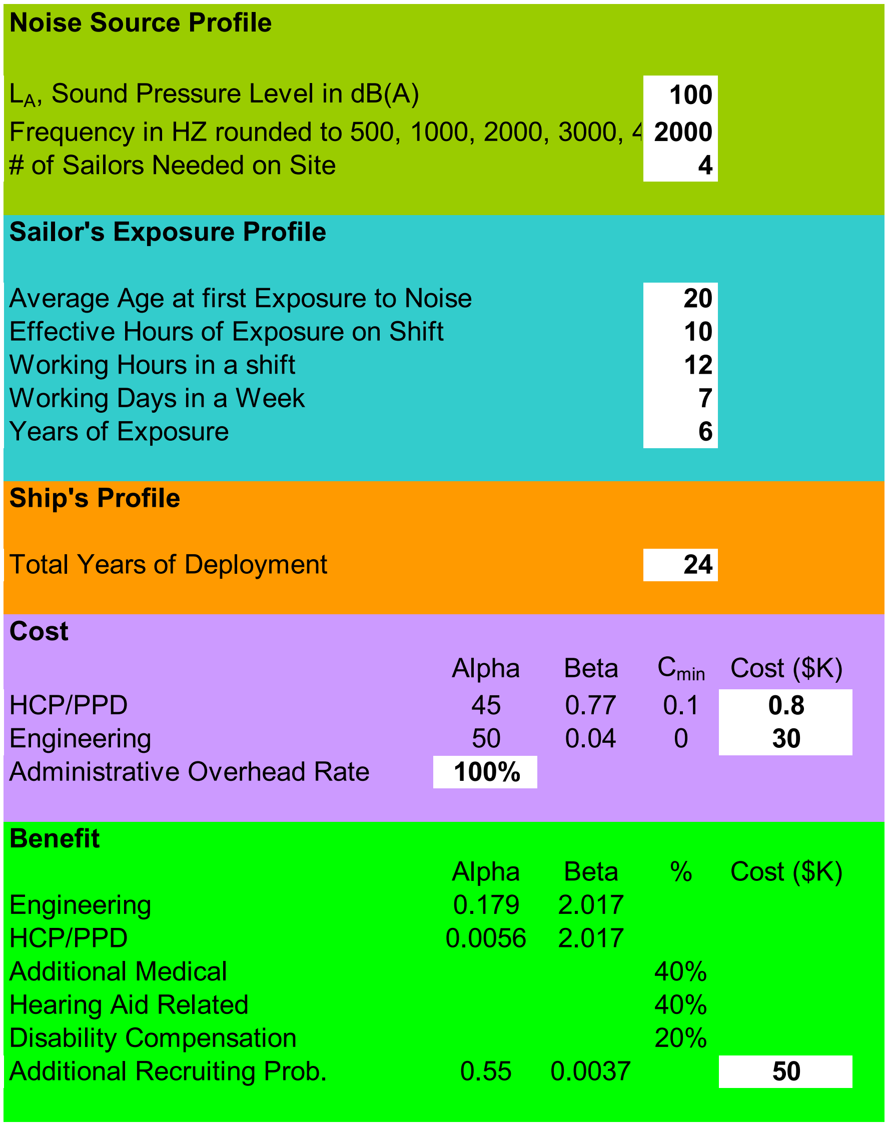
Assumptions, mathematical formulae, and program logic are explained in chapters 2 and 3 of the paper.

Input page

The input column on each sheet allows users to enter values for each noise source on a ship. Five color-coded blocks of information are needed, as shown in figure 7 below. These five blocks of information are: (1) information regarding the noise source, (2) the profile of a typical sailor working at the noise site, (3) the ship's profile, (4) information needed to calculate the cost of the noise reduction measures, and (5) information needed to compute the avoidable cost (benefit).

Figure 7 shows a sample set of input values. Note that only non-color coded cells will take values set by users. All other color-coded cells are password protected to avoid accidental alternations.

Figure 7. Sample input values



Noise Source Profile

L_A, Sound Pressure Level in dB(A)	**100**
Frequency in HZ rounded to 500, 1000, 2000, 3000, 4	**2000**
# of Sailors Needed on Site	**4**

Sailor's Exposure Profile

Average Age at first Exposure to Noise	**20**
Effective Hours of Exposure on Shift	**10**
Working Hours in a shift	**12**
Working Days in a Week	**7**
Years of Exposure	**6**

Ship's Profile

Total Years of Deployment	**24**

Cost

	Alpha	Beta	C_{min}	Cost ($K)
HCP/PPD	45	0.77	0.1	**0.8**
Engineering	50	0.04	0	**30**
Administrative Overhead Rate	**100%**			

Benefit

	Alpha	Beta	%	Cost ($K)
Engineering	0.179	2.017		
HCP/PPD	0.0056	2.017		
Additional Medical			40%	
Hearing Aid Related			40%	
Disability Compensation			20%	
Additional Recruiting Prob.	0.55	0.0037		**50**

In the dull green block named "Noise Source Profile," a user needs to input three pieces of information: (1) sound pressure measured in dB, (2) frequency in Hz, and (3) number of sailors needed to work at the site. Note that the frequency of noise source is conventionally rounded into six values – 500, 1000, 2000, 3000, 4000, and 6000.

In the dull blue block named "Sailor's Exposure Profile," a user needs to input five pieces of information of a "typical" sailor working at the site: (1) age at first exposure to the noise, (2) actual exposure hours in a shift, (3) number of hours in a shift, (4) number of working days in a week, and (5) total number of years of exposure. A "typical sailor" at the site can be described by average values of all sailors working at the site.[21]

In the brown block named "Ship Profile," a user needs to input two pieces of information: (1) the life expectancy of the ship and (2) the number of years of deployment.

The next two blocks in purple and bright green contains two types of input information: those non-color coded cells to be input by a user and those in color coded cells to be input by the calculator designer. The latter are values obtained from statistical estimation.

In the purple block named "Cost," a user needs to input three pieces of information: (1) the total cost (in thousand dollars) spent on HCP and PPD measures per sailor, (2) the total engineering cost (in thousand dollars) designated to reducing noise generated from this source, and (3) the assumed administrative overhead rate. We did keep this Block of data unlocked so users can do scenario sensitivity studies, since the impact of these variables on the outcome may be of interest to users.

In the last block in bright green named "Benefit," a user needs to input the recruiting cost per sailor. We again kept this cell unlocked to allow for scenario sensitivity studies since its impact on the outcome may be of interest to users.

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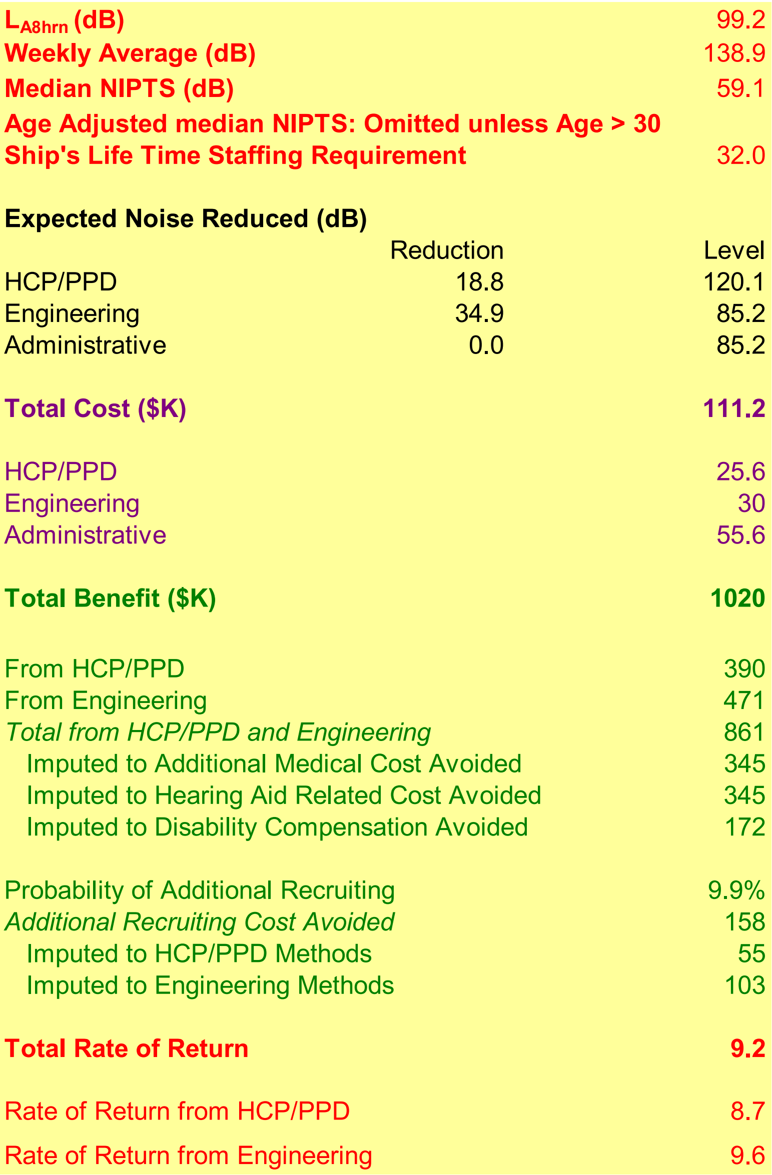
[21] In the future, if more accuracy is needed, it is possible to have a sailor's exposure profile imputed for each individual sailor.

Output page

As soon as the input column on the left is filled in by a user, the output results are immediately shown on the right column color coded in yellow, shown in figure 8 for each single source as well as on the output sheet for the whole platform, shown in figure 9.

Figure 8. Sample output for a single source



L_{A8hrn} (dB)		99.2
Weekly Average (dB)		138.9
Median NIPTS (dB)		59.1
Age Adjusted median NIPTS: Omitted unless Age > 30		
Ship's Life Time Staffing Requirement		32.0
Expected Noise Reduced (dB)		
	Reduction	Level
HCP/PPD	18.8	120.1
Engineering	34.9	85.2
Administrative	0.0	85.2
Total Cost ($K)		**111.2**
HCP/PPD		25.6
Engineering		30
Administrative		55.6
Total Benefit ($K)		**1020**
From HCP/PPD		390
From Engineering		471
Total from HCP/PPD and Engineering		861
Imputed to Additional Medical Cost Avoided		345
Imputed to Hearing Aid Related Cost Avoided		345
Imputed to Disability Compensation Avoided		172
Probability of Additional Recruiting		9.9%
Additional Recruiting Cost Avoided		158
Imputed to HCP/PPD Methods		55
Imputed to Engineering Methods		103
Total Rate of Return		**9.2**
Rate of Return from HCP/PPD		8.7
Rate of Return from Engineering		9.6

There are five blocks of output, with each being ink color-coded. The first block in red ink provides results on the equivalent sound pressure in dB for a normalized 8 working hour shift, normalized weekly average, median NIPTS, and the median NIPTS excluding age effect.[22]

The second block in black ink gives expected noise reductions and expected levels of noise reduced due to both HCP/PPD and Engineering methods. Note that we have assumed that administrative measures could be taken by altering, a sailor's working hours in a day, working days in a week, number of years exposed, and so forth. We do this just in case one wants to add administrative noise reduction methods in the future.

The third block in purple ink lists the expected costs of HCP/PPD and engineering methods, plus administrative overhead costs, which is based on the sum of the HCP/PPD and engineering costs. Total cost is simply the summation of the three items: (1) HCP/PPD costs, (2) engineering costs, (3) administrative overhead costs, assumed to be 100 percent for now.

The fourth block in green ink provides two sets of results related to expected benefits. The top set gives the expected benefits (avoidable cost) achieved by HCP/PPD and the engineering methods, respectively. The total benefits derived from HCP/PPD and engineering methods are imputed to three types of avoided cost: (1) additional medical cost avoided, (2) hearing aid related cost avoided, and (3) VA disability compensation avoided. The bottom set in this block gives the expected probability of additional recruiting incurred by high noise level and the associated expected additional recruiting cost avoided from the total dB reduction from both methods. The lower set gives the benefit from lower recruiting and training cost if the noise is reduced.

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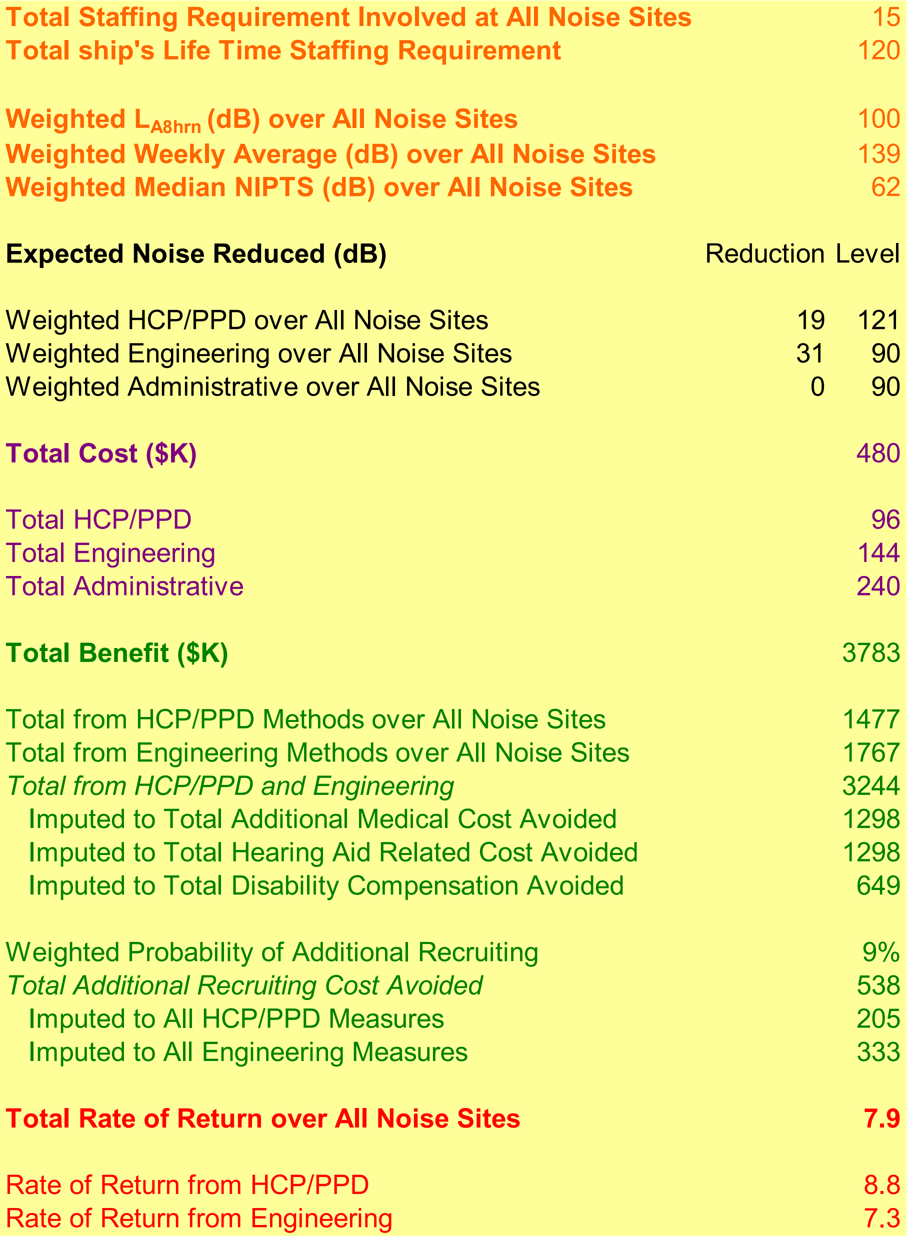
[22] The last item is not programmed in this version of the calculator. We can program this cell later if one believes many sailors start working at the site at various ages, or if the sound pressure at the source is sufficiently higher than 110 dB. This added sophistication will not change the results.

Finally, the last block in red ink lists the expected rates of return on investment from reducing noise on ships, including the total rate of return and the rates of return from investment on HCP/PPD and engineering methods, respectively.

Figure 9. Sample output for an entire platform



Total Staffing Requirement Involved at All Noise Sites		15
Total ship's Life Time Staffing Requirement		120
Weighted L_{A8hrn} (dB) over All Noise Sites		100
Weighted Weekly Average (dB) over All Noise Sites		139
Weighted Median NIPTS (dB) over All Noise Sites		62
Expected Noise Reduced (dB)	Reduction	Level
Weighted HCP/PPD over All Noise Sites	19	121
Weighted Engineering over All Noise Sites	31	90
Weighted Administrative over All Noise Sites	0	90
Total Cost ($K)		480
Total HCP/PPD		96
Total Engineering		144
Total Administrative		240
Total Benefit ($K)		3783
Total from HCP/PPD Methods over All Noise Sites		1477
Total from Engineering Methods over All Noise Sites		1767
Total from HCP/PPD and Engineering		3244
Imputed to Total Additional Medical Cost Avoided		1298
Imputed to Total Hearing Aid Related Cost Avoided		1298
Imputed to Total Disability Compensation Avoided		649
Weighted Probability of Additional Recruiting		9%
Total Additional Recruiting Cost Avoided		538
Imputed to All HCP/PPD Measures		205
Imputed to All Engineering Measures		333
Total Rate of Return over All Noise Sites		**7.9**
Rate of Return from HCP/PPD		8.8
Rate of Return from Engineering		7.3

Similar output items for the whole ship platform are given on the sheet titled “The Whole Platform.” There are a number of matters that need to be noted in figure 9. The first two lines report the total number of sailors involved in all noise sites at any given time and the ship’s life time staffing requirement. Aggregations of the seven variables are obtained by summing over the three sources of noise, by weighting the sum by number of total sailors. These aggregations are: L_{A8hrn}, weekly average, median NIPTS, noises reduced by HCP/preventive, engineering and administrative measures, and probability of additional recruiting. Items in cost and benefit blocks are simple summations over the three noise sources.

Maintenance, updates, and further improvements

Before this calculator is applied to a ship platform, input from the program manager of the ship on noise sources and staffing is needed. The current calculator is designed for a general type of ship, and more precise results can be obtained for a particular ship by working with the program manager of the ship to specify the functional form and parameter values that are pertinent to that ship. As this specific ship data becomes available, parameter values can then be re-estimated in order to improve the accuracy of the model.

The calculator provides a framework to encompass many future developments in noise reduction measures such as the use of ANR or berthing areas. Newer version of the calculator will be needed to reflect those new developments.

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Appendix C: Noise information on LHD

Table 8. Top noise compartments on the LHD-1 to 7 with greater than 89 dB

Location [a]	Cmpt No.	Use Cat	SB Cat	dB	Manning during GQ and cond IA (~ 60 hrs / month)	Manning during peacetime steaming (24 hrs / day)	Berthing com-partment (6-7 hrs / day)	Cleaned (~ 1 hr / day)	People working (6-7 hrs / day)
(1) Machinery Room # 2	6-81-0-E	D	H	102	17 people	12 people			5 people
Machinery Room # 2				96					
Machinery Room # 2				97					
(2) Machinery Room # 1	6-65-0-E	D	H	100	20 people	13 people			7 people
Machinery Room # 1				100					
Machinery Room # 1				98					
Machinery Room # 1				97					
Machinery Room # 1				96					
(3) Stern Gate Machinery No 1	4-125-1-E	D	H	98					4 people
Stern Gate Machinery Room No 1				95					
Stern Gate Machinery Room No 1				89					
(4) Vehicle Stwg	4-49-0-A	D	H	97					10 people
Vehicle Stwg				97					
(5) Fire Pump Room	5.5-97-0-E	D	H	97	Unmanned	Unmanned		1 people	2 people
Fire Pump Room	5.5-97-0-E	D	H	94					
(6) Injr test Area (ICE)	3-85-2-Q	E	E	97					3 people
Injr Test Area (ICE)				96					

Location [a]	Cmpt No.	Use Cat	SB Cat	dB	Manning during GQ and cond IA (~ 60 hrs / month)	Manning during peacetime steaming (24 hrs / day)	Berthing compartment (6-7 hrs / day)	Cleaned (~ 1 hr / day)	People working (6-7 hrs / day)
Injr Test Area (ICE)				92					
Injr Test Area (ICE)				90					
(7) Vestibule	7-121-1-L	D	D	97	Unmanned	Unmanned	Unmanned	Unmanned	Unmanned
(8) Fire Pump Room	5.5-99-0-E	D	H	96	Unmanned	Unmanned		1 people	2 people
(9) TO Bag Strm No. 1	02-13-4-A	D	H	96	Unmanned	Unmanned		Unmanned	Unmanned
(10) A/C Machinery Room	4-89-2-E	D	H	96	3 people	2 people		1 people	2 people
(11) Incinerator Room	1-70-1-Q	D	D	96				1 people	4 people
(12) Fan Room	01-51.5-1-Q	D	D	96	Unmanned	Unmanned		1 people	
(13) Repair 5A Stowage No. 2	1-85-2-A	D	H	95	11 people			2 people	
Prop Repair 5A Stowage No. 2	1-85-2-A	D	H	92					
(14) Propulsion Repair 5A No. 2	1-86-2-Q	E	E	95	11 people			2 people	
Propulsion Repair 5A No. 2	1-86-2-Q	E	E	92					
(15) Strm Ships' Store (COO)	4-77-1-A	D	H	94	Unmanned	Unmanned		1 people	
Strm Ships' Store (COO)	4-77-1-A	D	H	91					
(16)Emerg DG Rm No1 & A/C Plant	4-41-2-E	D	H	94	2 people			1 person	4 people
(17) RAS Sta	1-90-1-Q	E	E	94				1 people	2 people
RAS Sta	1-90-1-Q	E	E	91					
(18) Steering Gear Room No. 2	7-121-2-E	D	D	94	3 people	none		1 people	1 people
Steering Gear Room No. 2	7-121-2-E	D	D	91					

Location [a]	Cmpt No.	Use Cat	SB Cat	dB	Manning during GQ and cond IA (~ 60 hrs / month)	Manning during peacetime steaming (24 hrs / day)	Berthing compartment (6-7 hrs / day)	Cleaned (~ 1 hr / day)	People working (6-7 hrs / day)
Steering Gear Room No. 2	7-121-2-E	D	D	89					
(19) Fan Room	4-65-1-Q	D	D	93				1 people	
(20) SD Str, (Avn Flmb)	3-121-1-A	D	H	93				1 people	
SD Str, (Avn Flmb)	3-121-1-A	D	H	86					
(21) Avn Fuel Maint Shop and Rpr Team	01-125-1-Q	E	E	92				1 people	5 people
(22) I/O haul Machinery Room	3-87-2-E	D	H	92				1 people	1 people
(23) Engine Test Rpr (ICE)	3-82-2-Q	E	E	92				1 people	7 people
Engine Test Rpr (ICE)	3-82-2-Q	E	E	89					
(24) SD Strm Rpr Parts No. 7	4-101-2-A	D	D	92					2 people
(25) Fwd Cprsr Mchry Room	5-37-0-E	D	D	92				1 people	2 people
(26) Emerg Gen Rm. No. 2	3-114-2-E(LL)	D	D	91	2 people			1 people	2 people
Emerg Gen Rm. No. 2	3-114-2-E(UL)	D	D	90					
(27) Shaft Alley No. 6	7-105-2-E	D	D	91	1 people	none		1 people	
(28)Troop Living spce and Cas Ovf	01-41-0-L	B	B	91			Up to 30 troops		
(29)Steering Gear Room No. 1	7-121-3-E	D	D	91	3 people	none		1 people	
Steering Gear Room No. 1	7-121-3-E	D	D	91					
Steering Gear Room No. 1	7-121-3-E	D	D	90					
Steering Gear Room No. 1	7-121-3-E	D	D	88					

Location [a]	Cmpt No.	Use Cat	SB Cat	dB	Manning during GQ and cond IA (~ 60 hrs / month)	Manning during peacetime steaming (24 hrs / day)	Berthing com-partment (6-7 hrs / day)	Cleaned (~ 1 hr / day)	People working (6-7 hrs / day)
(30) Shaft Alley (Stbd)	7-89-3-E	D	H	91	1 people	none			
(31) Crew and Troop Galley	1-49-0-Q	D	D	90	5 people	12 people			
(32) Thaw Room	1-49-1-A	D	D	90	unmanned	unmanned			
(33) Ship Store Strm No. 8	5.5-97-0-A	D	H	90	unmanned	unmanned			
(34)Ship Store Strm No. 4	4-49-4-A	D	D	90	unmanned	unmanned			
(35) Repair 5A Stowage No. 1	1-84-6-A	D	H	90				1people	2 people
(36) Vestibule	02-13-6-L	D	H	90					
(37) Aft Compr Machinery Room	4-97-2-E	D	H	90				1people	2 people
(38) Stern Gate Machinery No. 2	4-125-2-E	D	H	90				1people	2 people
(39) Propulsion Repair 5A No. 1	1-84-2-Q	E	E	90	45 people			2 people	
(40) Propulsion Repair 5A No. 1	1-84-2-Q	E	E	90					
(41)Deball Comp Room	3-113-2-E	D	D	90					2 people

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a. Multiple measurements on the same Location are grouped together

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