

# A key to quieter seas: half of ship noise comes from 15% of the fleet

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Underwater noise pollution from ships is a chronic, global stressor impacting a wide range of marine species. Ambient ocean noise levels nearly doubled each decade from 1963-2007 in low-frequency bands attributed to shipping, inspiring a pledge from the International Maritime Organization to reduce ship noise and a call from the International Whaling Commission for member nations to halve ship noise within a decade. Our analysis of data from 1,582 ships reveals that half of the total power radiated by a modern fleet comes from just 15% of the ships, namely those with source levels above 179 dB re 1  $\mu$ Pa @ 1 m. We present a range of management options for reducing ship noise efficiently, including incentive-based programs, without necessarily regulating the entire fleet.

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## 1 Abstract

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4 to shipping, inspiring a pledge from the International Maritime Organization to reduce ship noise and a  
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9 necessarily regulating the entire fleet.

## 10 Introduction

11 At its June 2016 meeting, the Scientific Committee of the International Whaling Commission (IWC) agreed  
12 that chronic ocean noise is increasing in many regions and adversely affecting populations of whales and  
13 other cetaceans (IWC Scientific Committee, 2016). Emerging evidence links chronic ocean noise to negative  
14 effects not only on marine mammals (Rolland et al., 2012; Williams et al., 2015) but also fish (Popper and  
15 Hawkins, 2016) and invertebrates (Wale et al., 2013). Ships are a major source of chronic ocean noise,  
16 responsible for doubling low-frequency levels every decade throughout the second half of the 20th century

17 (McDonald et al., 2006; Andrew et al., 2011). In some coastal and other high-traffic areas, ship noise has  
18 reached levels that degrade habitat for endangered species of whales and other marine wildlife (Hatch et al.,  
19 2012; Erbe et al., 2014).

20 These developments have inspired a number of recent policy initiatives to reduce noise pollution from ships.  
21 Prominently, the International Maritime Organization issued voluntary guidelines in 2014, building on earlier  
22 targets (Wright, 2008) and encouraging industry to reduce underwater radiated ship noise in the 10-300 Hz  
23 band (Dekeling et al., 2014; IMO/MEPC, 2014). In 2016 the U.S. National Oceanic and Atmospheric  
24 Administration launched an agency-wide [Ocean Noise Strategy](#) to better integrate risk assessment and  
25 mitigation of chronic ambient noise pollution into federal planning actions. European legislation treats  
26 ocean noise as a pollutant, and requires member states ultimately to attain “good environmental status”  
27 with respect to noise across multiple marine regions (URN, 2014; Audoly et al., 2015; Garrett et al., 2016;  
28 [Merchant et al., 2016](#)). In some jurisdictions, most recently Canada, governments have committed themselves  
29 to regulate shipping noise, but none have yet devised a management system to meet a ship noise reduction  
30 target.

31 In addition to aspirational targets to improve global ocean health, efforts to reduce ship noise also have  
32 immediate implications for economic development and endangered species conservation. The southern res-  
33 ident killer whale (SRKW) is an endangered population with critical habitat that spans the international  
34 (Canada-U.S.) border and encompasses shipping lanes serving the ports of Vancouver (British Columbia,  
35 Canada) and Seattle-Tacoma (WA, U.S.). Both Canada and the U.S. have recognized ocean noise as a  
36 threat to SRKW recovery (NMFS, 2008; DFO Canada, 2011). There are a number of large-scale industrial  
37 development proposals pending for this region (Gaydos et al., 2015) that could increase ship traffic and raise  
38 ocean noise levels. Both countries must consider ocean noise in SRKW critical habitat when assessing envi-  
39 ronmental impacts of proposed developments, and balance economic growth with conservation of endangered  
40 species. All of SRKW summertime critical habitat is ensonified already at levels exceeding one European  
41 threshold defining good environmental status ([Christine Erbe et al., 2012](#)), so it could be argued that noise  
42 reduction has become a necessary precursor to additional industrial development in this region.

43 What would be required of industry to substantially reduce noise from commercial ships (which originates

44 primarily from cavitation at the propeller, but also from shipboard machinery noise transmitted through  
45 the hull)? To understand what would be necessary, we considered the quantitative noise reduction target  
46 reaffirmed in the summer of 2016 by the IWC's Scientific Committee, namely reducing the contributions of  
47 shipping to ocean ambient noise in the 10-300 Hz frequency band by 3 dB (halving the total radiated power)  
48 within 10 years, and by 10 dB within 30 years (IWC Scientific Committee, 2016). We explored various  
49 mechanisms to attain this -3 dB/decade target, including reducing the number, acoustic source level, or  
50 speed of ships.

## 51 Methods

52 We assessed four distinct management options by using an R script (see supplemental information) to analyze  
53 2,800 source level measurements of 1,582 unique, isolated ships recorded as they transited northbound in  
54 Haro Strait, a shipping channel within the Salish Sea (Veirs et al., 2016). For ships in the data set with  
55 multiple transits we averaged the source spectrum levels (power spectral density) over all available transits.

56 To assess the relative noise contributions of different ships in our sample of the local fleet (the population  
57 of 1,582 ships in 12 ship classes northbound in Haro Strait), we integrated the source spectrum levels for  
58 each unique ship to acquire the total power (watts) radiated by each ship in a frequency band relevant to  
59 SRKWs (10-40,000 Hz). This band is wider than the 10-300 Hz band stipulated in the noise reduction target  
60 endorsed by the IWC. We chose to broaden the band because ship noise at ranges less than ~3 km extends  
61 beyond 300 Hz to frequencies where SRKW hearing is most sensitive (Veirs et al., 2016).

62 After integration, we sorted the total radiated power levels for all ships, ranking them from lowest to highest.  
63 Then we summed the power from all ships, yielding the cumulative total radiated power – a distribution  
64 we used to assess quantitatively a range of management options that would accomplish a 3 dB reduction in  
65 the total noise radiated by this population of ships. Finally, we converted individual ship source levels from  
66 watts to dB re 1  $\mu$ Pa @ 1m. (Note, however, that we abbreviate the resulting broadband (10-40,000 Hz)  
67 source levels as “dB” in this paper for brevity.)

68 We used an iterative method to understand the first two management options: removal of gross polluters  
69 (ships with the highest source levels of the fleet); and reduction of gross polluter source levels to a threshold  
70 that achieves the desired halving of power overall. For the first option, we removed the loudest ship from  
71 the population and re-calculated the total radiated power of the remaining fleet. If the initial total power  
72 was not yet halved, then we repeated the process. For the second option, we also calculated the reduction  
73 threshold iteratively. We lowered the source level of the loudest ship to the level of the next-loudest ship in  
74 each iteration until the total power radiated by the fleet was halved.

75 To help managers more deeply understand the practical implications of these two management options, we  
76 tabulated the number of ships affected (Table 1). To allow easy extrapolation to the global fleet or other  
77 regional subpopulations of it, we also tabulated the number of affected ships as a percentage of both our  
78 population and, where applicable, the total number of ships in each class.

79 The third noise management option was motivated by the observation that for many ships a 1 knot reduction  
80 in speed leads to 1 dB reduction in broadband underwater source level (Veirs et al., 2016). We found the  
81 speed limit needed to achieve the 3 dB reduction iteratively by: reducing the speed of each loudest ship  
82 to the selected speed limit; making a proportional reduction in the source levels (assuming the -1dB/knot  
83 relationship applied to all ships); re-integrating the new source level distribution; and checking to see if the  
84 reduced total power equaled half of the initial total power.

85 The fourth management option was requiring a 3 dB reduction of every ship in the fleet. Assessing this  
86 option required no new computation.

## 87 Results and discussion

88 The cumulative distribution of source levels (Figure 1) in our dataset ranges from 141-186 dB and has two  
89 inflection points, with ~80% of the population having intermediate source levels of 165-180 dB. The absolute  
90 value the calibrated source levels in this distribution may differ in other regions (which may host a different  
91 subset of the global fleet) or in other studies of the Haro Strait fleet (e.g. with different assumptions about  
92 transmission loss), but the distribution of values will have a similar form.

93 From a policy perspective, the most important aspect of the source level distribution is that half the total  
94 power is radiated by just 15% of the ships in the fleet (i.e., those with source levels greater than 179.0 dB).  
95 More than two-thirds of these gross polluters are cargo and container ships, with each class containing ~90  
96 such vessels in our population (Table 1, Figure 2). About 43% of container ships are gross polluters, by far  
97 the highest proportion of any ship class in our dataset.

98 Management options could focus on gross polluters by targeting fleet size or operations. In the region where  
99 our data originated, for example, managers could halve the total power radiated by this ship population by  
100 removing the loudest 15% of the fleet ( $n \sim 240$  ships) or by reducing the source levels of the loudest 42.8%  
101 of the fleet ( $n \sim 677$  ships) to 175.4 dB (Table 1). These results confirm empirically the idea of dramatically  
102 reducing acoustic pollution by targeting the noisiest ships for quieting (Leaper et al., 2014). The maximum  
103 reduction required by the 175.4 dB threshold, about 10 dB, should be attainable with existing quieting  
104 technologies (Southall and Scholik-Schlomer, 2008) and techniques (Audoly et al., 2015), or for many types  
105 of new ships with only a 1% increase in design/build costs (Spence and Fischer, 2016).

106 Because container ships had the highest average source levels ( $178 \pm 4$  dB) of the 12 ship classes we ana-  
107 lyzed (Veirs et al., 2016), they would be most affected by policies that target gross polluters (Table 1). In  
108 our population of container ships, 43% would be affected by the removal option, while almost 90% would be  
109 affected by the noise reduction option. By contrast, some ship classes would be completely unaffected by any  
110 management option that limits source levels. No fishery, pleasure, or military ships in our population had  
111 source levels exceeding 175 dB, possibly due to military, fishery, and research classes having already adopted  
112 ship-quieting technologies (Southall and Scholik-Schlomer, 2008), including propulsion systems that reduce  
113 cavitation, quieter onboard machinery, and shock-absorbing mounts.

114 Of the management options considered, speed limits appear most likely to reduce noise quickly – by making  
115 an operational change, rather than undertaking replacements, retrofits, or maintenance. Because most ships  
116 can reduce their broadband source level by ~1 dB by slowing down by 1 knot (Veirs et al., 2016), in our  
117 study area the 3 dB noise reduction target could be met by enforcing a speed limit of 11.8 knots (6.1 m/s)  
118 which would affect 83% of the ship population. For comparison, the mean and standard deviation of the

119 speed distribution is  $14.1 \pm 3.9$  knots for the ship population and  $19 \pm 2$  knots for the fastest class, container  
120 ships (Veirs et al., 2016). While the compliance burden would fall more broadly across the fleet than with the  
121 removal or reduction options (Figure 2), faster-moving ships would be required to reduce speed more than  
122 other ships, and slow-moving classes would be unaffected. If a uniform speed limit of 11.8 knots conflicts  
123 with the “bare steerage” speed required for safe navigation of ships in a particular class, the 3 dB reduction  
124 could also be achieved by having all ships in the fleet decrease their speed by 3 knots (Figure 2).

125 Any noise reduction achieved by decreasing ship speed will increase the time that species are exposed to the  
126 lower noise levels. Behavioral response and masking are driven not only by the noise level, but also by a  
127 temporal overlap between the noise and the animal. A reduction of 3 dB in the total radiated power of ships  
128 does not address this temporal overlap, but in our study area, it would likely increase the functional acoustic  
129 space of SRKWs substantially and lower the maximum ship noise exposures that could cause behavioral  
130 responses or masking in the species (Holt, 2008; Williams et al., 2013, 2014, 2016). Such benefits should  
131 be weighed against the increase in temporal overlap that may result from speed reduction. At the same  
132 time, other environmental effects of a speed limit should be considered, including altered fuel efficiency (air  
133 pollution) and risk of collisions (oil spills and ships striking baleen whales).

134 Proven technologies and techniques (Southall and Scholik-Schlomer, 2008; Audoly et al., 2015) exist for  
135 reducing ship noise. Combinations of them, without necessarily altering speed, could be used to reduce source  
136 levels by 3 dB in each ship across the entire fleet, or just in gross-polluting ships. To date, however, minimal  
137 mitigation has been undertaken by the commercial shipping industry, either due to lack of regulation or  
138 incentives to adopt them. Management vehicles include, at least: regulated vessel speed limits in biologically  
139 important habitat, like those mandated off the U.S. East Coast to reduce ship strike mortality in North  
140 Atlantic right whales; tax incentives or subsidies to retrofit or replace noisy ships with quieter ones, for  
141 which designs already exist (Leaper et al., 2014); regulated noise emission standards for all or some ships  
142 entering into a state’s internal waters; or port-based incentives and other measures. As examples of the latter,  
143 the Port of Vancouver, one of the largest ports in SRKW critical habitat, is reducing berthing fees through  
144 its EcoAction program to reward ships that are accredited as quiet by ship-classification societies, and in  
145 2017 piloted a voluntary slow-down in Haro Strait with a speed limit of 11 knots (speed through water) in  
146 which compliant ships could receive a \$500 stipend.

147 Studies of the distribution of acoustic polluters, along with what determines the maximum and minimum  
148 source levels in each ship class, will help guide the creation of regional or port-devised incentives or regulatory  
149 requirements to reduce underwater noise pollution. Although our sample is drawn from one site in the  
150 northeastern Pacific Ocean, it represents one of the largest archives of calibrated source characteristics for  
151 ships anywhere in the world. If the distribution of source levels in our data set is statistically representative  
152 of the noise output from the global fleet, or other regional subsets of it, then our results may be used to  
153 assess options for managing oceanic noise beyond our study area.

## 154 Conclusions

155 The distribution of source levels in our ship population indicates an opportunity to halve radiated noise levels  
156 by managing as little as 15% of the fleet. If removal of the gross polluters is not feasible, reducing the source  
157 levels of the top 42.8% to an achievable threshold or setting a speed limit of 11.8 knots (affecting 83% of the  
158 fleet) could also yield major environmental improvements. Despite projections of ship noise rising through  
159 2030 (Frisk, 2012), optimal management of the global fleet could begin to reduce the current detrimental  
160 levels of noise without necessarily regulating the entire fleet.

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167 generation. All authors contributed to the writing of the manuscript.  
168



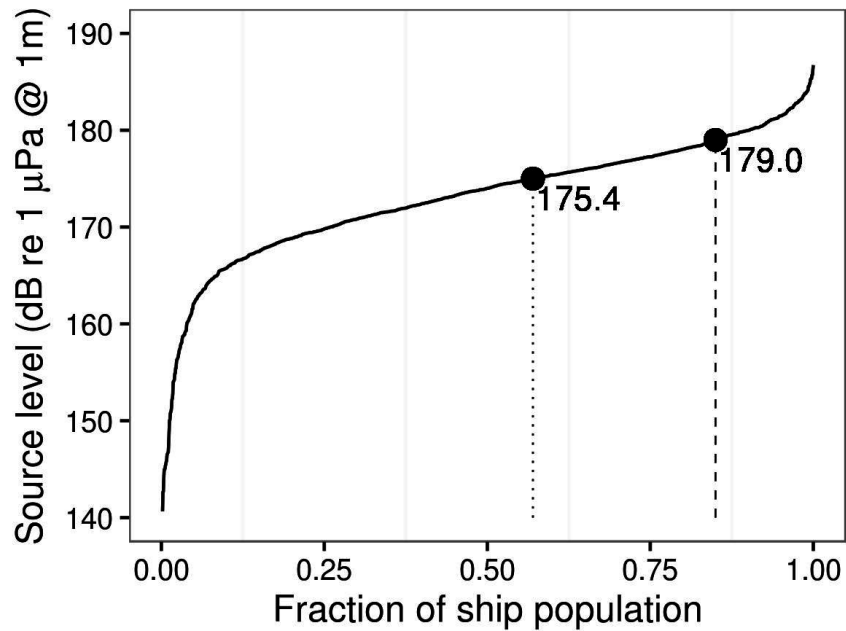
169 **Figures and tables**170 **Figure 1**

Figure 1: **Cumulative distribution of source levels with two management options** Cumulative distribution of source levels for the ship population (solid curve). Two management options for halving of the total power radiated by the fleet are depicted by vertical lines: removing the 15% of ships with source levels > 179.0 dB (dashed line); and reducing source levels of 42.8% of the ships to 175.4 dB (dotted line).

171 **Figure 2**

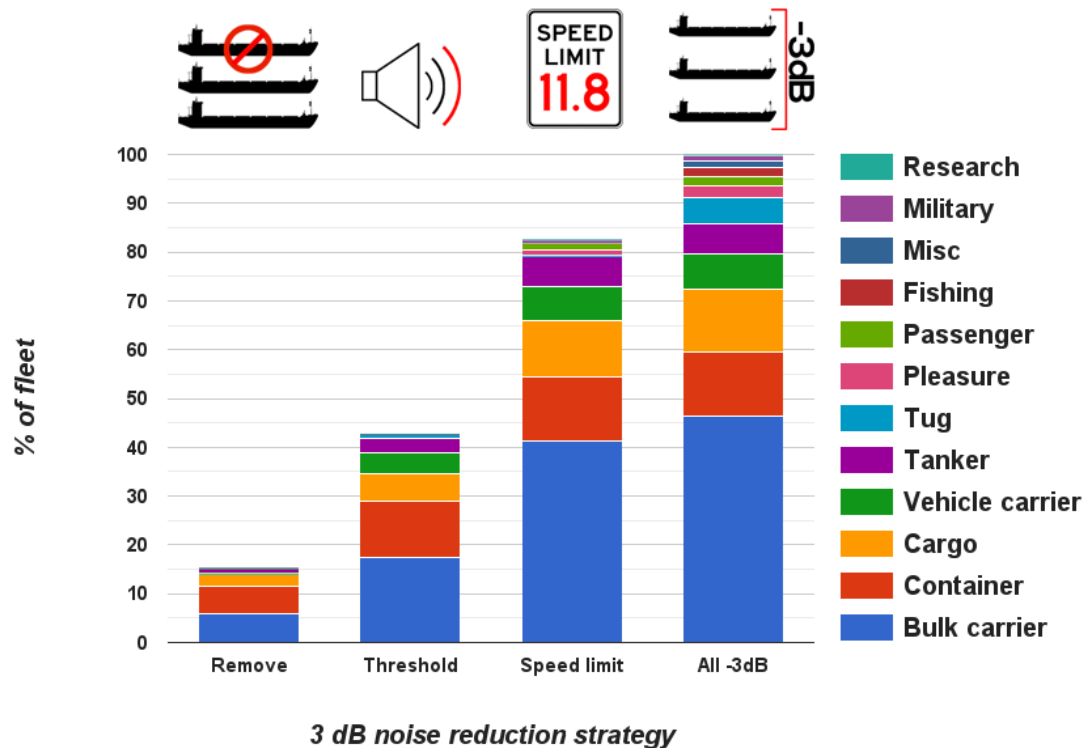


Figure 2: **Proportion of fleet affected by four noise reduction strategies** The height of each stacked bar represents the percentage of the fleet (population of 1,582 ships) that would be affected by four different strategies for halving the total radiated power. Removal of gross polluters affects 15%; limiting them to a noise threshold of 175.4 dB affects 42.8%; enforcing a speed limit of 11.8 knots affects 83%; and having all ships reduce their source level by 3 dB affects 100%. Colors indicate the classes of affected ships and the thickness of any colored bar section depicts the portion of the fleet that has affected ships in the class associated with the color.

172 **Table 1**

173

Management option:		Remove gross polluters (above 179 dB)			Quiet gross polluters (to 175.4 dB)		
Ship class	Total # of ships	# of ships	% of fleet	% of class	# of ships	% of fleet	% of class
All classes	1,582	240	15.2	N/A	677	42.8	N/A

Management option:		Remove gross polluters (above 179 dB)			Quiet gross polluters (to 175.4 dB)		
Ship class	Total # of ships	# of ships	% of fleet	% of class	# of ships	% of fleet	% of class
Bulk carrier	734	94	5.9	13	276	17.4	37.6
Container	207	90	5.6	43	184	11.6	88.9
Cargo	206	36	2.3	17	89	5.6	43.2
Vehicle carrier	111	5	0.3	5	66	4.2	59.5
Tanker	101	12	0.8	12	46	2.9	45.5
Tug	85	2	0.1	2	12	0.8	14.1
Pleasure	35	0			0		
Passenger	31	0			3	0.2	9.7
Fishing	28	0			0		
Miscellaneous	21	1	0.1	5	0		
Military	19	0			0		
Research	4	0			1	0.1	25.0

174 **Table 1. Proportions of fleet and classes affected by two management options aimed at gross**  
 175 **polluters**

176 One option removes gross polluters (ships with source levels greater than 179 dB) while the other requires  
 177 them to use quieting technologies or techniques to reduce their source levels below a threshold of 175.4  
 178 dB. The 2nd column lists the total number of ships in the fleet (“All classes”) and in each class. Then  
 179 for each option and ship class we tabulate the number of ships affected, along with that number expressed  
 180 as a percentage of the whole fleet (1,582 ships) and as a percentage of the ship class (where applicable or  
 181 non-zero).

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