

Methods to Minimize Commercial Vessel Generated Marine Acoustic Pollution



Abstract

Acoustic pollution is endangering marine life both physically and psychologically. Of the many sources of marine acoustic pollution, our team focused on the constant noise from commercial shipping. In collaboration with the United States Coast Guard, we reviewed professional and academic literature and interviewed experts in acoustic pollution. We identified and analyzed 33 methods that have the potential to reduce vessel noise based on six criteria: cost, noise reduction effectiveness, availability, implementation, maintainability, and efficiency. We determined that most methods were designed for efficiency, but also had the potential to reduce noise. To optimize these methods, they must be considered in the early design stages of new vessels.

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Acoustic pollution is endangering marine life by causing physiological and behavioral changes in oceanic species. Marine bioacoustics expert Christopher Clark described the problem as, “acoustical bleaching of the oceans, a human made cacophony that can tear apart the social networks of whales, adversely affecting survival and reproductive success” (Schiffman, 2016). Although international and US-based organizations are leading the attempt to reduce marine acoustic pollution, there are no specific mandatory regulations to support their efforts.

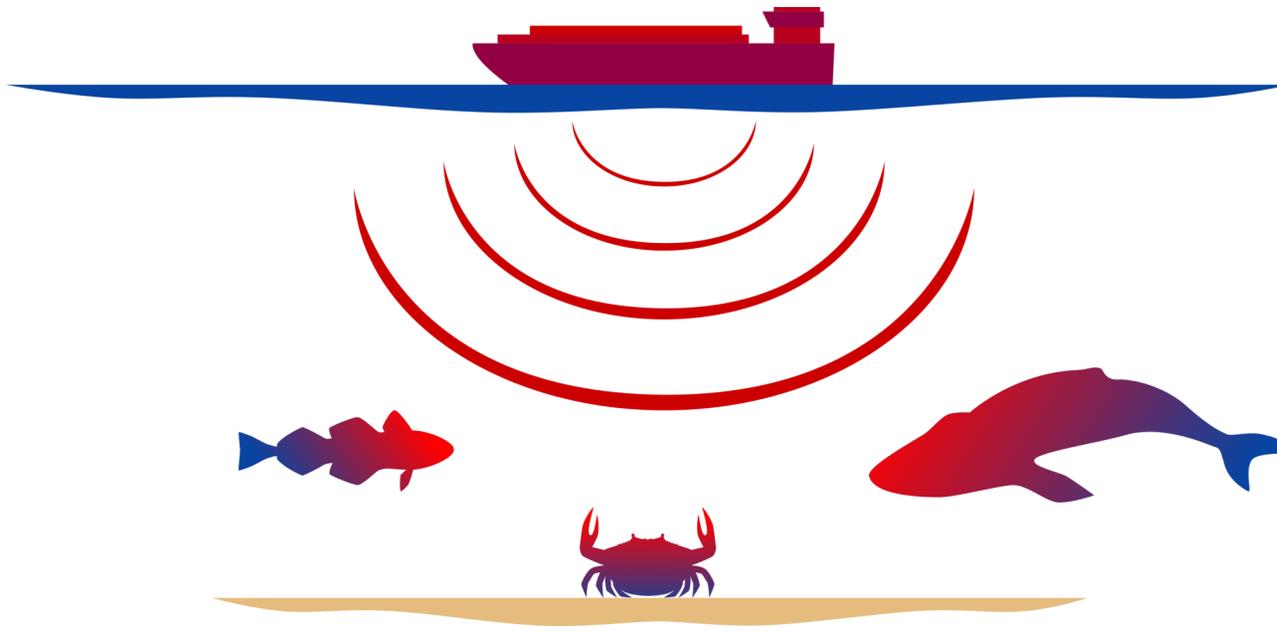
There are many prevalent sources of marine acoustic pollution. These include oil and gas drilling, military sonar, and commercial shipping vessels. Commercial shipping vessels, in particular large cargo vessels, produce a great deal of underwater noise as they travel. As of 2017 there were 50,155 ships in the worldwide commercial

fleet, of which 2,104 were American (United Nations Conference on Trade and Development, 2017). The noise they create causes a variety of adverse effects on marine life, ranging from permanent hearing damage to disruption of feeding, migration, and reproductive behaviors (National Fisheries Service, 2018; International Fund for Animal Welfare & Natural Resource Defense Council, n.d.). The negative effects of acoustic pollution on marine life continue to increase as the industry grows, but several methods can reduce this noise, including low-cavitation propellers and vibration-insulating motor mounts.

While no mandatory regulations on noise pollution currently exist, some organizations in the US and abroad have begun to create voluntary guidelines and identify solutions. One organization is the United States Coast Guard, which is heavily

involved in the promulgation and enforcement of various US maritime regulations, including regulations to address marine pollution. Working with the Coast Guard, we compared and evaluated innovative vessel designs, operational practices, and technologies with the potential to reduce vessel-generated acoustic pollution.

Over the course of 14 weeks our team reviewed extensive literature on available noise quieting solutions, and conducted interviews with naval architects, marine biologists, acoustic design consultants, and government organizations involved in shaping maritime policy. Our research ultimately resulted in a catalogue identifying the most effective noise reduction methods for commercial vessels, which the Coast Guard can reference and update in the future.



The Causes and Consequences of Marine Noise Pollution

Marine acoustic pollution is a complex problem, and its study is still in its infancy. While its sources and mechanisms are reasonably well understood, the exact effects - cumulative noise totals, damage thresholds, and net impacts on different populations - are difficult to quantify. This makes it a difficult issue to tackle, however, this has not stopped researchers from investigating the effects on marine life and potential solutions to reduce the effects.

Noise pollution threatens marine life

Marine acoustic pollution can be broadly defined as man-made underwater noise which causes harm to marine life. There are multiple sources of such pollution, and it affects many types of marine life.

The point at which marine noise reaches the level of pollution is currently a matter of debate among both scientists and policymakers. As of 2013, under the Marine Mammal Protection Act (MMPA), the United States placed the threshold of injury for mammals at a peak pressure of between 180 and 190 dB re 1 μ Pa (Erbe, 2013). By contrast, the National Fisheries Service (NFS) identified different thresholds of injury for five categories of mammals according to their auditory ranges, including three categories of cetaceans and two categories of pinnipeds (seals, walruses, and related species), as shown in Table 1. For each category, the NFS established thresholds

Table 1: Predicted levels of sound which induce permanent hearing damage (Threshold Shift) in different categories of marine mammals, divided by their hearing characteristics (adapted from Table ES3 from National Fisheries Service, 2018).

Hearing Group	Permanent Threshold Shift (Received Levels)	
	Impulsive Sound	Non-Impulsive Sound
Low-Frequency Cetaceans	Peak Pressure: 219 dB SEL _{24H} : 183 dB	SEL _{24H} : 199 dB
Mid-Frequency Cetaceans	Peak Pressure: 230 dB SEL _{24H} : 185 dB	SEL _{24H} : 198 dB
High-Frequency Cetaceans	Peak Pressure: 202 dB SEL _{24H} : 155 dB	SEL _{24H} : 173 dB
Phocid Pinnipeds (Underwater)	Peak Pressure: 218 dB SEL _{24H} : 185 dB	SEL _{24H} : 201 dB
Otariid Pinnipeds (Underwater)	Peak Pressure: 232 dB SEL _{24H} : 203 dB	SEL _{24H} : 219 dB

Note. Impulsive Sound is characterized as brief, with high rise times and rapid decay. Non-Impulsive Sound has none of these characteristics. Peak Pressure refers to the maximum level of a sound source. The Sound Exposure Level (SEL_{24H}) is a standard which accounts for total sound exposure from a source over a given period, in this case 24 hours. For full details see the referenced document.

for temporary or permanent hearing damage, as well as for impulsive sounds (sharp sounds with short rise and fall times) and non-impulsive sounds (sounds with gentler rise and fall curves) (National Fisheries Service, 2018). The MMPA and NFS have not set thresholds for other classes of marine life such as fish or molluscs, or for noise pollution that might negatively influence animal behavior.

Sound of any kind can travel large distances through the oceans. The speed of sound in water drops as temperature drops, and it rises as pressure rises (Figure 1). At the depth where these trends balance, the speed of sound is at its lowest, creating a horizontal channel (the “Sound Fixing

and Ranging” or SOFAR channel), which spans the whole ocean and allows sound waves to travel great distances (Ocean Explorer, n.d.). Because of this, small amounts of acoustic pollution can be felt across whole ecosystems, especially if the pollution originates near the poles where the channel is closer to the surface (Ocean Explorer, n.d.).

There are three primary sources of marine acoustic pollution. While seismic airgun surveys and military and civilian sonar pose their own challenges, the most pervasive form of ocean noise is that created by commercial shipping. Where other sources create periods of particularly intense noise, commercial ship noise is a

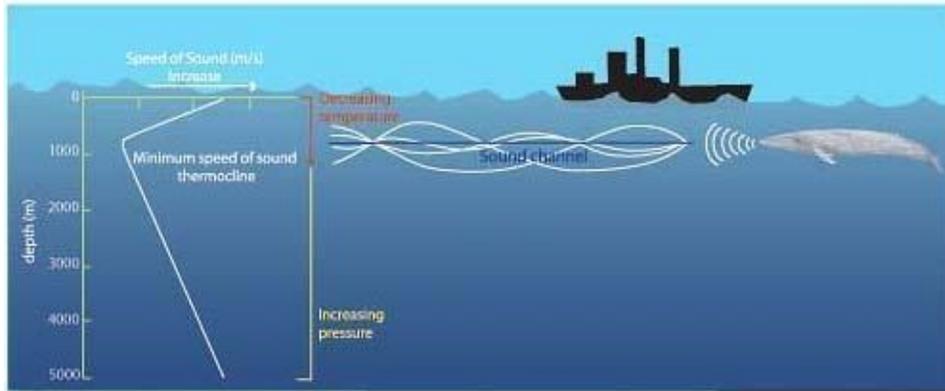


Figure 1. The SOFAR channel (NOAA Ocean Explorer, n.d.)

constant background hum that varies in intensity depending on location. This noise can be strong near major ports, where the rumble of cargo and passenger ships is joined by the noise of numerous tug boats, patrol boats, shuttles, and other smaller craft. Mitigation of ocean noise is a goal being pursued not only by conservationists, but also by engineers hoping to make all of these vessels more efficient (Schiffman, 2016).

The majority of data on the effects of marine acoustic pollution relates to mammals. Noise pollution poses a particular threat to whales because they use sound in a wide variety of feeding, mating, and social behaviors. Sustained noise can drown out the calls whales use to communicate, which inhibits their ability to navigate, feed, and reproduce. Intense noise may cause hearing loss and direct damage to other organs. Whales may become disoriented by noise and dive so deep or fast they suffer embolisms and other adverse outcomes. These symptoms can be seen in necropsies of beached whales, drawing a direct correlation between beaching events and marine acoustic pollution (Simmonds, 2014).

While less concrete data exist supporting the effects of noise on other types of marine life, such

species, such as cod, have also been noted in areas of high marine acoustic pollution. As the levels of marine acoustic pollution grow, many more species will likely see a decline in health and population numbers as depicted in Figure 2 (IFAW & NRDC, n.d.).

Commercial vessels contribute to noise pollution

Every day hundreds of vessels enter and leave ports around the world. These vessels cross the oceans, carrying cargo and passengers, and they play a vital role in the world economy. Such vessels can be

classified by weight and type of cargo. With research is ongoing. Stress responses in invertebrates (Filiciotto, Vazzana, Celi, Maccarron, Ceraulo, Buffa, Di Stefano, Mazzola & Buscaino, 2014) and various physical symptoms in fish have been recorded in experimental studies (Scholik & Yan, 2002). Decreased catches of commercially significant

classified by weight and type of cargo. With more than 50,000 ships, the world merchant fleet is the largest source of noise throughout the ocean. A ship's contribution to acoustic pollution depends both on its size and function. As shown in Table 2 larger ships create more acoustic pollution compared to smaller ships, although the cumulative acoustic pollution will depend on the number of vessels and the length of time at sea (Miller, n.d.).

Shipping traffic around the world is often concentrated in shipping lanes, especially near busy ports. Figure 2 (next page) shows a heatmap of the density of shipping lanes throughout the ocean over one year. In the more congested areas, the cumulative acoustic pollution is intense, but it has detrimental effects on migratory marine life far beyond these lanes.

Table 2: World fleet breakdown (adapted from Hatch, 2008, Royal Academy of Engineering, AD, 2017, and Surveyor, 2002)

Ship Type	Vessel Length (m)	Percentage of Fleet	Noise Contribution per Ship
Tanker	~450	37%	~182 dB
Bulk Carrier	~350 - 400	41%	~179 dB
Container		13%	
General Cargo	~25 - 350	6%	~163 dB
Cruise & Passenger		< 1%	
Services & Research		< 1%	
Tug/Tow Boat		< 1%	

Methods exist to reduce noise pollution

Rising levels of noise pollution in the oceans can be addressed through vessel design, operational practices, and retrofit technology. A combination of these strategies over the long term will be key to addressing the problems of rising noise in the ocean. The United States Coast Guard along with other national and international regulatory bodies are researching specific methods that reduce underwater ship-generated noise.

Ship manufacturers focus on the design of the hull and propeller to minimize marine ship noise. According to the International Maritime

Organization (IMO), the propeller is the greatest source of a ship's noise (IMO, 2014, p.3), due to propeller cavitation. Propeller cavitation is the creation and implosion of water vapor bubbles due to areas of increasing and decreasing pressure along the propeller blades (IMO, 2014, p.2). Propeller cavitation is commonly seen as the white foam trail behind a boat, distinct from the wake or wave that results from the hull pushing through the water. Hull form also has a direct impact on the noise generated from a vessel. The hull must be designed in conjunction with the propeller to maximize the inflow of water, reducing the degree of propeller cavitation (IMO, 2014, p.3).

Many new propellers are designed to increase the cavitation inception speed as a way

to reduce underwater noise. According to the IMO (2014), "Cavitation inception speed is the lowest ship speed at which cavitation occurs" (p.2). Increasing the speed at which cavitation occurs will allow ships to operate at higher speeds with less noise. There are many factors to consider when designing a propeller, including the diameter of the propeller, number of blades, pitch, skew, and sections. Yehia (2011) found propellers that are more skewed or 'swept back' increase the cavitation inception speed (see Figure 3). The role of increasing the skew is to reduce the pressure fluctuation on the surface of the propeller, which helps to reduce the amount of cavitation ("Evaluating skewed propellers", 2013).

Hull forms and propeller designs cannot be easily retrofitted to existing ships; these solutions are better suited for new ships. Current ships can reduce noise by modifying operational practices. Both existing and future ships can reduce ship noise simply by cleaning the propeller and hull regularly (IMO, 2014, p.5). If the hull surface is rough, it will increase the friction between the water and ship, putting more load on the propeller. Reducing load on the propeller will decrease cavitation, reduce noise, and increase fuel efficiency (IMO, 2014, p.5).

Sound-quieting technologies are flexible solutions that can be used in new ships and retrofitted to old ships. Two current approaches are the use of vibration-insulating mounts for on board machinery, and the use of a dual propulsion engine, specifically the diesel-electric engine. Malakoff (2010, p.1502-1503) explained the benefits of mounting engines and machinery on sound-absorbing platforms, although others note it would be impractical to use sound absorbing platforms for direct-drive diesel engines because

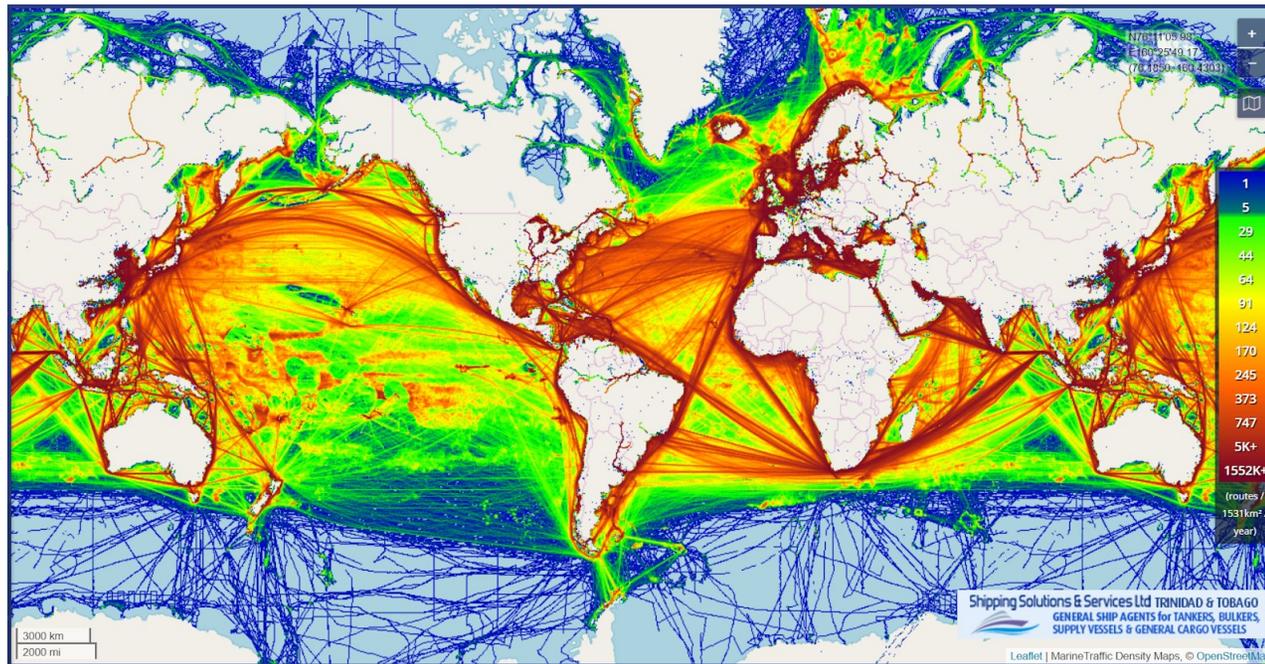


Figure 2: World trade routes, using a heat map gradient to highlight trade concentration (Marine Traffic, 2016-2017).

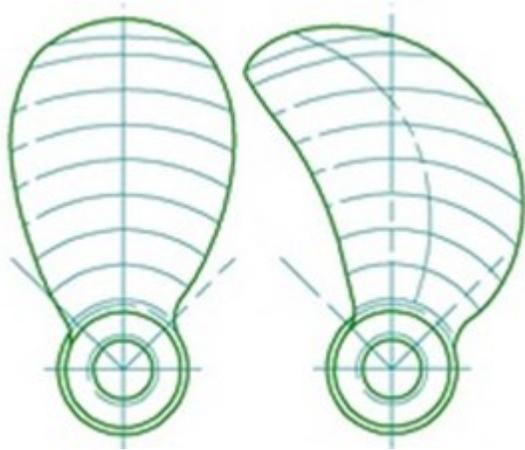


Figure 3. Skew of a propeller (Evaluating skewed propellers, 2013)

of the engine weight (Southall, 2005). The vibration-insulating mounts are more effectively used on the onboard machinery and smaller diesel engines. The engine itself is also an area to consider for reducing ship noise. The Royal Academy of Mechanical Engineering highlighted the cruise ship industry for adopting the diesel-electric propulsion system to reduce onboard noise (Royal Academy of Engineering, 2013, p.13). The IMO also suggested that diesel-electric propulsion systems be considered for newer ship designs, because they reduce underwater noise. Furthermore, these systems can be mounted on sound-absorbing mounts, unlike the conventional direct-drive diesel engines (IMO, 2014, p.4).

The challenge of reducing ship noise is not a challenge of technical design, but of increased manufacturing cost. The Chief of the Chamber of Shipping of America, Kathy Metcalf, explained that the problem is not with ship buyers, but with ship builders, who want to reduce cost to maximize profit. This is especially important in the highly competitive shipping industry

(Lubofsky, 2016). According to Malakoff, it is estimated that reducing noise from an oil tanker could cost almost three million dollars (2010), a cost that shipping manufacturers are unwilling to pay unless mandated. The technology to quiet ships is available but unlikely to be implemented until regulations are created. The current guidelines proposed by the IMO in 2014 are an important start to reducing noise pollution, but they require proper enforcement to pressure ship manufacturers.

Regulations have not kept pace with research

Marine acoustic pollution is considered a transboundary issue, and the scale of the problem is far too broad to implement regulations and policies on a local basis. Major contributors to research and policy formulation are the United States Coast Guard, the National Oceanic and Atmospheric Administration (NOAA), the International Maritime Organization, and other federal and independent organizations (Gedamke, 2016).

Maritime organizations have become more proactive in working to reduce marine acoustic pollution levels after research has shown the detrimental effects on marine life. NOAA, a leader in protecting marine life and environment,

created the “Ocean Noise Strategy Roadmap”, a 10-year implementation strategy to reduce underwater noise. This roadmap has four primary goals: (1) close educational gaps in understanding noise pollution and its environmental impact; (2) mitigate the effects of noise pollution by developing tools for assessing and decreasing noisy activities, and increasing public education on the impact of noise pollution on marine life; (3) enhance international relations; and (4) promote stakeholder coordination (Gedamke, 2016). NOAA worked with the IMO to develop a set of voluntary guidelines that outlined the primary sources of ship-related noise, and methods of operation and design considerations for designers, shipbuilders, and ship operators to reduce noise (IMO, 2014).

While no regulations mandate the reduction of marine acoustic pollution directly, several federal acts and guidelines frame the recommendations made by organizations and government agencies to protect marine habitats and species.

The United Nations Convention on Law of the Sea (UNCLOS), the legal framework for marine and maritime activities, indirectly acts against marine acoustic pollution. Article 194 of UNCLOS says that states must do what is necessary to protect the marine environment from any source of pollution, with “pollution of the marine environment” later being defined by UNCLOS as substances or energy directly or

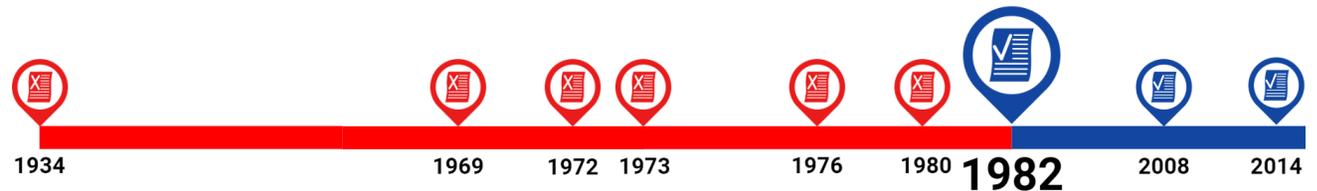


Figure 4. Timeline showing the dates of major climate legislation up to and following passage of the UNCLOS in 1982.

indirectly introduced into the marine environment by man. Although UNCLOS does not specify the types of pollution that fall under Article 194, sound or noise from commercial ships is a form of energy, so the argument can be made that UNCLOS must regulate acoustic pollution (Firestone, 2007).

In 2014, NOAA and the IMO developed non-mandatory guidelines for any commercial ship to advise designers, shipbuilders, and ship operators about marine acoustic reduction and the main sources of noise. The guidelines focus on propeller cavitation (the major contributor to underwater noise), hull shape, onboard machinery, and operational practices as ways to reduce the creation of noise from commercial ships. (IMO, 2014).

Government organizations have different responsibilities of enforcing regulations and policies in place to protect marine life. The NOAA is the chief agency that governs wildlife and marine protection acts, and any federal policies that aid in the conservation of marine species and their habitats (Gedamke, 2016). UNCLOS enforcement is the duty of the state according to its international rules and standards to prevent and reduce pollution of the marine environment established by international organizations, such as the IMO (“United Nations Convention”, 1982).

The Coast Guard takes action

The United States Coast Guard is interested in a plan to organize and compare methods of vessel designs, operational practices, and technologies that reduce marine acoustic pollution. Our project identified these methods, assessed their feasibility in reducing marine

acoustic pollution based on a set of performance and feasibility criteria, and created a catalog of the methods to summarize our findings.

Noise mitigation: Research strategies and results

The goal of this project was to compare and evaluate innovative vessel designs, operational practices, and technologies for the purpose of reducing vessel-generated marine acoustic pollution. To fulfill this goal, the team identified four main objectives:

1. Understand the nature of acoustic pollution and its effects on marine life.
2. Identify different engineering designs, operational practices, and technologies that reduce acoustic pollution.
3. Assess the feasibility of noise-reducing methods.
4. Build a catalog of methods that reduce acoustic pollution from commercial vessels.

To achieve these objectives, our team reviewed primary literature and conducted interviews with experts from government and

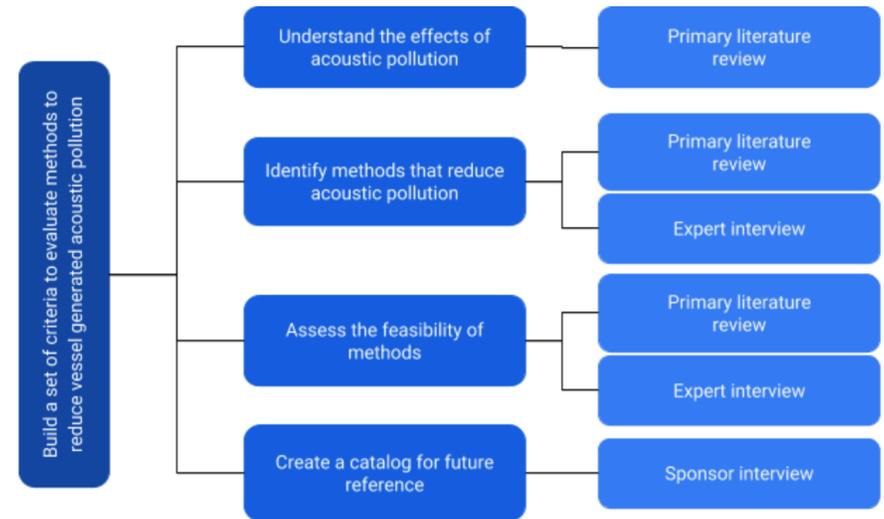


Figure 5: Goals, Objectives, and Analysis Techniques

private organizations. Figure 4 depicts the relationship between our overall project goal, the objectives to complete our goal, and the techniques we used to gather data. In what follows, we discuss our research strategies in more detail, and we present our findings.

Objective 1: How acoustic pollution affects marine life

We conducted a review of the literature to determine the levels at which underwater noise is considered pollution, the sources of acoustic pollution, and the effects it has on marine life. Our preliminary findings are discussed in the previous section of this report.

Once on site, we discovered more detailed information on the nature of the issue. First, we established the frequency ranges of concern.

Commercial shipping creates sound in a frequency range from about 1 Hz to 100,000 kHz. Coincidentally, the collected hearing range of most marine life is between 10 Hz and 110,000 kHz (Figure 5). Frequencies between 100 Hz and 1 kHz are particularly of concern, because this is the range heard by the widest variety of animals, and such low-frequency sounds travel most easily in water (Marine Environment Protection Committee, 2018). Retired NOAA consultant, Craig Johnson, explained that sound above 160 dB causes behavioral changes, while sound above 180 dB causes injury (Johnson, November 2018). We also established through an interview with

NOAA experts, Jason Gedamke, Jolie Harrison, and Leila Hatch, that noise pollution is typically classed as “sublethal”. While it is possible that noise can injure animals, it rarely causes direct fatalities, and its effects are primarily limited to stress symptoms. These can be immediately lethal in extreme cases such as whale beachings, but more commonly have subtler long-term effects on population viability.

We also identified ship components that create noise. Propeller cavitation is the most significant contributor, producing up to 75% of a ship’s noise output. Cavitation bubbles striking the rudder in particular create significant noise. Hull and propeller drag, especially due to

biofouling, also create noise due to the effect of drag on a vessel’s cavitation inception speed rather than direct noise from turbulence. Internal machinery noise was found to have an impact as well, however, it only has major impacts at low speeds.

Finally, we found additional details on the current regulatory environment surrounding marine noise pollution. Under the Marine Mammal Protection Act, operators engaging in activities which are likely to cause incidental harm to marine mammals are required to submit a “take” report (so called

for the act of “taking” from the environment) and receive a permit. Noise is considered a risk factor under this act, so noisy marine construction projects usually require a take permit, whereas noisy operation of commercial ships does not require a take permit.

After discussing the current voluntary IMO guidelines with industry experts and regulators including Chamber of Shipping America president Kathy Metcalf, it became clear that a major weakness of these guidelines is the lack of specific noise reduction benchmarks. This has been a major sticking point dividing the interested parties on this issue. To paraphrase Craig Johnson; biologists ask engineers how much noise can be reduced, engineers ask biologists how much it needs to be reduced by, and repeat. Despite this, NOAA representatives Jolie Harrison, Leila Hatch, and Jason Gedamke, are impressed with the speed at which these guidelines have become an international talking point. While definitive international regulations are likely years away, the question of noise pollution measurement and abatement will continue to be addressed.

Other environmental regulations have previously and will continue to impact shipping noise, particularly the upcoming 2020 fuel oil sulfur cap. This new IMO regulation will limit the sulfur content of marine fuel to just 0.5%, down from the current cap of 3.5%. One solution for ship owners seeking compliance is to switch fuel sources (Det Norske Veritas, 2018). In this case, ship owners may opt to switch to entirely new prime movers for their ships in order to reduce the long-term cost of these more expensive fuels. The potential noise benefits of some such replacement engines, such as hybrid drives and COGAS plants, are explored later in this paper.

Table 3: Experts Interviewed

Organization	Sector	Representatives
United States Coast Guard	Branch of US Armed Services	LT Braden Rostad Jaideep Sirkar
National Oceanic and Atmospheric Association	Government Agency	Jolie Harrison Leila Hatch Jason Gedamke
MAERSK	International shipping conglomerate	Dr. Lee Kindberg
Noise Control Engineering, LLC	Acoustical engineering firm	Jesse Spence
Chamber of Shipping of America	Representatives of US shipping companies	Kathy Metcalf
Marine Acoustics Inc.	Private acoustics consulting firm	William Ellison
ACENTECH	Private acoustics consulting firm	Michael Bahtiarian

Objective 2: Methods that reduce acoustic pollution

Based on our preliminary literature review, we identified 36 methods to reduce acoustic pollution, which were discussed previously and grouped into three categories: vessel design, retrofit technologies, and operational practices. With Coast Guard staff recommendations, we interviewed experts from federal and private organizations (see Table 3) and conducted further literature review to refine and shorten our preliminary list to 33 methods. Our interviews with experts covered the following topics: technical design aspects, practicality, environmental guidelines, and regulations (see Supplementary Materials Part C & D for interview protocol and questions). We determined that we would prioritize vessel design modifications and retrofit technologies over operational practices in our analysis. Specifically, we identified 10 promising methods on which to focus. The methods in bold below showed the highest potential to reduce noise while also improving operational efficiency.

1. Contracted and Loaded Tip Propeller
- 2. Controllable Pitch Propeller**
- 3. Highly Skewed Propeller**
4. Increasing number of Blades
5. Kappel Propeller
6. New Blade Section Propeller
7. Twisted Rudder
8. Hull form optimization
- 9. Costa Bulb**
10. Grothues Spoilers
- 11. Mewis Duct**
12. Pre-Swirl Stators
13. Rudder fins

14. Schneekluth Duct
15. Simplified Compensative Nozzle
16. Vortex generator
17. Combined propulsion (COGAS)
- 18. Diesel-electric propulsion**
19. Podded propulsion
20. Waterjet propulsion
21. Acoustic enclosures
22. Active insulation
- 23. Elastic mountings**
24. Optimization of engine foundation
25. Bubble Curtains
26. Anti-fouling paints
27. Biomimetic coating
- 28. Propeller cleaning ***
- 29. Hull cleaning ***
- 30. Propeller Boss Cap Fins**
- 31. Operational speed reduction**

* Hull and Propeller cleaning described together

Objective 3: Assess the feasibility of noise-reducing methods

The goal of this objective was to put together a comprehensive assessment of the advantages and disadvantages of all 33 methods in a summary matrix. Through literature review, we developed a set of criteria (Table 4) to evaluate the effectiveness of each method. The criteria were adapted from the design analysis presented at the 2007 NOAA International Symposium: Potential Application of Vessel-Quieting Technology on Large Commercial Vessels and

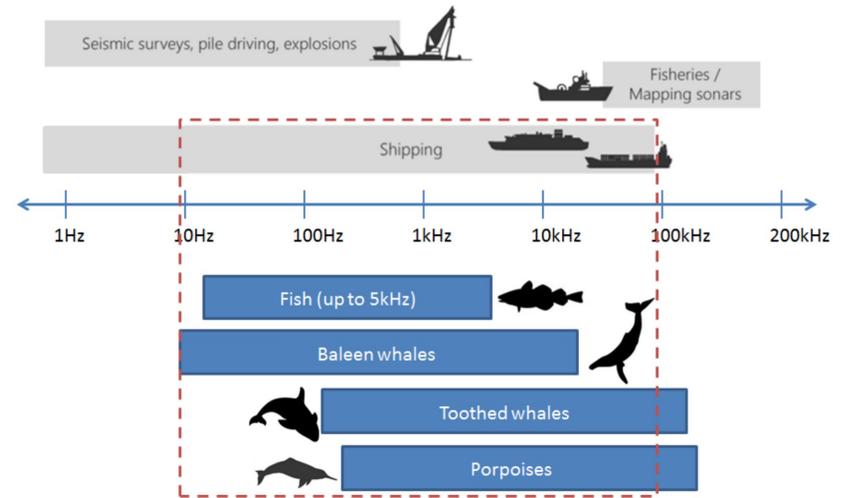


Figure 6: (Retrieved from IMO MEPC 73rd Session report, Figure 1): Sound frequency ranges generated by various human activities and their relation to marine animal hearing. The red dashed box represents the overlap with commercial shipping noise

the AQUO Consortium research project (see Supplementary Materials E & F). For each criterion, we used a scale to rate how well each method met the criteria. These rankings are defined further in Table 6. This scale was adapted from a study done by Hemmera (Hemmera Envirochem Inc., 2016) for commercial noise in the Port of Vancouver.

We compiled findings from our analysis into a matrix (see catalog for the full matrix). A portion of this matrix including the 10 most promising methods is shown in Table 5. Our analysis showed a relationship between the evidence of underwater noise reduction and improved fuel and hydrodynamic efficiency. This relationship is also supported by a Scripps study on Maersk's G-class container vessels (Kindberg, 2018). Below, we describe and provide a brief analysis of the 10 most promising methods in more detail.

Table 4: Analysis of selected methods

Method	Evidence of Noise Reduction	Market Availability	Cost	Implementation	Additional Maintenance	Efficiency Impact
Propellers						
Controllable Pitch Propeller	High	Yes	EV Cost: \$224,441 - \$336,662	EV/NB	Low	Positive
Highly Skewed Propeller	High	Yes	10-15% higher than conventional propeller	EV/NB	Low	Negative
Propeller Boss Cap Fins	Medium	Yes	\$55,000 - \$100,000	EV/NB	Low	Positive
Hull Alterations/Addons						
Costa Bulb	High	Yes	-	EV/NB	Low	Positive
Mewis Duct	High	Yes	-	EV/NB	Medium	Positive
Alternate Propulsion						
Diesel-Electric	High	Yes	For Cruiser with power of 15 MW cost was 28% more to implement than conventional system	NB	Medium	Positive
Vibration Insulation						
Elastic Mountings	High	Yes	-	NB	High	Neutral
Vessel Cleaning						
Hull Cleaning	Medium	Yes	Hull cleaning divers: \$1.5-2.5/m ² Hull cleaning robot: ~\$50,000	EV/NB	Low	Positive
Propeller Cleaning	Medium	Yes	~\$3,000	EV/NB	Low	Positive
Vessel Speed						
Operational Speed Reduction	Medium	Yes	-	EV/NB	Low	Positive

Controllable pitch propellers

The controllable pitch propeller is a mechanically complex propeller that has the ability to control ship speed through a constant propeller rpm and varying blade pitch. Vessels using CPPs commonly reduce speed by varying the pitch, but this causes a non-uniform inflow of water to the propeller, increasing the effects of cavitation. To avoid this increase in cavitation, it has been shown that varying shaft speed rather than the pitch will lead to a reduction in propeller noise (AQUO Consortium, 2015, D5.3). Some CPP's can reduce fuel consumption by varying the propeller rpm to operate at its optimal pitch (AQUO Consortium, 2015, D5.5). CPP's have become an increasingly popular form of propulsion, because their fine thrust control allows for easier maneuvering. This type of propeller is best applied to medium and high-speed ships that operate on coastal or shorter routes (AQUO Consortium 2015, D5.3), and has previously been applied to passenger and ferry ships, general cargo ships, and tug and trawling ships (Carlton, 2007).

The controllable pitch propeller has shown to significantly reduce the noise generated from a ship by reducing propeller cavitation at reduced speeds. A reduction of propeller noise by more 10 dB was achieved through reducing vessel speed from 15 knots to 11 knots. To reduce the speed, the CPP was set at the optimal design pitch, but the shaft speed was reduced. (AQUO Consortium, 2015, D5.3). The CPP is only feasible to reduce noise for vessels with the proper equipment setup to vary shaft speed, since changing pitch to reduce speed leads to more underwater noise. Implementing CPP on existing vessels can be done, but if the vessel does not have the ability to vary shaft speed, it will have

Table 4: Evaluation criteria used to analyze methods

Evaluation	Areas of Focus	Rating System
Evidence of Noise Reduction	Theoretical or measurable evidence that the method reduces noise	Low: Theoretical potential to reduce noise Medium: At least 1 study with evidence of noise reduction High: Quantitative measurement of noise reduction
Market Availability	Whether the product is commercially accessible, or still experimental	Yes: Commercially available No: Not commercially available, experimental
Cost	Cost of method and/or implementation of method	Report available data
Implementation	Feasibility to be applied as a retrofit or new build	RF: Can be done on a retrofit NB: Can be done on a newly built ship
Additional Maintenance	Risk of extra maintenance required to keep methods in optimal condition	Low: Little to no increase in maintenance Medium: Risk of increase in maintenance High: Definite increase in maintenance
Efficiency Impact	Whether the product has a positive or negative effect on operational efficiency	Positive: At least 1 study with evidence of improved operational efficiency (fuel, power, hydrodynamic) Neutral: Study shows no or insignificant impact on operational efficiency Negative: At least 1 study with evidence of decreased operational efficiency

to invest in upgrading its machinery to optimally use the CPP for reducing propeller noise. Controllable pitch propellers also have the potential to reduce fuel consumption by 20% when optimizing the control of the pitch and shaft speed (AQUO Consortium, 2015, D5.5). Overall the CPP can be an effective propeller design to achieve noise reduction when paired with the ability to optimize the control of both the propeller pitch and shaft speed.

Highly skewed propellers

The highly skewed propeller (HSP) reduces noise and vibrations through its increased skew, allowing the blade to gradually cut through the varying wake field and reduce cavitation. Reduced loading on a HSP tip can further decrease vibrations and noise from the propeller. HSP's are commonly used on warships and high powered merchant ships, where noise and vibrations need to be minimized (Renilson Marine Consulting, 2009).

Our team identified highly skewed propellers as a proven method to reduce underwater noise with minor efficiency and cost penalties. These propellers have been shown to reduce underwater noise by up to 10 dB in the low frequency range (AQUO Consortium, 2014, D5.1), which is the range used by most marine mammals. It achieves this by allowing the propeller to move through the varying wake field more gradually and improving cavitation patterns (Renilson Marine Consulting, 2009, p.16). The physical properties of skewed propellers are comparable to those of conventional propellers. They are no more susceptible to damage or blade erosion than conventional propellers (Hammer & McGinn, 1978). HSPs will incur a minor reduction in propeller efficiency of 5%, which can increase fuel consumption (Valentine & Chase, 1976). The cost of skewed propellers will vary depending on the amount of skew required. Minor prop skew will have similar prices to conventional propellers, whereas very highly skewed propellers can cost from 10-15% more (Renilson Marine Consulting, 2009, pg 17). Highly skewed propellers are a proven method to reduce noise, as evident by their use in warships (Renilson Marine Consulting, 2009, pg 17). With minor cost and efficiency penalties, the HSP is a method that should be explored further for the commercial shipping industry.

Costa Bulb

The Costa Bulb is a hull add-on that hydrodynamically integrates the propeller and the rudder. The bulb is attached to the rudder in line with the shaft of the propeller (Leaper, Renilson & Ryan, 2014). As the sea water is pressed backwards due to vortexing from the propeller, the water flows around the bulb and

fundamentally increases the efficiency of the propeller (Pettersson & Nerland, 2006). However, as the bulb protrudes laterally, it is in danger of damage from impacts or strong changes in pressure before the rudder blade itself would be threatened (Kluge & Lehmann, 2008).

We found the Costa Bulb to be highly effective in reducing underwater noise from propeller cavitation. A 5 dB reduction in noise has been claimed to be achieved by utilizing a Costa Bulb arrangement (Leaper, Renilson & Ryan, 2014). Along with claims of reducing underwater noise the Costa Bulb has also been linked with power savings. The inclusion of the Costa Bulb showed power savings between 4% and 8%, and average savings of 6.3% (Guiard, Leonard & Mewis, 2013; Minchev, Schmidt & Schnack, 2013). Information on the cost to purchase or install a Costa Bulb on an existing ship, or the cost to include it in new vessel designs is not readily accessible.

Mewis duct

The Mewis Duct is a hull add-on that reduces the ship's wake and rotational inefficiencies in the slipstream by the propeller fins. The only limitation to its ability to increase effectiveness is the requirement that the duct have a smaller diameter than the propeller itself. The duct refines many components of propeller flow, first equalizing and stabilizing propeller inflow and maximizing the thrust output. Next, the duct integrates a pre-swirl fin system acting as a type of endplate to the fins. As the hub to propeller diameter ratio increases, the effect of reducing inefficient vortexes also increases, also improving cavitation behavior. Vibrations are significantly lower according to crew feedback from retrofitted ships (Mewis & Guiard, 2011).



Figure 7: One blade from a Controllable Pitch Propeller on a Coast Guard cutter.

The Mewis Duct has proven to reduce underwater noise and propeller cavitation. It reduced pressure pulses up to 80%, which significantly reduces vibration excitation. The amount of noise reduction is unknown but based on crew feedback there is consensus that all vessels retrofitted with a Mewis Duct had significantly lower vibrations. Our team could not find the cost to purchase or install a Mewis Duct. It has shown to have an average power savings of 6.5%, which is appealing for fuel and cost savings. It has been on the market since 2008 and has been increasingly used to help recover ship wake and rotation losses (Mewis & Guiard, 2011).

Diesel-electric propulsion

Diesel-Electric propulsion is a hybrid system that is becoming more common on cruise liners and research vessels for the purpose of noise mitigation and fuel efficiency. For vessels with varying operational profiles, diesel-electric propulsion offers many advantages over the traditional two stroke diesel engine. These hybrid systems are much smaller and lighter than the mechanical diesel engine. This allows them to be elastically mounted, which further increases the noise reduction effectiveness. This form of propulsion is quieter than the two-stroke diesel and is flexible in terms of location and mounting. However, for traditional commercial shipping vessels, diesel-electric systems fall short because they have high initial costs and are less fuel efficient when used at a constant speed. Diesel-electric propulsion has been shown to decrease underwater radiated noise but requires careful thought for vessel implementation.

Being an electric hybrid system, diesel-

electric propulsion contributes lower engine noise than the two-stroke diesel widely used on commercial ships. A 10-20 dB reduction of machinery noise can be expected while using a diesel-electric system (AQUO Consortium, 2015, D5.5, Table 2.4). This is ideal for ships operating at low speeds, since machinery noise dominates at these speeds. Diesel-electric propulsion is most fuel efficient with vessels that have variable operating profiles, i.e. frequently changing speed, and are much less efficient on vessels that operate at a relatively constant speed. Most commercial ships operate at a constant speed and would see a decrease in fuel efficiency that will likely outweigh benefit of the noise reduction. A study by AQUO showed that a cargo ship would consume approximately 7.5% more fuel when using diesel-electric propulsion when compared to the standard mechanical diesel engine. Installing a diesel-electric system is also more expensive than installing a mechanical propulsion system. A case study for a cruise ship requiring 15 MW of power showed the cost for a diesel-electric engine was 28% more than a conventional diesel engine (AQUO Consortium, 2015, D5.5). This investment in the diesel-electric engine was returned in 2.2 years (AQUO Consortium, 2015, D5.5). The increased upfront costs and decrease in fuel efficiency make diesel-electric propulsion not feasible for commercial ships, despite being a very effective method at reducing onboard machinery noise.

Elastic mountings

Elastic mounting for vessel engines is a proven solution used to reduce onboard engine noise. It works to insulate the vibrations induced by engine operation from radiating through the hull into the ocean. Elastic mounts cannot be used on



Figure 8: A ship cleaning operation in progress

traditional slow speed two-stroke diesel engines because of the engine weight, but they can be used on smaller faster engines. It is important to optimize the stiffness of the mount and engine foundation to maximize noise reduction and avoid resonance effects.

Installing engines on elastic mounts can significantly reduce the overall machinery noise. They insulate the hull from vibrations induced by normal engine operation. Elastic mounts are feasible for vessels with medium or high-speed engines. For an elastically mounted medium speed engine it was shown to have a 20-40 dB noise reduction over the entire frequency range (AQUO Consortium, 2015, D5.4). However, elastic mounts cannot be used for the slow two-stroke diesel engine because of its weight. This makes elastic mounting only feasible for

commercial vessels that utilize the lighter, faster engines. For a ship that can utilize these mounts, there will be minimal additional maintenance and no negative impact on fuel efficiency. Information on the cost to purchase or install these mounts is not available but including these mounts in the initial vessel design will help to reduce their cost.

Propeller and hull cleaning

Propeller and hull cleaning provide an immediate reduction to the noise generated from commercial vessels. Removing biofouling on the ship is already widely used to improve ship efficiency by reducing hull and propeller drag. Reducing drag reduces the required output power which decreases the amount of noise generated. This also has the benefit of reducing propeller cavitation (International Maritime Organization, 2014; Hemmera Envirochem Inc., 2016), and turbulence (AQUO Consortium, 2014, D5.1). Cleaning operations must be performed regularly and require that the ship is dry-docked or anchored.

The amount of noise reduction that propeller and hull cleaning contribute is unknown but decreasing cavitation through regular propeller and hull cleaning reduces the intensity of low frequency noise from a vessel. Maintaining a clean ship proves to be a rewarding incentive, as it will greatly decrease a ship's fuel consumption. Propeller cleaning decreases fuel consumption up to 6%, while hull cleaning decreases fuel consumption between 7-30% (AQUO Consortium, 2014, D5.1, pg 71-72). According to a study done by Hemmera, the cost to clean both the hull and propeller is around \$26,600 - 34,200 (Hemmera Envirochem Inc., 2016). Cleaning the hull and propeller is the most accessible way to

reduce underwater noise and is cost effective and has great fuel efficiency benefits.

Operational speed reduction

Reducing vessel speed can immediately reduce noise, save fuel, and increase efficiency. Operating the ship below or close to the propeller's cavitation inception speed will eliminate cavitation effects and the noise it generates. A slower operating speed reduces the resistance experienced by the ship, decreasing the amount of power needed to move the vessel. This reduces fuel consumption and can generate large cost savings. Although operating at a lower speed can reduce noise and increase fuel efficiency, these savings may be offset by the fact that the onboard machinery is not optimized to operate at such low speeds, and longer voyages require extended crewing pay, among other economic factors. Therefore, it may be impractical for some commercial vessels to operate under such low speeds (AQUO Consortium, 2015, D5.5).

A ship can reduce its fuel consumption by 50% with a 20% reduction in speed, which significantly improves cost savings (AQUO Consortium, 2015, D5.5). However, reducing speed for commercial vessels is difficult as they are on strict time constraints, and a reduction in speed could lead to delayed deliveries. Traveling at reduced speeds can also create a safety risk during harsh weather and sea conditions. Similarly to propeller and hull cleaning, speed

reduction can be an effective, short-term strategy to implement on existing vessels without investing in retrofit technology.

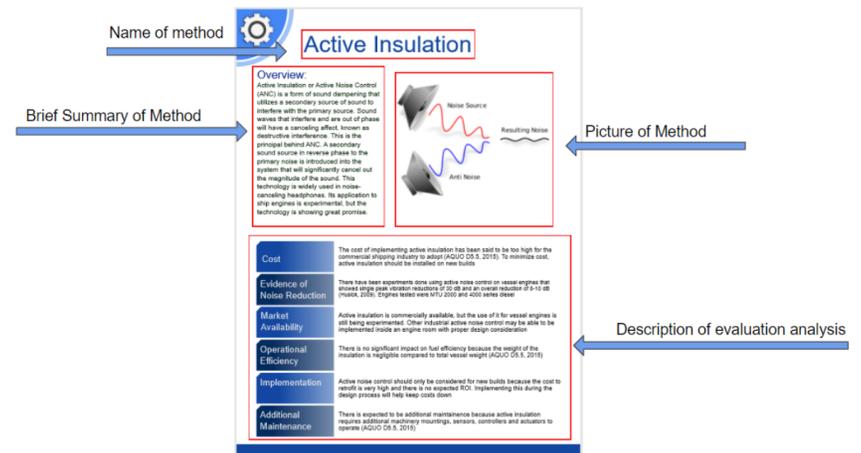


Figure 9: Sample for catalog pages

Propeller Boss Cap Fins

Propeller Boss Cap Fins (PBCFs) and Propeller Cap Turbines (PCTs) are similar structures which can be attached to the boss of a propeller. They consist of a group of small fins equal to the number of blades on the propeller and mounted just aft of the blades. These fins alter the performance characteristics of the propeller boss, reducing the pressure differential which creates the propeller vortex. The difference between PBCF and PCT is rooted in a fin shape: PBCFs consist of flat plates with uniform cross-sections, while PCTs consist of hydrofoils with variable cross-sections. Both systems exhibit comparable performance. Due to their reduction or elimination of the propeller vortex, PBCF/PCT are not compatible with some rudder upgrades.

According to Gassman, Kindberg, Wiggins, & Hildebrand the PBCF were one of the key upgrades in the Maersk G-Class retrofit program and may have contributed strongly to reducing those ship's radiated noise by 6-8 dB (Gassman, Kindberg, Wiggins, & Hildebrand, 2017). Estimates based on time to payoff information provided by manufacturer Wartsila indicate a possible cost range of \$57,000 to \$114,000, with ROI within as little as a year (Fathom Shipping, 2012; Pospiech, 2013). There are multiple manufacturers that claim an efficiency improvement range from 3-5% (Fathom Shipping, 2012; Pospiech, 2013; Mitsui O.S.K Lines, 2015). PBCFs are a proven method to reduce underwater noise, and improve a vessel's efficiency.

We chose to highlight the 10 most promising methods here, but for the full analysis we decided it was best to create a separate document that contained all 33 methods their respective ratings and analysis.

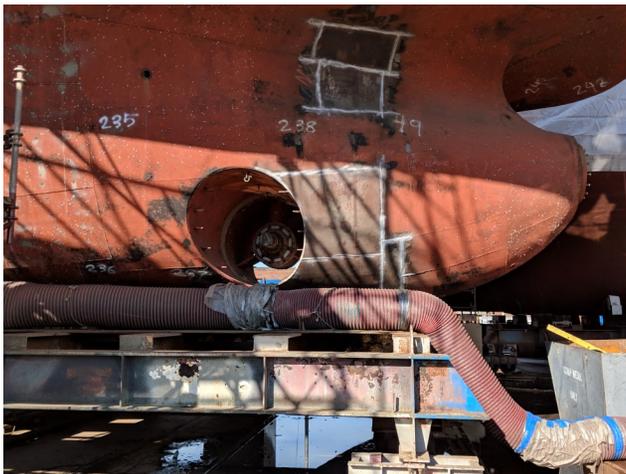


Figure 10: A lateral thruster aperture on a Coast Guard cutter.

Objective 4: Build a catalog of methods that reduce acoustic pollution from commercial vessels

Our final deliverable was a catalog compiling each of the technical and operational solutions we examined through our research. It was organized into three general sections reflecting distinct types of solutions we researched: Vessel Design, Operational Practices, and Retrofit Technologies. The catalog included the analysis matrix (see [title of catalog]) to provide broad information on the 33 methods. We included individual pages describing and evaluating each method in more detail. Figure 6 shows an annotated sample data sheet. The full catalog, *Catalog of Solutions to Reduce Marine Acoustic Pollution*, may be found at <https://digitalcommons.wpi.edu/studentprojectsandresearch/>

Future steps to silence acoustic pollution

In conclusion, our team researched multiple methods with varying effects on noise reduction and vessel efficiency. Impending emission and noise restrictions are beginning to encourage operators to adopt more efficient and quieter vessels, and the options have become plentiful with more than 30 potential noise mitigation solutions already on the market. Shipping vessels already implementing these technologies are clearing the way for quieter oceans.

Although there is evidence that these methods have the potential to reduce underwater noise, there are few data on their actual performance under operational conditions in the ocean, and further research and testing must be done to bridge this gap. This testing should be done on the individual methods themselves, but also using combinations of methods and mechanical setups, as seen on different ship types, to establish situational noise reduction levels. The level at which underwater noise becomes harmful to marine life has been agreed upon by marine biologists, but there is uncertainty about the level to which underwater noise must be reduced.

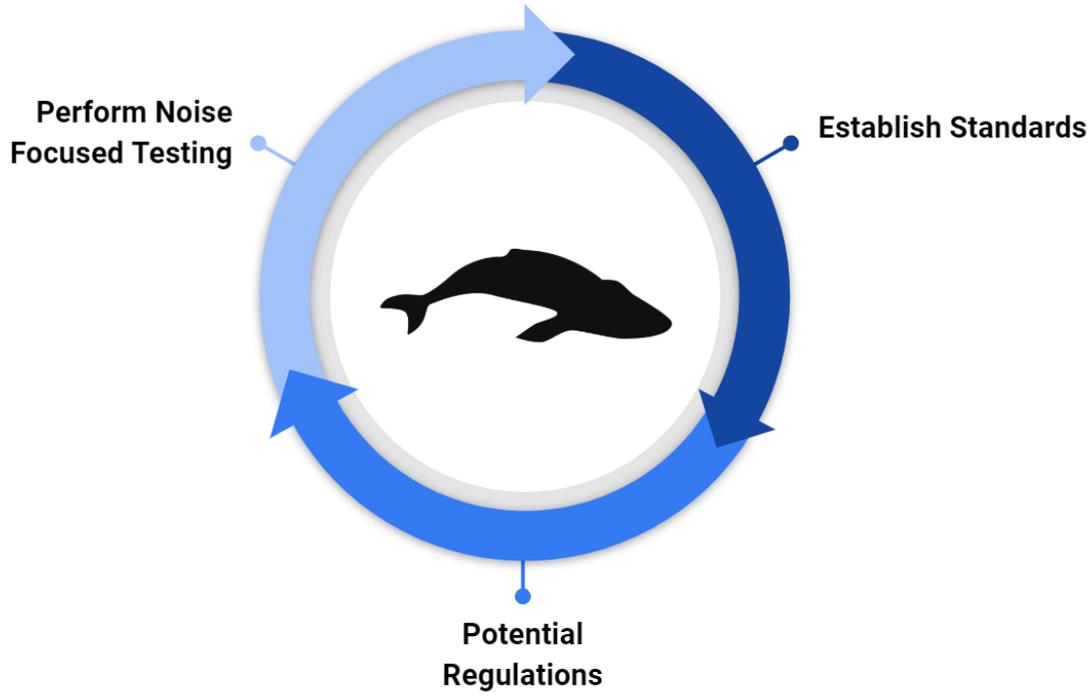
An important aspect of addressing these questions will be testing improved ships and components, both at model and full scales. Given the prominent contribution of propeller cavitation to underwater noise pollution, cavitation tunnel testing facilities will likely play a large part in this stage. Cavitation tunnels are large apparatuses analogous to wind tunnels which move water over rotating propellers to test their cavitation behavior. Most are equipped with cameras, pressure sensors, and microphones in order to gather as much information as possible. This makes them idea for gathering acoustic data on improved propellers. While their size and technical complexity makes these installations relatively rare, there are several currently operating in the US and Europe. A list of the cavitation tunnels for which we were able to find information is attached in Supplementary Materials, Part P. More data should also be collected on the relationship between noise reduction and fuel efficiency. The potential to incentivize noise reduction and solve two issues at once cannot be ignored.

In order to take regulatory action against acoustic pollution, it is important to standardize the measurement techniques, and what constitutes an acceptable noise level. Classification societies, such as the American Bureau of Shipping (ABS), and Det Norske Veritas (DNV), have already developed underwater noise notation for commercial and research vessels. These notations describe how a vessel can obtain a silent notation by outlining acceptable measurement procedures and noise levels. This is an important step in homogenizing how

vessel noise is measured and giving a noise reduction baseline. It will be important to continue to develop underwater noise notation and determine optimal ranges for how loud a ship can be. To effectively implement any noise reducing method, a target noise level should be identified. This will allow ship designers to optimally design existing or new vessels to be quieter. Underwater noise must be standardized for any regulatory action to be taken.

Perhaps the most important step is to ensure that this process of research, design, and

regulation is cyclical and continuous. Most of these methods are most effective on newly built ships as opposed to retrofits. So their continued development and application to new vessels will provide the greatest improvement in the long term. Through constant refinement of our capabilities and expectations, the issue of marine acoustic pollution can be managed for as long as commercial vessels travel the oceans.



Supplemental Materials for this project may be found at <https://digitalcommons.wpi.edu/studentprojectsandresearch/> by entering this report's title in the search bar. When the window appears, click on the appropriate project title and scroll down to "additional files".

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