Supplementary Materials

for

Methods to Minimize Commercial Vessel-Generated Marine Acoustic Pollution

December 14, 2018

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Sponsor: United States Coast Guard

These materials supplement the above named project report and are submitted to the faculty of WPI in partial fulfillment of the requirements for the Degree of Bachelor of Science

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Part B: Sponsor Background

The Coast Guard's history reaches back to the earliest years of the United States. In 1790 then-Treasury Secretary Alexander Hamilton proposed a "system of cutters" to safeguard American shipping. The ten vessels built for this purpose were under the command of the Department of the Treasury and were the only armed ships in federal service until 1798. Initially this service had no formal name, being alternately called the Revenue Service and the Revenue-Marine until the name Revenue Cutter Service was formalized in 1863. During peacetime the early Service's time was mainly occupied with hunting pirates, including privateers backed by European governments. The early cutters also served in the Quasi-War against France and the War of 1812, setting a precedent which would continue to see RCS (and later Coast Guard) vessels serve in both combat and support roles alongside the United States Navy into the present day (United States Coast Guard Historian's Office, n.d.).

Over time the mission profile of the RCS grew increasingly broad. In 1822 the cutters undertook their first environmental mission, sending ships up rivers to protect live-oak forests on public land from illegal cutting. Meanwhile their mandate to safeguard trade came to include port safety and maintenance, ship inspections, and other safety-related tasks. The first official rescue mission was conducted by the cutter *Gallatin* in 1831 at the behest of Treasury Secretary Louis McLane. The Revenue Cutter Service would eventually be merged with the volunteer Life-Saving Service in 1915 to form the Coast Guard. This combined organization inherited the mission profiles and traditions of both of its parents, safeguarding not only the economy of the nation but also the wellbeing of its sailors and coastal populations (United States Coast Guard Historian's Office, n.d.).

The Coast Guard's motto, *Semper Paratus*, Latin for "Always Ready," frames their commitment to current and future readiness. Their overarching mission is to ensure the United States' maritime safety, security, and stewardship. By being prepared to protect and serve the American people and the surrounding environment, they subsequently become an agile and professional armed force, law enforcer, regulator, and maritime first responder. With a bias for action, the US Coast Guard is an adaptive problem solver that is always watching to prevent future maritime disasters and to respond whenever needed.

The Coast Guard has six operation mission programs: maritime law enforcement, maritime response, maritime prevention, marine transportation system management, marine security operations, and defense operations. The USCG's 2017/18 budget of $10.67 billion covers both operational and recapitalization efforts for boats, aircraft, systems and infrastructure. With more than 56,000 members spread out over 100,000 miles of US coastline and inland waterways, the Coast Guard manages multi-mission fleets of 243 Cutters, 201 aircraft, and over 1,600 boats. Not only is the USCG an Armed Service, it is a first responder and humanitarian service whose goal is to aid people in distress be it at sea or ashore. The Coast Guard is also a part of the Intelligence Community and partners with legal authorities on matters relating to maritime transportation, hazardous materials shipping, bridge administration, oil spill response, pilotage, and vessel construction and operation. Seen in figures 1 and 2, the United States Coast Guard budget is relatively constant throughout the past five years, however less than 1% is allocated per year for environmental considerations.

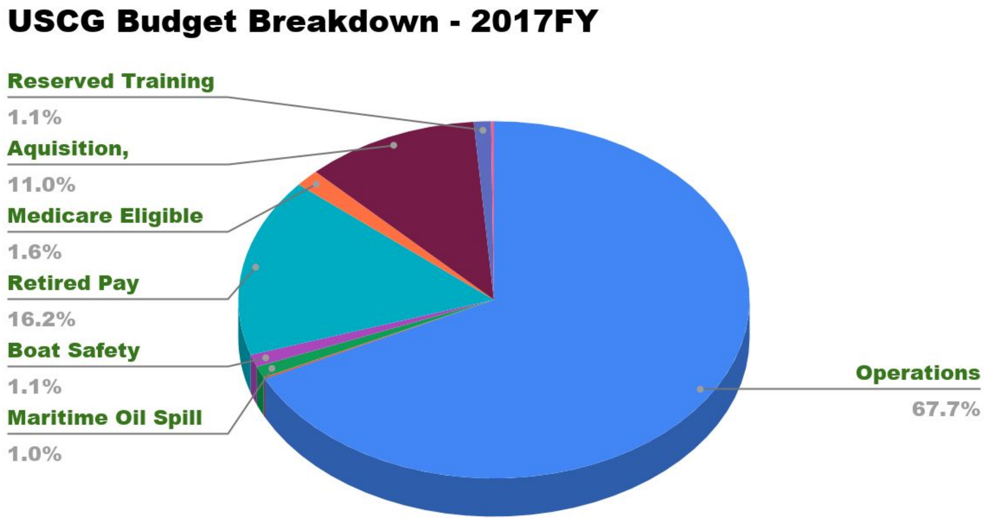

Figure 1: A pie chart showing the breakdown of the United States Coast Guard budget. Adapted from *the United States Coast Guard,* https://www.overview.uscg.mil/Portals/6/Documents/PDF/USCG_Overview.pdf?ver=2016-10-2

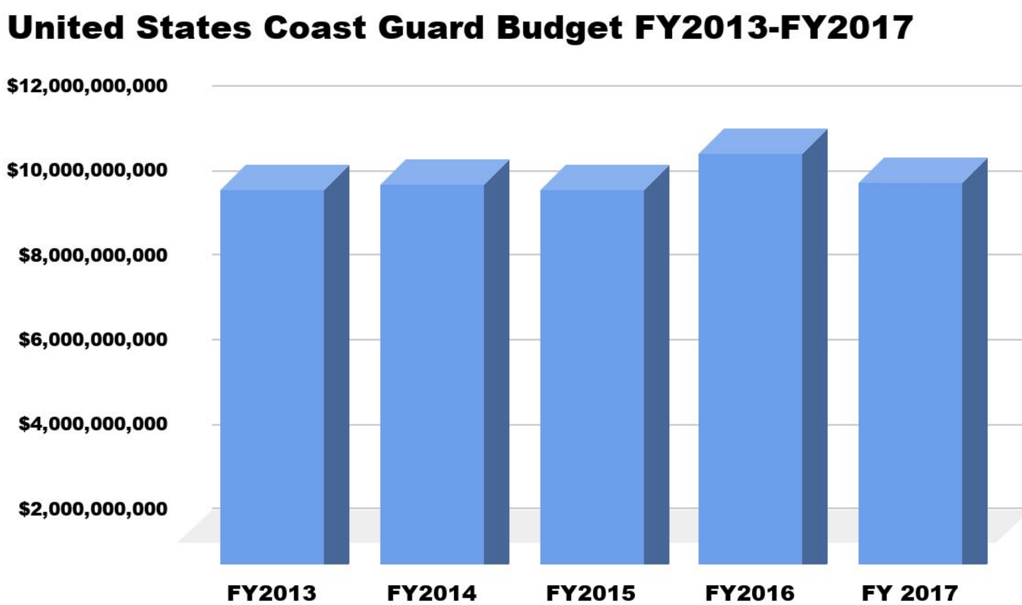

Figure 2: A bar chart presenting the past five yearly budgets for the United States Coast Guard. Adapted from *the United States Coast Guard,* https://www.overview.uscg.mil/Portals/6/Documents/PDF/USCG_Overview.pdf?ver=2016-10-2

The Assistant Commandant for Prevention Policy embodies the United States Coast Guard mission and vision of promoting maritime safety, security, and environmental stewardship through developing national regulations and policies. A division of the Assistant Commandant for Prevention Policy, the Commercial Regulations and Standards, lives this mission by creating and implementing engagement plans for international standards development, and establishing uniform operating standards and designs throughout commercial vessels through a technical compliance program (United States Coast Guard, n.d.).

Within the Commercial Regulations and Standards is the Office of Operating and Environmental Standards (OES), which aims to "develop and maintain maritime industry operating and environmental standards, regulations, and industry guidance to prevent deaths, injuries, property damage, and environmental harm by engaging all stakeholders, federal advisory committees, and international committees" (United States Coast Guard, n.d.).

Two divisions comprise the Office of Operating and Environmental Standards. These divisions are the Vessel and Facility Operating Standards Division and the Environmental Standards Division, exemplify the same mission by sharing three primary functions:

- "Develop and maintain standards and regulations for inspected and uninspected vessels, facilities, and offshore platforms"
- "Develop and maintain standards, regulations, and industry guidance for vessel, facility, and platform operations"
- "Develop and maintain regulations and guidance concerning operational pollution prevention, response, and removal" (United States Coast Guard, n.d.)

In addition to these three primary functions, the Vessel Operating Standards Division also collaborates with national and international environmental organizations to uphold maritime industry standards.

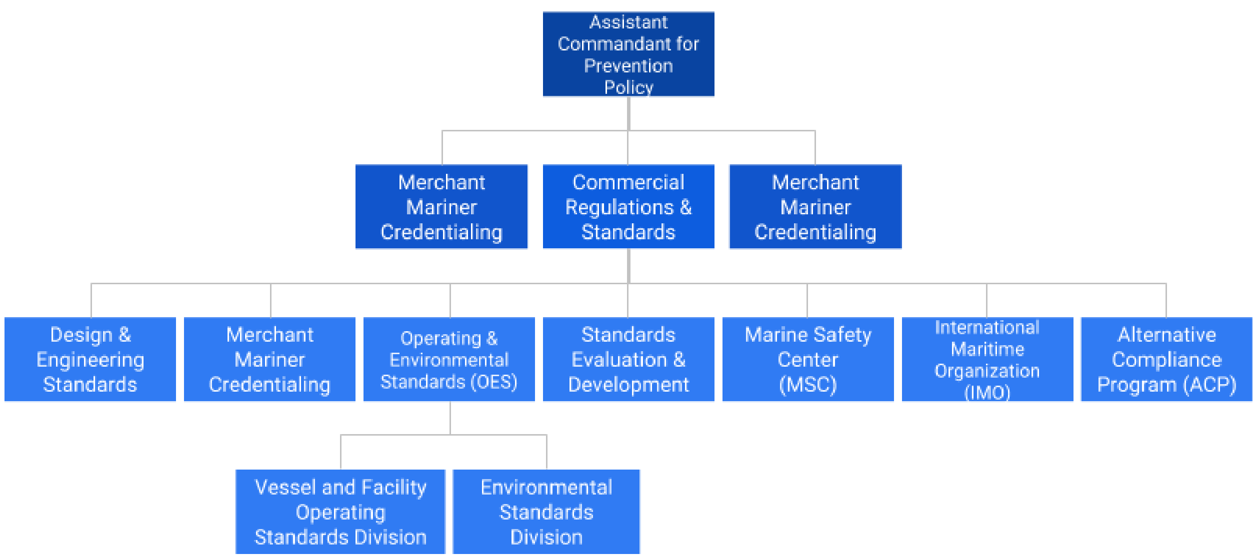

Figure 3: Structure of Assistant Commandant for Prevention Policy. Adapted from Assistant Commandant for Prevention Policy, In *United States Coast Guard*, n.d., Retrieved from https://www.dco.uscg.mil/Our-Organization/Assistant-Commandant-for-Prevention-Policy-CG-5P/

The major focus of the Environmental Standards Division is the Ballast Water Management (BWM) program for commercial ships in the United States. The BWM program upholds standards to ensure no exotic species or bacteria invade the ballast by using data from reports to recommend technologies to minimize the effects of invasive species in ballast water discharge on vessels. All vessels must comply with the Code of Federal Regulations, Subpart D - Ballast Water Management for Control of Nonindigenous Species in Waters of the United States, which requires vessel owners or operators to follow 1 of 6 ballast water management methods, conduct ballast water inspections, and submit an electronic report to the NBIC. The National Ballast Information Clearinghouse (NBIC) is comprised of the Coast Guard and the Smithsonian Environmental Research Center. The NBIC collects and analyzes data to achieve its primary goal: “to quantify the amounts and origins of ballast water discharged in US coastal systems and to determine the degree to which such water has undergone open-ocean exchange or alternative treatments designed to reduce the likelihood of ballast-mediated invasions by exotic species” (United States Coast Guard, n.d.).

The United States Coast Guard is concerned about the environmental impact of acoustic pollution in the sea because it parallels with one of their primary principles, “Protect the Sea (Stewardship)” (United States Coast Guard, 2012, p.3). The broad scope of this mission makes them the United States’ advocate for the sea. The Coast Guard ensures that all 3.4 million nautical square miles of maritime territory (United States Coast Guard, 2012, p.9) are safe and environmentally sound.

An emerging concern for the marine ecosystem according to Schiffman (2016) is an increase in acoustic pollution. Low frequency acoustic pollution is caused predominantly by large shipping vessels. The sound produced from shipping vessels is interfering with marine species’ communication, resulting in a direct impact on their survival (Schiffman, 2016). The Coast Guard’s Environmental Standards division is invested in research that will help them better understand the causes of this pollutant and subsequently determine methods to reduce it.

Running parallel to the mission of pollution prevention, is the Coast Guard’s close oversight of the commercial shipping industry, which evidently is tied into the rise of noise related pollution in the waters. With the shipping industry’s outdated fleets and constant need for more vessels, sound pollution is continuing to grow. It is important that the Coast Guard has a compilation of up to date information on the lastest ship designs, operational practices, and sound-quieting technology, allowing them to effectively implement and enforce strategies to reduce the overall acoustic footprint of commercial ships. By taking a proactive approach of continuously compiling new ideas on reducing vessel noise, the Coast Guard can carry out their mission to protect their seas.

Part C: Interview Preamble

We are a team of student researchers from Worcester Polytechnic Institute, in collaboration with the United States Coast Guard on a project to reduce marine acoustic pollution. We are conducting this interview in order to learn more about potential technologies, vessel designs, and operational procedures that might reduce underwater noise generated by commercial shipping. This interview is completely voluntary and you have the right to withdraw at any time. If we use information from this interview in our final report, we will give you an opportunity to review the material prior to publication. We expect the duration of the interview to be no longer than one hour. If you have any questions regarding the project or this interview, please do not hesitate to contact us at gr-DC18USCG@wpi.edu, or our liaison at the Coast Guard: Debbie Duckworth (Debbie.Duckworth@uscg.mil). Thank you for your participation.

Part D: Interview Questions

Introduction

1. How long have you worked with [insert organization]., and what is your particular area of expertise?
2. Based on our background research, it appears that there is a general consensus that noise pollution in the ocean is having significant adverse impacts on marine life, especially whales. These impacts may grow as the volume of shipping increases. We also understand that there are many existing and novel approaches to reduce noise pollution, ranging from ship designs to operational procedures. What do you see as some of the promising avenues to reduce noise pollution in the oceans, and what are the major obstacles preventing adoption of these approaches?

Technical Aspects

1. We are investigating the following types of commercial vessels: Tankers, Bulk Carriers, Container Ships, General Cargo Ships, Cruise & Passenger Ships, Services & Research Ships, and Tug/Tow Boats. What differentiating factors between these classes of vessels play a role in noise production?
2. What components of ships produce the most underwater noise?
    a. What design factors of these are adaptable versus fixed?
3. We have already researched [insert solution] and found [information]. What is your expert opinion on this method?
4. Do you have any knowledge of other new vessel designs or operational practices intended to reduce noise?
    a. What are the pros and cons of the solutions? (i.e. difficulties in implementing)
    b. How effective is this expected to be?
    c. Has this design been tested or evaluated?
        i. What was the outcome?
    d. Would we be able to access this research?
5. When proposing new vessel designs or operational practices, what are the biggest factors in determining its feasibility?
    a. Based on these factors, how feasible is [insert solution]?
6. Are you aware of any solutions to reduce noise from ships that harm the environment in other ways?

Practicality

1. Have you seen any correlation between methods that reduce noise and overall ship efficiency?
2. What might motivate an organization to adopt noise reducing technology?
    a. Are you aware of any incentive programs aimed at reducing ship noise?
    b. What is your opinion on incentive programs?
    c. What improvements would you make to these programs?
3. How available is [insert solution]?
    a. What would be the up-front cost to implement?
    b. What would be the ongoing cost to implement?
    c. What would be the potential savings due to increased efficiency?
4. What are the logistical limitations of [insert solution]? For example the material availability, crew training resources, regulations, or competitive advantages.

Environmental Guidelines and Regulations

1. We are aware that the IMO has guidelines for ship owners and designers to reduce underwater noise. How familiar are you with these guidelines?
    a. In your opinion, how effective are these guidelines?
2. Are you aware of any other existing guidelines on reducing underwater noise pollution?
    a. What is the scope (international, national, local, etc.)?
    b. What is the enforcement mechanism?
    c. What do they specify regarding noise levels, area, populations affected, etc?
3. Do you know of any regulations on noise pollution that are in the process of being drafted or implemented?
4. What are the challenges involved in drafting and implementing new environmental regulations?

Concluding Questions:

1. Can you suggest any resources or other organizations that we should look at?
2. If we have further questions regarding the topic as we continue our research, could we contact you?

Thank you!

Part E: Table we used to evaluate methods on noise reduction and cost

NOAA Symposium Analysis Table. Evaluating technical and operational solutions for vessel quieting. Retrieved from Southall, B. L. and A. Scholik-Schlomer. (2008). Final report of the NOAA International Conference: "Potential Application of Vessel-Quieting Technology on Large Commercial Vessels," 1-2 May, 2007, Silver Spring, MD, U.S.

NEW DESIGN OPTIONS FOR VESSEL-QUIETING				
Treatment	**Advantages/Benefits**	**Disadvantages/ Challenges**	**ROUGH Cost Estimates (Low, Med, High)**	**Anticipated GENERAL Magnitude of Quieting (Low, Med, High)**
Minimize Propeller Cavitation (propeller shape, configuration, size, etc.)	Reduction of tip vortex; reduction of pressure pulses; forward-skewed ducted props expected to increase cavitation inception speeds, hence lower cavitation noise levels (duct can serve for site of injecting air and also a *de facto* prop guard); "ring" propeller can eliminate tip vortex	Variable results in terms of quieting, operational efficiency	**Variable (potentially low)**	**High**
Minimize Propeller Cavitation (variable pitch propellers)	Good in terms of radiated noise at normal pitch; can identify minimum noise output	Poor in terms of operational efficiency; Potentially misused for speed control	**High**	**Variable (potentially high)**
Twin vs. Single Screw Propulsion Systems	Enables the use of large diameter propellers that turn more slowly; System redundancy is safety benefit	Only have half the thrust per system; major difference in the design of entire ship	**High**	**Variable (potentially high)**
Podded Propulsion (Azipods)	Potentially great improvement of wake	Not sufficiently powerful yet;	**High**	**Moderate (especially for**

	field; reduced cavitation; reduced vibration	high electrical noise; efficiency can be poor		**low-frequencies, but some high frequency tonal spikes)**
Hull Shape/Configuration	Improvement of wake field (may also improve efficiency)	Some difference in design of entire ship; Requires model testing	**Medium (highly uncertain)**	**High (especially for low frequency)**
Air Injection Systems (ducted air emission)	Air injection around the prop (bubble shield in front and around the propeller) could be advantageous in terms of noise (requires slightly more power); inject air around the propeller tips may work but has to be investigated	Navy-type approach is too expensive and difficult to maintain; May be some increase in radiated noise	**Medium**	**Uncertain**
Passive Equipment Mounts (Vibration Isolators)	Reduces Structure-borne path noise	Increasingly less effective for frequencies below 200 Hz for large diesel engines due to large mass; requires dynamically stiff foundations	**Mounts cheap but overall application can be very high**	**Medium to High (depending on frequency)**
Dynamic (Active) Equipment Mounts	Show significant promise; work well in other applications	Not widely available yet (still somewhat experimental)	**High**	**Potentially High**
Pump Isolations, Acoustic Filters, Pipe Hangers	Pretty simple generally	Takes some engineering effort; may not be relevant for consideration because of masking from propulsion noise	**Medium**	**Low to Moderate**

		on most large ships (very small point - way down the list)		
Acoustic Insulation	Reduces AB & SB Transmission; for engine room only	More directed to minimizing airborne versus underwater noise; This likely further down the list than propulsion systems	**Low [$1-$4/sq, ft]**	**Low to Moderate**
External and Internal Coatings (Dampening Products)	Relatively simple	Effectiveness depends on material 'compliance' and thickness; some limitations for internal coatings; maintenance can be very difficult on external coatings; Both only work at higher frequencies (200 Hz +); secondary consideration	**Low [$8-$12/sq, ft]**	**Low to Moderate**
Maintenance	Reduce machinery source level; can increase overall efficiency of propulsion and other systems	Cost can be significant if much greater than nominal schedule	**Variable**	**Variable (potentially moderate to high)**
RETROFITTING OPTIONS FOR VESSEL-QUIETING				
Treatment	**Advantages/Benefits**	**Disadvantages/ Challenges**	**ROUGH Cost**	**Anticipated GENERAL**

			Estimates (Low, Med, High)	Magnitude of Quieting (Low, Med, High)
Minimize Propeller Cavitation (propeller shape/configuration)	Reduction of tip vortex and pressure pulses; forward-skewed props should increase cavitation inception speeds	Variable results in terms of quieting, operational efficiency	**Variable (potentially low)**	**High**
Minimize Propeller Cavitation (variable pitch propellers)	Good in terms of radiated noise	Poor in terms of operational efficiency	**High to very high**	**Variable (potentially high)**
Passive Equipment Mounts (Vibration Isolators)	Reduces surface-borne path noise	Difficult as a retro-fit; Not effective for frequencies below 200 Hz for very large diesel engines due to large mass; requires dynamically stiff foundations	**High to very high**	**Low to Moderate**
Dynamic (Active) Equipment Mounts	Show significant promise; work well in other applications	Not widely available yet (still somewhat experimental)	**High to very high**	**Variable (potentially high)**
Pump Isolations, Acoustic Filters, Pipe Hangers	Relatively simple	Can be difficult as a retro-fit option	**Variable (potentially low)**	**Low to moderate**
Acoustic Insulation	Reduces AB & SB transmission	More directed to minimizing airborne versus underwater noise	**Generally low [$1-$4/sq, ft]**	**Low to moderate**
External and Internal Coatings (Dampening Products)	Relatively simple	Effectiveness depends on material ‘compliance’ and thickness	**Generally low [$8-$12/sq, ft]**	**Low to moderate**

OPERATIONAL OPTIONS FOR VESSEL-QUIETING				
Treatment	**Advantages**	**Disadvantages**	**ROUGH Cost Estimates (Low, Med, High)**	**Anticipated GENERAL Magnitude of Quieting (Low, Med, High)**
Speed Reductions	Appears to generally be one of the most promising ways to reduce vessel noise emission; should be some distinction between open-ocean and near-shore; Suggestion for some better routing/scheduling around busy ports	Economically, politically, logistically very difficult; limited benefit on local scale more application on regional scale	**Variable (potentially very high)**	**Variable (potentially high)**
Routing (Area Restrictions)	Avoiding were animals are operating in environments that do not favor long-range transmission	Economically, politically, logistically very difficult; Spatiotemporal aspects and environmental variability will prove challenging	**Variable (could be locally high)**	**Variable (could be locally high)**

Part F-1: Cavitation Tunnel Information used in final presentation

Table 2.7. Summarizing tests performed at UNIGE. Adapted from AQUO Consortium. (2014). *D2.5: Propeller noise experiments in model scale.* [PDF file]. Retrieved from http://www.aquo.eu/downloads/AQUO_D2.5_rev1_final.pdf

Type of test	Facility
Propeller characteristics curves	Cavitation tunnel
Cavitation bucket	
Cavitation extension visualization and photos	
Radiated noise measurements	
Pressure pulses measurements	

Part F-2: Table we used to determine method applicability to vessel families

Table 2.1. Common architectures and possible modifications for reducing underwater noise. Retrieved from AQUO Consortium. (2014). *D5.1: Comprehensive listing of possible improvement solutions and mitigation measures* [PDF file]. Retrieved from http://www.aquo.eu/downloads/AQUO_R5_9_List_Mitigation_Measures_rev1_0.pdf

Vessel family	Common type of machinery	Common propeller	Possible variable to improve URN
Tankers, bulk carriers and container vessel	Two stroke diesel engines.	Fixed pitch propeller (for large ships). Controllable pitch propeller (medium size ships)	Skewed propeller, CLT
RO-RO, RO-PAX, car carriers, general cargo	Two stroke diesel engines.	Fixed pitch propeller (for large ships). Controllable pitch propeller (medium size ships)	Skewed propeller, CLT.
Passenger ships	Four stroke diesel engines.	Controllable pitch propeller. Skewed propeller.	CLT
Cruise ships	Diesel electric	Fixed pitch and high skewed propeller	Podded propulsion (not so clear its advantages regarding URN).
LNG	Hybrid two stroke diesel engines -Gas Turbines	Fixed pitch propeller.	Skewed propeller, CLT.
High speed vessels	Four stroke diesel engines	Water jets.	Diesel/Turbine electric
Fishing vessel	Four stroke diesel engine	Fixed pitch propeller	Skewed propeller
Research vessels	Diesel electric	Skewed fixed pitch propeller	-

Part F-3: Table we used to establish frequency ranges in water

Table 2.3. Frequency band required for acoustic positioning in different water depths. Retrieved AQUO Consortium. (2014). *D5.1: Comprehensive listing of possible improvement solutions and mitigation measures* [PDF file]. Retrieved from http://www.aquo.eu/downloads/AQUO_R5_9_List_Mitigation_Measures_rev1_0.pdf

	Frequency Range	Water depth
Low Frequency	8 kHz to 16 kHz	>10m Operational to full ocean depth
Medium Frequency	18 kHz to 36 kHz	2km to 3.5km Problems beyond 3,500m
High Frequency	30 kHz to 60 kHz	1,500m
Extra High Frequency	50 kHz to 110 kHz	<1,000m Problems beyond 800m to 1,000m
Very High Frequency	200 kHz to 300 kHz	<100m Problems beyond 100m

Part F-4: Table we used to evaluate methods in different frequency ranges

Table 1-1. Foreseen effect of mitigation measures on ship URN - Qualitative assessment from a panel of specialists. Retrieved from AQUO Consortium. (2015). *D5.3: Assessment of the solutions to reduce underwater radiated noise* [PDF file]. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.3_Assessment_URN_reduction_rev1.0.pdf

Mitigation measure	Low freq.	Medium freq.	High freq.	Comments
Type of engine	+/++	+	0	When changing away from 2-stroke to 4-stroke with elastic mounts
Diesel-electric propulsion	++	++	0/++	More applicable to cruise vessels or special vessels
Podded propulsion	-	0	+	No foreseen improvements from diesel-electric propulsion
Reduction of TPK (turn per knots)	0/++	+/++	+/++	Consequences on on-board machinery to be considered
Elastic mountings	+	+/++	+/++	Generally considered to be not suitable for large 2-stroke engines
Auxiliary and main engine acoustic enclosure	0	0/+	0/+	More effect expected in medium/ high frequencies. More effect on interior noise than on underwater noise

Increase of the stiffness of machinery foundation	+/++	0/+	0	
Structural solutions (hull girder spacing, hull thickness, double hull)	0/+	0/++	0/++	Covers different aspects: hull/shaft interaction at LF, hull radiation factor.
Structural damping	0	+	0/+	
Bubble curtain (hull)	-/0	+/++	0/+	
Bubble curtain (propeller)	0/+	+	0/+	
Decoupling hull coating	0/+	+/++	+	
Hull optimization	0/+	0/+	0/+	Depends on the initial status (poor or good design)
Propeller blade design optimization	0/++	+/++	+/++	Improvement depends on the starting point, and whether it is focused only on noise or taking into account fuel efficiency
Non conventional propellers	-/+	0/+	-/+	Can be interesting if the design reduces cavitation
Propeller hub caps	0	0/+	0/+	Specific (hub vortex)

Wake Conditioning Devices (nozzles etc)	0/+	0/++	0/+	Depends on the initial status (poor or good hull design). Can improve noise in some cases and frequency ranges.
Optimized ship handling	0/++	0/++	0/++	Ship URN is known to go worse if not well maintained
Hull and propeller cleaning	0/+	0/+	0/+	Assessment is easier for the effect on fuel efficiency
Appropriate management of dynamic positioning system				Specific situation
Speed reduction	0/++	-/++	-/++	Possible degradation of URN in the case of CPP running off-design (low pitch)
Change in the propeller plant settings	0/+	0/++	0/++	May be beneficial in some cases

Part F-5: Table we used to determine technical method implementation

Table 1.1. Applicability of Design Solutions. Retrieved from AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency* [PDF file]. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf

Solutions Regarding Ship Design	Suitable for Retro-Fitting?	Suitable in new Designs?
Types of Propulsion - Machinery	No	Yes
Diesel-Electric Propulsion	No	Yes
Pod Propulsion	No	Yes
Reduction of TPK	No	Yes
Optimization of Hull Design	No	Yes
Control Strategies for CPP	Yes	Yes
Elastic Mounting	Yes	Yes
Active Insulation	Yes	Yes
Acoustic Enclosures	Yes	Yes
Propeller Blade Optimization	Yes	Yes
Non-conventional Propellers	Yes	Yes
Wake Conditioning Devices	Yes	Yes
Hull Girder and Thickness Modifications	No	Yes
Lightweight Materials	No	Yes
Double Hull	No	Yes
Other Structural Solutions	No	Yes

Bubble Curtains (*)	No	Yes
Decoupling Hull Coating	Yes	Yes
Propeller / Hull Cleaning	Yes	N/A
DPP Management	Yes	Yes

(*) Note: Installation of a bubble curtain system for retro-fitting can be envisaged but requires relatively important modifications (installation of pipework under the hull and a specific on-board system with an air compressor to generate the bubbles).

Part F-6: Table we used to determine operational method implementation

Table 1.2. Applicability of Operation Solutions. Retrieved from AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency* [PDF file]. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf

Traffic Control Measures	Suitable for In-Service Vessels?	Suitable for New Designs?
Speed Reduction or Change	Yes	N/A
Track Change	Yes	N/A
Optimized Trim	Yes	N/A
Speed Limit	Yes	N/A
Optimised Distance Between Vessels	Yes	N/A
Traffic Concentration	Yes	N/A
Traffic Dilution	Yes	N/A
Vessel Type Separation Scheme	Yes	N/A
Regulated Areas	Yes	N/A
Use of Bathymetry Features	Yes	N/A
Use of Geographical Features	Yes	N/A

Part F-7: Table we used for technical method impact on fuel efficiency

Table 1.3. Performance of Design Solutions. Retrieved from AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency* [PDF file]. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf

Solutions Regarding Ship Design	**Impact on Underwater Radiated Noise**	**Impact on Fuel Efficiency**
Types of Propulsion - Machinery		Discrepancy between what is most suitable for URN and for fuel efficiency
Diesel-Electric Propulsion		Can increase fuel efficiency but heavily dependent on ship operating profile
Pod Propulsion		Can provide fuel efficiency increases of up to 10% in certain cases
Reduction of TPK		Small improvement of around 1% per TPK in open water efficiency
Optimization of Hull Design		Can increase fuel efficiency
Control Strategies for CPP		Can improve fuel efficiency by up to 20%
Elastic Mounting		Small increases of around 0.7% in ship weight
Active Insulation		Small increases in ship weight
Acoustic Enclosures		Negligible Impact
Propeller Blade Optimization		More extreme designs for lower cavitation and URN can decrease efficiency
Non-conventional Propellers		Can improve fuel

		efficiency
Wake Conditioning Devices		Improvements in fuel efficiency range from 1 - 10%
Hull Girder and Thickness Modifications		Impact dependent on ship weight increase
Lightweight Materials		Impact dependent on ship weight increase
Double Hull		Can increase fuel efficiency but only in very limited cases
Other Structural Solutions		Can increase fuel efficiency but only in very limited cases
Bubble Curtains (*)		Very small decreases in efficiency with around 1% difference on achieved speed
Decoupling Hull Coating		Dependent on the weight of tiles and finish
Propeller / Hull Cleaning		Increases fuel efficiency significantly
DPP Management		Negligible impact

Part F-8: Table we used for operational method impact on fuel efficiency

Table 1.4. Performance of Operation Solutions. Retrieved from AQUO Consortium. (2015). *D5.5: Impact of Solutions on Fuel Efficiency* [PDF file]. Retrieved from http://www.aquo.eu/downloads/AQUO_D5.5_Impact_Fuel_Efficiency_rev1.0.pdf

Traffic Control Measures	Impact on Underwater Radiated Noise	Impact on Fuel Efficiency
Speed Reduction or Change		Reduction of speed can generally significantly increase fuel efficiency
Track Change		Dependant on distance, weather and geographical variations
Optimized Trim		Can improve fuel efficiency by 1-2%
Speed Limit		Reduction of speed can generally significantly increase fuel efficiency
Optimized Distance Between Vessels		Negligible direct impact
Traffic Concentration		Negligible direct impact
Traffic Dilution		Negligible direct impact
Vessel Type Separation Scheme		Negligible direct impact
Regulated Areas		Negligible direct impact
Use of Bathymetry Features		Impact only if this leads to shallow water operations or higher sea states
Use of Geographical Features		Impact only if this leads to shallow water operations or higher sea states

Part F-9: Table we used to determine frequency ranges of vessel noise

Table A-7. Typical characteristics of noise radiation from commercial vessels in different frequency ranges. Retrieved from AQUO (Achieve Quieter Oceans). (2015). Guidelines for regulation on UW noise from commercial shipping. FP7- Grant Agreement No. 314394. SONIC Deliverable 5.4

Frequency Range	Dominant Excitation Sources	Remarks
1 - 10 Hz	- 1st propeller harmonic, - main tonals of slow-speed engines	- UW sound largely filtered out by Lloyd Mirror effect
10 - 100 Hz	- higher tonals from propeller sheet cavitation, - broadband noise from various forms of cavitation, - main tonals from medium-speed main engines, auxiliary engines and generator sets	- Includes characteristic =50 Hz maximum as frequently observed at commercial vessels - Lloyd Mirror effect still relevant
100 - 250 Hz	- broadband noise from various forms of cavitation, - tonals from auxiliary machinery	- Lloyd Mirror effect small - high energy content - most pronounced decrease of source strength with increasing frequency
250 - 1000 Hz	- broadband noise from collapsing cavitation bubbles - tonals from propulsion gear meshing - tonals of high speed propulsion engines	- Lloyd Mirror effect negligible, - medium energy content
1kHz - 10kHz	- broadband noise due to cavitation phenomena - flow generated noise	- small energy content
10kHz - 50kHz	- flow generated noise	- very small energy content

Part G: Cavitation Tunnel Sites

List of cavitation tunnel facilities

Facility Name & Location	Ownership	Contact
CEHIPAR Cavitation Tunnel, Madrid, Spain	Instituto Nacional De Tećnica Aerospacial	http://www.inta.es/opencms/export/sites/default/ICTS-CEHIPAR/en/contacto/contacta-con-nosotros/
Emerson Cavitation Tunnel, Newcastle upon Tyne, England, UK	Newcastle University School of Marine Science & Technology	+44 (0)191 208 6000
Garfield Thomas Water Tunnel, University Park, PA, USA	Pennsylvania State University Applied Research Laboratory	https://www.arl.psu.edu/contact
Hamburg Ship Model Basin (HSVA), Hamburg, Germany	HSVA, Private Nonprofit Research Firm	https://www.hsva.de/company/contact.html
Krylov Large Cavitation Tunnel, Moscow, Russia	Krylov State Research Center	http://krylov-centre.ru/en/contacts/
Large Cavitation Tunnel (LCT), Memphis, TN, USA	US Navy Surface Warfare Center, Carderock Division	https://www.navsea.navy.mil/Home/Warfare-Centers/NSWC-Carderock/Contact-Info/
MARIN Cavitation Tunnel, Wageningen, Netherlands	Marine Research Institute Netherlands	http://www.marin.nl/web/Contact.htm
QinetiQ Cavitation Tunnel, Haslar, England, UK	Qinetiq	https://www.qinetiq.com/Contact
SINTEF Cavitation Tunnel, Trondheim, Norway	Stiftelsen for Industriell og Teknisk Forskning	https://www.sintef.no/en/contact-and-invoice-information/#/
SSPA Large Cavitation Tunnel, Göteborg, Sweden	SSPA Sweden AB	https://www.sspa.se/contact-us
UNIGE Cavitation Tunnel, Genoa, Italy	University of Genoa	+39 01020991

Part H: Supplemental Material References

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