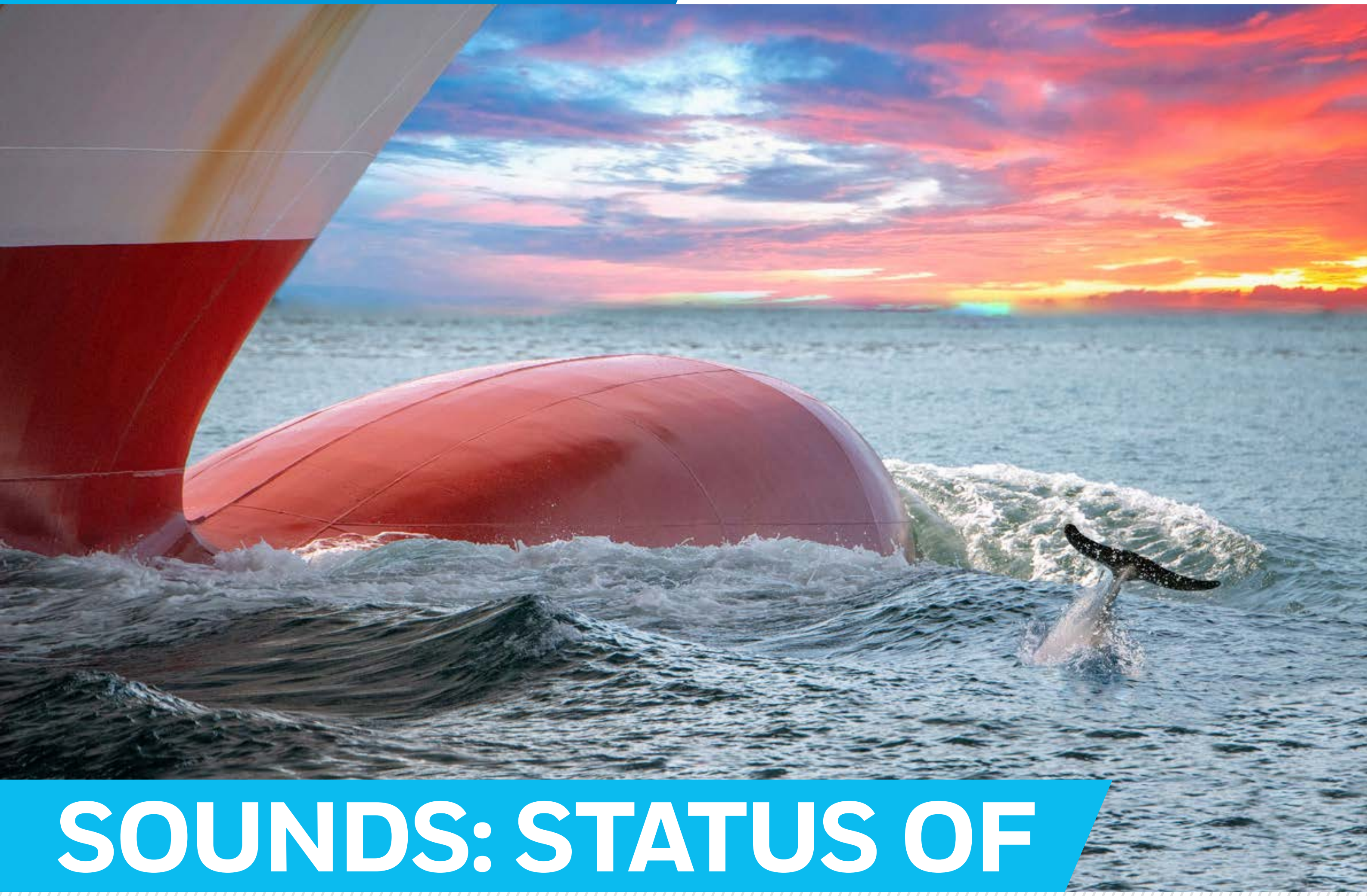
European Maritime Safety Agency



SOUNDS: STATUS OF UNDERWATER NOISE FROM SHIPPING

STUDY ON INVENTORY OF EXISTING POLICY, RESEARCH AND IMPACTS OF CONTINUOUS UNDERWATER NOISE IN EUROPE

Date: 20.08.2021

EMSA

SOUNDS – Status Of UNDerwater noise from Shipping

"Study on inventory of existing policy, research and impacts of continuous underwater noise in Europe"

Final Report

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Executive Summary

Shipping is known to be a primary contributor to anthropogenic noise in the oceans. Underwater radiated noise (URN) levels have increased faster than the size of the world fleet, with this trend set to continue. Despite the potentially harmful impacts of URN on marine fauna, and a significant body of knowledge from research projects, the subject currently has a low priority compared to other sustainability concerns within the shipping industry, such as greenhouse gas (GHG) emissions. Moreover, the absence of (international) policy and noise limits is slowing progress on mitigation. Nevertheless, efforts are being made to increase attention for the subject, exemplified by the recent agreement at the International Maritime Organisation (IMO) to review existing guidelines and propose future work. One of the most well-known programme to address ship noise abatement at operational level is the ECHO Program at the Port of Vancouver Fraser Authority, supported by Transport Canada, the scope of which has yet to be replicated elsewhere.

Within the European Union (EU), underwater noise has been addressed by the Marine Strategy Framework Directive's (MSFD) Good Environmental Status descriptor 11, where threshold limits are currently being proposed. With the arrival of the new European Green Deal in 2021, there is further impulse to make progress on the issue of URN in order to protect and restore ecosystems. Over the last 10+ years, numerous EU-funded research projects have contributed to knowledge on the subject, although this has not yet resulted in widespread action in terms of mitigation.

As part of its role of technical and scientific support with the preparation and implementation of EU legislation, the European Maritime Safety Agency (EMSA) commissioned this study to consolidate information on the subject of continuous URN from shipping, in order to derive recommendations for a future multi-stakeholder strategy within Europe. The study focussed on four main subject areas, with *noise sources*, *environmental impact* and *policy* providing the basis for the main goal, *mitigation*. Recognising the important role of a wide range of stakeholders, an extensive literature review was combined with stakeholder consultation in the form of a questionnaire and interviews.

The main source of URN from shipping is broadband propeller cavitation, radiating noise over a large frequency range. Machinery, primarily main propulsion engines, can also have an important contribution. Therefore, these are typically the mechanisms targeted by mitigation measures. Both measurements and modelling of ship noise are important for effective mitigation, with the standardisation of terminology and procedures, as well as uncertainty quantification, being the focus of recent and ongoing work. While deep water conditions have been treated thoroughly in the past, work on shallow water propagation effects – which are particularly relevant for much of EU coastal waters – is in progress, with final results expected in 2024. The limited access to Automatic Information System (AIS) data, required for experimental analyses and modelling purposes, also contributes to uncertainties, and should preferably be expanded.

In addition, the *simplification* of ship noise measurements is a rapidly developing subject, with several studies on the use of onboard sensors and drones recently published. Such technologies could help in increasing the amount of data available to researchers and policy makers in the future, as well as reducing costs for ship owners, when performed either on a voluntary or mandatory basis.

In terms of underwater noise monitoring, many researchers go beyond the suggestion of the MSFD to consider the 63 and 125 Hz one-third octave (OTO) bands, often analysing higher-frequency bands (up to 50 kHz), or broadband levels, related to the communication frequencies of specific marine fauna. There is also evidence that recreational craft – for which AIS transponders are not mandatory - might be the dominant noise generators in certain EU coastal waters, with these vessels typically producing sound at higher frequencies than larger merchant ships. It is therefore recommended that future efforts on policy and mitigation take a wide range of frequencies into account.

Considering the characteristics of sound propagation in water and anatomical adaptation, sound is used by fauna as the main mechanism to interact with the surrounding environment, being used for social interactions, reproduction, navigation, detection of obstacles and preys. Looking to the available information regarding hearing ranges and the use of sound by different species, an overlap with the most relevant noise sources from shipping is unequivocal. Responses to underwater noise levels have been observed for the main groups of species, marine mammals, fish and invertebrates. They correspond mainly to behavioural changes, masking and physiological responses. Behavioural responses, depending on the group, are reflected as for example, on changes of swimming and diving pattern, displacement or changes in the vocal behaviour, reflected on changes on the acoustic signals the animals produce. Most existing studies refer to the short-term impacts on species and there are still questions to answer about the chronic exposure to continuous underwater noise or about the significance of the responses that are identified at population level. Impacts of shipping noise have been addressed based on field observations, laboratory experiments and modelling approaches. Although most of the studies evidence responses to underwater noise from shipping, few of them provide a proper description of the source levels or the received levels at which the responses were observed. This presents a constraint on the assessment of the impacts in the presence of different vessels. It might be possible that the studies are focused on species that are easy to access, regarding field experiments, or easy to maintain, regarding lab experiments, since most of them do not focus on threatened species.

So far, several policies are being developed and implemented at different levels for managing underwater noise. These are being developed under the auspices of the Regional Sea Conventions, International Multi-party agreements and at European level. Only the guidelines released at IMO, providing recommendations for underwater noise reduction from shipping, are exclusively dedicated to the shipping industry. All the remaining policies are focused on continuous underwater noise. The Marine Strategy Framework Directive is the only piece of regulation implementing binding actions at European level. This work is being strongly supported by the initiatives developed under the Regional Sea Conventions such as OSPAR and HELCOM. An important aspect is the existence of working groups dedicated to the subject of underwater noise which allows for discussion among different stakeholders. National administrations and experts on underwater noise are the main stakeholders engaged in the working groups, but the participation of industry representatives is strongly encouraged.

Other policies that can be implemented are related to incentives. While numerous classification societies offer “Quiet Class” notations, few merchant vessels have, so far, been built with noise requirements. Ship owners could be encouraged to obtain such notations through incentive schemes, which may also accept voluntary sustainability certification as evidence of noise performance. Economic incentives have had some success in North America, with possible implementation in Europe requiring further attention. Revision of existing Quiet Class limits to account for different ship types could be used to improve both “acceptability” and “ambitiousness” of necessary noise reduction levels.

Combining relevant information on noise sources, environmental impact and policy, effective mitigation is a complex task, which needs to be assessed on a case-by-case basis, since factors including local marine traffic, marine fauna prevalence, and oceanographic conditions need to be considered. In addition, numerous possible solutions exist, whose impact in terms of, for example, GHG emissions and financial aspects, should be evaluated. This requires access to trade-off and cost-benefit analysis tools, as well as the cooperation of a large range of stakeholders. While significant progress has been made recently, particularly by the Port of Vancouver, further development and widespread application of such approaches is still required in Europe.

Although there are many options for ship noise abatement, in the absence of mandatory regulations, it has been widely suggested that measures aimed at reducing GHG emissions, which also produce an improvement in noise performance, may be the most acceptable solution; a “win-win” situation, given the low priority action on ship URN currently has compared to ship air pollution. However, it would also be prudent to prepare for noise limits and improve industry readiness for the construction of new quiet ships. “Demonstrator” vessels could help in this regard, in order to highlight potential noise performance improvements using available technologies while optimising cost. The first example of such a ship is the *ONEX Peace*, an Aframax tanker which achieved DNV SILENT-E class notation in 2021, following a collaboration between owner, shipyard, researchers and the class society.

Given the wide range of activities being performed by multiple stakeholders in relation to ship URN, and the diverse data sources required for modelling purposes, the efficiency of research & development work, as well as noise management could be significantly enhanced by establishing a common data repository. Several repository tools are currently being used but access may be limited, and there may be overlap between the databases. A common open-source EU repository would improve standardisation, ensure the efficient sharing and reuse of data and provide a quick overview of existing information and missing data.

Managing underwater radiated noise from ships is a multi-sectoral challenge which requires coordination between different policies and stakeholders to reach the main goal of underwater noise reduction. The engagement of shipping and shipbuilding industries is crucial since it allows the sustainable development of mitigation measures at the source. At the same time, there is the need to keep working on understanding the impact of underwater noise from shipping and what are the main drivers. The combination of different expertise will be aided by the adoption of common terminology and standardisation.

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Acronyms

ABS	American Bureau of Shipping
ACCOBBAMS	Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area
AIS	Automatic Identification System
ASCOBANS	Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas
BV	Bureau Veritas
CBD	Convention on Biological Diversity
CCS	China Classification Society
CIS	Cavitation inception speed
CMS	Convention on the Conservation of Migratory Species of Wild Animals
CPA	Closest point of approach
CPP	Controllable-pitch propeller
DNV (GL)	Det Norske Veritas (Germanischer Lloyd)
ECHO	Enhancing Cetacean Habitat and Observation
EMSA	European Maritime Safety Agency
ESI	Environmental Ship Index
EU	European Union
FPP	Fixed-pitch propeller
GES	Good Environmental Status
GHG	Greenhouse gas emissions
HELCOM	Helsinki Commission (Baltic Marine Environment Protection Commission)
Hz	Hertz
IACS	International Association of Classification Societies
IMO	International Maritime Organisation
ISO	International Organisation for Standardization
ITTC	International Towing Tank Conference
IUCN	International Union for Conservation of Nature
KR	Korean Register
MARIN	Maritime Research Institute Netherlands
MEPC	Marine Environmental Protection Committee
MSFD	Marine Strategy Framework Directive
MSL	Monopole source level
OSPAR	(Convention for the) Protection of the Marine Environment of the North-East Atlantic
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
OTO	One-third octave
PBCF	Propeller boss cap fins
RINA	Registro Italiano Navale
RNL	Radiated noise level
SL	Source level
SPL	Sound pressure level
TC	Transport Canada
UN	United Nations
URN	Underwater radiated noise
VFPA	Vancouver Fraser Port Authority
VMS	Vessel Monitoring System

1. Introduction

1.1 Background to the study

The oceans have an important role in supporting ecosystems and regulating the global climate. With increasing pressure of human activities at sea, there is a need to develop management strategies that allow for its sustainable use. As part of this effort, better understanding of human activities with potential to affect marine ecosystems is required.

Anthropogenic underwater sounds generated intentionally or unintentionally, as result of human activities, are recognised as pollutants of the marine environment, since they represent a form of energy that can negatively impact marine environment (IMO, 2014; UNCLOS, 1982). In this context, noise refers to sound that interferes with animals' ability to use the underwater acoustic environment, which is the case for most anthropogenic activities. Underwater noise is therefore also relevant for the new European Green Deal (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en), which aims at (among other things) "*preserving and restoring ecosystems and biodiversity*."

Numerous species rely on sound to survive, including communication, finding mates, feeding and protection. Throughout the years, it has become clear that anthropogenic noise can negatively impact species at different levels, depending on exposure conditions and the animal's condition, by reducing their ability to detect natural cues, physiological and physical damage of sensory organs and, in severe situations, death. Underwater radiated noise (URN) from shipping is recognised as one of the main pervasive sources contributing to the underwater acoustic soundscape (Hildebrand, 2009; Thomson & Barclay, 2020), and was included as a dedicated chapter in the recently published Second World Ocean Assessment (Širović et al., 2021). Although the size of the total world shipping fleet tripled between 1948 and 2008 – equivalent to a 5 dB increase in noise levels (Hildebrand, 2009) – the measured increase is in fact 20 dB since the 1950s, indicating that individual ships have become noisier (Frisk, 2012). The noise levels generated by marine traffic are illustrated in Figure 1, with these predicted to almost double by 2030 (Kaplan & Solomon, 2016).

While noise can be defined as unwanted sound which interferes with the normal functioning of a system, in this study we also use the term "noise" to refer to sound, partly due to the difficulty in defining what constitutes noise, as well as following what is found in the literature. This more general use of the term noise is common, as evidenced for example, by the widely-adopted term URN, although we note that there is a drive towards clearly separating these two terms as part of terminology standardisation (ISO, 2017).

In this context, "continuous" noise levels are the primary driver of this increase, and hence are the focus of the majority of studies on the subject (including this one). Therefore, in this study we are concerned with the contribution of underwater sound generated by the continuous operation of marine vessels to ocean ambient noise levels. Continuous noise contrasts with "impulsive" noise, which is typically characterised by high-energy short time-scale "bursts" of sound emission, which are mostly generated intentionally in the context of shipping, e.g., sonar. An overview of anthropogenic noise sources is provided by Širović et al. (2021).

Furthermore, in terms of vessel types, this study covers not only merchant shipping, or "marine traffic", but also includes vessels such as recreational craft. Naval vessels and inland watercraft are not considered.

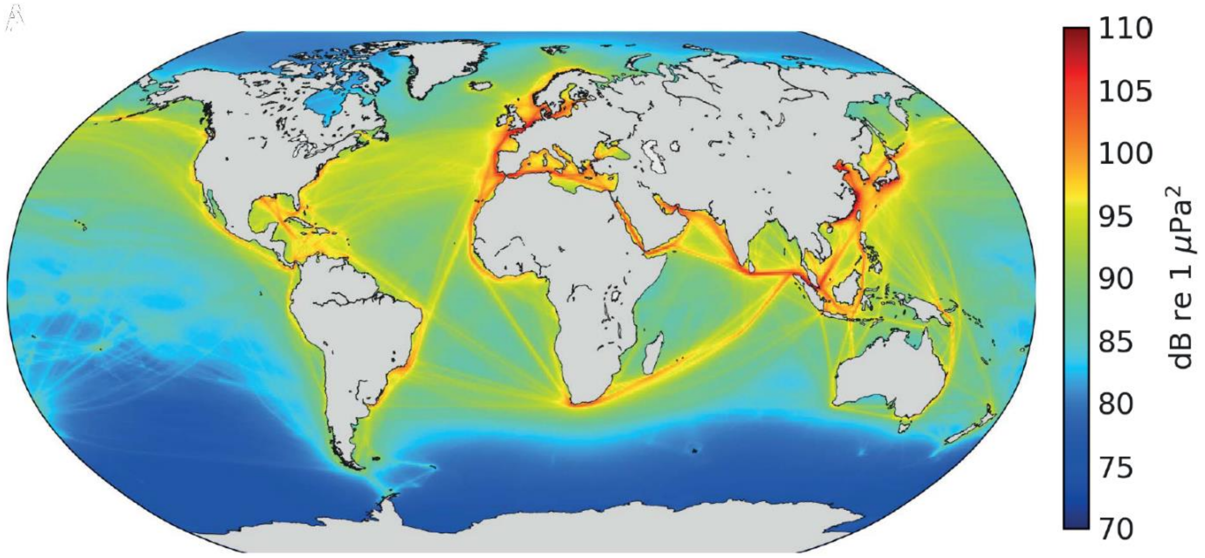


Figure 1 Average sound level due to shipping in 2014 at 100 Hz, estimated using AIS data. Reproduced from Duarte et al. (2021). High sound levels are found in multiple shipping lanes in European waters, including the Atlantic, Baltic, Mediterranean and North Sea regions.

Although several studies address the impact of shipping noise on marine fauna (Erbe et al., 2019a; Holles et al., 2013), quantifying the link between marine traffic, continuous underwater noise and the effect on marine ecosystem is still in its infancy. Some important questions such as *"what are sustainable thresholds levels?"*, *"can we relate shipping noise sources with specific impacts?"*, *"what are the most effective mitigation measures?"* are still unanswered.

One relevant aspect related to underwater noise pollution is its transboundary nature, which requires cooperation at international and regional level. It is therefore being addressed by high-level international bodies, such as the European Union and United Nations. Instruments being developed by the International Maritime Organization (IMO), such as the "Guidelines for reduction of underwater noise from commercial shipping to address adverse impacts on marine life" (IMO, 2014) and the Marine Strategy Framework Directive at European level (EU, 2017), as well as other regional agreements, are playing a key role to move forward on the topic in Europe.

Furthermore, addressing the issue of underwater radiated noise from shipping requires a multi-disciplinary, multi-party approach, involving a wide range of stakeholders, including researchers, authorities, classification societies and environmental organisations, ship designers, builders, operators and owners, among others. Therefore, next to the identification of research needs, it is important to engage with stakeholders as part of the definition of future strategy.

1.2 Scope of work

The main aim of this work is summarising the status regarding continuous underwater radiated noise from shipping in European waters, and providing recommendations on possible future activities, thereby allowing EMSA to support the European Commission and EU Member States in the discussions taking place at an international level at IMO. The work is focused on four main topics:

- Characteristics and quantification of noise sources from various ship types.
- Impacts on marine fauna.
- Existing policies, including guidelines, decisions, resolutions and regulations.
- Mitigation measures, for the abatement of ship noise and noise-related impact.

1.3 Report structure

Following the Introduction and Methodology sections, the report is structured into four main sections, addressing the rationale of *"a source, with the potential to impact the marine environment, that needs to be managed and mitigated"*. Thereafter, sections focussing on a case study and the results of the stakeholder survey are included. The report ends with conclusions, and recommendations on future strategy for effective mitigation. The sections can be summarised as follows:

- **Section 1 Introduction** provides a general overview and motivation for this study.
- **Section 2 Methodology:** describes the methods used for literature review and stakeholder engagement.
- **Section 3 Noise sources:** describes the main sources of underwater noise from different types and designs of ships, regarding frequency and spectra, including operational modes and onboard equipment.
- **Section 4 Environmental impacts:** the potential impacts from URN from shipping are described for different group of species, highlighting their main categories related to the marine environment. Whenever possible, relations are made with ship noise to identify research gaps. Available tools for impact assessment and cumulative impacts are also consider under this section.
- **Section 5 Policy:** focuses on policies, guidelines, decisions, resolutions and regulations on URN from ships, that have potential repercussions at European level. Also, it looks into controls and regulations that are being implemented at Coastal State level, industry agreements and voluntary measures that are being adopted, including incentives.
- **Section 6 Mitigation measures:** this section focus on different types of mitigation measures, including technical and operational and its assessment regarding feasibility and efficiency.
- **Section 7 Survey results**: an overview is provided of the main results following analysis of the stakeholder questionnaire.
- **Section 8 Case study:** presents an overview of the work being developed by Transport Canada and the ECHO Program.
- **Section 9 Concluding remarks:** this section summarises the findings of the study.
- **Section 10 Recommendations**: suggestions for future strategy on the subject of ship URN, and its mitigation, are provided.

Additional sections include the References and appendices:

- **Appendix A Database field definitions:** contains a description of the fields that were considered in the database associated with the literature study.
- **Appendix B Questionnaire:** includes the questionnaire, with the rationale behind each question and targeted stakeholder group also provided.
- **Appendix C List of interviews:** overview of persons interviewed, including their organisation and identified stakeholder group.
- **Appendix D Summary of members represented in the ECHO Program:** List of members of the Advisory Working Group, Vessel Operators Committee and Acoustic Technical Committee of the ECHO Program
- **Appendix E Glossary of acoustic terminology:** definition of some of the main terms referred to in the study.
- **Appendix F Summary of EU projects on URN:** includes a list of Europeans projects addressing URN.

2. Methodology

To address the scope of work, the study was based on literature review and stakeholder consultation (Figure 2).

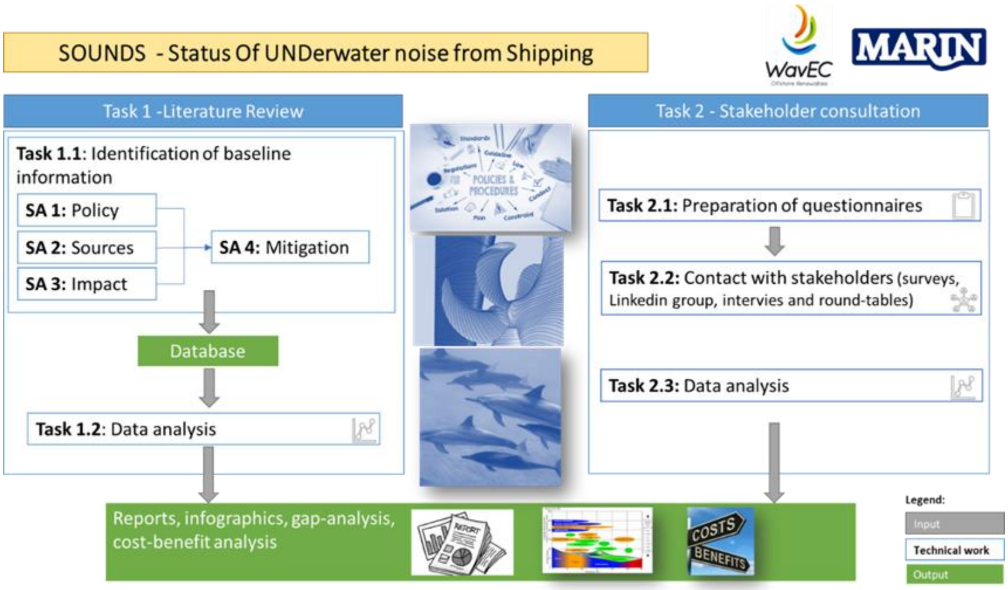


Figure 2 Scope of work of the SOUNDS project, including identification of the subject areas (SA).

2.1 Literature review

Regarding the literature review, the work was carried out based on two main tasks, including compilation and analysis of relevant information related to each subject area (SA1: Policy, SA2: Noise sources, SA3: Environmental impact, SA4: Mitigation measures).

The literature review was based on sources and material available, according to the following criteria:

- **Policy:** Official documents released by different regulatory and policy bodies, including Agreements, European Directives, national legislation with focus on underwater noise, and when available particularly related with shipping noise; documents that provide standard terminology.

- **Noise sources:** Peer-reviewed papers and technical reports with higher number of citations with reference to continuous sources of noise, including information about the frequencies and spectra; studies dealing with standards for measuring and modelling URN.

- **Environmental impact:** Peer-reviewed scientific papers and technical reports dealing with underwater noise from shipping, maritime traffic; with marine fauna (e.g. fish, marine mammals, invertebrates); studies that measure, observe or modelled responses (masking, behaviour, hearing sensitivity); studies measuring hearing thresholds, or presenting audiograms for the different species.

- **Mitigation measures:** Scientific papers, technical reports and promotional material dealing with mitigation measures for underwater noise; studies that test or model the results of the application of mitigation measures; studies dealing with propeller and engine noise mitigation; studies addressing operational measures for noise mitigation.

To compile the information a search on the internet using keywords or combination of keywords. e.g. *"underwater noise"*, *"ship noise"*, *"underwater noise impact"*, *"underwater noise mitigation"* was carried out. Selection of keywords and combination were adapted according to the task and the level of information gathered during the process. Examples of websites and databases that were consulted include IMO, OSPAR, research project websites, European

Commission, Science Direct, ResearchGate and Mendeley. Relevant studies indicated by stakeholders during interviews, questionnaires, or informal discussions resulting from liaison activities were also considered. A total of 309 sources were reviewed.

Information on the selected sources was compiled in a dedicated database to facilitate analysis and provide input for stakeholder consultation. The details about the database, including definition of the fields is provided in Appendix A.

Depending on the task and the objectives to be addressed, qualitative and/or quantitative methods were used:

- **Noise sources:** For each source of noise a typical frequency range and source level are presented. Graphics considering the interval of frequencies registered for each noise source were produced and the typical spectral features are highlighted.

- **Environmental impacts:** The study focuses on marine mammals, fish and invertebrates, specifically on the species that occur in the sub-regions of European Seas used for the implementation of the Marine Strategy Framework Directive (MSFD) (Figure 3). For each group of species, the main range of vocalizations or sounds produced by the animals were identified. When available the audiograms were also considered to compare them with shipping noise sources. Regarding marine mammals the review carried out by Erbe et al. (2019) was considered as the baseline. Regarding fish, the main commercial species were considered. For the invertebrates, considering the number of references, all studies were considered. The frequency and sound pressure level at what the impact was observed were considered, when available, to assess any pattern on impacts.

- **Policy:** A qualitative analysis was performed in order to characterise the regulatory framework and policies that are being implemented related to underwater noise and underwater noise from shipping. International and Regional agreements were analysed, as well as European Directives and other documents produced by relevant organizations.

- **Mitigation measures:** Considering the findings of the literature review, and the inputs from the environmental sources and impacts, each identified solution was analysed in terms of estimated cost-benefit, taking frequency thresholds into account where possible. The applicability and popularity of the most promising technologies were assessed as part of the stakeholder engagement.

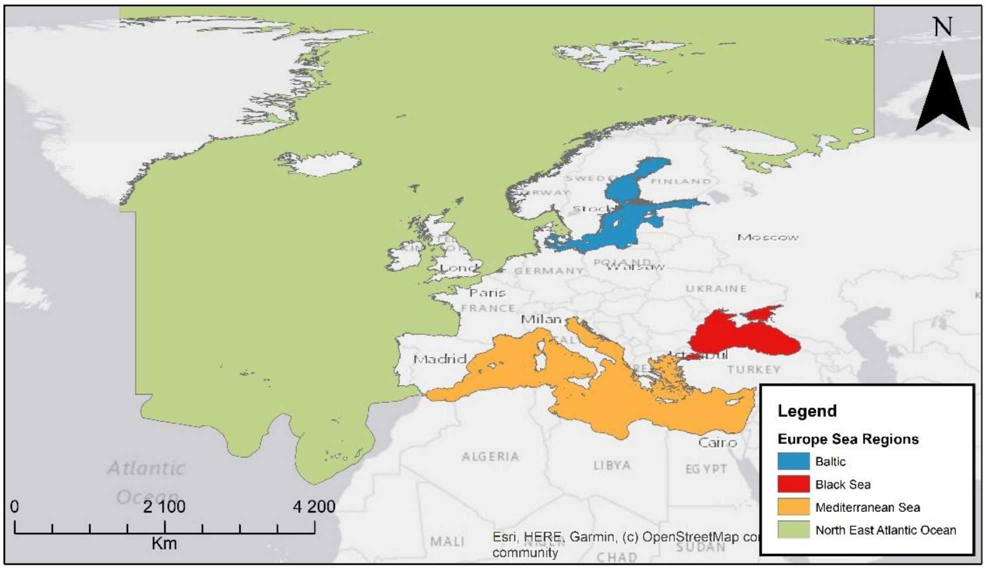


Figure 3 – Spatial extent of European Seas regions, listed in the Marine Strategy Framework Directive and other surrounding seas of Europe, considered for environmental impact assessment. Source: European Environment Agency.

2.2 Stakeholder consultation

The stakeholder consultation was performed based on two main actions:

- a survey to collect the views of a wide range of stakeholders in Europe.
- dedicated interviews.

The range of stakeholders approached is summarised in Table 1, drawing on existing contacts from EMSA, WavEC and MARIN. Those contacted were also encouraged to share the questionnaire within their EU network.

Table 1 – Example of stakeholders contact during the study.

Stakeholder group	Contact route
Shipbuilders (shipyards)	Forums, technology platforms, industry associations, commercial clients, trade shows, conferences
Marine suppliers	Forums, technology platforms, industry associations, commercial clients, trade shows, conferences
Classification societies	Forums, technology platforms, conferences, various EU projects
Naval architects	Forums, technology platforms, industry associations, commercial clients, trade shows, conferences
Engine manufacturers	Forums, technology platforms, industry associations, trade shows
Associations of ship owners	Technology platforms, industry associations
Ship owners	Forums, technology platforms, industry associations, trade shows
Ship managers	Forums, industry associations
Ship's master	Commercial clients
Crew	Commercial clients
IMO	Contacts from various projects and meetings
European Commission	Contacts from various projects and meetings
Research organisations	Contacts from various projects and meetings
Port State Control authorities	Contacts from various projects and meetings
Maritime and Environmental organisations	Contacts from various projects and meetings

The questionnaire was prepared based on insights from the literature review, and was divided into five sections:

1. Professional position, and experience of respondent with regards to URN.
2. Relationships between stakeholders with regards to URN.
3. Opinions on possible mitigation approaches.
4. Questions about availability of data for studying URN.
5. Recommendations for future work.

A complete version of the questionnaire including the rationale for each of the questions can be consulted in Appendix B. The questionnaire was open until 7 May 2021, and a total of 100 answers have been received. In the questionnaire, the option was given for respondents to share their contact details in case they were willing to participate in interviews and/or round table discussions. Close-ended questions were analysed using basic quantitative statistics (e.g., % of answers with the same result), while open-ended questions were analysed to categorise the answers according to specific keywords and extract information relevant for each of the four main tasks of the study.

Dedicated interviews with focus on individual companies and organisations were conducted based on the information gathered during the literature review and the questionnaire. Relevant findings from interviews were incorporated into the report at the appropriate location. A list of persons interviewed is provided in Appendix C.

Data protection and consent procedures for the participation of Stakeholders has been considered according to the General Data Protection Regulation (GDPR) Regulation (EU) 2016/679.

3. Noise sources

3.1 Introduction

Characterising and understanding the noise sources generated by vessels is important for the purpose of accurate impact assessment, and effective mitigation. This section discusses characteristics of the various noise sources present on board typical merchant vessels, followed by aspects of ship source level estimation, including measurement and modelling.

In this document, unless otherwise stated, the terms “low”, “medium” and “high” frequencies refer to the ranges proposed by ISO 2016, vis. 10 to 100 Hz, 125 to 16,000 Hz, and >20,000 Hz, respectively. The frequencies are given in base 10 one-third-octave (OTO), or decidecade, bands, which is the recommended way of presenting ship broadband noise levels (ISO, 2017).

3.2 Noise sources on board ships

3.2.1 General characteristics

Ships generate continuous noise over a wide range of frequencies, from 1 Hz up to about 100 kHz (Bretschneider et al., 2014), although frequencies up to 20 kHz are the ones typically studied. The spectrum contains tonal, narrowband and broadband components, with the highest source levels typically found at low frequencies – below the 10th harmonic of the blade passage frequency (BPF). Both tonal and broadband sound are important in the context of environmental impact on marine animals: the former can generate the highest levels, while the latter radiates more sound energy in total over a large frequency range. Broadband noise is therefore more likely to radiate at frequencies which coincide with those used by marine animals. The effect of the character of shipping noise on marine species is the subject of ongoing research, as will be discussed further in Section 4.

Three main categories of noise source which can contribute to a ship source level spectrum are (Ross, 1976; Abrahamsen, 2012):

- Machinery noise, generated by the main and auxiliary plant on board.
- Flow noise, due to the flow around the ship hull.
- Propeller noise, which concerns all flow phenomena occurring due to the propeller.

An overview of noise sources from merchant ships is given in

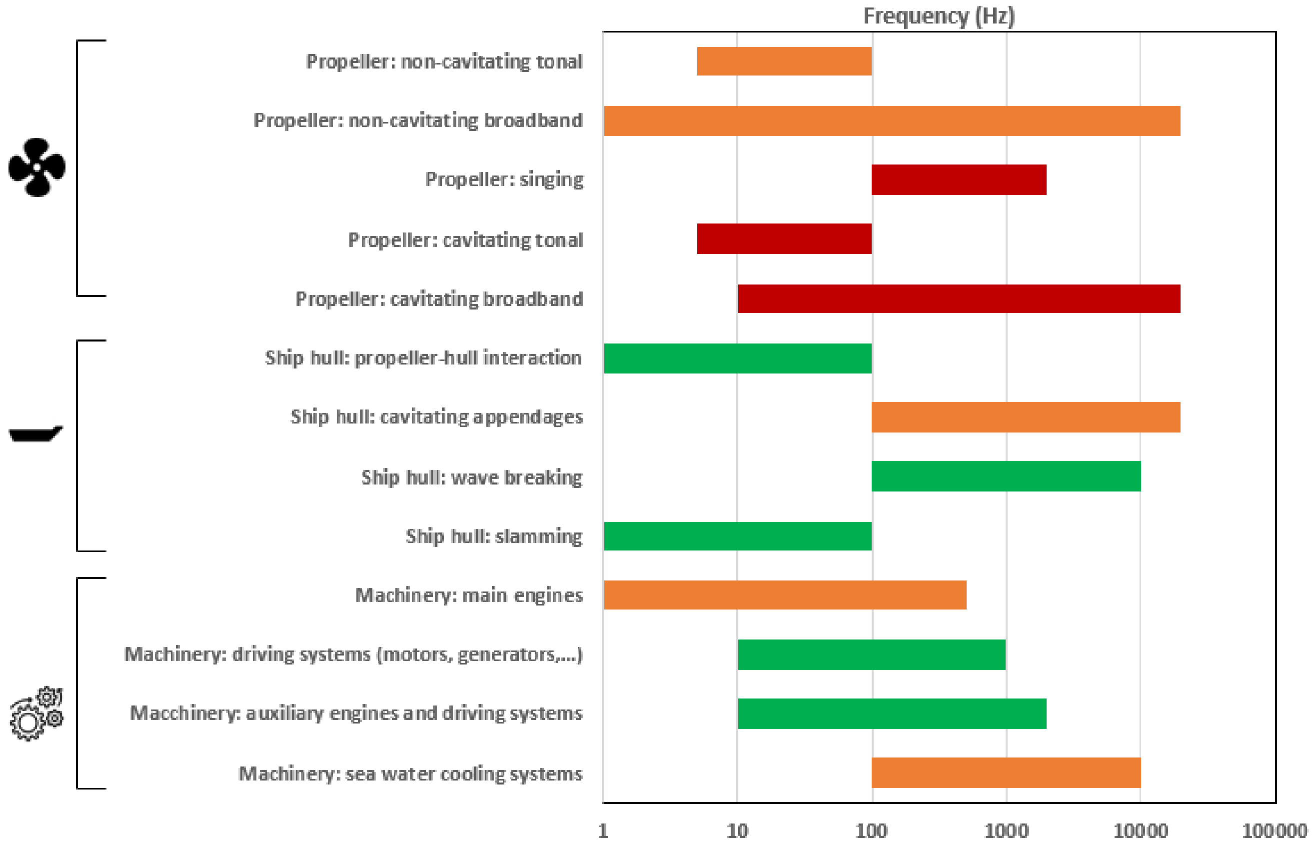


Figure 4, including the expected contribution to URN. The most important noise sources will be discussed in more detail in the remaining sections of this chapter.

When propeller cavitation is present, this noise mechanism typically dominates, especially the broadband part of the spectrum. Since most merchant vessels use screw propellers for propulsion, and experience cavitation at their design speed, propeller cavitation is typically the focus of research activities on URN from shipping. Note that while propeller singing – vibration due to coherent vortex shedding from the trailing edges of the blades – may produce high noise levels, it does not occur often for merchant ships. Machinery noise, particularly from the main engine, remains relevant however, since it generates strong tonal noise at low frequencies, and is present over a wide range of vessel speeds.

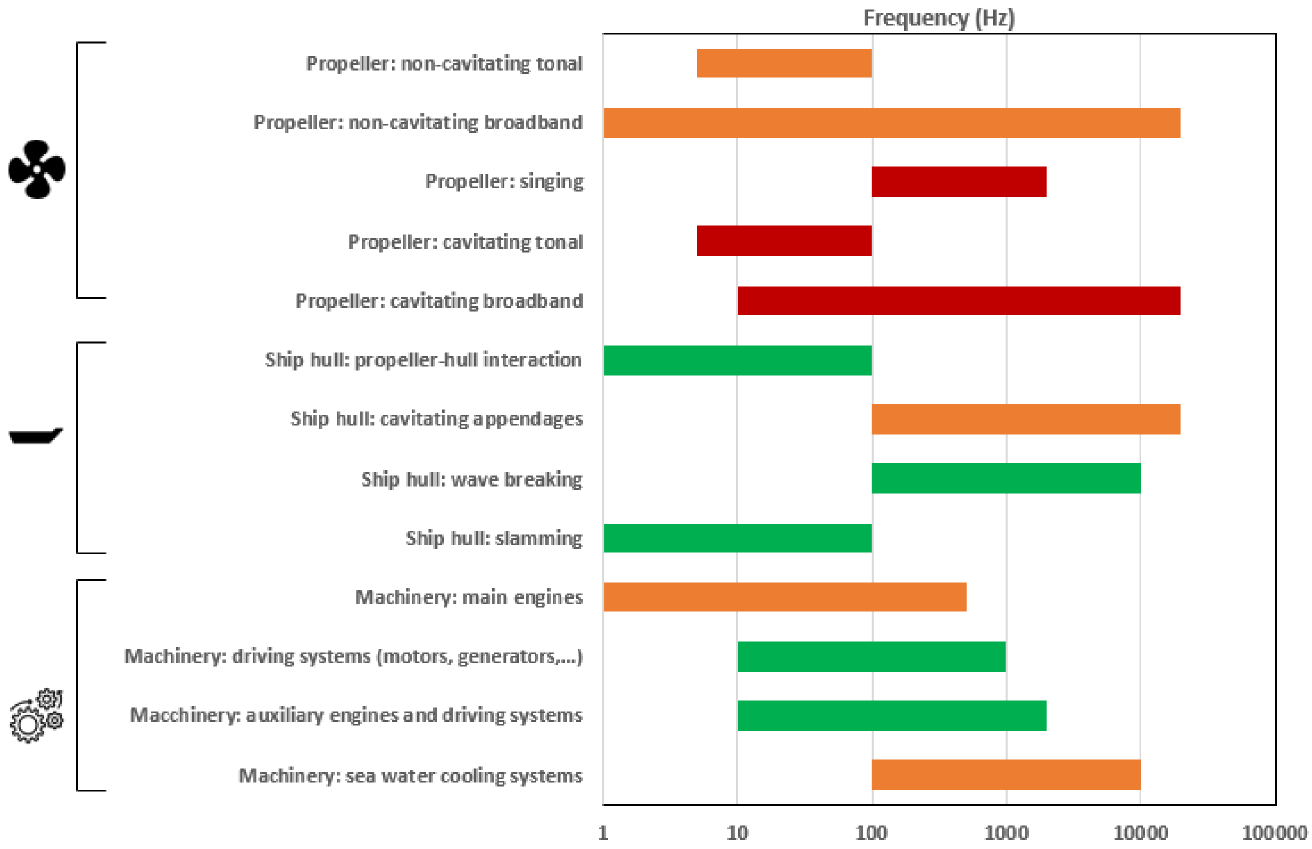


Figure 4 Overview of continuous underwater noise sources from ships, in terms of frequency range and expected contribution to URN (Bretschneider et al., 2014): red – high contribution; orange – medium contribution; green – low contribution. Tonal sources occur at harmonics of the propeller blade passing frequency, as well as ship hull natural frequencies in the case of propeller-hull interaction noise. The frequency ranges given are indicative of merchant vessels, up to the 10th BPF.

Example measured source level spectra are given in Figure 5, for a containership. At low frequencies, the spectra are characterised by harmonics of the propeller blade passing frequency and main engine firing frequency, which generate the highest spectral levels. The broadband part of the spectrum for frequencies above ~ 50 Hz exhibits an approximately constant decay with increasing frequency of about 20 dB/decade (indicated by dashed lines in Figure 5. This part of the spectrum is primarily caused by propeller cavitation, and contributes most to the broadband integrated source level, and the total amount of acoustic energy the ship generates.

It is important to note that, although the highest noise source levels occur at low frequencies, this does not necessarily mean that they are the primary sources leading to environmental impact. While long wavelengths (low frequencies) do propagate further underwater than higher frequencies, potentially increasing the range at which impact occurs, these sound waves are affected more by the Lloyd's mirror effect – the interference of sound with the free surface – which typically results in a significant reduction in received noise levels at low frequencies. This is illustrated in Figure 5, and will be discussed further in Section 3.3.1, which covers measurements of ship URN.

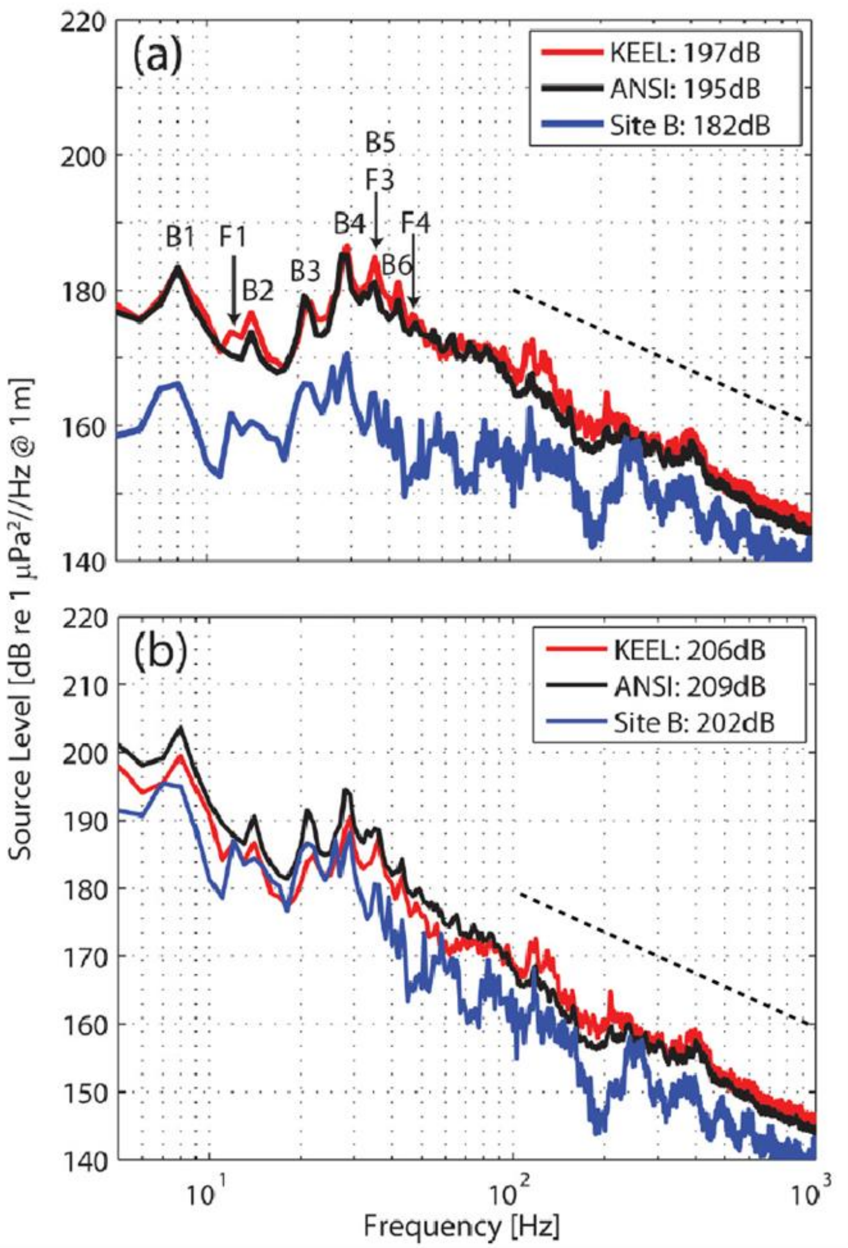


Figure 5 Narrowband spectral source levels for the containership CSCL South China Sea, reproduced from Gassmann et al. (2017). Measurements were performed in deep water, using different procedures (KEEL, ANSI), and at a different location (Site B). Broadband source levels integrated between 5 Hz and 1 kHz are included in the legend. The spectra in the top figure have not been corrected for the Lloyd's mirror effect, while those in the bottom figure have. The frequencies identified by 'B' and 'F' refer the blade passing frequency harmonics and main engine firing frequency harmonics, respectively. Dashed lines have been added to indicate the decay slope of broadband cavitation noise.

3.2.2 Propeller cavitation

Cavitation is the formation of vapour due to the local pressure dropping below the vapour pressure i.e., phase change at constant temperature. Cavitation commonly occurs on ship propellers due to the high loading on the propeller blade. Noise is generated by cavitation over a wide range of frequencies due to the oscillation and collapse of bubbles of different sizes (Bosschers, 2018).

The speed at which cavitation starts to form is called the cavitation inception speed (CIS), and is typically associated with a large increase in noise levels. Above CIS, as the thrust force generated by the propeller increases, so does the amount of cavitation, in most cases resulting in higher noise levels. However, the absolute noise levels for a given ship depend on numerous other factors, including size, hull design (wake field), propeller design, and loading condition.

Various forms of cavitation can be present (at the same time) due to the propeller action. The main forms are depicted in Figure 6, which fall into three general categories: bubble, sheet, and vortex cavitation. Since bubble cavitation is avoided in propeller designs due to the high risk of blade erosion, sheet and (tip) vortex cavitation are the most relevant for URN.

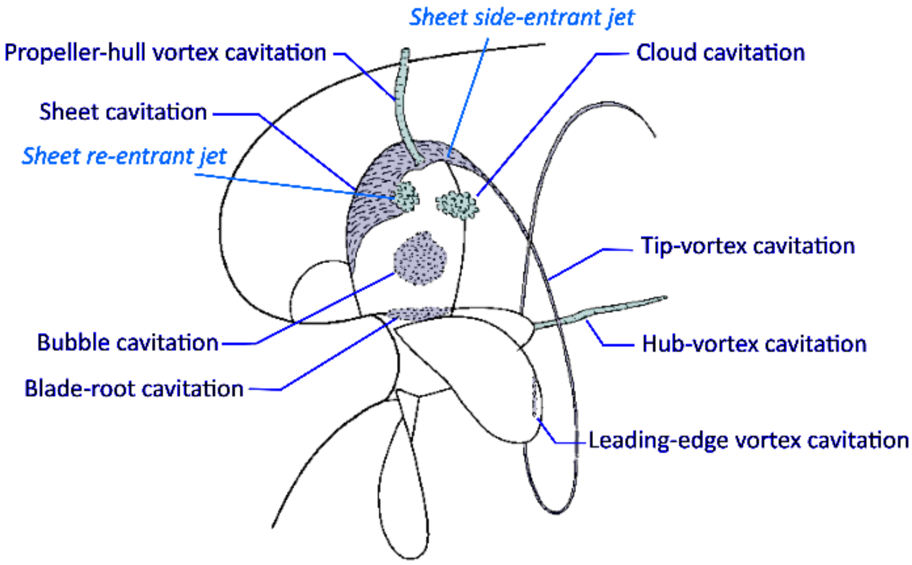


Figure 6 Types of propeller cavitation (dark blue), reproduced from Bosschers (2018), adapted from ITTC procedure 7.5-02-03-03.2.

Sheet and tip vortex cavitation generate both narrow- and broadband sound. BPF is caused by the blade passing through the wake of the ship hull, causing the sheet cavity to grow and shrink. Broadband noise is also generated at higher frequencies due to bubbles being shed from the main sheet cavity. Tip vortex cavitation results in broadband noise over a wide range of frequencies, typically seen as a characteristic *"hump"* in the sound spectrum, centred between the 4th (as in Figure 5) and 8th BPF harmonics. This form of cavitation is typically the first to occur, and – for well-designed passenger vessels and yachts – remains the only form at the design speed. It is therefore often the primary (broadband) noise source generated by a ship and has received wide research attention.

Other forms of propeller cavitation can generate significant noise, such as blade root and propeller-hull vortex cavitation, although these rarely occur on merchant vessels. Hub vortex and rudder cavitation are more common but are not expected to result in high noise levels due to the lower flow speeds, and thus reduced cavitation dynamics, relative to the blade tip.

In typical propeller designs, some cavitation is allowed – and is in most cases unavoidable – in order to achieve a satisfactory propeller efficiency. Primary design considerations are avoidance of cavitation erosion, and acceptable hull excitation forces, although URN can also be taken into account, for example using multi-objective optimisation (Lloyd et al., 2020; Miglianti et al., 2020).

3.2.3 Machinery

Machinery noise in the context of underwater radiated noise refers to the structure-borne noise and vibrations generated by onboard machinery, which radiates from the ship hull. Being the largest piece of machinery, the main propulsion engine can be the primary noise source in this context, although other engines, motors and auxiliary equipment, such as pumps, can also generate significant noise depending on the vessel type and its operating condition. Figure 7 illustrates the paths by which machinery noise is radiated through the ship structure.

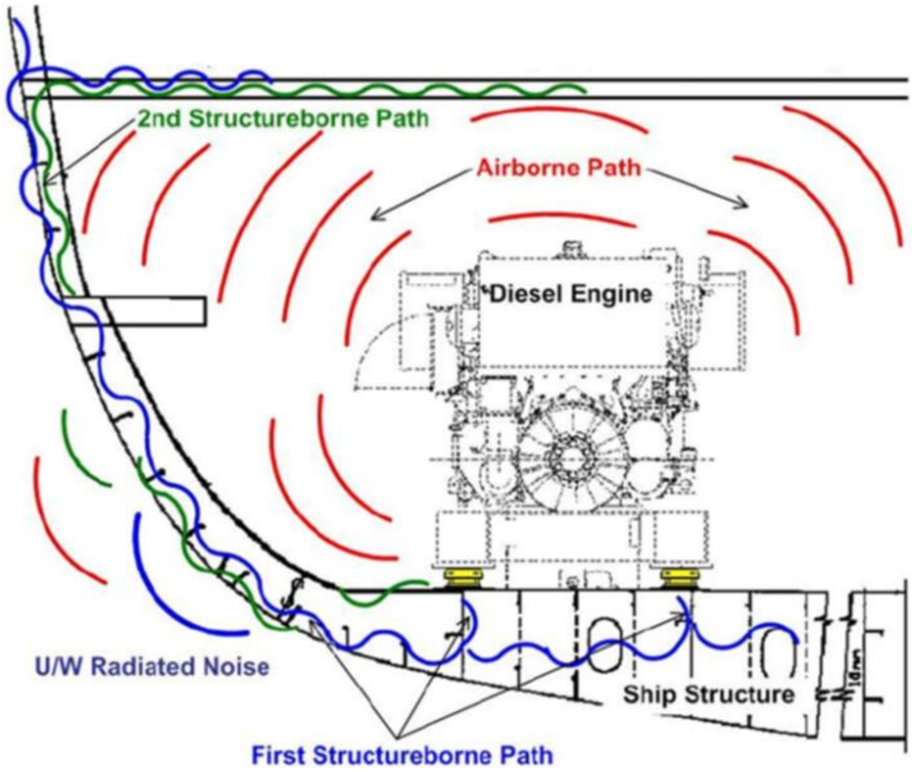


Figure 7 Underwater noise radiation paths from onboard machinery, reproduced from Spence & Fischer (2017).

Noise from machinery tends to be tonal in nature, originating from rotating or reciprocating machines, at frequencies corresponding to harmonics of the propeller shaft rate and engine firing rate. In addition, natural frequencies of the ship structure may also be excited. The frequency range at which the noise is generated depends mainly on the type of engine, and mode of operation. Large slow-speed engines are the most commonly used propulsion plant for large merchant vessels and generate noise at very low frequencies (less than 10 Hz). This increases for medium-speed and high-speed engines which operate at higher rotation rates and use a gearbox to drive the propeller shaft. Furthermore, since most vessels are equipped with fixed-pitch propellers (FPPs), the tonal noise will shift to higher frequencies as the vessel's speed increases. For vessels fitted with controllable-pitch propellers (CPPs), the engine is more likely to be operated at a constant rotation rate, in order to drive auxiliary equipment such a generator sets that require a fixed shaft rate. This means that machinery noise has a lower dependency on ship speed than cavitation noise and will be the primary noise source at speeds below CIS. Mitigation of machinery noise will therefore be of particular importance for vessels operating at low speeds, or in cavitation-free conditions for large proportions of time.

3.3 Ships as noise sources

3.3.1 Measuring ship URN

Measurements of ship URN are essential as part of impact assessment and mitigation exercises. They contribute to the understanding of noise characteristics of different vessel types, as well as the dependence of noise levels on various design and operational parameters, as well as seasonal effects on ambient noise (Mustonen et al., 2019). Furthermore, such measurements can be used to determine source levels, which are required for obtaining "Quiet" ship certifications (Ainslie et al., 2020), or as input for sound mapping and environmental impact assessment tools (Audoly et al., 2017). When analysing such measurements, the individual noise sources present on board a particular vessel may not be easily distinguishable from each other, although some spectral features may be clearly identifiable based on literature and knowledge of the vessel operating condition. However, in most cases, the primary purpose is to determine the total (spectral) source level of a particular vessel.

Two main types of URN measurements can be distinguished: dedicated and opportunistic. Dedicated measurements concern noise trials of a specific vessel. These may be performed following classification society or other recommended procedures, as described for instance in ITTC (2017), for verifying noise-related design specifications using class rules. More extensive trials are sometimes carried out for research or troubleshooting purposes, which may involve measurements at a range of ship speeds, engine settings and propeller pitch settings. Various pieces of machinery may also be run individually in order to characterise their noise radiation. Opportunistic measurements are made when vessels pass a listening or monitoring station, in order, for example, to estimate the shipping URN levels in the vicinity, or analyse temporal (daily, annual) trends. Therefore, the data recorded will represent noise levels for typical local marine traffic, with numerous vessel types and operating conditions included. Data processing and analysis then requires additional information, primarily automatic identification system (AIS) data, in order to determine individual vessel source levels and categorise or aggregate their source level spectra.

For both types of measurement, the accurate estimation of ship URN source levels is the primary goal, yet this remains far from trivial. Chion et al. (2019) identified differences of up to 30 dB between ship source levels reported in the literature, for similar ship types and speeds, related both to how the sound was measured, and corrected to source levels. The effect of following different procedures, and performing measurements at different locations, is illustrated in Figure 5. In the figure legend, 'KEEL' refers to measurements using a bottom-mounted hydrophone at the centreline of the shipping lane, while the 'ANSI' data were obtained following ANSI/ASA (2009) procedures using a free-hanging hydrophone array mounted close to the shipping lane (~ 500 m). The results from 'Site B' were measured at a much greater distance from the shipping lane (~ 3000 m). While dedicated noise trials employ a closest point of approach (CPA) typically of the order of one ship length (Bureau Veritas, 2017), opportunistic measurements are more likely to be carried out over a wider range of distances. This makes the accuracy of the source level derived from the latter more susceptible to (errors in) the correction for propagation loss.

Correcting received levels to source levels involves accounting for various geometric, bathymetric, and oceanographic effects, therefore requiring additional information about the local environment (Karasalo et al., 2017). Despite the recent publication of industry guidelines (ISO, 2016, 2019b; ITTC, 2017), until their widespread adoption, large differences in noise source levels can be expected depending on the procedures used for measuring and processing the data. This means that high levels of uncertainty can be expected when comparing results for, e.g., the same vessel measured using different procedures, and different vessels measured in different locations following the same procedures. However, proposals have been made to standardise terminology, and align measurement and analysis procedures in order to reduce uncertainty and aid comparisons (Ainslie et al., 2020), with the subject also currently being addressed by the URN working group of the International Association of Classification Societies (IACS) (Bureau Veritas, private communication, 2021). When following ISO (2016) procedures, measurement uncertainties in the low-, medium- and high-frequency ranges are 5 dB, 3 dB and 4 dB respectively, with additional uncertainties related to the conversion to source levels (ISO, 2019b). Moreno (2014) estimated the total uncertainty of source levels to be around 7 dB, with the dominant contribution arising from propagation loss.

When received levels are corrected back to source levels assuming geometrical spreading losses, these are referred to as the *"affected"* or dipole source levels, or more commonly, radiated noise levels (RNL). This is typically a simplification, with the determination of the *"monopole"* source levels (SL) requiring an estimation of the propagation loss, which accounts for all differences in acoustic pressure between the source and receiver (ITTC, 2017). One of the main contributors to the propagation loss at low frequencies is the Lloyd's mirror effect, which refers to the interference pattern caused by the sum of sound received directly, and that reflected by the sea surface. When this is not taken into account as part of data analysis, the source level can be under-predicted by tens of decibels (Gassmann, Wiggins, et al., 2017), i.e., the difference between the RNL and SL is significant. Therefore, it is important to correct for this phenomenon in order to obtain accurate predictions of ship source levels for the development and validation of noise models, which are used for sound mapping (Audoly & Meyer, 2017; MacGillivray & de Jong, 2021). Simple models are available for the Lloyd's mirror effect (ISO, 2019b), which are also used in some classification society procedures (e.g., Bureau Veritas, 2017). Such models require an assumed source depth as input, which may be straightforward for dedicated noise measurements, but less so for data from monitoring stations. Analysis of these recordings rely on AIS data, which may not include accurate information on ship draught, since this is entered manually (MacGillivray et al., 2020). Baudin and Mumm (2015) identified a list of desirable parameters to be added to AIS data for improved SL predictions, including automatic updating of vessel draught.

A notable feature of existing work in this area is a focus on deep water URN measurements (ISO, 2019a, 2019b), for which corrections for propagation loss are simpler than those required in the shallow waters common to European coastal areas with high levels of ship traffic. Although propagation loss can be determined from dedicated measurements (Johansson et al., 2015) or computations (Bagočius & Narščius, 2018; Binnerts et al., 2019; Tollefsen & Dosso, 2020) for a specific location, this may not always be possible, and heuristic approaches are currently recommended by classification societies i.e., corrections assuming cylindrical spreading loss. As mentioned in ITTC (2017), there are variations in these procedures, which will contribute to uncertainties in ship URN source levels estimated from measurements in shallow water. This is presently being investigated by both ISO and IACS working groups, although the outcomes of this work are not expected until circa 2024.

Importantly, together with the Lloyd's mirror effect, shallow water propagation effects reduce radiated and received noise levels (Bagočius & Narščius, 2018), which may contribute to reduced environmental impact (Baudin & Mumm, 2015). However, this increases the relative contribution of higher-frequency noise sources, which may influence the selection of effective mitigation actions. Smaller recreational vessels have been identified as the dominant contributors to sound levels in some European coastal regions (Hermannsen et al., 2019), although this also depends on the distribution of ship types in a particular area. The lack of AIS transmitters on board smaller vessels complicates both determination of the source levels from measurements, and the noise footprint (contribution of a single vessel to a sound map). Although fishing vessels without AIS transmitters can be tracked using Vessel Monitoring Systems (VMS), the same is not true for recreational craft.

Due to the relative complexity in analysing URN measurements using deployed hydrophones, source level estimations using on-board sensors have gained popularity (Foeth & Bosschers, 2016; Jeong et al., 2021; Larsen et al., 2021). Indeed, the use of onboard sensors is allowed under classification society procedures (DNV GL, 2018), although for a limited range of vessels - namely, those with diesel-electric propulsion systems - and Quiet Class notations. Agreement between source levels determined using on-board and off-board sensors is reported to be within 3 dB, although this deteriorates at low frequencies (Larsen et al., 2021). Such measurements typically involve mounting a hydrophone or pressure sensor in the ship hull above the propeller, thereby removing the need for advanced propagation loss correction methods. A further advantage is that the vessel does not have to sail close to a deployed hydrophone to perform noise measurements, thereby saving time and money, and data can be continuously collected and analysed. It should be noted that the proximity of the sensor to the propeller tip means that the measured sound levels derive from propeller cavitation and not machinery. This approach is also interesting from a research perspective, since the effect of various changes in vessel operating condition – such as draught, hull fouling and propeller fouling – on source levels (an associated parameters such as CIS) can be examined over long time periods. Further investigations into this approach are being performed in the PIAQUO project.

The use of airborne drones for performing dedicated URN trials is also being investigated (Atlar et al., 2021), although this approach is still at an early stage of development. The use of a drone simplifies hydrophone deployment, and eliminates flow noise due to the system moving with the current. Atlar et al. (2021) reported a good agreement between drone and traditional measurement approaches above 800 Hz, claiming reduced background noise below this frequency, although more extensive validation of the technique is required. Drone URN measurements may be attractive when simplified single-hydrophone setups in shallow water are permissible, although following existing deep-water measurement procedures could prove challenging. In general, any approach to reduce the cost and logistical complexity of performing ship URN measurements could help engage ship owners, since these factors are prohibitive in the case of voluntary measurements (Maersk, private communication, 2021).

3.3.2 Monitoring programmes and databases

Monitoring of ambient sound in European waters is necessary for the assessment of good environmental status (GES) proposed in the Marine Strategy Framework Directive of the European Union (EU, 2017), motivating the publication of guidance on the establishment of monitoring activities (Dekeling et al., 2014). Numerous sound monitoring activities have been performed in European waters, including the Baltic (Karasalo et al., 2017), Eastern Mediterranean (Papadakis et al., 2018), Ionian (Viola et al., 2017), Atlantic (Santos-Domínguez et al., 2016) and North (Jansen & De Jong, 2017) Seas. The data from Santos-Domínguez et al. (2016) has been made publicly available at https://atlanttic.uvigo.es/underwaternoise/, and includes sound recordings for a small sample of vessels. In the United States of America, centralised passive acoustic data management is facilitated by the National Oceanic and Atmospheric Administration (NOAA, 2017), with standardised processing tools also made available for (statistical) comparisons across monitoring sites (Wall et al., 2021). Other recent monitoring efforts include the ECHO Program in British Columbia, Canada (analyses reported by MacGillivray et al., (2020)), which are described in Section 8.

Other ship noise databases have been collated based (primarily) on data available in the literature. Pennucci & Jiang (2018) reported such an exercise, although the database does not appear to be publicly available. In the SONIC project, an open-access ship URN database (http://vesselnoise.soton.ac.uk/view/vessel/) was generated using a combination of literature and dedicated measurements performed during the project. One disadvantage of such databases however is the variety of procedures and definitions used across the data sources, such as how the data was measured and how the source levels were derived. This should be stated for each entry in the database, and where necessary, corrected for when performing comparisons (Chion et al., 2019).

3.3.3 Source level models

Simplified models of ship source levels are important as input for noise footprint predictions, and the generation of sound maps, which ultimately support marine spatial planning activities. Numerous models have been developed, starting from World War II data (Ross, 1976) up to the present day (MacGillivray & de Jong, 2021). Reviews of various models found in the literature have been made by Liefvendahl et al. (2015) and Chion et al. (2019). Most models predict broadband spectral source levels, although blade rate only models have also been derived (Gray & Greeley, 1980). Three main types of models can be identified:

1. Ensemble model, based on fitting a spectrum to a dataset of ship noise measurements (Wales & Heitmeyer, 2002). The resulting model covers all ship types and operating conditions and is therefore only a function of frequency.

2. Parametric models, using a baseline spectrum (similar to an ensemble model) scaled using logarithms of a small number of main ship-related parameters, primarily speed, and size; either length (Breeding et al., 1996) or displacement (Ross, 1976). These parameters are available from AIS data. The spectral levels are calibrated using reference values for the chosen parameters.

3. Composite parametric models, which predict a total spectrum based on the logarithmic sum of a number of separate models for different noise generation mechanisms (Audoly et al., 2014; Wittekind, 2014). Such an approach aims to improve on the parametric model predictions by modelling the frequency dependency of the total source level spectrum in more detail. However, in the case of the Wittekind model, this requires additional input parameters, which are not readily available from AIS, such as block coefficient, cavitation inception speed, and engine mass.

The most commonly used models are parametric models, since they account for ship-specific dependencies in a simplified manner. The more complex Wittekind model has been applied in a limited number of studies, with Jalkanen et al. (2018) using it to generate sound source maps, estimating the unknown input parameters empirically. Karasalo et al. (2017) noted a less good agreement between model predictions and measurement data for passenger vessels and tugs, which results from the model having been derived and validated for cargo vessels.

This deficiency has been addressed in other models by the inclusion of an explicit dependency on ship type. This is achieved by defining different values depending on ship type for one or more reference parameters, for example speed (Brooker & Humphrey, 2015; MacGillivray & de Jong, 2021) or length (Audoly et al., 2014). The categories of vessel selected vary between studies, but are typically similar to those used for reporting URN measurement results e.g., bulker, containership, tanker, cruise ship, vehicle carrier. A simpler approach was used by Jiang et al. (2020), in splitting vessels into two categories based on length, with the boundary defined at 200 metres, which in that case separated containerships (> 200 m) from tankers (< 200 m). Importantly, the new 'JOMOPANS-ECHO' (J-E) model of MacGillivray & de Jong (2021) includes an estimate of the statistical uncertainty, which is found to be 6 dB. An additional advantage of the model is the conversion of results to a fixed source depth (6 metres is chosen), which simplifies sound propagation loss calculations. The deficiencies of two historical models, and improvements of the new model are illustrated in Figure 8. The results of the J-E model show significant improvements over historical models in terms of agreement with measurement data, especially at low frequencies. Clear differences in the general spectral shape between ship types are also evident, with cruise vessels and tugs exhibiting peak sound levels at medium frequencies, compared to low frequencies for cargo vessels and tankers, an effect not captured by other existing models. While noting that the Wittekind model was reported to perform worse for these first two ship types (Karasalo et al., 2017), it is also important to highlight that these vessels represent less than 10 percent of the global fleet, based on IMO number, with tankers, bulk carriers and containerships constituting the major part.

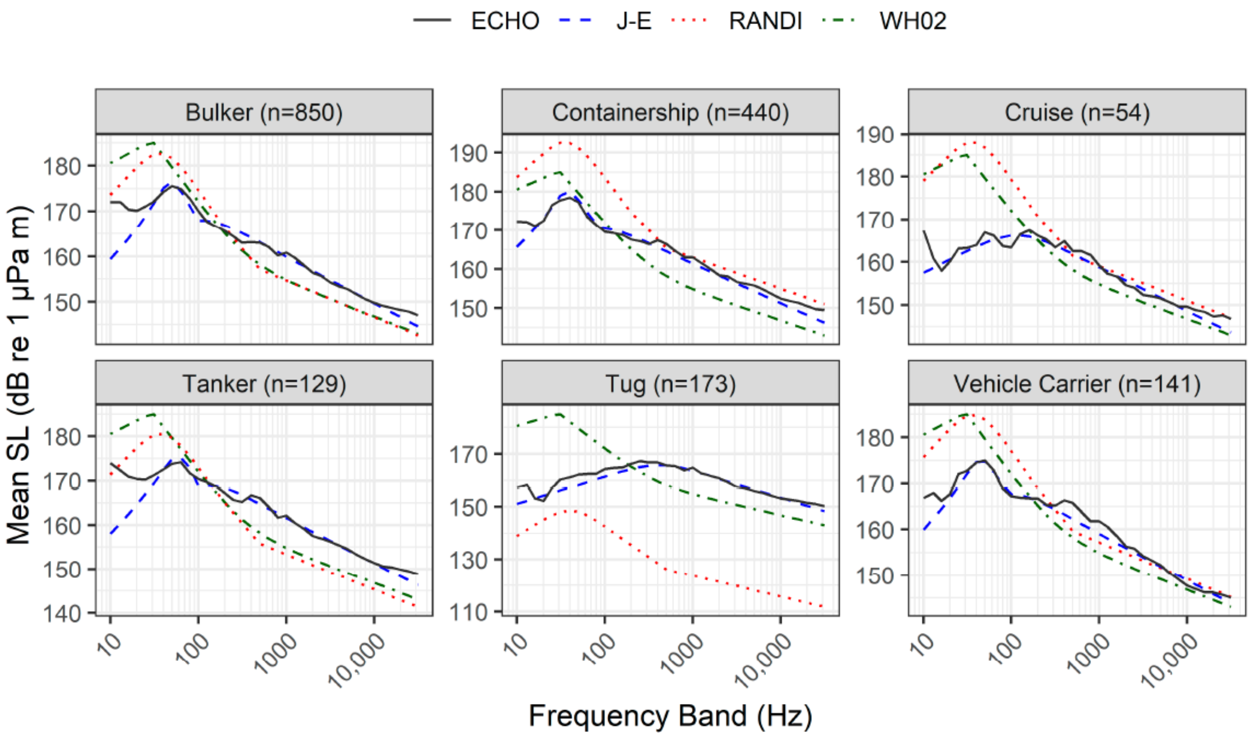


Figure 8 Example results for mean source level using several models, compared to measurement data from the ECHO program. The models are JOMOPANS-ECHO (J-E), RANDI, and Wales & Heitmeyer (WH02). Reproduced from MacGillivray & de Jong (2021).

Parametric models, even when including ship type dependency, remain simplified approximations of ship source levels. It may not be possible to identify exact ship type from AIS data; vehicle carriers and containerships cannot be definitively identified from other types of cargo vessels, for example (MacGillivray & de Jong, 2021). This lack of detailed ship type information could have a strong influence on model predictions, given the high dependency – typically sixth power – on speed, and the large variations in design speed between different ship types. Furthermore, effects such as controllable pitch propeller operation mode are not explicitly included. Although these types of propellers are fitted to many types of vessels, including coasters and ferries, the URN they produce can increase significantly at low speeds, when the propeller pitch is reduced (Traverso et al., 2015; McIntyre et al., 2021). Expansion of AIS data, as proposed by Baudin and Mumm (2015), would help in this regard. Suggested additional parameters include more specific ship type categories, propeller type and diameter, vessel design speed and corresponding propeller rotation rate, main engine type, and block coefficient. A more realistic option is to extract ship particulars from appropriate databases, using the vessel identification numbers obtained from AIS. However, since these databases are commercially available, the increasing modelling accuracy would come at an additional cost.

It is also important to note that since most source models are derived or validated using opportunistic measurement data, they are only be applicable to vessels carrying AIS transponders i.e., of more than 300 gross tonnes. This means that their suitability for use as part of sound mapping depends on the distribution of vessel types operating in the region of interest. This may be particularly relevant in European coastal waters, in which large numbers of small (recreational) vessels operate in shallow water depths (Hermannsen et al., 2019). In their study, Hermannsen et al. reported 83% non-AIS vessels, of which more than two-thirds were sailing boats. They analysed the distribution of vessel types present when noise events expected to result in environmental impact on harbour porpoises occurred, for OTO frequencies 125 Hz, 2 kHz and 16 kHz. While at 125 Hz, the presence of AIS-equipped vessels during noise events was higher relative to their overall presence, a trend of increasing presence for motorised non-AIS boats is seen at higher frequencies, reaching 58% in the 16 kHz OTO band. While the low count of AIS vessels in the study may not be representative of the majority of EU coastal regions, these results motivate monitoring ambient noise for frequencies higher than those specified in the MSFD (Dekeling et al., 2014), as well as the inclusion of recreational craft in mitigation activities.

3.3.4 Propagation loss models

Propagation loss estimation is an important part of ship noise assessment; it is required for the derivation of source levels from received levels, and for the prediction of noise footprint based on source levels. This is particularly important when the distance between the source and receiver is large, or the water depth is considered to be acoustically shallow. For deep-water sound measurements at typical CPAs, the Lloyd's mirror effect will be the dominant contribution to propagation loss (ISO, 2019b), while in shallow water, the influence of reflections from the seabed will increase. The influence of bathymetry is larger for shorter propagation distances, while seabed properties will be more relevant over longer distances (Farcas et al., 2020). Variation in sound speed depth profile is more important for deep water meanwhile (Pregitzer et al., 2021). Although definitions for shallow water in the literature vary, 150 metres is a common limit (Bosschers et al., 2021). Due to the high proportion of shallow water in European coastal areas, accurate propagation modelling is an important subject.

Propagation loss can be computed using numerical models, where the selection of a suitable model depends on the water depth and frequency range of interest (Pregitzer et al., 2021). A review of propagation loss models is provided by Wang et al. (2014) and Etter (2012), while simplified approaches for shallow water have also been proposed (Bagočius & Narščius, 2018), aiming to reduce the computational expense required for producing sound maps. Not only does an appropriate model need to be used, but several environmental inputs need to be provided, such as sound speed depth profile, bathymetry, and seabed geoacoustic properties. The accuracy of model predictions will diminish when these properties or characteristics are unknown, or only available with a limited spatial resolution.

Several examples of the application of underwater acoustics propagation models to shallow water scenarios can be found in the literature (Binnerts et al., 2019; Colin et al., 2015; Sertlek et al., 2019; Sipilä et al., 2019). Binnerts et al. (2019) defined test cases for the evaluation of several acoustic propagation models, providing recommendations for their usage. They found a good agreement between all tested models for a range-independent scenario (constant depth), with higher discrepancies observed for a range-dependent case, with sloping bathymetry. The authors also concluded that in selecting an appropriate model, the desired accuracy should be balanced against the uncertainty of the environmental input parameters. This was also investigated by Sipilä et al. (2019), who compared measured and computed propagation loss in shallow water. Despite a generally good agreement between the two approaches, they report differences of up to 10 dB in propagation loss depending on the sea bottom sediment geoacoustic properties. Meanwhile, Sertlek et al. (2016) found that the influence of the sound speed depth profile on shallow water sound map results was small (up to 1.7 dB).

3.3.5 Sound maps

While propagation loss simulations result in noise footprint predictions, i.e., the SPL of an individual ship at arbitrary number of locations, environmental impact assessment requires the cumulative SPL from the marine traffic within the geographical area of interest. Computing the noise footprint on a grid of receiver points for all vessels present at a certain time (based on AIS) and summing their contributions results in a sound map of the ambient noise due to shipping. This can be compared to other ambient noise sources, such as wind (Sertlek et al., 2019; Farcas et al., 2020), in order to assess the anthropogenic contribution to the ambient underwater soundscape. Farcas et al. (2020) defined the "ship noise excess" for this purpose, as shown in Figure 9 (b), while also presenting temporal statistics in terms of percentiles of exceedance, calculated on an annual basis, providing an additional level of information for marine spatial planning. The results can be presented for selected frequency bands, or integrated to give a broadband level, as in the example shown in Figure 9. Note that it is common to present depth-averaged results for simplicity.

Sound maps have been generated in numerous EU-funded projects, including BIAS, AQUO, SONIC, JOMOPANS and JONAS, based on predictions of SPL. Due to their importance for environmental impact assessment, and the fact that fish and invertebrates are sensitive to acoustic velocities as opposed to pressures (Nedelec et al., 2016), in the EU Horizon 2020 SATURN project, sound maps based on particle motion will also be developed. Although particle motion can be derived from sound pressure measurements under simplified conditions, in shallow water direct measurements may be needed, requiring specialised instrumentation and analysis techniques (Nedelec et al., 2016).

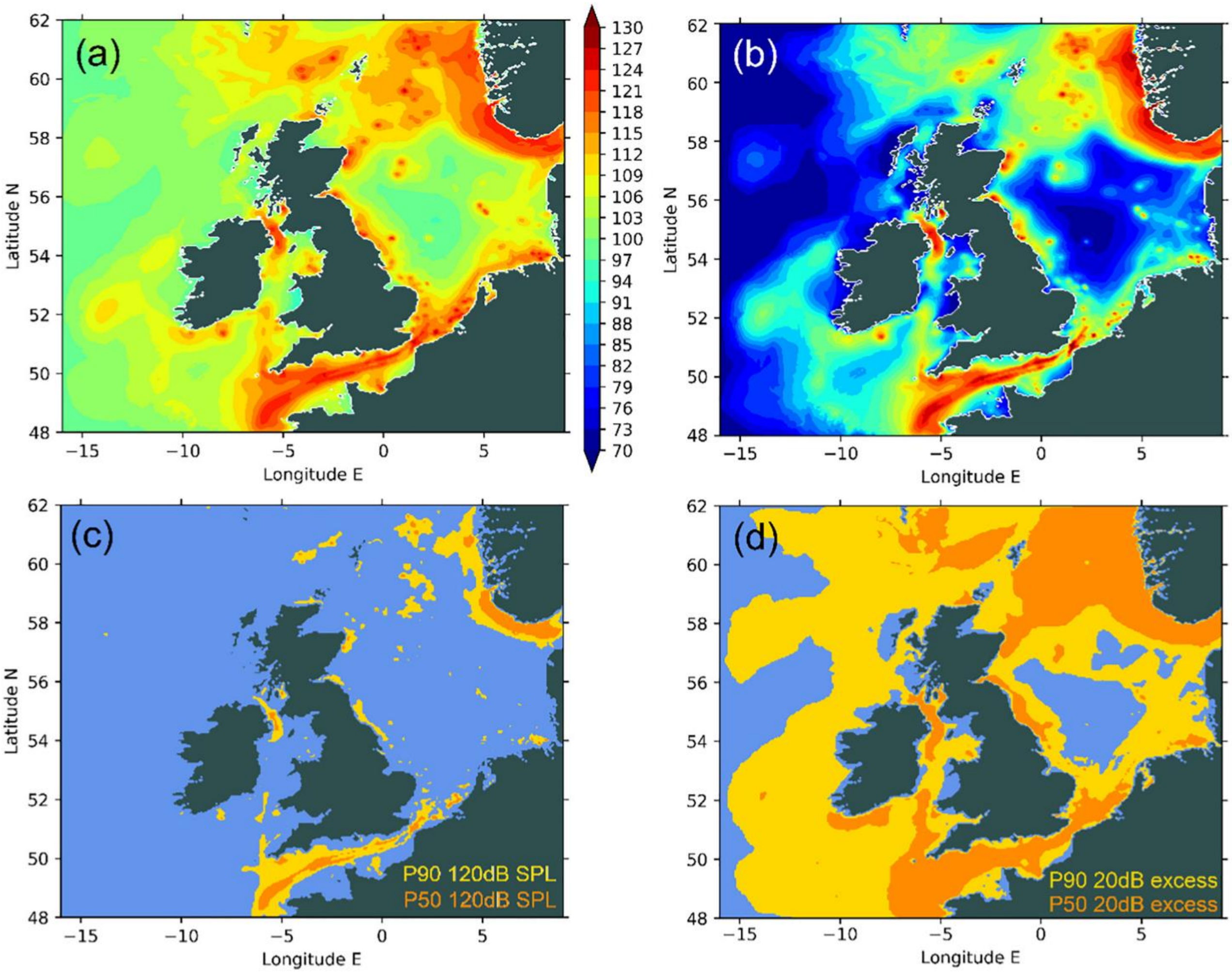


Figure 9 Example broadband (63-4000 Hz) sound maps for the North Sea for 2017, reproduced from Farcas et al. (2020). (a) and (b) show the total (ship plus wind) and excess (ship minus wind) noise maps respectively, with (c) and (d) depicting the 50th and 90th percentiles (based on annual statistics) above the indicated levels, for the same quantities as (a) and (b).

4. Environmental impacts

Environmental impacts of underwater noise radiated from shipping are one of the main drivers to implement policies to reduce underwater noise levels. Sound represents a very important role on survival of several underwater species allowing them to gather information and interact with environment. Therefore, relevant aspects of marine life can be at stake due to underwater noise pollution.

4.1 Marine mammals

Marine mammals include different groups of species:

- Cetaceans: dolphins and whales.
- Pinnipeds: seals, sea lions and walruses.
- Sirenians: manatees and dugongs.
- Marine fissipeds: polar bears and sea otters.

While cetacean species are exclusively underwater animals, pinnipeds and marine fissipeds are considered amphipods, which means that they can use air and water habitats. Considering that this study focuses on Europe and the impacts of underwater noise from shipping, this section will include the groups of species that occur in European waters and that use sound underwater. Therefore, sirenians (O'Shea & Powell, 2001) and sea otters (Ghoul & Reichmuth, 2014) were excluded from the analysis.

Marine mammals are the group which most published studies focus on. How the animals respond to underwater noise is complex and depends on several factors such as age, sex, hearing sensitivity, behavioural state, presence of offspring, and proximity to shoreline (NRC, 2003).

4.1.1 Cetaceans

Cetaceans use sound for several activities including social interactions, finding preys, avoiding obstacles, and navigation. For these activities they are not only able to detect sounds from the environment but are also able to produce different types of acoustic signals, according to the species, using larynx or, regarding cetaceans, using air sacs located near the blowhole.

For social interactions different sounds can be produced according to the species. Whistles are very common for marine mammals in particular toothed whales. There is evidence that whistles can be used when dolphins meet or join a group at sea (Quick & Janik, 2012; Shapiro, 2006), known as signature whistles, but can also be used to maintain close contact as for example between mother and calf (Janik & Sayigh, 2013) or to maintain cohesion among the groups (Riesch et al., 2006). Signature whistles are particularly well studied for bottlenose dolphins (*Tursiops truncatus*) (Janik & Sayigh, 2013) but there is evidence that they are also used by other species, as for example, spotted dolphins (*Stenella plagiodon*) and common dolphins (*Delphinus delphis*) (Caldwell et al., 1973; Fearey et al., 2019). Clicks are also used as social vocalization, some examples are related with the use of codas, stereotyped click sequences, by sperm whales to maintain clans, (Rendell & Whitehead, 2003) or the use of specific patterns of clicks by harbour porpoises (*Phocoena phocoena*) (Clausen et al., 2011).

According to the characteristics, clicks can be grouped in two main categories, echolocation clicks and burst pulsed sounds. Echolocation clicks, used by dolphins (Au, 2018), allow the animals to actively obtain a sense of its surroundings, as for example detection of obstacles during navigation (Popper, 1985). Burst pulsed sounds can be used in different contexts, including social interactions, as for example the squeals produced by sperm whales (Weir et al., 2007), feeding, as for example buzzes to capture preys used by Risso's dolphins (*Grampus griseus*) (Arranz et al., 2016), or agonistic/aggressive interactions (Blomqvist & Amundin, 2004).

Figure 10 presents the overlap on frequency range regarding the different sources of underwater noise from shipping and the different types of vocalisations emitted by cetacean species. Figure 11 represents the different activities where cetacean species can use sound.

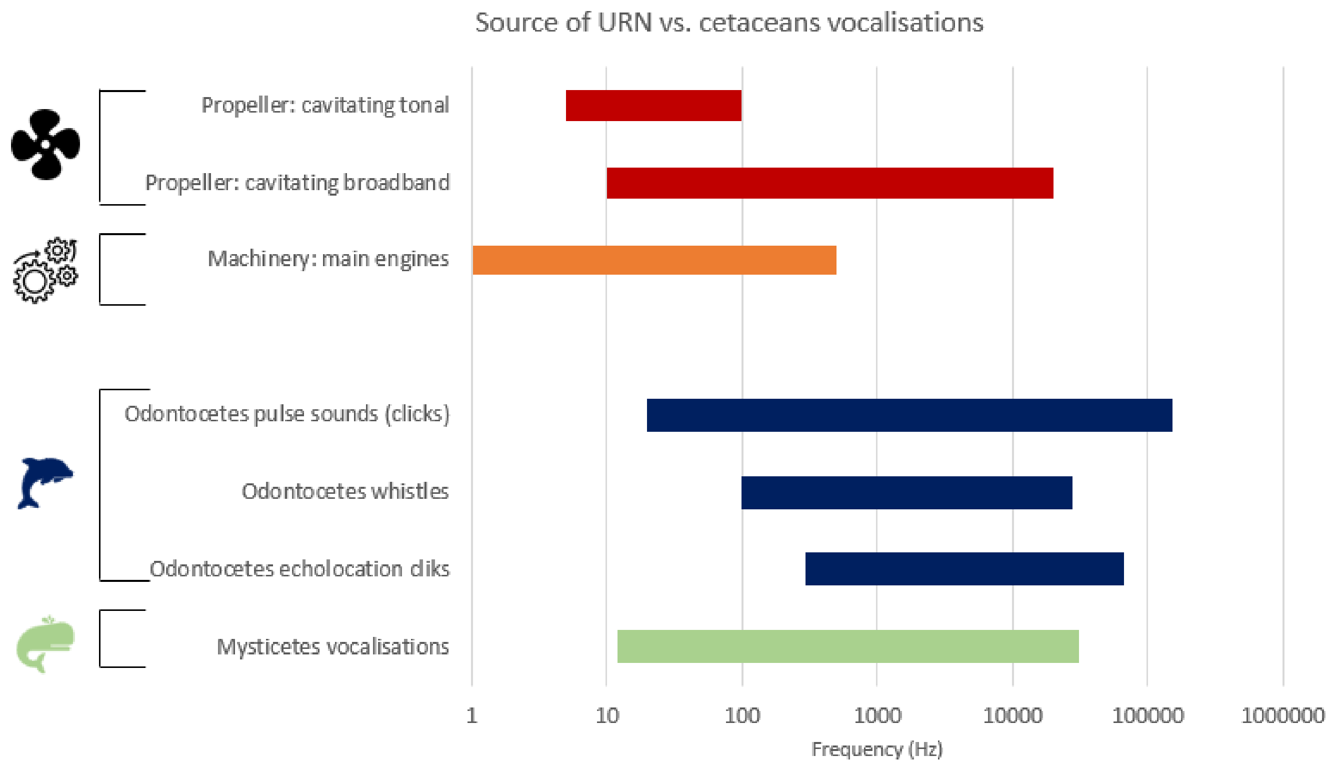


Figure 10 - Frequency range of shipping noise and different types of vocalisations produced by cetaceans. The frequency ranges are based on the minimum and maximum value of frequency found in literature for the different types of vocalisations. The red colour indicates high contribution for URN and orange medium contribution.

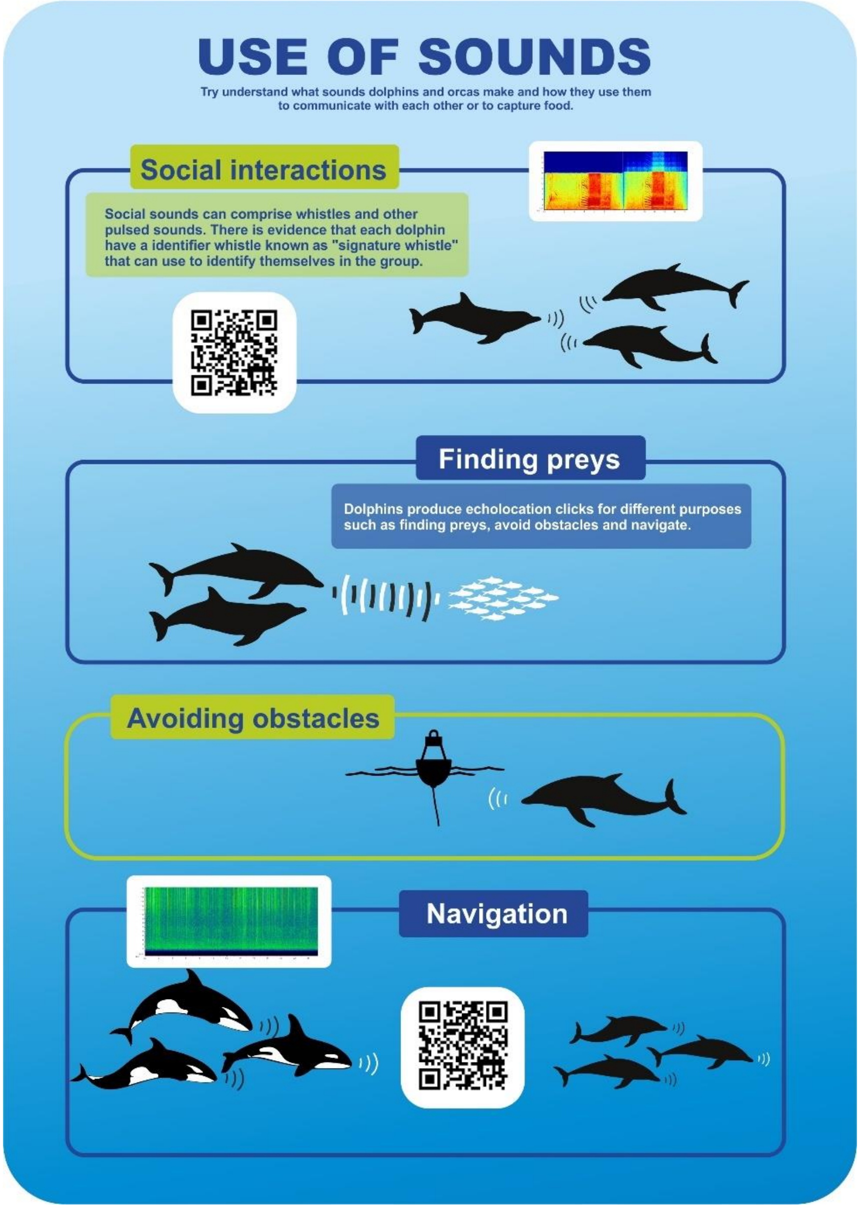


Figure 11- Use of sound by cetacean species. The sounds are indicative of the situation where they can be found and not directly related with the species represented in the picture.

Species occurring on Europe Seas – marine regions listed in the MSFD and surroundings seas

From the analysis performed by Erbe et al. (2019), that reviews the studies related to the impact of underwater noise from shipping on marine mammals, 23 species stated in the studies can occur in European Seas. Four species are classified as “endangered”, “critically endangered” or “vulnerable” according to the International Union for Conservation of Nature’s Red List of Threatened species[1] (IUCN, 2021) which indicates the risk for extinction. Figure 12 represent the structure of categories and its relationship with the risk of extinction

[1] https://www.iucnredlist.org/

Table 2, presents the list of species occurring in European Seas and adjacent waters, indicating the most abundant species and common species in some of the regions.

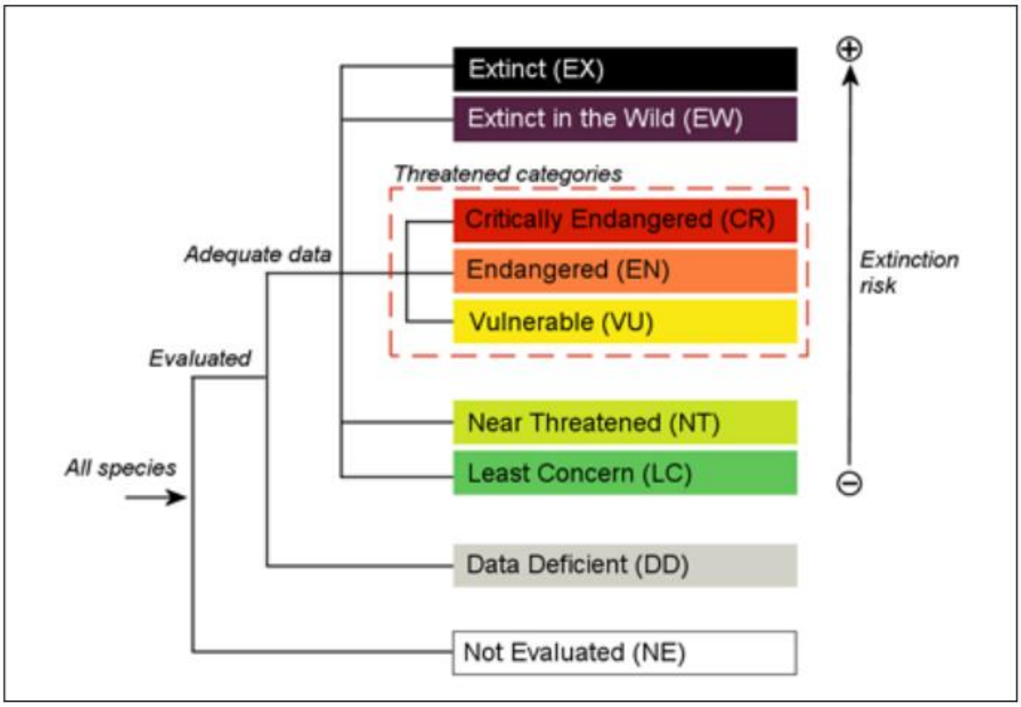


Figure 12 - Structure of the IUCN Red List categories (IUCN, 2012)

Table 2 – List of cetacean species occurring in Europe Seas where impacts from underwater noise related to shipping were identified. Species marked with (*) correspond to abundant species in European Atlantic waters, (**) species common in the Atlantic region (Hammond et al., 2017), (***) indicate common species in the Mediterranean region. The conservation status is according to the IUCN Red List of Threatened Species.

Common name	Scientific name	Conservation status
Odontocetes		
Atlantic Spotted Dolphin	*Stenella frontalis*	Least concern
Atlantic White-sided Dolphin	*Lagenorhynchus acutus*	Least concern
Beluga Whale	*Delphinapterus leucas*	Least concern
Common Bottlenose Dolphin (*)	*Tursiops truncatus*	Least concern
Common Dolphin (*)	*Delphinus delphis*	Least concern
Harbor Porpoise (*)	*Phocoena phocoena*	Least concern
Killer Whale (**) (***)	*Orcinus orca*	Data deficient
Long-finned Pilot Whale	*Globicephala melas**	Least concern
Narwhal	*Monodon monoceros*	Least concern
Short-finned Pilot Whale	*Globicephala macrorhynchus*	Least concern
Sperm Whale (*)	*Physeter macrocephalus*	Vulnerable
Spinner Dolphin	*Stenella longirostris*	Least concern
Striped Dolphin (*)	*Stenella coeruleoalba*	Least concern
White-beaked Dolphin (*)	*Lagenorhynchus albirostris*	Least concern
Short-finned Pilot Whale	*Globicephala macrorhynchus*	Least concern
Blainville's Beaked Whale (*)	*Mesoplodon densirostris*	Least concern
Cuvier's Beaked Whale (***)	*Ziphius cavirostris*	Least concern
Mysticetes		
Blue Whale (**)	*Balaenoptera musculus*	Endangered
Bowhead Whale	*Balaena mysticetus*	Least concern
Bryde's Whale	*Balaenoptera edeni*	Least concern
Common Minke Whale (*)	*Balaenoptera acutorostrata*	Least concern
Fin Whale (*)	*Balaenoptera physalus*	Vulnerable
Gray Whale	*Eschrichtius robustus*	Least concern
Humpback Whale	*Megaptera novaeangliae*	Least concern
North Atlantic Right Whale (**)	*Eubalaena glacialis*	Critically endangered

Focusing on the most abundant and common species for which impacts of underwater noise impacts were identified, a review was made on their hearing range. Shipping noise overlaps in part with the hearing range of most the species (Figure 13).

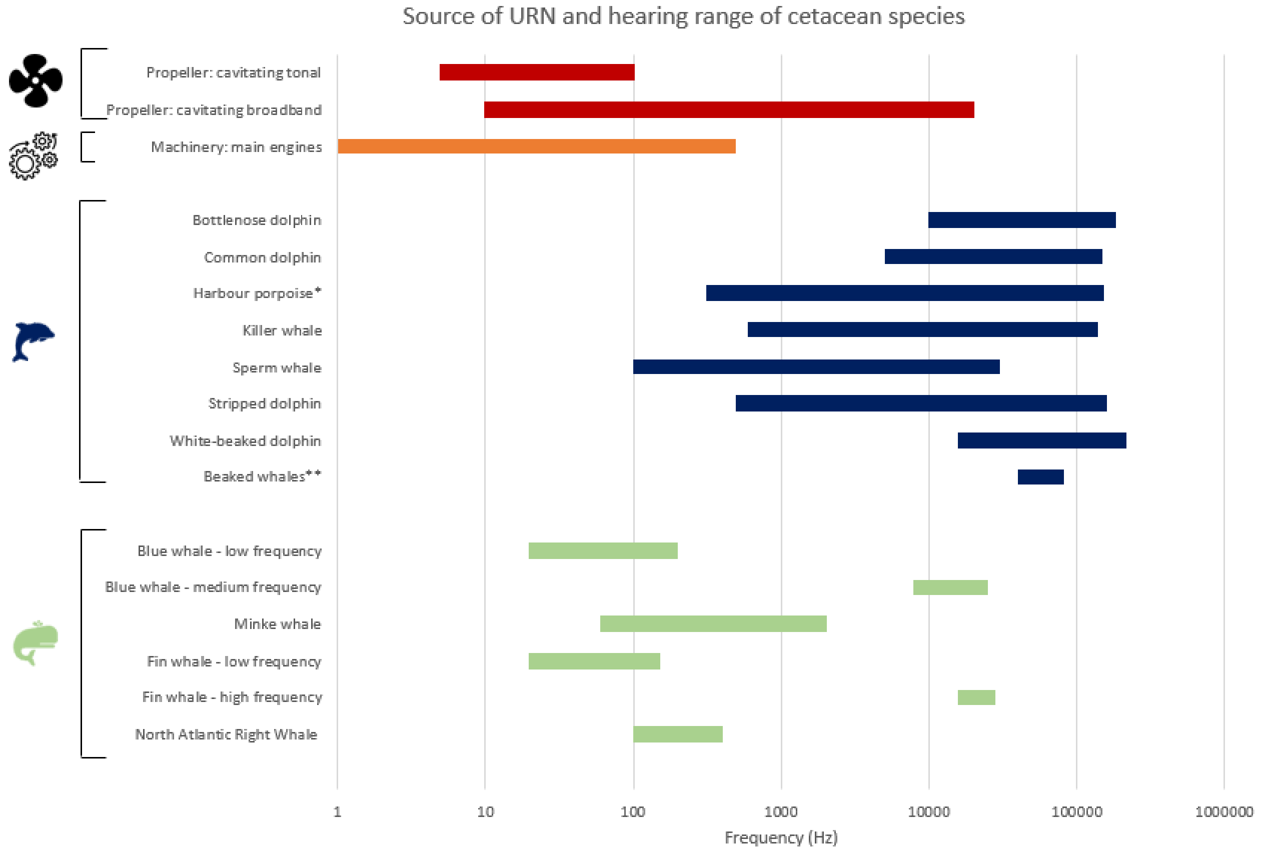


Figure 13 Frequency range of shipping noise and hearing range of cetacean species. A distinction is made between odontocetes (dolphin species) and mysticetes (baleen whales) considering the difference in their hearing sensitivity.

Evidence of impacts related to shipping noise

Several studies provide evidence that shipping noise can affect cetaceans leading to behavioural and acoustic responses, auditory masking and stress (Erbe et al., 2019a). Common behavioural changes can include changes on diving, swimming direction and changes in group structure (Bedjer et al 2006b; Nowacek et al., 2001, Williams et al., 2014, McKenna, 2011). Common acoustic responses include, change in frequency of the calls (Heiler et al., 2016), duration (Blomqvist & Amundin, 2004, May-Collado & Wartzok, 2008) and call amplitudes (Holt et al., 2009). These impacts are documented for different types of vessels (Table 3), although many studies do not specify the type of vessels or operational conditions or include more than one category.

- **Changes in vocal behaviour**: The rate of vocalizations can increase or decrease in the presence of vessels. For example, bottlenose dolphins can reduce the rate of whistles and echolocation clicks in the presence of vessels (Luís et al., 2014) but Buckstaff (2004) refers that they tend to increase the rate after the vessel passes, probably as an attempt to keep the group together. It was also observed that in the presence of calves the animals increase the number of whistles probably in order to maintain mother/calf pair (Guerra et al., 2014). Buckstaff (2004) was able to identify changes in whistle rate and the number of whistles in relation to estimated received levels ranging from 115 to 138 dB re 1 µPa. Castellote et al. (2012) found that fin whales 20-Hz note duration shortened, bandwidth, centre frequency and peak frequency decreased in the presence of high background noise levels resulting from shipping.

- **Changes in diving and swimming patterns:** Au & Green (2000) evidence that humpback whales appeared to swim faster in the presence of boats, however, they indicate that is very difficult to assess if the reaction was caused by the noise from the vessels or if it is related to other factors such as the size or shape of the vessel. The reactions were observed in the presence of an infltable boat where the highest spectral peak was 121 dB at 3.1 kHz.

- **Reduction in the communication range:** a study carried out by Castellote et al. (2018)**,** provides evidence the potential for commercial shipping to mask beluga whale communication and hearing, with commercial shipping peaked in the band centred at 630 Hz and a SPL was above 115 dB re 1 µPa^2/Hz.

- **Foraging behaviour:** A study from Aguilar Soto et al. (2006) provided evidence that Cuvier's Beaked Whale present shorter vocal phase during a foraging dive in the presence of a commercial ship. This was observed at a received level of 136 dB rms re 1µPa, in the frequency range between 356 Hz and 44.8 kHz. However, a study carried out by André et al. (2017) showed no evidence that shipping noise influences the behaviour of sperm whales. Blair et al. (2016), provided evidence that humpback whales change their foraging behaviour, presenting slower descent rates and fewer side-roll feeding events per dive with increasing ship noise related to a large ship. Noise levels or frequency ranges were not described in this study.

- **Physiological:** Few studies analyse physiological responses of marine mammals to underwater noise from shipping. In 2012, Rolland et al., highlighted the possibility of chronic stress in the North Atlantic Right Whale due to the exposure to low-frequency ship noise, after detecting a decrease on baseline levels of stress-related faecal hormone metabolites associated with reduction of underwater noise levels as a consequence of a reduction of ship traffic.

- **Impact on the auditory system:** A study conducted by Au & Green (2000), provided evidence that levels of noise produced by inflatables with outboard engines, larger coastal boats with twin inboard diesel engines and, small water plane area twin hull (SWATH) ships are unlikely to affect the auditory system of humpback whales.

Not all studies refer to operational conditions of the vessels, but those that do, usually refer to the speed. Few of them mention the noise source levels, received levels or changes in background noise levels due to the presence of vessels. This presents a constraint on the identification of frequencies and sound pressure levels of observed impacts. Another limitation is related to the standardization of information being reported. The studies referring to the noise source levels, received levels or changes in background noise levels due to the presence of vessels do not use a common metric. Some examples mention the frequency range of the record and the broadband sound pressure levels, while others opt to refer only to the frequency of the observed response.

Table 3 – Documented impacts from underwater noise from shipping on cetacean species. Adapted from (Erbe et al., 2019).

Type of vessel	Documented impacts
Boat	Acoustic changes Behavioural changes: movement speed and direction Altered behaviour states Reduction communication range
Commercial ships	Auditory masking Reduction on close communication range Behavioural changes: (diving, swimming speed, increase of surface time) Changes on acoustic behaviour
Ferry	Changes on acoustic behaviour
Fishing vessel	Behavioural changes: modification of social structure
Icebreakers	Behavioural changes Changes on acoustic behaviour Communication masking
Ships	Behavioural changes: Altered swim direction
Small vessels	Behavioural changes: blow rate Temporary threshold shift Avoidance

Tourism vessels	Behavioural changes
Whale-watching	Behavioural changes: swimming pattern, diving behaviour Changes on acoustic behaviour: call duration

4.1.2 Pinnipeds: seals, sea lions and walruses

As previously mentioned, pinnipeds are amphibious and have the potential to use airborne and underwater sounds. They can produce sound using larynx using the same mechanisms of land mammals. To what concerns hearing, they have some adaptations that potentiate their ability to use sound underwater when compared with land mammals or sea otters for example.

Table 4 – List of pinnipeds species where evidence of noise disturbance from shipping was registered (based on (Erbe et al., 2019). Conservation Status is stated according to the IUCN Red List of Threatened Species.

Common name	Scientific name	Conservation status
Bearded Seal	*Erignathus barbatus*	Least concern
Grey Seal	*Halichoerus grypus*	Least concern
Harbor Seal	*Phoca vitulina*	Least concern
Harp Seal	*Pagophilus groenlandicus*	Least concern
Ringed Seal	*Pusa hispida*	Least concern

Underwater sounds produced by pinnipeds correspond mainly to pulsed sounds, some of them similar to the ones produced by cetaceans. Frequency range will depend on the type of vocalization and group of species. Considering the different families, vocalizations produced by seals can range from 20 Hz to 40kHz, sea lions from 1 to 6 kHz and walruses from 10 Hz to 10kHz (Figure 14).

Considering underwater hearing frequency ranges, existing studies indicate that pinnipeds have better sensitivity for sound above 1kHz. Therefore, it is clear that sources of shipping noise overlap the hearing range of pinnipeds (Figure 14).

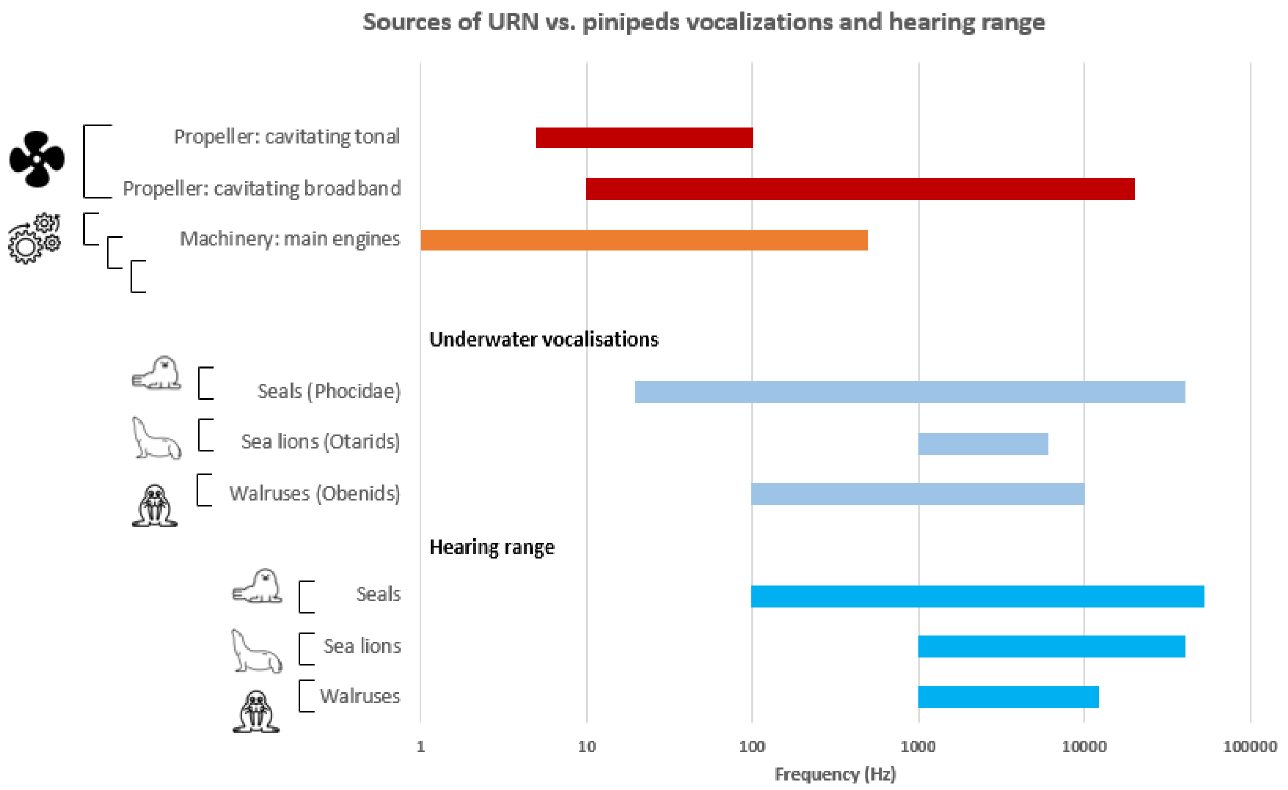


Figure 14 Frequency range of underwater noise sources from shipping and frequency range of hearing and vocalisations produced by pinnipeds. Red colour regarding propeller sound indicates high contribution to underwater noise, and orange colour indicates medium contribution to underwater noise.

Evidence of impacts related to shipping noise

Few studies address the impact of underwater noise on pinnipeds that can be found in European waters (Erbe et al., 2019). Most of the studies do not have direct evidence that the response observed is directly related to underwater noise from shipping. However, these studies mention the observation of responses in the presence of high background noise levels as a result of shipping. Potential effects of noise from shipping are:

- **Behavioural changes:** including, look, dive and swim away behaviour (Harris et al., 2001; Fletcher et al., 1996) and aggressive behaviour (Osterrieder et al., 2017). Mikkelsen et al., (2019) demonstrated that the interruption of functional behaviours (e.g. resting) in some cases coincides with high-level vessel noise.

- **Masking:** Gabriele et al. (2018) evidence that behavioural changes may lead to a reduction of communication space. Potential for masking, understood has reduced ability to detect, recognize, or understand sounds of interest because of interference by other sounds was also observed by Bagočius (2015). According to this study the detection distance of calls between animals of the same species can be significantly reduced in the presence of local shipping. The experiment was conducted considering the record of a ro-ro passenger ship passing at the speed of 20 knots at 200 m from the hydrophone, but SPL values are not stated.

- **Vocal changes**: Terhune et al. (1979), demonstrated a marked decrease in seal vocalizations occurred following the arrival of a vessel. The relatively loud motor noises of the vessel completely masked the seal calls (within a 2-km or more radius). The author suggested that this might result from a behavioural change of the seal or a displacement of the animals.

These impacts are related to different types of vessels, including trawlers, seismic tugboats and unspecified vessels (Erbe et al., 2019).

4.2 Fish

Sound is a key sensory cue used by fishes to perceive their environment (Popper et al., 2014; Slabbekoorn et al., 2010). They use sound for communication, navigation, orientation, mating, foraging, and predator avoidance (Fay & Popper, 2000; Popper, 2003; Slabbekoorn et al., 2010). All fish species studied to date can detect sound (Slabbekoorn et al. 2010; Popper & Fay, 2011) typically in the range of 30 to 5,000 Hz, overlapping with relevant sources of shipping noise (Figure 15).

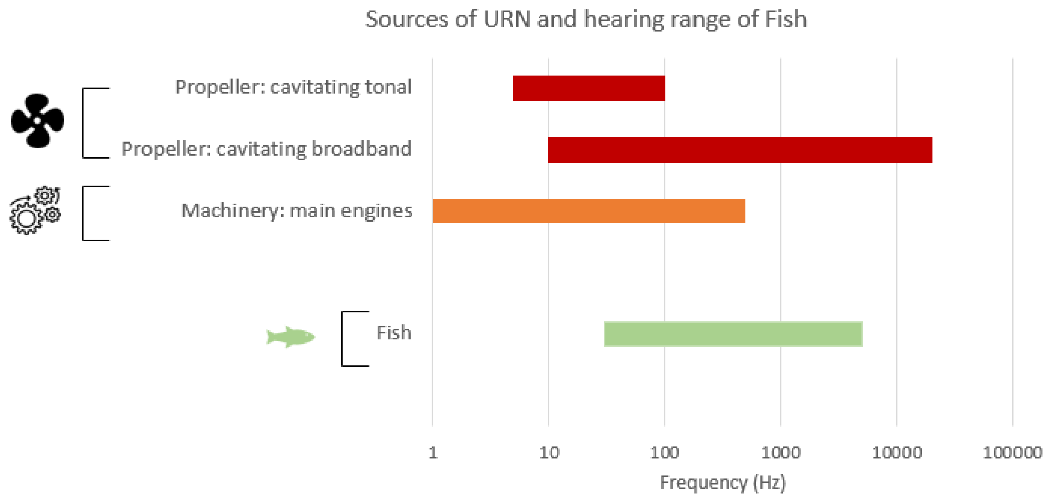


Figure 15 - Sources of underwater noise from shipping and hearing range of fish species. The red colour regarding propeller noise indicates high contribution to underwater noise and orange, medium contribution.

A large number of published papers and reports have pointed out short-term, transient effects and long-term, chronic effects on fish caused by noise from small boats to ships, around the world. Such effects were observed from monitoring surveys and from laboratory or modelling experiments (see for example a review in Weilgart, 2018).

Evidence of impacts related to shipping noise

Short-term effects are generally related to noise acting as a distracting stimulus, a stressor, or by masking important acoustic cues or signals (e.g., Velasquez Jimenez et al., 2020) such as altering species' home ranges and swimming behaviours, and influencing the outcome of predator-prey interactions (Domenici & Blake, 1997; Ivanova et al., 2020; Velasquez Jimenez et al., 2020). The many short-term effects from noise may have implications for survival or ability to reproduce (fitness) of a species, potentially leading to serious longer-term effects in the overall population dynamics, structure, and functioning (Ivanova et al., 2020; Slabbekoorn et al., 2010; Weilgart, 2018).

The effects of anthropogenic noise on fish are often grouped into anatomical, physiological and behavioural responses (e.g., Hawkins & Popper, 2017; Kunc et al., 2016). According to de Jong et al. (2020) the underlying mechanisms that influence those responses can be defined as (i) stress, (ii) masking, and (iii) hearing-loss.

- **Stress inducing behavioural responses:** Stress can affect signalling and avoidance behaviour, growth, sexual maturation, reproduction, immunity, and survival (Nichols et al. 2015, de Jong 2020). The primary response to stress (within seconds) is associated with neurological and hormonal responses, priming the animal for a fight-flight or freeze response. There are several works (e.g., Sebastianutto et al. 2011, Nedelec et al. 2015, La Manna et al. 2016) that show that URN from shipping caused longer fish flight reactions together with more individual fish performing them, increased the amount of hiding, and caused resident fish to be more submissive and to win less physical encounters. The secondary response (which peaks within 15 minutes) is associated with changes in concentration in a suite of hormones (e.g., cortisol). Nichols et al. (2015) showed that cortisol responses in fish subjected to underwater ship noise playbacks vary among species (e.g., European perch, common carp, gudgeon, goldfish). Nonetheless, it seems that predictability in the timing of noise events matter, with lower predictability (i.e., a random pattern of noise) causing more stress (Nichols et al. 2015, de Jong e al. 2020). Other authors (Celi et al. 2016) found that 10 days of vessel noise playbacks (123-136 dB RMS re 1 µPa) to gilthead sea bream (*Sparus aurata*) produced significant biochemical changes in the blood or plasma (e.g., cortisol, ACTH, glucose) showing clear primary and secondary stress response to maritime vessel traffic. The tertiary response to stress may set in if stress is prolonged (for example, for animals that remain close to a busy shipping route), leading to chronic stress which may induce physiological changes such a decrease in body condition, reduction in growth, and a hampered immune system. After 2–3 weeks of continuous stress, reproductive physiology may also be impaired (de Jong et al. 2020).

- **Masking:** URN from shipping can overlap in frequency with, and therefore mask, biologically significant signals and acoustic cues. Masking of sounds made by prey organisms may result in reduced feeding with effects on growth. Masking of sounds from predators may result in reduced survival. Masking of spawning signals may reduce spawning success and affect recruitment (the process by which very young, small fish survive). Masking of sounds used for orientation and navigation may affect the ability of fish to find preferred habitats including spawning areas, affecting recruitment, growth, survival, and reproduction (Hawkins & Popper 2017, de Jong et al. 2020).

- **Hearing loss:** either temporary or permanent hearing loss, and impaired temporal resolution can be caused by high-intensity acute noise, as well as prolonged exposure to lower intensity noise (de Jong et al. 2020). Hearing-loss involves a physiological or anatomical change in the animal and will have similar, but prolonged effects compared to masking. Impairment of hearing may affect the ability of animals to capture prey and avoid predators, and cause deterioration in communication between individuals, affecting growth, survival, and reproductive success (Hawkins & Popper 2017, de Jong et al. 2020). The most serious impacts, which have population consequences, are on survival and reproduction (fitness). Noise may have many detrimental effects on a species fitness, for example on mate localisation and choice and on courtship, reduced spawning, heightened parental aggression and defensive behaviour, often leading to lower offspring survival (e.g., Nedelec et al. 2017, Krahforst et al. 2017, de Jong et al. 2018, Weilgart 2018, de Jong et al. 2020). For many fish species, the spawning period may be particularly sensitive to impacts from noise and hamper a much larger fraction of the population compared to other periods of the year (e.g., Colin et al. 2003, Pörtner & Farrel 2008).

4.3 Invertebrates

The group of invertebrates include a variety of species, such as lobsters, crabs, octopus, corals, anemones, sea stars, sea urchins and shrimps. The mechanisms on how they use sound (produce and detect) have not been studied in detail, with exception for spiny lobsters, semi-terrestrial crabs and snapping shrimp. It is assumed that invertebrates do not respond to acoustic stimulus but to particle motion instead (Breithaupt, 2002; Popper & Hawkins, 2018), which relates to the vibrations of the medium where sound wave propagate. These animals use specialized structures such as external sensory hairs, internal statocysts and other sensory organs to detect pressure changes. Regarding sound production, marine invertebrates are able to produce sound by rubbing two body parts together, known as stridulation (Moulton, 1957), or rapid muscle contractions, usually in relation to defence and courtship behaviour. As an example, Vermeij et al (2010), evidenced for the first time an auditory response in the invertebrate phylum Cnidaria, which includes jellyfish, anemones, and hydroids as well as corals, responding to reef sounds during settlement.

Evidence of impacts of underwater noise

Similar to marine mammals and fish, there is evidence that invertebrates can present behavioural reactions, morphological and physiological changes, and damage of sensitive organs. Behavioural reactions can include irritation behaviour, such as those detected for seahorses (tail adjustment and stationary time) (Anderson et al., 2011), adjustments on digging behaviour, increasing depth with increased sound intensity, such as that detected for razor clams (*Sinonovacula constricta*) Peng et al. (2016), and, changes on escaping behaviour (inking and jetting), in particular in the frequency band from 100 to 300 Hz for sound pressure levels above SPL above 140 dB re 1µPa, for the cuttlefish (*Sepia officinalis*) (Samson et al., 2014). Walsh et al. (2017) provided evidence that noise exposure can be critical for crustaceans, giving the example of a hermit crab that approaches a new shell faster, spending less time investigating it and entering it faster, when exposed to white noise.

Physiological and morphological changes can also occur, including body malformations and the delay in development of scallop larvae, when subject to playback of seismic pulses (De Soto et al., 2013) and increasing stress hormones and the level of parasites in internal organs (Anderson et al., 2011) when seahorses in quiet tanks and noisy tanks were compared.

High noise levels can result in damage of sensitive organs, as was demonstrated by André et al. (2011) Solé et al (2013) and Solé et al. (2016), in a noise exposure experiment carried out for three cephalopod species (Mediterranean squid, *Illex coindetii*, and on the European squid *Loligo vulgaris*, cuttlefish, *Sepia officinalis*, and jellyfishes, *Cotylorhiza tuberculate* and *Rhizostoma pulmo*), when subjected to sinusoidal wave sweeps ranging from 50 to 400 Hz and sound pressure levels of 157 dB and peak levels up to 175 dB. Recently, Solé et al. (2017), undertook offshore controlled exposure experiments, with sinusoidal wave sweeps which provided evidence that cuttlefish can suffer injuries from anthropogenic sources when exposed at levels ranging from 139 to 142 dB re 1 μPa2 and from 139 to 141 dB re 1 μPa2, at 1/3 octave bands centred at 315 Hz and 400 Hz, respectively.

Other effects observed are that invertebrates can become accustomed to acoustic stimulus. Some examples are the habituation of cuttlefish to 200 Hz tone at 165dB, after a first subtitle reaction of avoidance to the acoustic stimulus (Samson et al. 2014) and the reduction of irritation behaviour of seahorses after the first week of the experiment (Anderson et al., 2011).

Evidence of impacts related to shipping noise

When subject to ship noise the reactions are like the ones previously mentioned with most of the studies corresponding to laboratory experiments. Behavioural and physiological impacts are the most common. However, it is also possible that the animals do not present any response (Stocks et., 2012).

Behavioural reactions include:

- **Changes in locomotive patterns** for common prawn (Filiciotto et al., 2016) and (*Palaemon serratus*) and Mediterranean spiny lobster (*Palinurus elephas*) (Filiciotto et al., 2014) when subject to different types of boats (recreational boats, fishing, ferry and hydrofoil) in the frequency range from 300 to 3000 Hz. Locomotive patterns appear to be related with social aspects, since when in group lobsters presented higher velocity, distance moved, mobility and moving (*Filiciotto et al., 2014*). Stocks et al. (2012) suggests that swimming activity of larvae of different species can be affected when subject to outboard vessel noise. The same study suggests that the impact can be related to the nutritional conditions since unfed larvae did not respond to sound.

- **Changes in settlement behaviour**. It is suggested by different studies that vessel noise increase settlement of mussel larvae, regarding velocity and size of settlers. According to Jolivet et al. (2016), in the presence of a boat equipped with diesel motor, passing at low speed, settlement of mussel larvae increases in 27 %, but the size of settler decreases. For a playback experiment of 125-m long steel-hulled passenger and freight ferry, operating ship-based generator power supply and the main forward propulsion engines off and no other machinery operational during the recordings, and most of energy between 100 and 1000 Hz, mussels present faster settlement (Taylor et al., 2012). According to the same authors the impact appeared to be correlate with the intensity of the sound.

  The same evidence was found by McDonald et al., (2014) for an ascidian species when subjected to the noise produced by a 25-m long steel-hulled fishing vessel operating with a ship-based generator power supply and no other operational machinery. Based on laboratory experiments faster settlement and metamorphosis and, higher larval survival rates were observed when they were exposed to the underwater noise produced by the vessel generator. The study also considered field observations of biofouling levels on the hull and it was observed that biofouling levels were higher in the sites closest to the generator and where sound levels were higher. Settlement conditions play an important role on the spread of invasive or non-indigenous species, suggesting that underwater noise from vessels running the generators in ports can act as an important cue on settlement.

  Other studies indicate that noise vessels particularly those on berths may be attracting, as well as promoting, the settlement and growth of the larvae of key fouling organisms of vessel hulls via acoustic emissions (Stanley et al., 2014).

- **Protective reactions.** Wale et al (2013a) provide evidence that in the presence of vessel noise at low speed (<10 knots), and sound pressure level between 148 to 155 SPL (ferry, container ship and LPG tanker), shore crabs (*Carcinus maenas*) present slower reaction to retreat to shelter and right themselves faster when in the wrong position.

Physiological impacts include:

- **Increasing of stress**. This is evidenced by an increase in stress hormones in the common prawn when subjected to playback of different boats (Filiciotto et al., 2014). Wale et al. (2013b) showed that shore crab, *Carcinus maenas*, increases oxygen consumption in the first exposure to ship noise, ranging from 148 to 155 dB (frequency range not stated) and this reaction is size dependent with heavier crabs, showing a stronger response than lighter individuals. The same study indicated the potential for habituation, since repeated exposure to ship-noise playback produced no change in physiological response

- **Limiting bioaccumulation and slowing down growth rate**. An example is the study carried out by Charifi et al. (2018), based on playback experiments of cargo vessel noise passing at a speed below 9 knots, with sound pressure level between 138 and 150 dB re1µPa, within the frequency range from 20 Hz to 20 kHz, detecting the impact for oysters. Oysters exposed to URN from shipping accumulated less Cadmium in their gills, probably due a reduction of valve activity, and the growth rate was slower. Therefore, the authors suggested the protective effect of metal bioaccumulation but at the same time the potential risk in terms of ecosystem productivity.

- **Morphological effects:** Vessel noise effects embryo development and mortality of larvae. According to Nedelec et al., (2014), vessel noise, from an outboard motorboat with 25 horsepower engines, reduced successful development of embryos by 21% of sea hare (*Stylocheilus striatus*) and contributed to a 22% increase in mortality of recently hatched larvae.

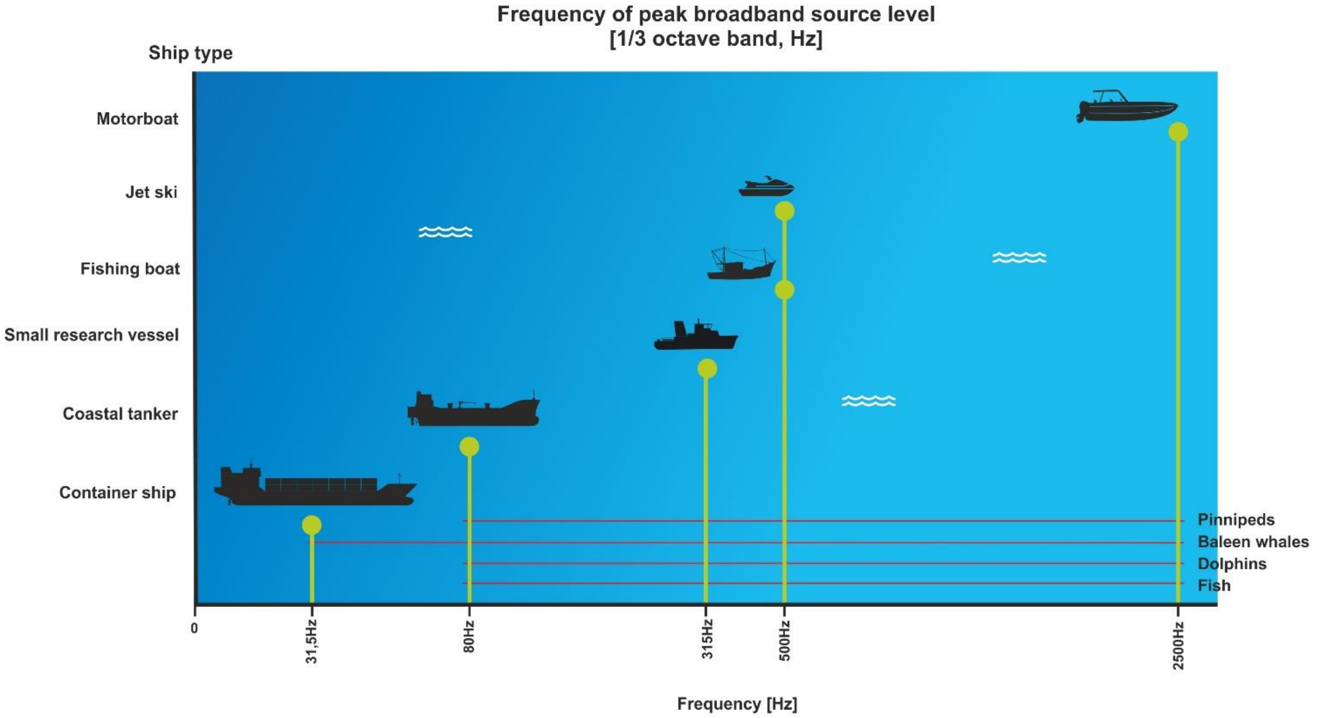


Figure 16 - Different vessel types and overlapping of hearing range of different groups of species. The frequency associated with each vessel type represents the frequency of the peak broadband source level, to the nearest OTO band. The following sources were used: container ship – Gassmann et al. (2017); coastal tanker – Johansson et al. (2015); small research vessel – Brooker et al. (2016); fishing boat – Peng et al. (2018); jet ski – Erbe (2013); motorboat – Mensinger et al. (2018).

4.4 Cumulative impacts

According to the European Environment Agency, cumulative impacts refer to *"the impacts arising from a range of activities throughout an area or region, where each individual effect may not be significant if taken in isolation. These include a time dimension, since they should calculate the impact on environmental resources resulting from changes brought about by past, present and reasonably foreseeable future actions. This entails a good understanding of different pressures in a particular region as well as knowledge about the species with potential to be affecedt. According to existing knowledge these factors can be individually addressed but when identified, is not possible yet to establish the combinations of different stressors whose reduction will most likely to prevent adverse consequences to ecosystem"*[2]. As an example, with respect to the underwater radiated noise from shipping cumulative impacts might result from the growth in volume of traffic, combined with different levels of sound exposures and the effect of other noise sources.

Risk maps and noise budgets have been recommended to address cumulative noise impacts. This approach considers spatio-temporal characteristics of sources and species, and requires the development of international databases to allow a quantitative analysis of cumulative and synergistic impacts (OceanCare, 2020).

[2] European Environment Agency Glossary, https://www.eea.europa.eu/help/glossary/eea-glossary/cumulative-impacts

5. Policy

This section addresses different types of policies that have be implemented to manage underwater noise from shipping, including regulations, measures adopted, industry agreements and voluntary measurements.

5.1 Measures adopted by multiparty agreements

5.1.1 International Conventions

The United Nations Convention on the Law of the Sea

The United Nations Convention on the Law of the Sea establishes the international regulatory framework for all uses involving the ocean and its resources aiming to *“promote the peaceful uses of the seas and oceans, the equitable and efficient utilization of their resources, the conservation of their living resources, and the study, protection and preservation of the marine environment”*. The Convention was opened for signature on 10 December 1982 in Montego Bay, Jamaica. Although its name is linked to the United Nations, this organisation does not have a direct operational role in the implementation of the Convention, which is played by several organisations, such as IMO, the IWC and the International Seabed Authority.

Under this Convention *"pollution of the marine environment means the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities”*. Considering that sound is a form of energy, with potential to affect the marine environment, it can be considered a pollutant. The framework for pollution prevention is set on Part XII of the Convention, which lays down the rules for protection and preservation of the marine environment. Several Articles highlight the need for multilateral and global efforts and cooperation on the assessment and monitoring of the potential effects of polluting activities.

However, the only reference to noise in the Convention relates to the use of explosives for research purposes (Article 246, in the Convention). Other considerations, such as the reference to the conservation and management of the living resources of the high seas (Part VII, Section 2 in the Convention) and the rules and national legislation to prevent, reduce and control pollution of the marine environment (Part XII, Section 5), may indirectly apply to underwater noise, in the sense that noise can have a negative impact on several species. In practice, most of the considerations are applied through regional conventions and international organisations.

Convention on the Conservation of Migratory Species of Wild Animals (CMS)

The Convention on the Conservation of Migratory Species of Wild Animals, also known as the Bonn Convention, is an environmental treaty of the United Nations for the conservation and sustainable use of migratory animals and their habitats, laying the legal foundation for internationally coordinated conservation measures throughout a migratory range. In practice this acts as a framework Convention and the agreements may range from legally binding treaties to less formal instruments and can be adapted to the requirements of particular regions.

In October 2017, UNEP/CMS/Resolution 12.14 on adverse impacts of anthropogenic noise on cetaceans and other migratory species was adopted. This *“endorses the CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities”* attached as Annex of the Resolution and welcomes the Technical Support Information contained in UNEP/CMS/COP12/Inf. These guidelines aim to ensure that decision-makers are presented with sufficient evidence to make an informed judgement of impacts of a proposed activity, including shipping noise. Updated information may be consulted at https://www.cms.int/guidelines/cmsfamily-guidelines-EIAs-marine-noise.

Other two agreements relevant for underwater noise management that have resulted from this convention:

- Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS, http://www.accobams.org/).
- Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS, https://www.ascobans.org/).

Several initiatives related with anthropogenic noise were led by ACCOBAMS, namely:

- Resolutions to support the implementation of measures for balancing human activities at sea and cetacean conservation: 2.16 (2004); 3.10 (2007): 4.17 (2010); 5.15 (2013); 6.17 & 6.18 (2016); 7.13 (2019). The last resolution sets out the guidelines to address the impact of anthropogenic noise on cetaceans in the ACCOBAMS area.

- Mediterranean Strategy on Underwater Noise Monitoring: This work aims, in collaboration with the Barcelona Convention, at laying down the methodological basis for a future implementation of a basin-wide monitoring programme on underwater noise.

- Stakeholder involvement: the "Guidance on underwater noise mitigation measures" was developed in 2013. This guide was conceived to support the implementation of noise mitigation measures by industry and is the result of cooperation between representatives of the industry, scientists and NGOs.

Under ASCOBANS underwater noise is recognized as a threat to cetacean species. In 2008 an Intersessional Working Group on the Assessment of Acoustics Disturbance was formed and based on their work, guidelines for best practice mitigation measures were released, focusing on three main activities: naval sonars, seismic surveys and pile-driving (Bräger et al., 2012).

Convention on Biological Diversity (CBD)

The Convention on Biological Diversity entered into force in December 1993 and it has three main objectives: 1) the conservation of biological diversity; 2) the sustainable use of the components of biological diversity; 3) the fair and equitable sharing of the benefits arising out of the utilisation of genetic resources.

Regarding underwater noise, an important step was taken in October 2014, when the conference of the parties to the Convention on Biological Diversity at its twelfth meeting adopted Decision XII/23 on "Marine and coastal biodiversity: Impacts on marine and coastal biodiversity of anthropogenic underwater noise and ocean acidification, priority actions to achieve Aichi Biodiversity Target 10 for coral reefs and closely associated ecosystems, and marine spatial planning and training initiatives."

In this decision, Parties and other Governments, as well as local communities and other relevant stakeholders, were encouraged *"to take appropriate measures, as appropriate and within their competencies, and in accordance with national and international laws, to avoid, minimize and mitigate the potential significant adverse impacts of anthropogenic underwater noise on marine and coastal biodiversity"*, through research, raising awareness and taking management actions. The complete text for this Decision is available at https://www.cbd.int/doc/decisions/cop-12/cop-12-dec-23-en.pdf, reference to paragraph 3.

In the decision of 2014, reference to other Agreements and organisations such as the CMS and International Maritime Organisation (addressed below) are made. Later, in December 2016, the Convention adopted Decision CBD/COP/DEC/XIII/10, which further addresses the impacts of marine debris and anthropogenic underwater noise on marine and coastal biodiversity, where the previous decision (Decision XII/23) is recalled. The complete text is available at https://www.cbd.int/doc/decisions/cop-13/cop-13-dec-10-en.pdf.

Currently, there is no specific working group related to underwater noise.

5.1.2 Regional Conventions

Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention)

The OSPAR Convention entered into force in March 1998, aiming to prevent and eliminate pollution in order to protect the maritime area against the adverse effects of human activities so as to safeguard human health and to conserve marine ecosystems and, when practicable, restore marine areas of the North-East Atlantic which have been adversely affected. According to the Convention, pollution means *"the introduction by man, directly or indirectly, of substances or energy into the maritime area which results, or is likely to result, in hazards to human health, harm to living resources and marine ecosystems, damage to amenities or interference with other legitimate uses of the sea"*. The topic of underwater noise is addressed by the Environmental Impacts of Human Activities Committee under the Intersessional Correspondence Group on Underwater Noise.

Monitoring and assessment of underwater noise is split in impulsive noise and ambient noise. In 2015 OSPAR adopted an Ambient Noise Monitoring Strategy (Agreement 2015-05), assuming that monitoring should be undertaken at an acoustic basin scale. The first pilot study was established in the North Sea by JOMOPANS project (https://northsearegion.eu/jomopans/), funded by the Interreg North Sea Region, and expected to be extended to other regions. Currently, the JONAS project (https://www.jonasproject.eu/), funded by the Interreg Atlantic Region, is mapping noise and assessing exposure to a number of sensitive species in the wider Atlantic area.

Based on the outcome of these projects, a descriptive indicator to assess continuous noise is being developed. The Guidance for Monitoring of underwater noise developed under the Common Implementation Strategy for the Marine Strategy Framework Directive was adopted by the OSPAR Commission (OSPAR Agreement 2014-08).

HELCOM

The Baltic Marine Environment Protection Commission – also known as the Helsinki Commission (HELCOM) – is an intergovernmental organisation (IGO) and a regional sea convention in the Baltic Sea area. A regional platform for environmental policy making, HELCOM was established in 1974 to protect the marine environment of the Baltic Sea from all sources of pollution and all Baltic Sea coastal countries are signatory parties.

A dedicated working group, on noise was created, the HELCOM Expert Network on Underwater Noise (EN-Noise), to implement commitments of the Ministerial Declaration related to underwater noise. The overall objective is to contribute to the development of an action plan and coordinate the actions with other regional conventions, such as OSPAR, and with the MSFD. The group articulates with other working groups as for example the Maritime Working Group that address the topics related with prevention of pollution from ships.

An important project supporting the action of HELCOM was the BIAS project, Baltic Sea information on the Acoustic Soundscape. The objective was to demonstrate that is possible to have regional cooperation regarding transboundary issues as underwater noise. Important outcomes of the projects, such as sound maps of the Baltic Sea allowed to identify the main acoustic pressure providing evidence that the two frequency bands being proposed by the MSFD (63 and 125 Hz) are not good indicators to assess environmental status and another frequencies band should be considered (2 kHz).

Regarding reporting of continuous underwater noise levels HELCOM adopted the database hosted by ICES.

A draft of HELCOM Recommendation on the Regional Action Plan on Underwater Noise is currently being discussed and supported by different parties and it is expected to be released this year.

The Convention for the Protection of the Mediterranean Sea Against Pollution (Barcelona Convention)

This Convention was adopted on 16 February in Barcelona and entered into force in 1978. In 1995 was amended and renamed as Convention for the Protection of the Marine Environment and Coastal Region of the Mediterranean. It was adopted in the framework of the Mediterranean Action Plan and togethers with its seven Protocols constitute the principal regional legally binding Multilateral Environmental Agreement in the Mediterranean.

In the Decision IG.22/7 - Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast and Related Assessment Criteria of this Convention, the parties are encouraged to develop monitoring programmes related to underwater noise. The work encouraged in this decision was proposed with the support of experts from the Joint ACCOBAMS/ASCOBANS/CAMS Working Group on Noise.

5.1.3 European Directives

In the European Union, underwater noise is addressed by two main directives: the Marine Strategy Framework Directive (MSFD), which requires the monitoring of underwater noise levels and its adverse effects in EU waters; and the Environmental Impact Assessment (EIA) directive requiring the impact assessment of individual public and private projects.

The Marine Strategy Framework Directive

The Marine Strategy Framework Directive (2008/56/EC) aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend. It is the first EU legislative instrument related to the protection of marine biodiversity, as it contains the explicit regulatory objective *"biodiversity is maintained by 2020"*, as the cornerstone for achieving GES. It was adopted in June 2008.

The MSFD established eleven qualitative descriptors of GES which must be further determined and assessed. Descriptor 11 concerns the introduction of energy, including underwater noise, and requires that it must be at levels that do not adversely affect the marine environment. A technical subgroup under the Working Group on GES was established in 2010 to provide advice on how Descriptor 11 should be determined and assessed (TSG Noise).

The criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment of predominant pressures are laid down in the Annex of the Commission Decision (EU) 2017/848 of 17 May 2017, part I. According to the Commission Decision (EU) 2017/848, GES for underwater noise must be assessed based on two criteria elements, one of them being *"Anthropogenic continuous low-frequency sound"*, where shipping noise is included. The criteria are that the spatial distribution, temporal extent and levels of anthropogenic continuous low-frequency sounds do not exceed levels that adversely affect populations of marine animals, which requires Member States establishing threshold values for these levels through cooperation at Union level, taking into account regional or sub-regional specificities. The threshold values and the associated standard protocols are still in the process of being developed for monitoring underwater radiated noise from ships in the European marine environment.

Environmental Impact Assessment Directive

The EIA Directive (85/337/EEC) is in force since 1985 and establishes the adoption of procedures to assess the environmental effects of public and private projects which are likely to have significant effects on the environment. The 1985 Directive was amended three times being codified by Directive 2011/92/EU of 13 December 2011 which was in turn amended in 2014 by Directive 2014/52/EU. Until the approval of MSFD, the main legal framework to monitor underwater noise was this Directive and, indirectly, the Habitats Directive (92/43/EEC), which establishes a strict protection regime for all cetacean species. The need to prevent harm to marine mammals led to the adoption of noise monitoring programmes in the Environmental Impact Assessments of maritime activities with potential risks for cetacean populations.

According to the EIA procedure, the developer should provide the competent authority with information on the environmental impact - the EIA report - which could be previously identified in the scoping stage. After that the environmental authorities and the public are informed and consulted. After the consultation period, the competent authority decides and informs the public about the decision which the public can challenge before the courts.

Shipping activity is not identified as one of the activities that should be subject to environmental impact assessment.

5.1.4 International Organisations

International Maritime Organization

The International Maritime Organization (IMO) is a specialised agency of the United Nations with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. Being the shipping industry an international industry, IMO is the forum that allows discussing the regulations and standards and its adoption and implementation at international level.

The issue of underwater noise is led by the IMO Marine Environment Protection Committee, which in 2008 agreed to develop non-mandatory technical guidelines to minimise the introduction of underwater noise into the oceans, which were approved in 2014, entitled – *"Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life (circular MEPC.1/Circ.833)"*. These are focused on primary sources of underwater noise and also include definitions and underwater noise measurement standards. On the adoption of the guidelines, the complexity of the issue and the lack of information was recognised, in particular, regarding the measurement and reporting of underwater sound radiating from ships. The guidelines resulted from contributions of specialists that were nominated by National representatives. While they do not currently have a binding effect, this was seen as paramount by the (associations of) ship owners interviewed, in order to maintain a "level playing field" in terms of the costs of ship design, construction and operation.

Very recently, the Marine Environment Protection Committee at its 76th session (MEPC 76), held remotely from 10 to 17 June 2021, agreed to commence further work on underwater noise from ships. The MEPC agreed to include a new output on the review of the 2014 Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life (MEPC.1/Circ.833) and identification of next steps.

The Sub-Committee on Ship Design and Construction (SDC) has been assigned to coordinate the work since the review of the Guidelines mainly relates to technical issues. The work is likely to include identifying: barriers to uptake and implementation of the Guidelines; measures to further prevent and reduce underwater noise from ships, including options to integrate new and advancing technologies and/or vessel design solutions; areas that require further assessment and research; an acceptable means of measuring existing ship noise profiles following ISO or international standards; and develop a proposal for a program of action and/or next steps to further prevent and reduce underwater radiated-noise based on the findings of the review. The target completion year for the work is 2023.

International Whaling Commission

The International Whaling Commission, established in 1946, is the international body in charge of conservation of whales and the management of whaling. Nowadays, besides whaling management, the work also addresses conservation issues including underwater noise.

Anthropogenic noise is set as a priority threat in the Strategic Plan 2016-2026 of the Conservation Committee and is also being considered at the Scientific Committee *"to better understand the impact of noise on cetaceans, and the effectiveness of different approaches to reducing exposure"*. The steps to be undertaken by the Commission are set up on the 2018 Resolution on Anthropogenic Underwater Noise. Additionally, the Commission is actively engaged in discussions in other international for a, including the United Nations consultative process on Ocean and the Law of the Sea and the International Maritime Organization, by regularly updating on the impact of underwater noise.

Updated information about the actions undertaken by IWC regarding underwater noise can be consulted at https://iwc.int/anthropogenic-sound.

International Council for the Exploration of the Sea (ICES)

ICES is an intergovernmental marine science organisation, meeting societal needs for impartial evidence on the state and sustainable used of the seas and oceans. It aims to advance and share scientific understanding of marine ecosystems and the services they provide, and to use this knowledge to generate state-of-the-art advice for meeting conservation, management, and sustainability goals. It sets out six science priorities: 1) ecosystem science, 2) impacts of human activities, 3) observation and exploration, 4) emerging techniques and technologies, 5) conservation and management science and 6) sea and society. The work of ICES is accomplished through Expert Groups and workshops managed by the Steering Groups.

Underwater noise is addressed in the Working Group on Shipping Impacts in the Marine Environment, which investigates management and mitigation measures that can be used to reduce or eliminate sources of ship-based pollution and synthesize scientific progress in addressing single stressors, such as pollutant discharge, underwater noise, and ship strikes. The Council has a Data Centre with underwater noise dataset collections both for impulsive and continuous underwater noise. These portals assemble data supplied by contracting parties to OSPAR (North East Atlantic) and HELCOM (Baltic Sea).

A relevant contribution to the shipping industry is related to the creation of a standard for the underwater radiated noise of research vessels by issuing the Cooperative Research Report, No. 209 (Mitson, 1995), with application on fishery research vessels. This specification was created aiming to reduced bias in fishery research (by avoiding an artificial concentration of fish below the vessel) and to prevent noise from being integrated as signal or from contaminating the fish echoes received and processed by acoustic survey equipment.

Table 5 summarises relevant documents with reference to shipping noise and existing working groups addressing underwater noise.

Table 5 – Summary of relevant documents and existing working groups.

Multiparty agreement	
Documents	
CMS	UNEP/CMS/Resolution 12.14 on adverse impacts of anthropogenic noise on cetaceans and other migratory species
CMS	CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities
ACCOBAMS	Resolutions to support the implementation of measures for balancing human activities at sea and cetacean conservation: 2.16 (2004); 3.10 (2007): 4.17 (2010); 5.15 (2013); 6.17 & 6.18 (2016); 7.13 (2019)
CBD	Decision XII/23 on "Marine and coastal biodiversity: Impacts on marine and coastal biodiversity of anthropogenic underwater noise and ocean acidification, priority actions to achieve Aichi Biodiversity Target 10 for coral reefs and closely associated ecosystems, and marine spatial planning and training initiatives."
CBD	Decision CBD/COP/DEC/XIII/10, which further addresses the impacts of marine debris and anthropogenic underwater noise on marine and coastal biodiversity
HELCOM	HELCOM Recommendation on the Regional Action Plan on Underwater Noise (under development)
Barcelona Convention	Decision IG.22/7 Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast and Related Assessment Criteria (UNEP(DEPI)/MED IG.22/28)
European Commission	Directive 2008/56/EC - Marine Strategy Framework Directive
European Commission	Annex of the Commission Decision (EU) 2017/848 of 17 May 2017
IMO	Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life (MEPC.1/Circ.833)
Working groups	
ASCOBANS	Working Group on the Assessment of Acoustics Disturbance
European Commission	TG-Noise working group
HELCOM	HELCOM EN-Noise working group
ICES	Working Group on Shipping Impacts in the Marine Environment
IMO	Sub-Committee on Ship Design and Construction

5.2 Class and voluntary certifications

5.2.1 Classification societies

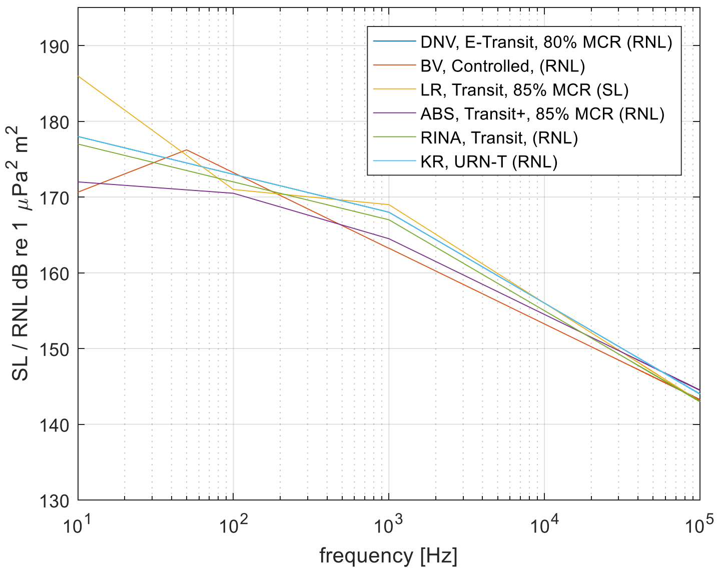
Twelve Classification Societies are recognised by the European Commission. Seven of them have implemented voluntary class notations related to underwater noise motivated by environmental concerns (prior to MSFD), the MSFD and the Guidelines issued by IMO (see summary provided in Table 3). Most of the class notations are recent, have being released in 2018 and 2019, with DNV being the first society to publish procedures and rules for ship noise in 2010. Prior to concern about environmental impact of merchant shipping on marine animals, URN requirements for ships were primarily limited to naval and research vessels. ICES (Mitson, 1995) published the first limits for fishery research vessels, which have subsequently been adopted and adapted by classification societies.

Bureau Veritas noted that very few vessels have so far obtained a “Quiet Class” notation, since this is not required in their design specifications. Up to now the vast majority of ships possessing a Quiet Class notation are research vessels. However, in 2017, *Celebrity Eclipse* became the first cruise ship to obtain DNV’s Silent-E class notation (DNV GL, 2017), while the Aframax tanker *ONEX Peace* was awarded the same notation in 2021, becoming the first cargo vessel to do so (DNV, 2021). Some harbours are applying discounts on harbour rates to vessels that hold a class notation for underwater noise, for example the Port of Vancouver Fraser Authority.

Table 6 – Overview of classification society “Quiet Class” notations.

Classification society	Name	Year	Driver	Applicable to	Reference
DNV AS (DNV GL)	SILENT (5 class notations)	2018	Environmental concerns	vessels using hydroacoustic equipment; seismic vessels; fishery vessels; research vessels; “environmental”	DNV GL (2018)
Bureau Veritas SA	NR614 Underwater Radiated Noise	2017	MSFD	self-propelled merchant vessels	Bureau Veritas (2017)
Lloyd's Register Group LTD	ShipRight (3 class notations)	2018	IMO and MSFD	merchant vessels	Lloyd’s Register (2018)
American Bureau of Shipping (ABS)	Underwater noise (2 class notations)	2018	IMO and MSFD	self-propelled merchant vessels	ABS (2018)
China Classification Society (CCS)	Guidelines for ship underwater radiated noise	2018	Environmental impacts	“ships”	CCS (2018)
RINA Services S.p.A.	RINA DOLPHIN (2 class notations)	2019	Environmental impacts	merchant vessels and yachts	RINA (2017b, 2017a, 2017c)
Korean Register (KR)	Guidances for Underwater Radiated Noise (2 class notations)	2021	Not stated	not stated	Korean Register (2021)

A comparison of the classification society limits is given in Figure 17, grouped according to the two main conditions used: a “transit” condition, typically around the ship’s service speed, and a “quiet” condition, at a lower speed, generally around 10-11 knots. Large differences between the limits are seen in terms of level and slope, particularly at low frequencies. Note that some rules used SL and others RNL. These discrepancies have led to proposals for rule alignment in order to aid interpretation and comparison of results carried out following different procedures (Ainslie et al., 2020). The study includes the suggestion to set “achievable” limits by examining percentiles of URN data sets, while also distinguishing between different ship types. This topic is not yet being addressed within the IACS working group on URN however.



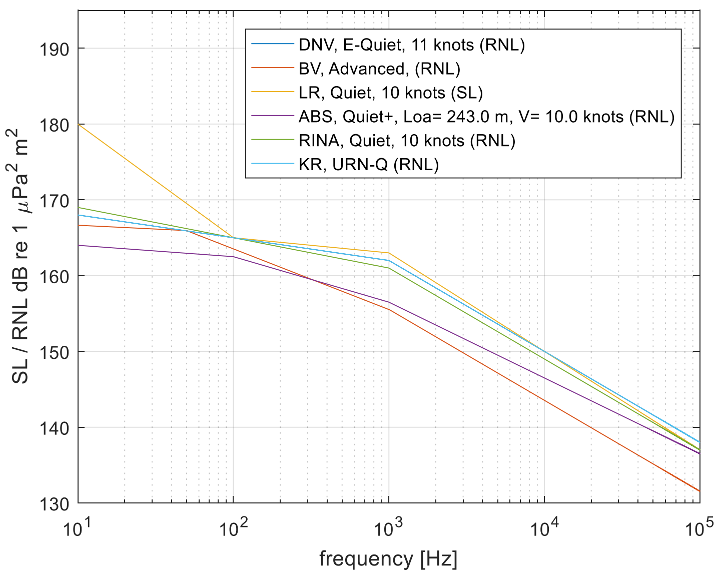


Figure 17 Comparison of classification society URN limits: "transit" condition (top); and "quiet" condition (bottom). Figure reproduced from Bosschers et al. (2021). Note that CCS limits are not included, since these are only provided for ships "operating hydro-acoustic equipment".

5.2.2 Voluntary certifications

Despite a lack of mandatory regulation for ship URN, ship owners may choose to qualitatively assess the noise performance of their fleet through voluntary certification programmes. While several such programmes exist, covering numerous types of pollution from ships, Green Marine environmental certification program[3] is the only one to include URN. Certification is a means of encouraging continuous improvement in terms of environmental performance at fleet level, allowing owners to demonstrate their sustainable credentials, and is, for example accepted as evidence to qualify for discounted harbour dues at the Port of Vancouver within the ECHO Program. Although the voluntary certification offered by Green Marine has been operational in North America since 2008, it was only established in Europe in 2019. Last year, 12 French fleets were certified (across a range of sustainability indices), with scores for URN ranging from minimum to maximum (Marcoux et al., 2021). The assessment criteria are set and reviewed

[3] https://green-marine.org/europe/

annually by expert working groups. In terms of URN, they recommend improving annual performance by concentrating on quietening the oldest vessels in the fleet.

The adoption of URN criteria within the Environmental Ship Index[4] (ESI) is also under discussion (private communication, Port of Amsterdam, April 2021). The aim of the ESI is to encourage performance (improvements) for individual ships in terms of air emissions, which go beyond those mandated by IMO. While this approach cannot yet be implemented for URN, effective ship noise reduction could be achieved, should European ports or coastal states encourage the widespread adoption of voluntary certifications. The use of incentives based on voluntary certification would also help engage, and stimulate cooperation between, stakeholders in the absence of science-based noise limits (Bureau Veritas, private communication, 2021). On the other hand, the ship owners and associations of ship owners interviewed expressed a clear preference for mitigation through international policy, vis. IMO, containing well-defined noise limits or reduction targets, and had not yet seriously considered voluntary certification.

[4] https://www.environmentalshipindex.org/

6. Mitigation measures

6.1 Introduction

Effective mitigation of ship URN combines knowledge from the subjects addressed in the previous three sections, as well as the ability to estimate the effect of a certain mitigation measure on the overall sound field in a specific geographical area of interest. Furthermore, noise reduction should also be considered within the broader issue of environmental sustainability of shipping; that is, alongside greenhouse gas (GHG) emissions; and together with socio-economic factors. Therefore, trade-off or cost-benefit analyses may be important in the decision-making process when implementing mitigation measures. The ship owners and associations of ship owners interviewed for this study emphasised that GHG emissions are their current focus, with noise having a low priority due to a lack of drivers. However, this may change should awareness of noise impacts from clients increase.

A wide range of measures for mitigating ship URN have been proposed and applied. Overviews of the various measures can be found in academic papers (Renilson et al., 2013; Spence & Fischer, 2017), technical reports (Baudin & Mumm, 2015; C. de Jong et al., 2020; Strietman et al., 2018) and policy documents (IMO, 2014). Quantitative evaluation and comparison of solutions for reducing ship noise have also been published (Chmelnitsky & Gilbert, 2016; Hilliard et al., 2018; Kendrick & Terweij, 2019; McHorney et al., 2018). In their evaluation, as well as their effectiveness in reducing URN, other factors including cost, impact on fuel efficiency, feasibility of implementation and applicability (both range of ship types and suitability for both newbuild and retrofit) are taken into consideration. Given the pre-existing mandatory limitations on GHG emissions from ships– for example through the Energy Efficiency Design Index (IMO, 2011) – preferable URN mitigation solutions will often be those which are not detrimental to GHG emissions, or which offer the possibility to reduce URN while improving fuel efficiency. This was demonstrated by Gassmann, Kindberg et al. (2017), who reported URN reductions from ships retrofitted for improved fuel efficiency without any specific requirement to quieten the vessels. The Royal Association of Netherlands Shipowners commented that there is a trend towards lower installed power in vessels, in order to reduce GHG emissions. This could also improve noise performance.

For new vessels, the earlier URN requirements are included in the ship design and construction process, the more effective and cost-efficient the resulting mitigation, with lower impact on the rest of the design. Maersk expressed the view that owners are unlikely to accept (high) additional costs unless URN is included in design requirements, although these could also result from a lack of flexibility from the shipyard to accommodate “non-standard” design specifications. However, for shipyards with experience in building quiet vessels, the inclusion of some noise reduction measures could be achieved at low additional cost if implemented correctly (Freire Shipyard, private communication, 2021). Nevertheless, this typically requires collaboration with noise consultants and marine suppliers, and is not widespread in the (European) shipbuilding industry. This suggests that a combination of knowledge transfer, and selection of appropriate measures for reducing GHG and URN emissions simultaneously, could be important in achieving “cost-acceptable” quiet ships. The world’s first cargo vessel with Quiet Class notation was made possible through a collaboration between owner, shipyard, research institute and classification society (DNV, 2021).

In terms of the existing fleet, Veirs (2018) estimated that half of the total radiated sound power comes from just 15% of the ships sailing, suggesting that the most effective options for short-term noise management involve focusing on the noisiest vessels. Assuming an overall 3 dB reduction strategy, the study shows that removing the noisiest ships affects the lowest proportion of the fleet, while imposing noise or speed limits would affect higher numbers of vessels.

Mitigation measures are typically divided into two main categories: *“technical”* or *“design”* measures, which can apply to both new or existing vessels; and *“operational”* measures, for the existing fleet. Some of the main approaches for vessel quieting are presented here under these two headings.

6.2 Technical measures

Technical measures are now discussed, grouping them according to the two main noise sources identified in Section 3 – the propeller, and machinery – with the remaining measures presented afterwards.

6.2.1 Propeller

Since propeller cavitation noise typically dominates ship source level spectra over a wide range of frequencies, this source mechanism has received a lot of attention in terms of mitigation possibilities.

Propeller concept

The screw propeller is by far the most common ship propulsor (Carlton, 2007). Increasing propeller diameter and/or number of blades, and decreasing rotation rate, all serve to reduce the loading on the blades, which results in smaller cavitation extents. The practical implementation of such strategies however may be limited by technical constraints, such as the main engine rotation rate for optimal fuel efficiency.

Furthermore, the selection of marine engine type often influences the choice of propeller type: fixed-pitch propellers are preferred for low-speed engines, while controllable-pitch propellers are more commonly applied in combination with medium- and high-speed engines. As explained in Section 3.3.3, CPPs can produce more noise than FPPs operating at the same condition, due to the relatively higher thrust loading at design speed, and presence of face side cavitation at low speeds. Therefore, it is recommended to operate CPPs following the ‘combinator curve’, whereby both propeller pitch and shaft rotation rate are changed simultaneously. This is often difficult in practice however, due to the presence of a shaft generator which operates at a fixed rotation rate (Baudin & Mumm, 2015).

Alternative propulsors, such as cycloidal or podded propulsors, may result in reduced cavitation noise, although they require large modifications to the ship hull design and general arrangement, limiting their applicability to only a number of vessel types. Podded propellers, which make use of diesel-electric propulsion systems, may result in reduced engine noise, although additional noise from the motors may be introduced (Kendrick & Terweij, 2019). Until now the noise reduction potential of cycloidal propulsors has not been demonstrated in the open literature.

Inflow to the propeller

The inflow to the propeller (hull wakefield) has a large influence on noise, since variations in flow velocity lead to fluctuations in propeller loading, and therefore increased cavitation dynamics and noise radiation. This means that the homogeneity of the wakefield should be improved, which can be achieved by optimizing the hullform, or applying a *‘wake improvement device’*, such as a stator fin or duct. These devices are typically aimed to improving propulsive efficiency, meaning they may allow the concurrent reduction of fuel consumption and URN.

Other propulsion improvement devices, such as propeller boss cap fins (PBCFs) and rudder bulbs, could also lead to noise reduction by improving propeller efficiency and reducing cavitation (Renilson et al., 2013). Reductions of up to 8 dB in median source level have been measured for containerships retrofitted with PBCFs, although a number of other modifications were also made to the vessels (Gassmann, Kindberg, et al., 2017).

Propeller blade geometry

The design of the propeller blade affects both efficiency and URN. Design variables include pitch, camber, chord length, thickness, sectional profile and skew (Carlton, 2007). Efficiency and URN present conflicting objectives in the propeller design process, due to their opposing dependency on thrust - a higher efficiency results in lower local pressures on the blades, leading to more cavitation. This has led to the adoption of optimisation techniques in propeller design, in order be able to examine the trade-off between efficiency and noise when selecting an appropriate propeller design (Lloyd et al., 2020). This is demonstrated in Figure 18, where the optimisation objectives are behind efficiency (propeller operating in a wakefield), URN, and hull pressure fluctuation levels (in relation to onboard comfort requirements). Results such as this help in the selection of a propeller which is more likely to satisfy multiple design requirements.

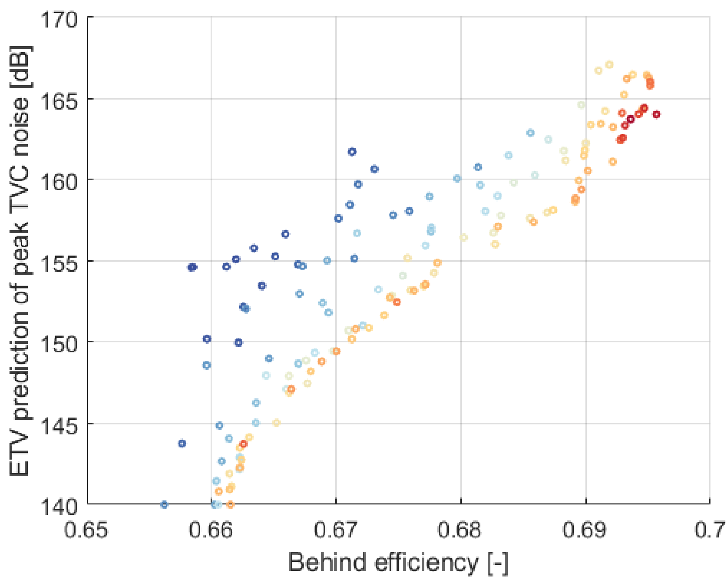


Figure 18 Example results from a propeller optimisation (Lloyd et al., 2020). Each point represents a different propeller design from the final generation of the optimisation. The abscissa shows the propeller behind efficiency, and the ordinate the peak spectral source level using a semi-empirical model for tip vortex cavitation. Colour represents the amplitude of the hull pressure fluctuations, where blue is low and red is high.

Air injection into the cavitation

Strong and sudden changes in cavity volume result in increased noise levels (Bosschers, 2018). This can be reduced by injecting air into the cavity; the presence of non-condensable gas dampens the collapse and leads to lower URN. This has been applied to naval vessels for decades (e.g. Prairie or Agouti systems), but is yet to be adopted for merchant ships. From measurements performed in the SONIC project, this approach was found to result in URN reductions of 10-15 dB in the frequency range 40-400 Hz (Baudin & Mumm, 2015).

6.2.2 Machinery

Propulsion machinery selection

The most common propulsion engines for large merchant ships are low–speed (two-stroke) diesel engines, due to their superior efficiency, yet they can radiate significant noise underwater due to their large size and difficulties in isolating them from the ship hull structure. However, for certain ship types, alternative propulsion machinery arrangements may be realizable.

Medium-speed engines can be elastically mounted, resulting in improved isolation from the ship hull, and reduced noise. However, if a gearbox is required, this may lead to an additional source of machinery noise. This type of engine is suitable for smaller merchant vessels, of which many are found in European coastal waters, although these ships are often equipped with CPPs. Therefore, the selection of low-noise propulsion machinery also needs to account for the possible implications on propeller cavitation noise already detailed in Section 3.2.2.

High-speed engines can always be resiliently mounted and are more easily located away from the ship hull due to their compact size, thereby providing possibilities to reduce URN. However, they are expensive, less efficient and limited in terms of maximum power, compared to low- and medium-speed engines. This limits their applicability to small or specialized vessel types (Baudin & Mumm, 2015).

Diesel-electric propulsion systems offer the possibility to mount the diesel engines higher up inside the ship structure in order to better isolate them from the hull plating, as well as high fuel efficiency. Such systems are expensive however, meaning they are often used for vessels where URN or onboard noise levels are a primary design requirement, such as research, naval or cruise vessels.

Resilient mounting

Isolating any piece of machinery from the ship structure can reduce structure-borne noise. The level of noise reduction depends on the type of machinery; for medium- and high-speed diesel engines it can be up to 10 and 20 dB respectively (Baudin & Mumm, 2015). However, resilient mountings do require some additional maintenance during the vessel's lifetime.

Structural design

The ship structure can be designed to reduce structure-borne noise and radiation from the hull. This may involve stiffening of parts of the structure or designing stiffeners and plating to avoid natural frequencies coinciding with excitation frequencies of the machinery on board.

6.2.3 Other

Reduced power requirement

Lowering the required installed power of a vessel can indirectly reduce its URN. It may allow a smaller main engine to be selected, as well as lowering the thrust the propeller is required to deliver, thereby reducing cavitation noise. This can be achieved in a number of ways, such as optimising the hull form for lower resistance, utilising air injection systems, reducing the design speed of the vessel, or adding supplementary propulsion systems to lower the required propeller thrust, such as sails or Flettner rotors (C. de Jong et al., 2020). Note however that wind assistance could negatively impact the vessel hydrodynamics, such as inflow to the propeller and propeller loading distribution, and therefore requires careful incorporation into a ship design. This may include considerations such as operation of the main propulsion machinery away from its design point, and the adoption of a CPP together with combinator curve, in order to optimise propeller performance (both in terms of URN and efficiency) at multiple vessel speeds and power requirements.

Air bubble curtain

Another approach which can be used to mitigate URN is to generate an air bubble curtain around the aft part of the ship hull, also often referred to as a "*Masker system"* Such systems were developed to reduce machinery noise from naval vessels, with similar systems applied to some merchant ships, in particular passenger vessels, for reducing onboard noise (Lloyd et al., 2020). A sketch is shown in Figure 19. The system results in an insertion loss due to the impedance difference between air and water, but requires tuning in order to reduce noise across the desired frequency range. Note that such a system is distinct from an air lubrication system[5] aimed at reducing ship hull frictional resistance (Mäkiharju et al., 2012), since a Masker system is only applied at the stern of the vessel and does not generate an air layer along the hull.

The contribution of the bubbles themselves to the total radiated sound has not been reported but is expected to be small provided there is sufficient separation between the bubble natural frequencies and the excitation frequencies generated by the ship (Lloyd et al., 2020).

[5] An air lubrication system can have a separate indirect effect on URN, by reducing the vessel resistance and therefore lowering the required propeller thrust.

Figure 19 Sketch of Masker system applied to a merchant vessel, courtesy of the SATURN project.

6.3 Operational measures

Operational measures concern changes to how the ship is operated aimed at reducing URN. Baudin & Mumm (2015) distinguish between measures which can be taken by the ship operator/master, i.e. on an individual ship basis, and those taken by authorities, i.e. on a geographical basis.

6.3.1 Ship operator

Real-time monitoring

It may be possible to provide additional information to the ship's Master, or make better use of the available information, in order to mitigate URN. For example, optimising vessel trim can reduce required power and therefore also propeller cavitation noise. If CPPs are operated following combinator curves, both higher fuel efficiency and lower noise may be achieved. Another possibility is to install sensors to monitor cavitation, such that an appropriate speed can be selected depending on where the vessel is sailing. This type of approach is not yet widely adopted, and require further development before widespread adoption is possible. More generally, the application of "just in time" logistics principles could help lower the total sound energy emitted along a route by allowing a vessel to reduce its average speed, an approach which is favoured by the Royal Association of Netherlands Shipowners (private communication, 2021). This is being implemented by the Port of Rotterdam (https://www.portofrotterdam.com/en/tools-services/portxchange), while one study estimated that it could save up to 23% in GHG emissions when applied to containerships (Arjona Aroca et al., 2020).

Maintenance

Hull and propeller fouling is known to (in most cases) increase frictional resistance and reduce propulsive efficiency (Song et al., 2020), therefore also likely leading to a degradation in noise performance. Regular cleaning helps alleviate these effects by avoiding higher thrust loading on the propeller at service speeds. Quijano et al. (2018) attempted to measure the effect of hull and propeller cleaning on noise, although no benefits could be demonstrated due to the uncertainty levels of the sound data, and the vessel operating condition. This provides further motivation for reducing the uncertainty of ship URN measurements, to allow mitigation measures with low expected noise reduction (< 5 dB) are to be quantified and assessed.

Coatings can also be applied to the ship hull to reduce resistance, or avoid the accumulation of bio-fouling; see e.g., Cho et al. (2021).

6.3.2 Authorities

Authorities can attempt to mitigate URN by applying various controls to ship traffic within their area of jurisdiction, with the most appropriate approach depending on the local situation i.e. the distribution of ship types, the species of marine fauna present, and the geographical characteristics (Baudin & Mumm, 2015). A main advantage of operational measures imposed by authorities is their effect on all ship traffic, compared to technical measures, which require (re)designing individual (classes of) vessels to reduce URN.

Marine spatial planning

Based on knowledge of the specific areas in which sensitive species are found, and therefore where URN should be reduced, ship traffic can be regulated to minimise impact. Three main approaches can be identified:

- Traffic concentration, to limit high noise levels within a restricted area. In doing so use can be made of the fact that the loudest vessels dominate the overall sound field due to the logarithmic superposition of multiple (incoherent) noise sources. For example, an individual ship's URN will contribute negligibly (< 0.5 dB) to the overall sound field in the presence of another vessel with a source level 10 dB higher.

- Traffic dilution, which aims for a homogeneous sound field by separating vessels evenly in the traffic lane.

- Geographical exploitation, which makes use of the local marine environment to reduce noise impact. This could entail absorbing or blocking sound using trenches or islands, and utilising the cut-off frequency of shallow water, which results in frequencies below a certain limit not propagating due to the low water depth (Baudin & Mumm, 2015). This was proposed by the AQUO project, although its effectiveness was not quantified.

Speed limits

Limiting speed – also referred to as slow steaming – result in lower propeller thrust loading for all ships in a given area, with the intention of reducing their individual noise footprints. The measure is relatively simple to implement, following either a maximum speed for all vessels, or a percentage reduction in design speed for individual vessels. At lower speed, a vessel spends more time transiting a given area, meaning that the Sound Exposure Level could increase if the Sound Pressure Level does not decrease sufficiently. This is not expected to be a problem for most vessels, since source level models use a sixth-power dependency on speed, while the increase in transit time is proportional to the speed reduction. However, for vessels with higher noise levels at low speeds, such as those with CPPs, this approach may be less effective. Noise reductions resulting from slow steaming depend on ship type: Joy et al. (2019) reported a median reduction in SPL of 3.1 dB when all vessels were requested to limit their speed through the water to 11 knots, while noise levels of containerships were found to reduce by up to 11.5 dB during the same voluntary slowdown trial (MacGillivray et al., 2019). Based on simplified analyses, Leaper (2019) estimated that a 10% speed reduction of all ships would result in about 40% less sound energy being emitted, assuming equivalent total cargo carrying capacity i.e., a larger fleet.

Both Maersk and the Royal Belgian Shipowners' Association were positive about slow steaming, and saw it is a potential solution to reducing noise as well as GHG emissions. Maersk noted however that it should be carefully accounted for in scheduling to avoid issues such as increased emissions on other parts of a route, delays in berthing, and increasing the number of vessels required.

Noise labels

Focusing on the fact that the loudest vessels dominate the overall sound field, the practice of requiring noise labels aims to prohibit individual "noisy" vessels from sailing in a particular area. Given the absence of mandatory URN limits for ships, authorities may choose to accept various types of evidence for low noise design and operation of a particular vessel. This could be a classification society "Quiet Class" notation, or a voluntary environmental certification programme. Economic incentives in the form of reduced harbour dues have also been used to encourage uptake of URN notations (Chmelnitsky & Gilbert, 2016).

6.4 Selection of appropriate measures

The appropriate selection of mitigation measures is a complex task, and needs to be evaluated on a case-by-case basis (C. de Jong et al., 2020). Effective mitigation requires assessment of vessel noise footprint and derivation of sound maps, with information on ship traffic, source levels, and propagation loss as input. Furthermore, the sensitive marine fauna present and the potential impacts on them need to be included, although this may have to be assumed due to lack of detailed information or knowledge. One example is Cominelli et al. (2019), who reported the development of an advanced geovisualisation tool to study the mitigation of noise impact on Southern Resident Killer Whales through traffic lane management. Such an approach aims to maximise noise reduction while minimising impact on vessel operation, although the study did not model a range of mitigation options. Frameworks for evaluating the noise reduction due to different mitigation approaches in a pragmatic way have been proposed and demonstrated (Audoly et al., 2017; Williams et al., 2019), although the latter study adopted "aspirational reductions > 3 dB, thereby acknowledging that biologically relevant targets are not yet known".

More advanced decision-making tools have also recently been developed for modelling the trade-off within sustainable development between URN reduction, GHG emissions, economic and social factors (Vakili et al., 2020). So-called Multiple Criteria Decision-Making algorithms are utilised, based on Monte Carlo simulations. Model inputs include assumptions about the speed, fuel consumption of noise source level of marine traffic for a specific case study, with the algorithm allowing comparison of alternative scenarios. The study forms part of a wider policy framework proposed by the same authors (Vakili et al., 2020a; 2020b), who make the case for a multi-disciplinary approach to mitigation, taking into account socio-economic impacts of URN, and emphasising the need for economic incentives alongside technical and operational measures. Merchant (2019) also proposed policy approaches to ship URN abatement. Emphasis is placed on the need for a combination of “command-and-control" and “incentive-based” intervention to effectively and efficiency manage the existing fleet, while in the context of new vessels, incentives could also play a role - next to mandatory noise standards - to help industry in applying innovative noise reduction technologies. The European Marine Board[6] also recommend including the environmental benefits of marine anthropogenic activities in trade-off analyses. By way of example, the transportation of wind turbine blades by ship in order to increase renewable energy capacity.

In the European context, further attention will be paid to this aspect in the EU Horizon 2020 SATURN project. Looking ahead, due to the recent publication of research on this topic, it remains unclear to what degree such noise management approaches will be adopted.

[6] The European Marine Board will release its own policy recommendations on anthropogenic underwater noise in Autumn 2021.

7. Survey results

A total of 100 people representing 17 groups of stakeholders and 70 organisations participate in the survey. 35% were from the Netherlands, 12% from Spain and the remaining percentage from other countries such as Cyprus, Estonia, Portugal, Greece, United Kingdom, Finland, Germany, Ireland, France, Sweden, Italy, Belgium and Denmark (Figure 20).

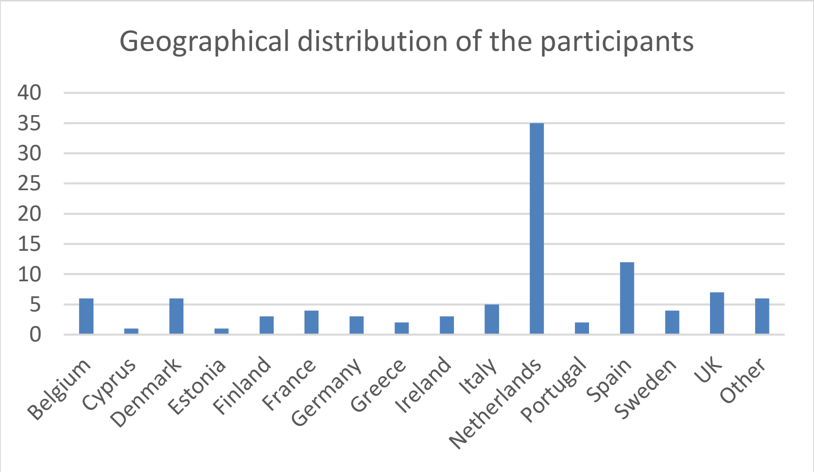


Figure 20 - Geographical distributions of the participants in the survey.

29% of respondents were from research organisations, addressing several topics such as noise and vibration, underwater acoustics, and environmental impacts (Figure 21). Around 90% considered themselves to have from moderate to expert level of experience on underwater radiated noise from shipping. When asked about the policies that they are aware of, most refer to the MSFD and some of them to IMO Guidelines.

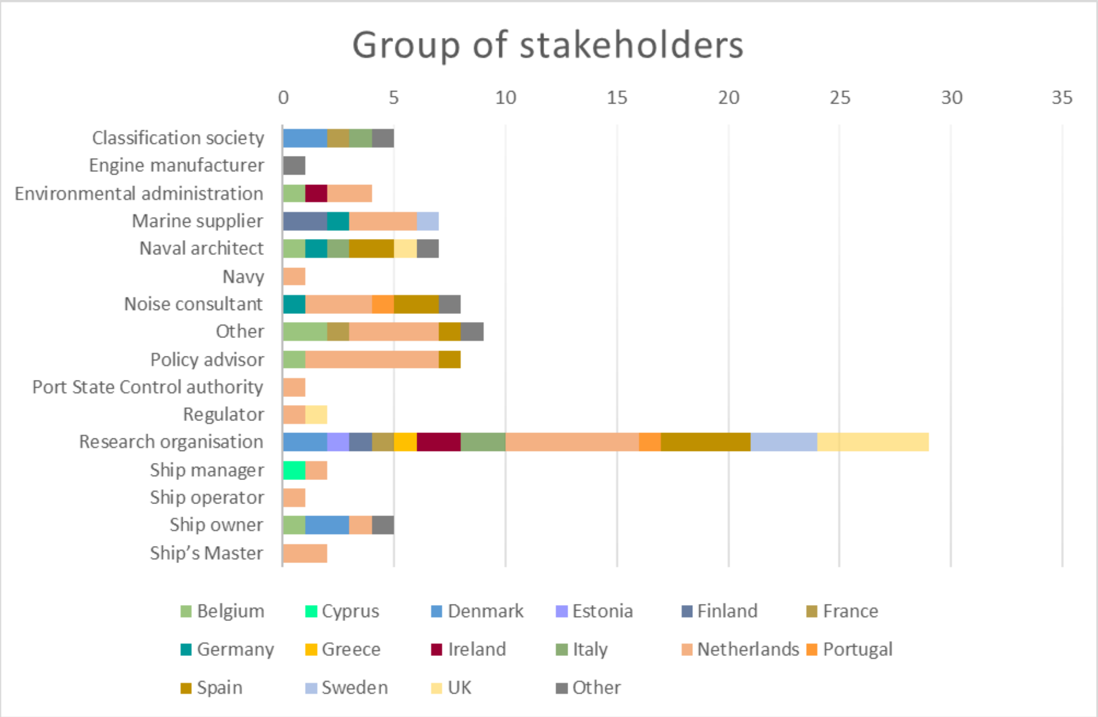


Figure 21- Group of the stakeholders represented in the study an respective geographical distribution.

Regarding potential interactions among different stakeholders, when requiring assistance on underwater noise, participants expressed they contact by order of preference: 1) a research institute, 2) a noise consultant, 3) a classification society and 4) environmental administration authority. These results suggest an important role of research institutions as the primary source of knowledge or information. Figure 22 presents the potential relationships between stakeholders, suggesting a poor interaction between industry and administration.

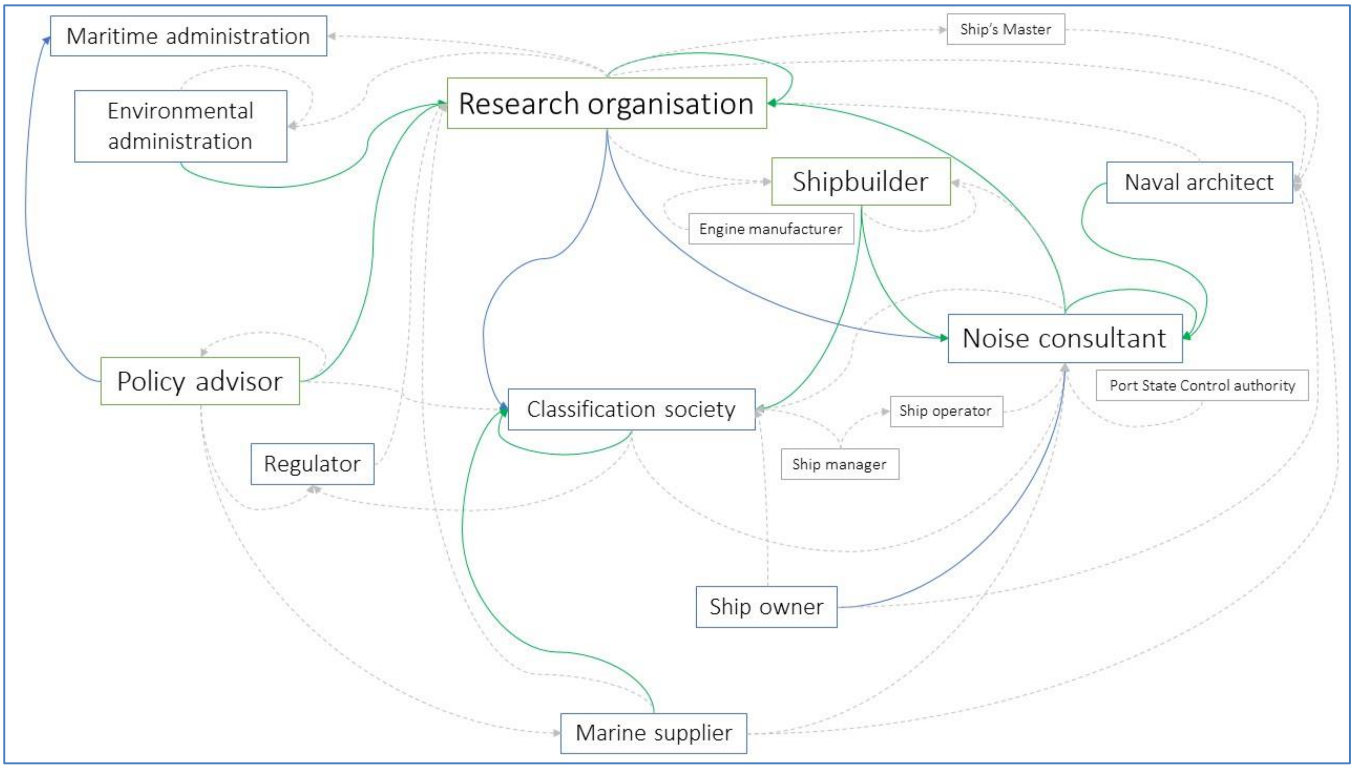


Figure 22 - Relationship between different stakeholders. A green link indicates a preferred contact and corresponds to a higher number of answers, a blue link indicates other potential interactions, a grey dashed link corresponds to results with one or two answers. Grey boxes correspond to stakeholders represented by one or two people, blue boxes correspond to stakeholders represented by three to seven people, and green box corresponds to stakeholders represented by more than eight people.

Nine out of ten people answering the question related with the use of guidelines and relevant documents on their work were researchers and eight of them selected the option of Marine Strategy Framework Directive, two consulted the IMO Guidelines and two the CMS Guidelines.

When asked about their motivation to address the topic of URN from shipping a higher number of people indicated environmental awareness of stakeholders (49 answers) and Policies (46 answers) and only few responders from the industry indicated economic reasons.

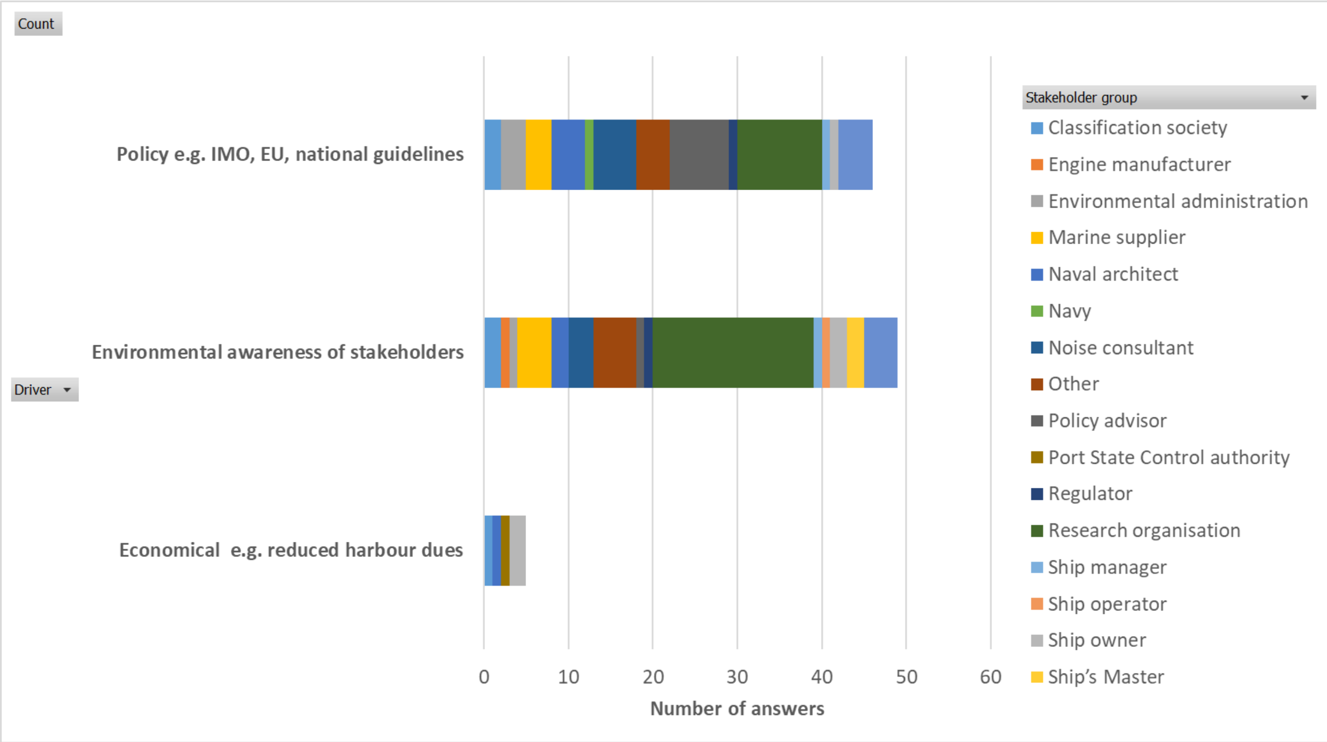


Figure 23 - Drivers to address the topic of underwater noise from shipping.

Focusing on technical questions related to the mitigation measures, the participants indicated that (Figure 24):

- Propeller design, alternative propulsion machinery, and resilient mounting of machinery were considered most effective.
- Slow steaming, traffic routing, hull and propeller cleaning, wake improvement devices, air injection systems and noise isolation materials were considered ineffective by some respondents.
- Wake improvement devices, controllable pitch propellers and air injection systems were the options for which the fewest respondents had an opinion.

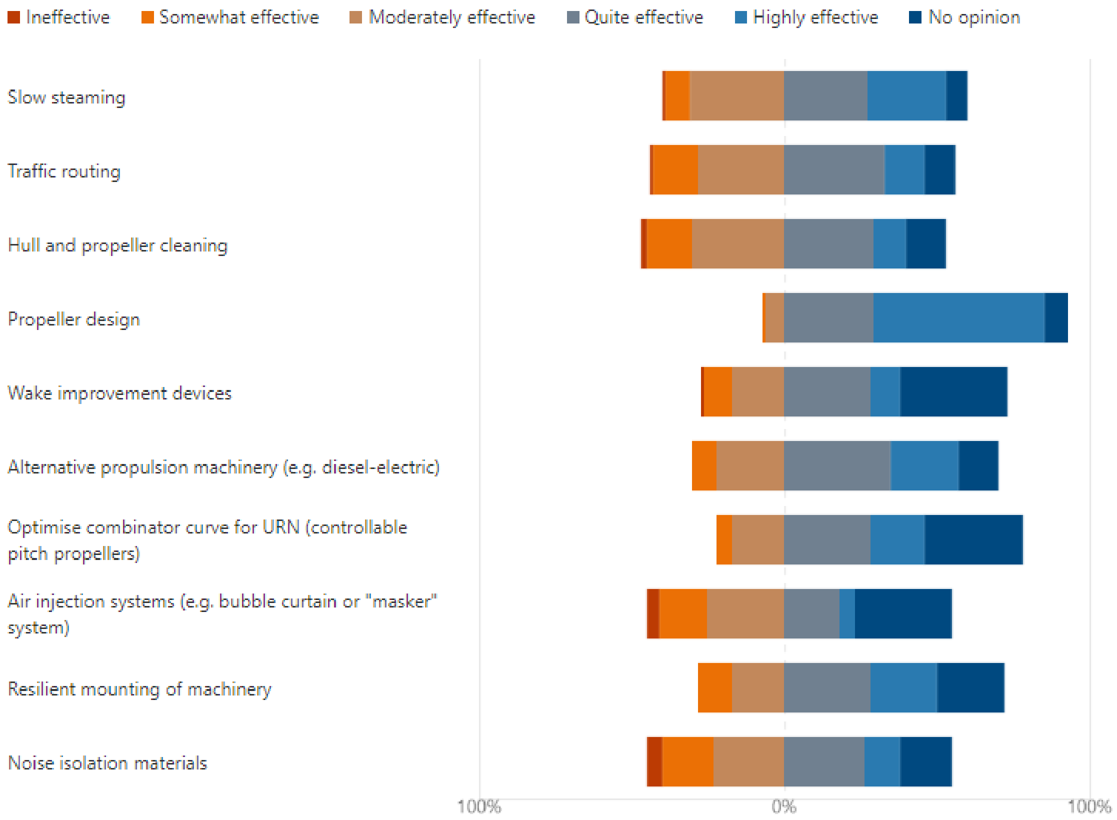


Figure 24 - Effectiveness of mitigation measures according to the participants.

When asked about the feasibility of adopting of mitigation measures (Figure 25) the results indicate that:

- Propeller design, hull and propeller cleaning, and resilient mounting of machinery are considered the most realistic measures.
- Air injection systems are the option with the highest percentage stating *“unrealistic”.*

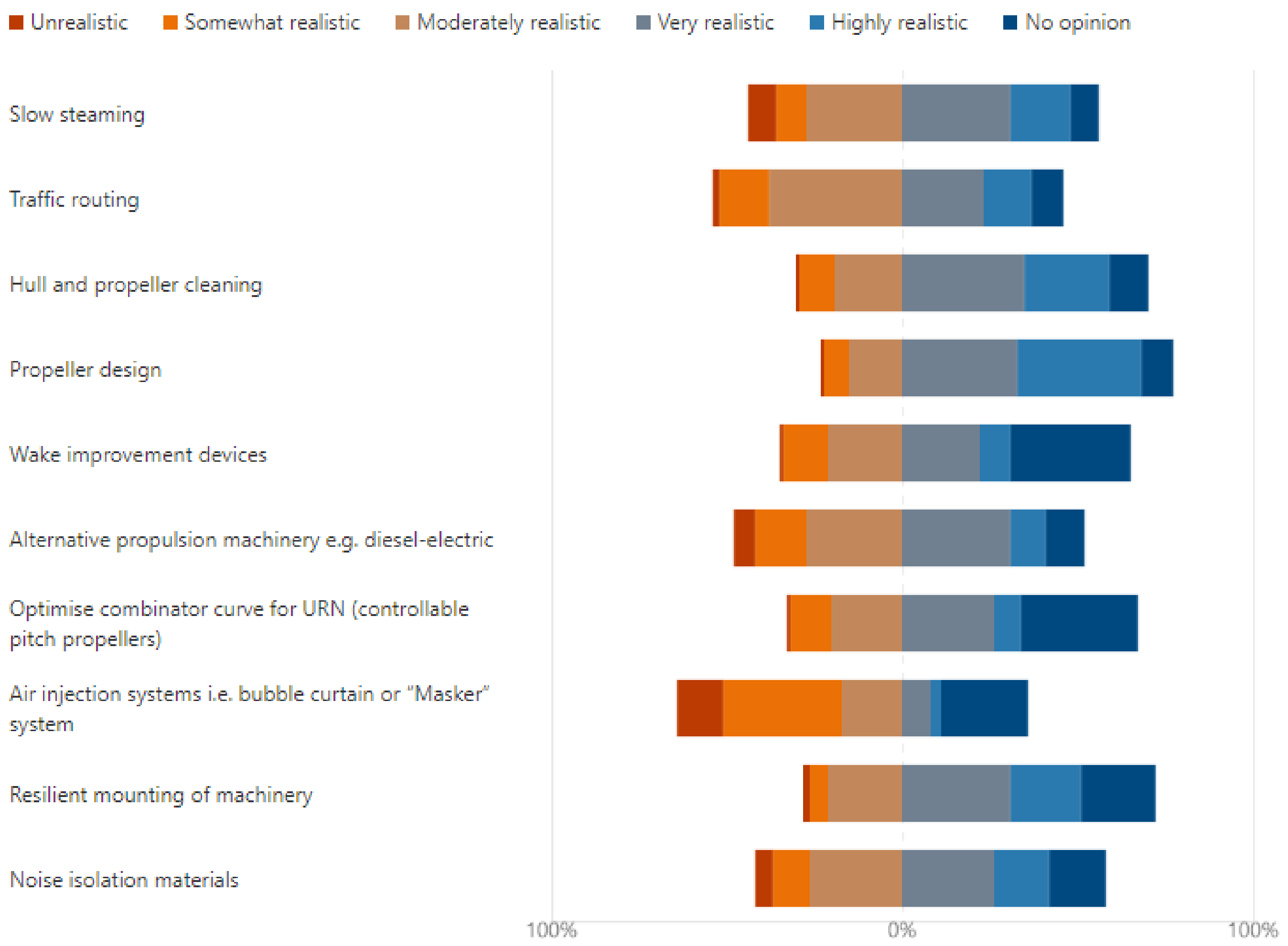


Figure 25 - Feasibility of mitigation measures according to the participants in the survey.

The results also show that Automatic Identification System data is being used by nearly 60% of respondents in work related to underwater noise, and of this number about two-thirds would like to have more data, or have enough data but think it would be beneficial to have more. 80% said that it would be beneficial if vessels of less 300GT be fitted with AIS or another tracking system. When asked about what additional information they would be interested to have access to, the most popular answers included technical details about the vessel, existing noise measurements, noise curves, environmental data (e.g. wind, sediment, water temperature) and wider AIS coverage.

Regarding data sharing, it was interesting to observe that a high percentage admit that they would benefit from using data sharing platforms, but that they are currently not using such tools to share information. The small percentage already using such platforms referred to the HELCOM underwater noise database hosted by ICES, working groups (without being specific), Wozep, JASCO portal ship sound, EMODnet, and one being developed under JONAS project.

Regarding preparedness of the European maritime sector for mandatory regulation, half of responders assume that Europe is very unprepared or unprepared, 24% neither prepared nor unprepared and only 22% considered somewhat prepared.

To conclude, when asked about lessons that we can learn from outside Europe, 35% do not know or do not have an opinion and almost 15% referred to Canada, indicating aspects such as regulation, URN targets, mechanisms of incentives, industry collaboration and dedicated research. This result was one of the drivers to select the case study presented in Section 8. Other factors that were mentioned were preparation for technological developments, cooperation, learning from results of research projects, improve data sharing, regulatory framework and mitigation measures.

8. Case study: The ECHO Program

This section presents a case study based on the ECHO Program- (Enhancing Cetacean Habitat and Observation), an initiative led by the Vancouver Fraser Port Authority in Canada. This is one of the port authority's flagship environmental programmes that is both a part of its vision for the Port of Vancouver to be the world's most sustainable port and its federal mandate to facilitate Canada's trade sustainably through the port. The programme focuses on the impact of underwater noise from shipping and appears to be one of the more advanced on this subject and hence the reason it is highlighted in this report.

How did it start?

The initiative was motivated by the Species at Risk Act, a piece of Canadian legislation to prevent wildlife species in Canada from disappearing by protecting endangered or threatened organisms and their habitats. This Act determines the need to prepare a recovery strategy for species listed as extirpated, endangered or threatened. Within this context, the Northern resident population of killer whales was designated as "threatened", and the Southern resident population as "endangered", by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2001, and therefore required the development of a recovery strategy.

In 2008, the first recovery strategy for the transient killer whale (*Orcinus orca*) in Canada was released, and underwater noise was recognised as one of the main threats to killer whales. Later, in 2011, the strategy was amended to provide additional clarification regarding critical habitat for northern and southern resident killer whales (Figure 26). At this point it was determined that the Island of Vancouver played an important role for the population of killer whales.

In 2014, the Vancouver Fraser Port Authority (VFPA), recognising that vessels calling at the Port of Vancouver transit through southern resident killer whale critical habitat, took the lead on launching the "Enhancing Cetacean Habitat and Observation (ECHO) Program", aiming "to better understand and reduce the cumulative effects of shipping on at-risk whales throughout the southern coast of British Columbia" (Vancouver Fraser Port Authority, 2016).

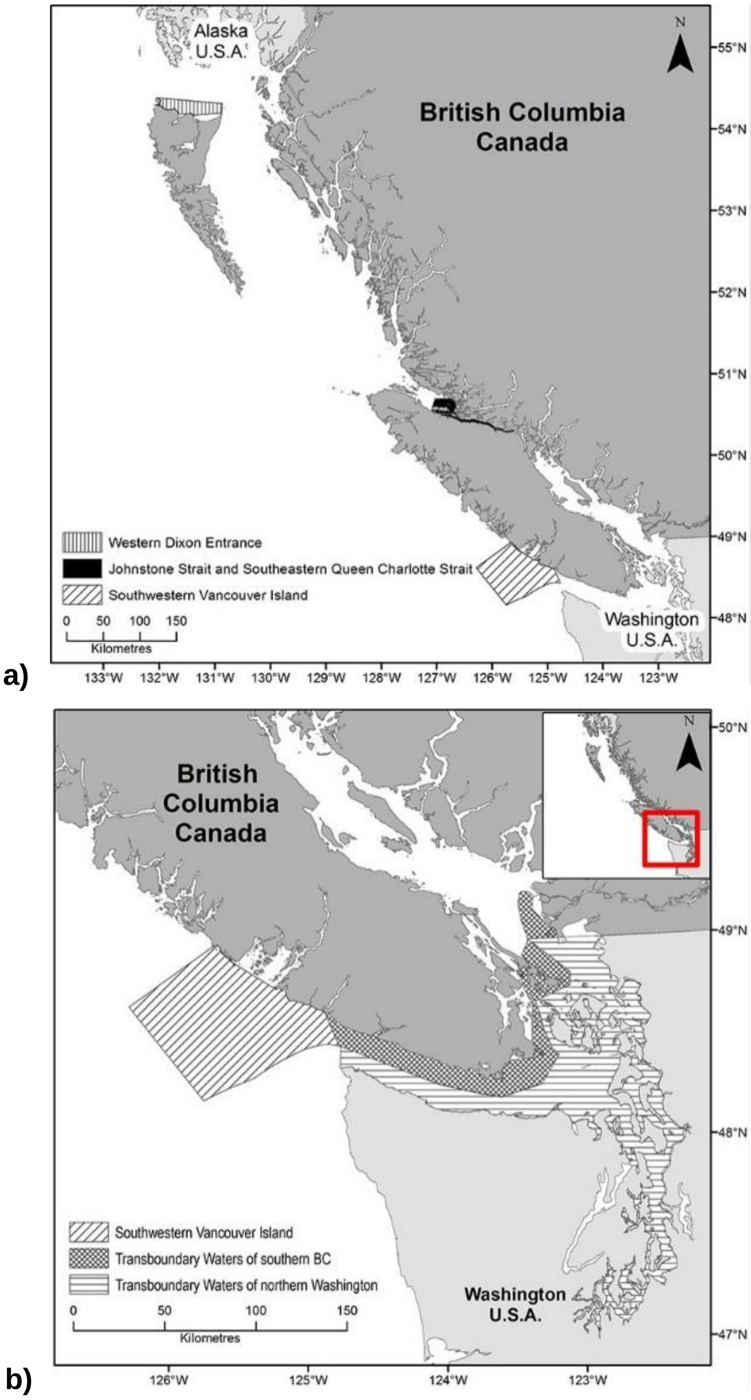


Figure 26 - Critical habitats areas identified for a) Northern Resident Killer Whales and b) Southern Resident Killer Whales[7].

[7] https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/recovery-strategies/northern-southern-killer-whales-2018.html#toc11

The objectives of the ECHO Program:
The ECHO Program aims to better understand and manage the impact of cumulative shipping activities on at-risk whales throughout the southern coast of British Columbia. This is achieved through:

- individual short-term projects.
- scientific studies.
- educational initiatives.

The combination of these initiatives contributes to fill knowledge gaps around vessel-related cumulative regional threats and informs the development of mitigation solutions and management options (Vancouver Fraser Port Authority, 2016).

How is it being implemented?
The ECHO Program is led by the VFPA, and independently managed by a programme management team who reports to the VFPA. This team receives advice and recommendations from a volunteer advisory working group and associated technical committees; the vessel operators committee, and the acoustic technical committee which help guide the direction of the program. Figure 27 illustrates the management structure of the programme.

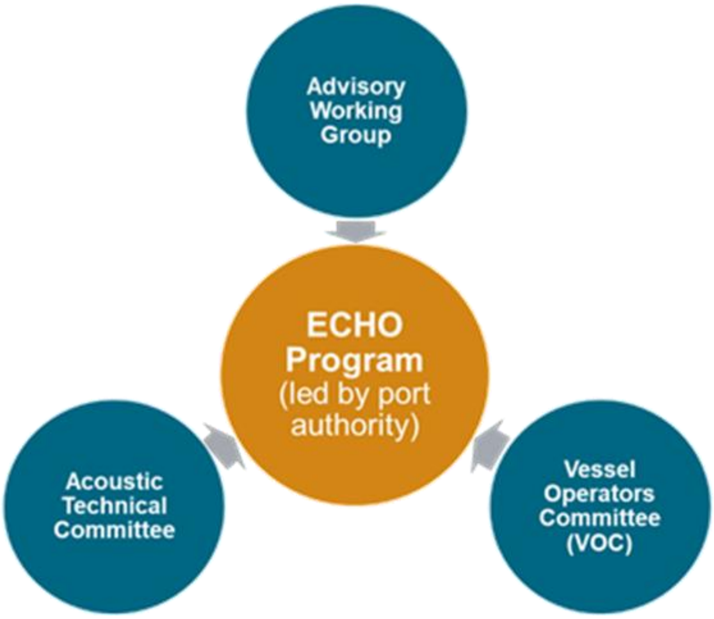


Figure 27- ECHO Program management structure.

The role of the acoustic technical committee is to provide technical and scientific advice in the development and execution of ECHO Program research, mitigation and management projects, and is composed of marine mammal biologists, acousticians, naval architects and others with specific technical knowledge around the sources and impacts of underwater noise (Vancouver Fraser Port Authority, 2016).
The vessel operators committee was established in 2016 to help provide the ECHO Program team with advice, support and guidance pertaining to potential mitigation options that may directly impact the shipping industry (Vancouver Fraser Port Authority, 2017).
In May 2019, the Government of Canada entered into a first-of-its-kind Species at Risk Act, Section 11 conservation agreement with Vancouver Fraser Port Authority, Pacific Pilotage Authority and five marine transportation industry partners to support the recovery of the southern resident killer whales. The agreement formalizes the role of the ECHO Program and the participation of the marine industry and government to continue working collaboratively over a five-year term, with a focus on reducing acoustic and physical disturbance of large commercial ships operating in southern resident killer whale critical habitat.
The conservation agreement management committee was formed by the nine signatory parties of the *Species at Risk Act, Section 11 Conservation Agreement to Support the Recovery of the Southern Resident Killer Whale*. The purpose of the committee is to oversee the implementation and effectiveness of the conservation agreement, and to provide a collaborative forum to discuss and resolve issues regarding the interpretation and implementation of the agreement, as needed.

Appendix D summarises the organisations that are currently represented in the working group and technical committees. ECHO Program meetings with the different working group and technical committees are facilitated by an independent organisation with expertise in stakeholder engagement (Vancouver Fraser Port Authority, 2021).

In 2014, the ECHO Program received seed funding from the VFPA and additional support from government and industry partners. Over the years, other stakeholders have also committed direct financial support or in-kind contributions of equipment, resources, and staffing at either the programme level or for specific projects. The programme has received direct financial support or in-kind contributions from the following organisations:

- Vancouver Fraser Port Authority (Industry)
- Fisheries and Oceans Canada (Environment)
- Fraser River Pile and Dredge (Industry)
- JASCO Applied Sciences (Research organisation)
- Oceans Networks Canada (Research organisation)
- Ocean Wise Conservation Association (Environment)
- Pacheedaht First Nation (Local communities)
- Trans Mountain Corporation (Contractor)
- Transport Canada (Government)
- Tsleil-Waututh Nation (Local communities)
- University of Victoria (Research organisation)

2020 marked the completion of the first year of a five-year funding agreement with Transport Canada (TC), who through the Marine Research and Development Innovation Centre, support the ECHO Program projects and initiatives to better understand and manage threats posed by vessel underwater noise. As part of the agreement, TC receives quarterly updates and reports on the relevant projects and initiatives conducted through the ECHO Program.

At the beginning of the programme, uncertainty about the impacts of shipping on killer whales was high. The implementation of short-term projects and scientific studies allowed the step-by-step reduction of knowledge gaps, important to develop mitigation measures and management options. The first step was to understand the baseline conditions regarding the presence of the animals, the baseline underwater noise levels and the contribution of different vessels to the soundscape. The assessment was based on the installation of hydrophones in representative regions, close to the main shipping lanes, as well as in a killer whale foraging area (Joy et al., 2019). To complement this work, desk-based studies, including literature review and modelling exercises were carried out. The combination of results allowed the Program Management Team to propose experimental trials for vessel slowdown and rerouting from critical areas. The results of initial studies informed the adaption of subsequent trials. For example, regarding the period of application and definition of speed reductions per vessel type.

The slow down trial

In 2017, the ECHO Program management team initiated the first voluntary slowdown trial for vessels approaching the harbour. The main objective was to study the relationship between slower vessel speed and vessel noise, and the resultant effect on killer whales. The voluntary trial was planned and coordinated by the ECHO Program with input and assistance from the ECHO Program advisory working group and vessel operators committee. Results from the 2017 slowdown trial demonstrated that slowing ship speed can be an effective way of reducing the underwater noise generated by ships. The approach was refined in 2018 by implementing dynamic start and end dates for the slowdown and identifying optimum speeds for different vessel types in order to maximise vessel participation. The level of participation has been increasing over the years, starting with 61% in 2017, rising to 91% in 2020, demonstrating the commitment of the shipping industry in addressing the issue of URN.

Although ambient noise results are still being analysed for 2020, preliminary analysis showed a ~3 decibel (dB) reduction in sound pressure (or a 50% reduction in sound intensity) resulting from slowdown initiatives (Vancouver Fraser Port Authority, 2021). This preliminary data is in agreement with the results of modelled scenarios (Williams et al., 2019). In addition, the number of vessels joining the initiative has increased from 61% in 2017 to 91% in 2020. Even without a target for noise reduction, the results are promising, both in terms of mitigation and engagement.

Incentives for the shipping industry

Since 2017 underwater noise has been included as a criterion in the VFPA's incentive programme – the EcoAction Program[8]. Ships that meet the criteria on vessel and engine technologies to reduce underwater noise, or that hold recognised Quiet Class notations, qualify for harbour dues discounts. Prior to this, a desk study was carried out by a consultancy company with experience on underwater noise and its effects on marine mammals, to identify vessel quieting options. Based on this study's findings, the port authority added new incentive criteria to include harbour dues discounts for quieter ships. These are summarised in Table 7. Specific to the underwater noise criteria, in 2017, 33 vessel calls achieved bronze-level discount, rising to 44 in 2018, 35 in 2019 and 32 in 2020. Also in 2019, the Port of Vancouver welcomed the first vessel to receive a gold level discount for a Quiet Class notation. This indicates that the incentive programme has been somewhat effective, although the lack of gold- and silver-level discounts – which are specifically related to URN – suggests that the bronze-level technologies may also have been taken with the aim of reducing GHG emissions.

Table 7 – Summary of EcoAction Program URN incentive levels.

Level	Discount (%)	Criteria	Examples
Gold	47	Quiet Class notation	ABS, BV, DNVGL Silent Class, LR, RINA
Silver	35	Voluntary certification	Green marine
Bronze	23	Cavitation-reducing technologies	Pre-swirl stator, Wake equalising duct, Propeller boss cap fins, Twisted rudder

The keys to success

Based on the results being achieved in this Program and the increasing on voluntary participation it can be considered a successful project. Based on the interview with Transport Canada and ECHO Program it was possible to identify four main factors contributing to that:

- **Collaborative approach**

One successful aspect of this initiative is that it is based on a collaborative approach. Before setting the parameters and proposing the voluntary measures there was an exhaustive work to involve different stakeholders, including scientists, maritime industries, conservation and environmental groups, First Nations individuals and governmental agencies. The initiatives include workshops, dedicated meetings and the development of educational materials.

- **Science-based decisions and adaptive management**

The first step was understanding the baseline scenario: what are the underwater noise levels in different sites, how the different vessels contribute to the underwater soundscape and how they sound like. Having this, the first trials were proposed to be adopted voluntarily by the industry. Based on the assessments carried out it was possible to identify what work well what did not, and based on that adapt the solutions, continue with the program or abandon some ideas. The possibility to show the results based on scientific information was the key for informed decisions.

- **Educational materials**

An important part of the ECHO program is related to the education of relevant stakeholders and preparation of dedicated materials for this purpose. Education materials take the form of infographics explaining the impacts of underwater noise on killer whales and how the mariners can make a difference for the whales, as well as guidelines about the different species inhabiting the area, how the mariners can identify them and the procedures they should adopt. To raise awareness about the materials, dedicated sessions were organised to present the materials, which were then made available on the programme website. It was evident to the program managers that the more the people were informed about the issues, the greater their engagement and the higher the impact of the proposed actions.

[8] The EcoAction Program is a reward programme for those that follow responsible environmental management practices. More information about the programme can be found here.

- **Funding contributions**

The commitment of both industry and government stakeholders provided the right support for the development of a long-term programme. Potential impacts on marine mammals are influenced by many different factors requiring a robust and standardised monitoring programme to distinguish between natural variability and noise resulting from human activity. The possibility to continue improving monitoring activities allows to better understand the natural environment and assess potential changes that might result from shipping activity.
Besides all the scientific evidence on the application of mitigation measures deriving from the programme, the work also has a strong impact on the development of policies and government commitment.
ECHO Program have been providing relevant information about the impact of shipping on the population of resident killer whales. Transport Canada, responsible for transportation policies and programmes, have been engaged in the programme since the beginning of the process, recognising the importance of scientific-based information to support decisions on agreements and implementation of measures. In 2019, TC started the Quiet Vessel Initiative, a 5-year programme aiming to evaluate the most promising technologies, vessel designs, retrofits and operational practices to make vessels quieter. The goals of the initiative were defined using both the experiences from the ECHO Program and findings of the workshop “Quieting Ships to Protect the Marine Environment” held at IMO in January 2019, and organised by TC (IMO, 2019). In addition, the results from the ECHO Program have supported the proposal from Canada, Australia and the United States to undertake a review of the 2014 IMO Guidelines, which was recently accepted at MEPC 76.

Summary
The ECHO Program is the largest coordinated effort on ship noise abatement to have been performed to date and has also spurred broader national vessel quietening activities in Canada. The success of the programme results from a combination of a clearly defined problem – environmental impact of ship noise on killer whales – together with a step-by-step approach to knowledge and mitigation development, and wide-ranging stakeholder engagement to be able to effectively address the various scientific and socio-economic aspects. A well-defined program management structure helps in achieving this. In terms of URN mitigation, both technical (through incentives) and operational (vessel slowdown and rerouting) have been implemented, while management tools have also been developed to aid in the decision-making process. Despite an absence of biology-based noise reduction targets (globally), such tools are essential for effective marine spatial planning, and should also be further developed in the European context

9. Concluding remarks

The *SOUNDS* - "Status Of UNDerwater noise from Shipping" - project began by summarising the current knowledge and opinions on the subject of continuous underwater radiated noise from ships, in order to provide recommendations for possible future strategies on how to address the subject effectively. The study consisted of a literature review divided into four main areas: Noise Sources, Environmental Impacts, Policy and Mitigation. Recognising the important role of a wide range of stakeholders, a questionnaire was distributed and dedicated interviews were held, helping to gauge opinion and readiness on the various aspects raised during the study.

The following main conclusions can be drawn from the work performed:

- There is a high level of engagement with the subject of URN from shipping, both within the EU and globally, particularly in North America. This is evidenced, for example, by several noise monitoring programmes, and the large number of academic publications in the last few years. However, the issue is not (yet) a priority for industry, with a lack of drivers to motivate action (based on the reduced number of industry representatives in regional working groups).
- In June 2021, Canada, Australia and the United States had a proposal to review the MEPC.1/Circ.833 guidelines, representing an important step forward in the global effort to reduce ship URN. This work is expected to commence towards the end of 2021 and conclude in 2023. From 2022 on, URN will also be included in discussions on GHG emissions at IMO.
- The subject of URN impact on the marine environment is being addressed through collaboration between many stakeholders, both at an EU research level, and industry level, such as in the recent webinars organised by the Belgian government and Transport Canada.
- Some of the knowledge and tools developed during recent EU projects are being applied in continuing work, although several gaps still exist, such as uncertainties in the estimation of ship source levels from measurements and environmental impact. Further crucial work in these areas is expected to be completed by around 2024.
- While the vast majority of studies into ship URN concern merchant vessels, there is evidence that recreational craft (which generate noise at higher frequencies) can dominate certain soundscapes, and therefore be the main cause of potential environmental impact.
- Modelling is a key activity which can support the development and implementation of mitigation measures. At European level, an open, advanced and integrated modelling programme would provide an added value to all stakeholders.
- Standardisation on methods and terminology, both for measurement and modelling, will support multi-disciplinary work into noise impact and mitigation. Work in this area is ongoing, for example, by ISO.
- Although studies evidence the impact of underwater noise, few of them establish a direct relationship between underwater noise and shipping. Received and source levels, as well as the frequency range, are not always stated and there is no consistent reporting, making it difficult to assess levels of impact or identify critical frequencies.
- Behavioural responses (including acoustic) occur in all groups of species but are frequently related to cetacean species. Regarding fish, physiological responses are common. However, this might be related to the ease in implementing the studies (e.g. it is easier to assess behavioural changes in cetacean species than in fish, and the opposite for physiological impacts, that are easier to assess in fish than cetaceans).
- Few studies report the impact of noise from shipping on river species. Some recently approved EU projects will address short-term and cumulative long-term impacts of noise from shipping and boats on three representative groups: mammals, invertebrates and fish.
- There are large number of species inhabiting European Seas that are sensitive to underwater sound, with four that are considered to be under threat of extinction.
- Regarding cumulative impacts from shipping, it is important that this is aligned also with other sources of continuous underwater noise (e.g. offshore renewables energy systems which will see an exponential growth in the coming years).
- The absence of environmental thresholds and proper understanding about the mechanisms of impact are a limiting factor on the establishment of mandatory regulation. Yet according to contacts from industry this is a "must" for effective noise mitigation while maintaining a "level playing field", in terms of the competitiveness of the European shipbuilding and shipping industries.
- Selecting suitable mitigation measures remains a challenging task. This is due to the fact that there are many options for reducing URN, and assessments need to be made on a case-by-case basis, potentially taking

additional environmental and economic factors into account. This not only requires expert knowledge and tools, but access to a wide range of data from multiple sources.

- A lack of access to measurement data and model benchmark results, and a central repository or database, hampers the efficiency of activities focussed on (for example) sound mapping and marine spatial planning.

10. Recommendations

The ultimate goal of effective mitigation of URN from shipping requires a future strategy addressing the issue at multiple levels and involving multiple stakeholders. The recommendations resulting from this report were derived from both the findings of the literature review and stakeholder opinions, as well as the example case study. They are divided into the four main areas covered by the report (i.e. sources, impacts, policy and mitigation actions), as well as one additional areas, namely data management.

Noise sources:

- Develop a standardised method for performing and evaluating ship noise measurements, focusing on uncertainty quantification and its reduction, and measurements in shallow water. Synthesis of existing and ongoing work into unified procedures, which will help to facilitate comparison between vessels and measurement locations, as well as quantify the effects of mitigation measures more accurately.
- Perform further research into the uncertainties of propagation modelling, particularly in shallow water. This could include additional benchmark cases, which have to be made open source to the whole URN research community.
- Develop an EU-wide modelling programme, combining advanced ship noise source level models with propagation models to produce sounds maps for different vessels in order to understand the pressure of different activities and how they can be managed. In addition, develop the capability to model and evaluate different scenarios, over different time periods, technical and operational measures, and policy initiatives.
- Consider the expansion of AIS data and its availability, or its linking with other ship databases, to better facilitate URN measurement and prediction through easier access to relevant ship particulars.
- Perform additional studies focused on smaller (non-AIS equipped) vessels, in order to better characterise their contribution to the total soundscape.
- Support the development of real-time monitoring system for underwater noise at the source and consider the addition of this information in association of reporting systems or AIS data.

Environmental impacts:

- Promote long-term monitoring programmes to increase confidence regarding datasets on priority species (e.g. information about hearing thresholds, vocalisations and habitat use.
- Promote a consistent reporting procedure and raising awareness near the research community by creating a common language about the topic (e.g. adopt a common classification for the different type of vessels, units and information to be reported).
- Support the development of research programmes that allow the development of validate and calibrated sounds maps based on environmental thresholds.
- Promote the use of the tools developed by regulators and national administrations.

Policy:

- Increase confidence regarding adoption of mandatory regulation transferring the lessons learned regarding the adoption of mandatory regulation applied to other descriptors, such as GHG emissions.
- Development of dedicated research programmes that could support adaptive management and industry engagement.
- Initiate activities to raise awareness of URN, at different levels (local, regional and international). Understanding the concerns of different stakeholders and how they can be part of the solution. Engagement of ship owners, shipyards and marine suppliers is seen as key to the success of delivering quiet ships at affordable cost.
- Promote the participation of shipping industry stakeholders on working groups related to underwater noise and definition of thresholds.
- Work on the establishment of Underwater Noise Emissions Control Areas similar to the work done for air emissions from marine fuels.
- Promote training courses related with underwater noise from shipping dedicated to National Administrations (Maritime and Environmental Administration) and National representatives at IMO.
- Promote the Guidelines from IMO at the industry level, including dedicated sessions for stakeholder addressed in the guidelines: designers, shipbuilders, and ship operators.
- Promote the participation of industry representatives (for example ship associations) in relevant working groups (for examples OSPAR and MSFD).
- Promote ships adopting Quiet Class notations calling at European harbours.

- Expand classification society Quiet Class notations to distinguish between different ship types. This could lead to both more “achievable” limits for certain vessels, while also introducing more “ambitious” targets for others.

Mitigation:

- Support the development of a quiet ship “demonstrator”, from design to operation, bringing together a range of expertise and tools from the relevant stakeholders. Assume ambitious noise reduction targets to increase the chances of compliance with future mandatory regulation based on ongoing research into environmental impacts.
- Develop geovisualisation and noise management tools to aid decision making through evaluation and comparison of mitigation scenarios.
- Investigate large-scale application and evaluation of operational mitigation measures in European waters, taking inspiration from the findings of the ECHO Program.
- Evaluate the expected effectiveness of incentives, voluntary certification and noise labels, and investigate how they can best be applied in the European context.

Data management:

- Work towards a common repository for data and research related to underwater noise from shipping. A common repository would improve standardisation, ensure the efficient sharing and reuse of data and provide a quick overview about existing information and missing data. A federation of existing and new platforms could be realised, potentially with centrally-located metadata for ease of reference. Review the needs of multiple stakeholders with the aim of avoiding overlapping functionality where possible.

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References

Abrahamsen, K. (2012). The ship as an underwater noise source. *Proceedings of Meetings on Acoustics*, 17, 070058. https://doi.org/10.1121/1.4772953

ABS. (2018). *Guide for Classification Notation: Underwater Noise*. *July*.

Ainslie, M. A., Hannay, D. E., Macgillivray, A. O., & Lucky, K. (2020). Proposed alignment of measurement and analysis procedures for quiet ship certifications. In *Technical Memorandum 02024*.

Anderson, P. A., Berzins, I. K., Fogarty, F., Hamlin, H. J., & Guillette, L. J. (2011). Sound, stress, and seahorses: The consequences of a noisy environment to animal health. *Aquaculture*, *311*(1), 129–138. https://doi.org/https://doi.org/10.1016/j.aquaculture.2010.11.013

André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., Van Der Schaar, M., López-Bejar, M., Morell, M., Zaugg, S., & Houégnigan, L. (2011). Low-frequency sounds induce acoustic trauma in cephalopods. *Frontiers in Ecology and the Environment*, *9*(9), 489–493. https://doi.org/10.1890/100124

ANSI/ASA. (2009). *Quantities and procedures for description and measurement of underwater sound from ships, Part 1: General requirements.* (S12.64-2009/Part 1).

Arjona Aroca, J., Giménez Maldonado, J. A., Ferrús Clari, G., Alonso i García, N., Calabria, L., & Lara, J. (2020). Enabling a green just-in-time navigation through stakeholder collaboration. *European Transport Research Review*, *12(1)*. https://doi.org/10.1186/s12544-020-00417-7

Arranz, P., DeRuiter, S. L., Stimpert, A. K., Neves, S., Friedlaender, A. S., Goldbogen, J. A., Visser, F., Calambokidis, J., Southall, B. L., & Tyack, P. L. (2016). Discrimination of fast click-series produced by tagged Risso's dolphins (Grampus griseus) for echolocation or communication. *Journal of Experimental Biology*, *219*(18), 2898–2907. https://doi.org/10.1242/jeb.144295

Atlar, M., Fitzsimmons, P., Zoet, P., Troll, M., Stark, C., Sezen, S., Shi, W., Aktas, B., Sasaki, N., Turkmen, S., & Taylor, D. (2021). Underwater noise measurements with a ship retrofitted with PressurePores™ noise mitigation technology and using HyDrone™ system. *Proceedings of 11th International Symposium on Cavitation*.

Au, W. W. L. (2018). Echolocation. In *Encyclopedia of Marine Mammals* (pp. 289–299). Elsevier. https://doi.org/10.1016/b978-0-12-804327-1.00113-8

Audoly, C., Gaggero, T., Baudin, E., Folegot, T., Rizzuto, E., Salinas Mullor, R., Andre, M., Rousset, C., & Kellett, P. (2017). Mitigation of underwater radiated noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO project. *IEEE Journal of Oceanic Engineering*, *42*(2), 373–387. https://doi.org/10.1109/JOE.2017.2673938

Audoly, C., & Meyer, V. (2017). Measurement of radiated noise from surface ships – Influence of the sea surface reflection coefficient on the Lloyd's mirror effect. *Acoustics*.

Audoly, C., Rousset, C., & Leissing, T. (2014). AQUO Project - Modelling of ships as noise source for use in an underwater noise footprint assessment tool. *Proceedings of Inter-Noise 2014*.

Bagočius, D., & Narščius, A. (2018). Simplistic underwater ambient noise modelling for shallow coastal areas: Lithuanian area of the Baltic Sea. *Ocean Engineering*, *164*(July), 521–528. https://doi.org/10.1016/j.oceaneng.2018.06.055

Baudin, E., & Mumm, H. (2015). Guidelines for regulation on UW noise from commericial shipping (projects AQUO-SONIC). In *SONIC deliverable 5.4*.

Binnerts, B., de Jong, C., Karasalo, I., Ostberg, M., Folegot, T., Clorennec, D., Ainslie, M. A., Warner, G., & Wang, L. (2019). Model benchmarking results for ship noise in shallow water. *Proceedings of 5th Underwater Acoustics Conference and Exhibitions*.

Blomqvist, C., & Amundin, M. (2004). High-Frequency Burst-Pulse Sounds in Agonistic/Aggressive Interactions in Bottlenose Dolphins, Tursiops truncatus. *Echolocation in Bats and Dolphins*, *1983*.

Bosschers, J. (2018). *Propeller tip-vortex cavitation and its broadband noise*. University of Twente.

Bosschers, J., Boucheron, R., Pang, Y., Park, C., Pearce, B., Sato, K., Sipilä, T., Testa, C., & Viviani, M. (2021). Specialist committee on hydrodynamic noise. In *Final Report and Recommendations to the 29th ITTC*.

Breeding, J. E., Pflug, L. A., Bradley, M. H., Walrod, M. H., & McBride, W. (1996). Research Ambient Noise Directionality (RANDI) 3.1 - Physics description. In *NRL/FR/7176-95-9628*.

Breithaupt, T. (2002). The Crustacean Nervous System. *The Crustacean Nervous System*, *January 2001*. https://doi.org/10.1007/978-3-662-04843-6

Bretschneider, H., Bosschers, J., Choi, G. H., Ciappi, E., Farabee, T., Kawakita, C., & Tang, D. (2014). Specialist committee on hydrodynamic noise. In *Final report and recommendations to the 27th ITTC*.

Brooker, A., & Humphrey, V. (2015). Noise model for radiated noise/source level. In *SONIC deliverable 2.3*.

Brooker, A., & Humphrey, V. (2016). Measurement of radiated underwater noise from a small research vessel in shallow water. *Ocean Engineering*, *120*, 182–189. https://doi.org/10.1016/j.oceaneng.2015.09.048

Bureau Veritas. (2017). *Underwater radiated noise, Rule Note NR 614 DT R00 E*.

Caldwell, M. C., Caldwell, D. K., & Miller, J. F. (1973). Statistical evidence for individual signature whistles in the spotted dolphin, *Stenella plagiodon*. *Cetology*, *16*.

Carlton, J. (2007). *Marine propellers and propulsion* (2nd ed.). Butterworth-Heinemann.

CCS. (2018). *Guidelines for underwater radiated noise of ships*. China Classification Society.

Charifi, M., Miserazzi, A., Sow, M., Perrigault, M., Gonzalez, P., Ciret, P., Benomar, S., & Massabuau, J. C. (2018). Noise pollution limits metal bioaccumulation and growth rate in a filter feeder, the Pacific oyster Magallana gigas. *PLoS ONE*, *13*(4). https://doi.org/10.1371/journal.pone.0194174

Chion, C., Lagrois, D., & Dupras, J. (2019). A meta-analysis to understand the variability in reported source levels of noise radiated by ships from opportunistic studies. *Frontiers in Marine Science*, *6*(November), 1–14. https://doi.org/10.3389/fmars.2019.00714

Chmelnitsky, E., & Gilbert, M. (2016). Vessel quieting design, technology, and maintenance options for potential inclusion in EcoAction program Enhancing Cetacean Habitat and Observation Program. In *Report 302-045.03*.

Cho, Y., Jeon, K. H., Lee, S. B., Park, H., & Lee, I. (2021). Evaluation of in-service speed performance improvement by means of FDR-AF (frictional drag reducing anti-fouling) marine coating based on ISO19030 standard. *Scientific Reports*, *11*(1), 1–11. https://doi.org/10.1038/s41598-020-80107-5

Clausen, K. T., Wahlberg, M., Beedholm, K., Deruiter, S., & Madsen, P. T. (2011). Click communication in harbour porpoises, Phocoena phocoena. *Bioacoustics*, *20*(1), 1–28. https://doi.org/10.1080/09524622.2011.9753630

Colin, M. E. G. D., Ainslie, M. A., Binnerts, B., De Jong, C. A. F., Karasalo, I., Ostberg, M., Sertlek, H. O., Folegot, T., & Clorennec, D. (2015). Definition and results of test cases for shipping sound maps. *MTS/IEEE OCEANS 2015 - Genova: Discovering Sustainable Ocean Energy for a New World*. https://doi.org/10.1109/OCEANS-Genova.2015.7271461

Cominelli, S., Leahy, M., Devillers, R., & Hall, B. G. (2019). Geovisualization tools to inform the management of vessel noise in support of species' conservation. *Ocean and Coastal Management*, *169*. https://doi.org/10.1016/j.ocecoaman.2018.11.009

NRC (2003). *Ocean Noise and Marine Mammals*. The National Academies Press. https://doi.org/10.17226/10564

de Jong, C., Harmsen, J., Bekdemir, C., & Hulskotte, J. (2020). Reduction of emissions and underwater radiated noise for the Belgian shipping sector. In *TNO 2020 R11855*.

de Jong, K., Forland, T. N., Amorim, M. C. P., Rieucau, G., Slabbekoorn, H., & Sivle, L. D. (2020). Predicting the effects of anthropogenic noise on fish reproduction. In *Reviews in Fish Biology and Fisheries* (Vol. 30, Issue 2, pp. 245–268). Springer. https://doi.org/10.1007/s11160-020-09598-9

De Soto, N. A., Delorme, N., Atkins, J., Howard, S., Williams, J., & Johnson, M. (2013). Anthropogenic noise causes body malformations and delays development in marine larvae. *Scientific Reports*, *3*. https://doi.org/10.1038/srep02831

Dekeling, R. P. A., Tasker, M. L., Van der Graaf, A. J., Ainslie, M. A., Andersson, M. H., André, M., Borsani, J. F., Brensing, K., Castellote, M., Cronin, D., Dalen, J., Folegot, T., Leaper, R., Pajala, J., Redman, P., Robinson, S. P., Sigray, P., Sutton, G., Thomsen, F., … Young, J. V. (2014). Monitoring guidance for underwater noise in European seas Part II: Monitoring guidance specifications. In *JRC Scientific and Policy Report EUR 26555 EN*. https://doi.org/10.2788/27158

DNV. (2021). DNV awards first merchant vessel SILENT-E notation. https://www.dnv.com/news/dnv-awards-first-merchant-vessel-silent-e-notation-200156

DNV GL. (2017). Silence is golden. In Cruise update. https://www.portvancouver.com/wp-content/uploads/2017/03/Cruise-Update-Issue-2017-Silence-is-golden.pdf

DNV GL. (2018). *Rules for classification, Part 6 Additional class notations, Chapter 7 Environmental protection and pollution control*.

Domenici, P., & Blake, R. W. (1997). The kinematics and performance of fish fast-start swimming. *Journal of Experimental Biology*, *200*(8), 1165–1178.

Duarte, C. . M., Chapuis, L., Collin, S. P., Costa, D. P., Eguiluz, V., Erbe, C., Halpern, B. S., Havlik, M. N., Gordon, T. A. C., Merchant, N. D., Meekan, M., Miksis-Olds, J. L., Parsons, M., Predragovic, M., Radford, A. N., Radford, C. A., Simpson, S. D., Slabbekoorn, H., Staaterman, E., … Juanes, F. (2021). The soundscape of the anthropocene ocean. *Science*, *Accepted m*(aba4658). https://doi.org/10.1126/science.aba4658

Erbe, C. (2013). Underwater noise of small personal watercraft (jet skis). *The Journal of the Acoustical Society of America*, *133(4)*, EL326-30. https://doi.org/10.1121/1.4795220

Erbe, C., Marley, S. A., Schoeman, R. P., Smith, J. N., Trigg, L. E., & Embling, C. B. (2019). The Effects of Ship Noise on Marine Mammals—A Review. *Frontiers in Marine Science*, *6*(October). https://doi.org/10.3389/fmars.2019.00606

Etter, P. C. (2012). Advanced applications for underwater acoustic modeling. *Advances in Acoustics and Vibration*, *2012*. https://doi.org/10.1155/2012/214839

EU. (2017). Commission decision (EU) 2017/848 of 17 Mat 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU. *Official Journal of the European Union*, *125*, 43–74. https://doi.org/10.1088/1751-8113/44/8/085201

Farcas, A., Powell, C. F., Brookes, K. L., & Merchant, N. D. (2020). Validated shipping noise maps of the Northeast Atlantic. *Science of the Total Environment*, *735*, 139509. https://doi.org/10.1016/j.scitotenv.2020.139509

Fay, R. R., & Popper, A. N. (2000). Evolution of hearing in vertebrates: The inner ears and processing. *Hearing Research*, *149*(1–2), 1–10. https://doi.org/10.1016/S0378-5955(00)00168-4

Fearey, J., Elwen, S. H., James, B. S., & Gridley, T. (2019). Identification of potential signature whistles from free-ranging common dolphins (Delphinus delphis) in South Africa. *Animal Cognition*, *22*(5). https://doi.org/10.1007/s10071-019-01274-1

Filiciotto, F., Vazzana, M., Celi, M., Maccarrone, V., Ceraulo, M., Buffa, G., Arizza, V., de Vincenzi, G., Grammauta, R., Mazzola, S., & Buscaino, G. (2016). Underwater noise from boats: Measurement of its influence on the behaviour and biochemistry of the common prawn (Palaemon serratus, Pennant 1777). *Journal of Experimental Marine Biology and Ecology*, *478*, 24–33. https://doi.org/10.1016/j.jembe.2016.01.014

Filiciotto, F., Vazzana, M., Celi, M., Maccarrone, V., Ceraulo, M., Buffa, G., Stefano, V. Di, Mazzola, S., & Buscaino, G. (2014). Behavioural and biochemical stress responses of Palinurus elephas after exposure to boat noise pollution in tank. *Marine Pollution Bulletin*, *84*(1–2), 104–114. https://doi.org/10.1016/j.marpolbul.2014.05.029

Foeth, E. J., & Bosschers, J. (2016). Localization and source-strength estimation of propeller cavitation noise using hull-mounted pressure transducers. *Proceedings of the 31st Symposium on Naval Hydrodynamics, Monterey, CA, USA*.

Frisk, G. V. (2012). Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. *Scientific Reports*, *2*(1), 2–5. https://doi.org/10.1038/srep00437

Gassmann, M., Kindberg, L. B., Wiggins, S. M., & Hildebrand, J. A. (2017). Underwater noise comparison of pre- and post-retrofitted MAERSK G-class container vessels. In *MPL TM-616*.

Gassmann, M., Wiggins, S. M., & Hildebrand, J. A. (2017). Deep-water measurements of container ship radiated noise signatures and directionality. *The Journal of the Acoustical Society of America*, *142*(3), 1563–1574. https://doi.org/10.1121/1.5001063

Ghoul, A., & Reichmuth, C. (2014). Hearing in the sea otter (Enhydra lutris): auditory profiles for an amphibious marine carnivore. *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology*, *200*(11). https://doi.org/10.1007/s00359-014-0943-x

Gray, L. M., & Greeley, D. S. (1980). Source level model for propeller blade rate radiation for the world's merchant fleet. *Journal of the Acoustical Society of Amerrica*, *67*(2), 516–522.

Guerra, M., Dawson, S. M., Brough, T. E., & Rayment, W. J. (2014). Effects of boats on the surface and acoustic behaviour of an endangered population of bottlenose dolphins. *Endangered Species Research*, *24*(3), 221–236. https://doi.org/10.3354/esr00598

Hammond, P. S., Lacey, C., Gilles, A., Viquerat, S., Börjesson, P., Herr, H., Macleod, K., Ridoux, V., Santos, M. B., Scheidat, M., Teilmann, J., Vingada, J., Øien, N., Gillespie, D., Leaper, R., Sveegaard, S., & Antonio Vázquez, J. (2017). *Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys Authors and Partners: Additional project personnel: Equipment development*. *May*.

Hawkins, A. D., & Popper, A. N. (2017). A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. *ICES Journal of Marine Science*, *74*(3), 635–651. https://doi.org/10.1093/icesjms/fsw205

Heiler, J., Elwen, S. H., Kriesell, H. J., & Gridley, T. (2016). Changes in bottlenose dolphin whistle parameters related to vessel presence, surface behaviour and group composition. *Animal Behaviour*, *117*, 167–177. https://doi.org/10.1016/j.anbehav.2016.04.014

Hermannsen, L., Mikkelsen, L., Tougaard, J., Beedholm, K., Johnson, M., & Madsen, P. T. (2019). Recreational vessels without Automatic Identification System (AIS) dominate anthropogenic noise contributions to a shallow water soundscape. *Scientific Reports*, *9*(1), 1–10. https://doi.org/10.1038/s41598-019-51222-9

Hildebrand, J. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series*, *395*, 5–20. https://doi.org/10.3354/meps08353

Hilliard, L. C., McHorney, D. H., Palmieri, M. R., & Pelella, G. M. (2018). *Catalog of solutions to reduce marine acoustic pollution*.

Holles, S. H., Simpson, S. D., Radford, A. N., Berten, L., & Lecchini, D. (2013). Boat noise disrupts orientation behaviour n a coral reef fish. *Marine Ecology Progress Series*, *485*, 295–300. https://doi.org/10.3354/meps10346

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K., & Veirs, S. (2009). Speaking up: Killer whales (Orcinus orca) increase their call amplitude in response to vessel noise . *The Journal of the Acoustical Society of America*, *125*(1), EL27–EL32. https://doi.org/10.1121/1.3040028

IMO. (2011). Amendments to the annex of the protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the protocol of 1978 relating thereto, *MEPC.203(62)*.

IMO. (2014). Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life*; MEPC.1/Circ.833*.

IMO. (2019). Quieting ships to protect the marine environment workshop summary report, *MEPC 74/INF.36*.

ISO. (2016). *ISO 17028-1:2016 Underwater acoustics - Quantities and procedures for description and measurement of underwater sound from ships - Part 1: Requirements for precision measurements in deep water used for comparison purposes.*

ISO. (2017). *ISO 18405:2017 Underwater acoustics - Terminology*.

ISO. (2019a). *ISO 17028-2:2019 Underwater acoustics - Quantities and procedures for description and measurement of underwater sound from ships - Part 1: Requirements for precision measurements in deep water used for comparison purposes.*

ISO. (2019b). *ISO 17028-2:2019 Underwater acoustics - Quantities and procedures for description and measurement of underwater sound from ships - Part 2: Determination of source levels from deep water measurements.*

ITTC. (2017). ITTC - Recommended procedures and guidelines. Underwater noise from ships, full-scale measurements. In *7.5-04-04-01*.

Ivanova, S. V., Kessel, S. T., Espinoza, M., McLean, M. F., O'Neill, C., Landry, J., Hussey, N. E., Williams, R., Vagle, S., & Fisk, A. T. (2020). Shipping alters the movement and behavior of Arctic cod (Boreogadus saida), a keystone fish in Arctic marine ecosystems. *Ecological Applications*, *30*(3). https://doi.org/10.1002/eap.2050

Jalkanen, J.-P., Johansson, L., Liefvendahl, M., Bensow, R., Sigray, P., Östberg, M., Karasalo, I., Andersson, M., Peltonen, H., & Pajala, J. (2018). Modeling of ships as a source of underwater noise. *Ocean Science Discussions*, 1–18. https://doi.org/10.5194/os-2018-48

Janik, V. M., & Sayigh, L. S. (2013). Communication in bottlenose dolphins: 50 years of signature whistle research. In *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology* (Vol. 199, Issue 6). https://doi.org/10.1007/s00359-013-0817-7

Jansen, E., & De Jong, C. (2017). Experimental Assessment of Underwater Acoustic Source Levels of Different Ship Types. *IEEE Journal of Oceanic Engineering*, *42*(2), 439–448. https://doi.org/10.1109/JOE.2016.2644123

Jeong, H., Lee, J. H., Kim, Y. H., & Seol, H. (2021). Estimation of the noise source level of a commercial ship using on-board pressure sensors. *Applied Sciences (Switzerland)*, *11*(3), 1–20. https://doi.org/10.3390/app11031243

Jiang, P., Lin, J., Sun, J., Yi, X., & Shan, Y. (2020). Source spectrum model for merchant ship radiated noise in the Yellow Sea of China. *Ocean Engineering*, *216*, 107607. https://doi.org/10.1016/j.oceaneng.2020.107607

Merchant, N. D. (2019). Underwater noise abatement: Economic factors and policy options. Environmental Science and Policy, 92, 116–123. https://doi.org/10.1016/j.envsci.2018.11.014

Johansson, A. T., Hallander, J., Karlsson, R., Langstrom, A., & Turesson, M. (2015). Full scale measurement of underwater radiated noise from a coastal tanker. *MTS/IEEE OCEANS 2015 - Genova: Discovering Sustainable Ocean Energy for a New World*. https://doi.org/10.1109/OCEANS-Genova.2015.7271771

Jolivet, A., Tremblay, R., Olivier, F., Gervaise, C., Sonier, R., Genard, B., & Chauvaud, L. (2016). Validation of trophic and anthropic underwater noise as settlement trigger in blue mussels. *Scientific Reports*, *6*(September). https://doi.org/10.1038/srep33829

Joy, R., Tollit, D., Wood, J., MacGillivray, A., Li, Z., Trounce, K., & Robinson, O. (2019). Potential benefits of vessel slowdowns on endangered southern resident killer whales. *Frontiers in Marine Science*, *6*, 1–20. https://doi.org/10.3389/fmars.2019.00344

Kaplan, M. B., & Solomon, S. (2016). A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. *Marine Policy*, *73*, 119–121. https://doi.org/10.1016/j.marpol.2016.07.024

Karasalo, I., Ostberg, M., Sigray, P., Jalkanen, J.-P., Johansson, L., Liefvendahl, M., & Bensow, R. (2017). Estimates of source spectra of ships from long term recordings in the Baltic Sea. *Frontiers in Marine Science*, *4*(June), 1–13. https://doi.org/10.3389/fmars.2017.00164

Kendrick, A., & Terweij, R. (2019). Ship underwater radiated noise. In *Report 368-000-01 Rev 5*.

Korean Register. (2021). Guidances for Underwater Radiated Noise. In *GC-37-E*.

Kunc, H. P., McLaughlin, K. E., & Schmidt, R. (2016). Aquatic noise pollution: Implications for individuals, populations, and ecosystems. In *Proceedings of the Royal Society B: Biological Sciences* (Vol. 283, Issue 1836). Royal Society of London. https://doi.org/10.1098/rspb.2016.0839

Larsen, G., Dupuis, J., & Gilroy, L. (2021). Results from off-board noise prediction study in ORCA-class training vessel. In *Scientific report DRDC-RDDC-2021-R003*.

Leaper, R. (2019). The role of slower vessel speeds in reducing greenhouse gas emissions, underwater noise and collision risk to whales. *Frontiers in Marine Science*, *6*, 1–8. https://doi.org/10.3389/fmars.2019.00505

Liefvendahl, M., Feymark, A., & Bensow, R. (2015). Methodology for noise source modelling and its application to Baltic Sea shipping. In *Technical report 2015:161*.

Lloyd's Register. (2018). *ShipRight Design and Construction, Additional Design Procedures, Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise*.

Lloyd, T., Foeth, E., Lafeber, F. H., & Bosschers, J. (2020). Progress in the prediction and mitigation of propeller cavitation noise and vibrations. *Proceedings of 26th HISWA*.

Luís, A. R., Couchinho, M. N., & dos Santos, M. E. (2014). Changes in the acoustic behavior of resident bottlenose dolphins near operating vessels. *Marine Mammal Science*, *30*(4), 1417–1426. https://doi.org/10.1111/mms.12125

MacGillivray, A., Ainsworth, L., Zhao, J., Frouin-Mouy, H., Dolman, J., & Bahtiarian, M. (2020). ECHO vessel noise correlations study. In *Technical report 02025*.

MacGillivray, A., & de Jong, C. (2021). A reference spectrum model for estimating source levels of marine shipping based on Automated Identification System data. *Journal of Marine Science and Engineering*, *9*(4), 369. https://doi.org/10.3390/jmse9040369

MacGillivray, A. O., Li, Z., Hannay, D. E., Trounce, K. B., & Robinson, O. M. (2019). Slowing deep-sea commercial vessels reduces underwater radiated noise. *The Journal of the Acoustical Society of America*, *146*(1), 340–351. https://doi.org/10.1121/1.5116140

Mäkiharju, S. A., Perlin, M., & Ceccio, S. L. (2012). On the energy economics of air lubrication drag reduction. *International Journal of Naval Architecture and Ocean Engineering*, *4*(4), 412–422. https://doi.org/10.2478/ijnaoe-2013-0107

Marcoux, F., Citores, A., Huc, P., & Lelong, E. (2021). Performance report 2020. In *Green Marine Europe*.

May-Collado, L. J., & Wartzok, D. (2008). A comparison of bottlenose dolphin whistles in the atlantic ocean: Factors promoting whistle variation. *Journal of Mammalogy*, *89*(5), 1229–1240. https://doi.org/10.1644/07-MAMM-A-310.1

McDonald, J. I., Wilkens, S. L., Stanley, J. A., & Jeffs, A. G. (2014). Vessel generator noise as a settlement cue for marine biofouling species. *Biofouling*, *30*(6), 741–749. https://doi.org/10.1080/08927014.2014.919630

McHorney, D. H., Pelella, G. M., Hilliard, L. C., & Palmieri, M. R. (2018). *Methods to minimize commercial vessel-generated marine acoustic pollution*.

McIntyre, D., Lee, W., Frouin-Mouy, H., Hannay, D., & Oshkai, P. (2021). Influence of propellers and operating conditions on underwater radiated noise from coastal ferry vessels. *Ocean Engineering*, 232, 109075. https://doi.org/10.1016/j.oceaneng.2021.109075

Mensinger, A. F., Putland, R. L., & Radford, C. A. (2018). The effect of motorboat sound on Australian snapper Pagrus auratus inside and outside a marine reserve. *Ecology and Evolution*, *8(13)*, 6438–6448. https://doi.org/10.1002/ece3.4002

Merchant, N. D. (2019). Underwater noise abatement: Economic factors and policy options. *Environmental Science and Policy*, *92*, 116–123. https://doi.org/10.1016/j.envsci.2018.11.014

Miglianti, L., Cipollini, F., Oneto, L., Tani, G., Gaggero, S., Coraddu, A., & Viviani, M. (2020). Predicting the cavitating marine propeller noise at design stage: A deep learning based approach. *Ocean Engineering*, *209(January)*, 107481. https://doi.org/10.1016/j.oceaneng.2020.107481

Mitson, R. B. (1995). Underwater noise of research vessels: Review and recommendation. *Cooperative Research Report*, *209*, 1–61. https://doi.org/https://doi.org/10.17895/ices.pub.5317

Moreno, A. (2014). European URN standard measurement method. In *AQUO deliverable D3.1*.

Moulton, J. M. (1957). Sound Production in the Spiny Lobster Panulirus argus (Latreille). *Biological Bulletin*, *113*(2), 286–295. https://doi.org/10.2307/1539086

Mustonen, M., Klauson, A., Andersson, M., Clorennec, D., Folegot, T., Koza, R., Pajala, J., Persson, L., Tegowski, J., Tougaard, J., Wahlberg, M., & Sigray, P. (2019). Spatial and temporal variability of ambient underwater sound in the Baltic Sea. *Scientific Reports*, *9*(1), 1–13. https://doi.org/10.1038/s41598-019-48891-x

Nedelec, S. L., Radford, A. N., Simpson, S. D., Nedelec, B., Lecchini, D., & Mills, S. C. (2014). Anthropogenic noise playback impairs embryonic development and increases mortality in a marine invertebrate. *Scientific Reports*, *4*(Figure 1), 13–16. https://doi.org/10.1038/srep05891

Nedelec, S. L., Campbell, J., Radford, A. N., Simpson, S. D. and Merchant, N. D. (2016) Particle motion: the missing link in underwater acoustic ecology. Methods in Ecology and Evolution, 7, pp. 836-842. https://doi.org/10.1111/2041-210X.12544.

NOAA (2017) *Passive acoustic data collection*. National Centers for Environmental Information, Asheville, North Carolina, USA. https://doi.org/10.25921/PF0H-SQ72.

O'Shea, T. J., & Powell, J. A. (2001). *Sirenians* (J. H. B. T.-E. of O. S. (Second E. Steele (ed.); pp. 436–446). Academic Press. https://doi.org/https://doi.org/10.1016/B978-012374473-9.00433-1

OceanCare. (2020). UNEP/CMS/COP13/Inf.9 Best Available Technology (BAT) amd Best Envrionmental Practice (BET) for three noise sources: shipping, seimic arigun surveys, and pile driving. *Convention on Migratory Species - 13th Meeting of the Conference of the Parties*, *February 2020*, 1–7.

Papadakis, P., Piperakis, G., Skarsoulis, E., Orfanakis, E., & Taroudakis, M. (2018). Pilot experiments for monitoring ambient noise in Northern Crete. *Proceedings of 11th European Congress and Exposition on Noise Control Engineering*, 2811–2816.

Peng, C., Zhao, X., Liu, S., Shi, W., Han, Y., Guo, C., Jiang, J., Wan, H., Shen, T., & Liu, G. (2016). *Effects of anthropogenic sound on digging behavior, metabolism, Ca 2+ /Mg 2+ ATPase activity, and metabolism-related gene expression of the bivalve Sinonovacula constricta OPEN*. https://doi.org/10.1038/srep24266

Peng, Z., Fan, J., & Wang, B. (2018). Analysis and modelling on radiated noise of a typical fishing boat measured in shallow water inspired by AQUO project's model. *Archives of Acoustics, 43(2)*, 263–273. https://doi.org/10.24425/122374

Pennucci, G., & Jiang, Y.-M. (2018). Extracting acoustic source information of shipping noise for dynamic ambient noise modelling. *Journal of Shipping and Ocean Engineering*, *8*(1), 10–20. https://doi.org/10.17265/2159-5879/2018.01.002

Popper, A. N. (1985). Echolocation in Whales and Dolphins. *Trends in Neurosciences*, *8*, 36–37.

https://doi.org/10.1016/0166-2236(85)90016-5

Popper, A. N. (2003). Effects of anthropogenic sounds on fishes. *Fisheries*, *28*(10), 24–31. https://doi.org/10.1080/09524622.2008.9753822

Popper, A. N., & Hawkins, A. D. (2018). The importance of particle motion to fishes and invertebrates. *The Journal of the Acoustical Society of America*, *143*(1), 470–488. https://doi.org/10.1121/1.5021594

Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., Coombs, S., Ellison, W. T., Gentry, R. L., Halvorsen, M. B., Løkkeborg, S., Rogers, P. H., Southall, B. L., Zeddies, D. G., & Tavolga, W. N. (2014). Sound Exposure Guidelines. In *Sound Exposure Guidelines for fishes and sea turtles: a technical report prepared by ANSI-Accredited Standards Committee S3/SC1 and registeres with ANSI*. https://doi.org/10.1007/978-3-319-06659-2_7

Pregitzer, P., Lau, F., Vaz, G., & Cruz, E. (2021). Underwater acoustic impact of a marine renewable energy device. *Proceedings of IX International Conference on Computational Methods in Marine Engineering*.

Quick, N. J., & Janik, V. M. (2012). Bottlenose dolphins exchange signature whistles when meeting at sea. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1738), 2539–2545. https://doi.org/10.1098/rspb.2011.2537

Quijano, J., Li, Z., & Whitt, C. (2018). M/V/ Cygnus underwater radiated noise level measurements in Conception Bay, NL: Coast Guard patrol vessel noise analysis before and after hull cleaning and propeller cleaning to investigate potential noise savings. In *Technical report 01655*.

R Stocks, J. (2012). Response of Marine Invertebrate Larvae to Natural and Anthropogenic Sound: A Pilot Study. *The Open Marine Biology Journal*, *6*(1), 57–61. https://doi.org/10.2174/1874450801206010057

Rendell, L. E., & Whitehead, H. (2003). Vocal clans in sperm whales (Physeter macrocephalus). *Proceedings of the Royal Society B: Biological Sciences*, *270*(1512), 225–231. https://doi.org/10.1098/rspb.2002.2239

Renilson, M., Leaper, R., & Boisseau, O. (2013). Hydro-acoustic noise from merchant ships – impacts and practical mitigation techniques. *Proceedings of the 3rd International Symposium on Marine Propulsors*, 201–208.

Riesch, R., Ford, J. K. B., & Thomsen, F. (2006). Stability and group specificity of stereotyped whistles in resident killer whales, Orcinus orca, off British Columbia. *Animal Behaviour*, *71*(1), 79–91. https://doi.org/https://doi.org/10.1016/j.anbehav.2005.03.026

RINA. (2017a). *Amendments to Part A and Part E of "Rules for the classification of Yachts designed for commercial use", Pt A, Ch 1, Sec 2: New additional class notation: "Dolphin Yacht."*

RINA. (2017b). *Amendments to Part A and Part E of the "Rules for the Classification of Pleasure Yachts ", Pt A, Ch 1, Sec 2: New additional class notation: "Dolphin Pleasure Yacht."*

RINA. (2017c). *Amendments to Part A and Part F of "Rules for the Classification of Ships", Pt A, Ch 1, Sec 2: New additional class notation: "Dolphin Quiet Ship" and "Dolphin Transit Ship."*

Ross, D. (1976). *Mechanics of underwater noise* (1st editio).

Samson, J. E., Mooney, T. A., Gussekloo, S. W. S., & Hanlon, R. T. (2014). Graded behavioral responses and habituation to sound in the common cuttlefish Sepia officinalis. *Journal of Experimental Biology*, *217*(24), 4347–4355. https://doi.org/10.1242/jeb.113365

Santos-Domínguez, D., Torres-Guijarro, S., Cardenal-López, A., & Pena-Gimenez, A. (2016). ShipsEar: An underwater vessel noise database. *Applied Acoustics*, *113*, 64–69. https://doi.org/10.1016/j.apacoust.2016.06.008

Sertlek, H. Ö., Binnerts, B., & Ainslie, M. A. (2016). The effect of sound speed profile on shallow water shipping sound maps. *The Journal of the Acoustical Society of America*, *140*(1), EL84–EL88. https://doi.org/10.1121/1.4954712

Sertlek, H. Ö., Slabbekoorn, H., ten Cate, C., & Ainslie, M. A. (2019). Source specific sound mapping: Spatial, temporal and spectral distribution of sound in the Dutch North Sea. *Environmental Pollution*, *247*, 1143–1157. https://doi.org/10.1016/j.envpol.2019.01.119

Shapiro, A. D. (2006). Preliminary evidence for signature vocalizations among free-ranging narwhals (Monodon monoceros) . *The Journal of the Acoustical Society of America*, *120*(3), 1695–1705. https://doi.org/10.1121/1.2226586

Sipilä, T., Viitanen, V. M., Uosukainen, S., & Klose, R. (2019). Shallow water effects on ship underwater noise measurements. *Proceedings of Inter.Noise*.

Širović, A., Evans, K., Garcia-Soto, C., Hildebrand, J. A., Jesus, S. M., & Miller, J. H. (2021). The second world ocean assessment. In *Vol II, Chap. 20*.

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., & Popper, A. N. (2010). A noisy spring: The impact of globally rising underwater sound levels on fish. In *Trends in Ecology and Evolution* (Vol. 25, Issue 7, pp. 419–427). https://doi.org/10.1016/j.tree.2010.04.005

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., & André, M. (2013). Ultrastructural Damage of *Loligo vulgaris* and *Illex coindetii* statocysts after Low Frequency Sound Exposure. *PLoS ONE*, *8*(10). https://doi.org/10.1371/journal.pone.0078825

Solé, M., Lenoir, M., Fontuño, J. M., Durfort, M., Van Der Schaar, M., & André, M. (2016). Evidence of Cnidarians sensitivity to sound after exposure to low frequency noise underwater sources. *Scientific Reports*, *6*. https://doi.org/10.1038/srep37979

Solé, M., Sigray, P., Lenoir, M., Van Der Schaar, M., Lalander, E., & André, M. (2017). Offshore exposure experiments on cuttlefish indicate received sound pressure and particle motion levels associated with acoustic trauma OPEN. *Nature Publishing Group*. https://doi.org/10.1038/srep45899

Song, S., Demirel, Y. K., & Atlar, M. (2020). Penalty of hull and propeller fouling on ship self-propulsion performance. *Applied Ocean Research*, *94*(October 2019), 102006. https://doi.org/10.1016/j.apor.2019.102006

Spence, J. H., & Fischer, R. W. (2017). Requirements for reducing underwater noise from ships. *IEEE Journal of Oceanic Engineering*, *42*(2), 388–398. https://doi.org/10.1109/JOE.2016.2578198

Stanley, J. A., Wilkens, S. L., & Jeffs, A. G. (2014). Fouling in your own nest: Vessel noise increases biofouling. *Biofouling*, *30*(7), 837–844. https://doi.org/10.1080/08927014.2014.938062

Strietman, W. J., Michels, R., & Leemans, E. (2018). Measures to reduce underwater noise and beach litter: An assessment of potential additional measures for the Netherlands. In *Report 2018-087*.

Taylor, P., Wilkens, S. L., Stanley, J. A., & Jeffs, A. G. (2012). Induction of settlement in mussel (*Perna canaliculus*) larvae by vessel noise. *Biofouling*, *28*(1), 65–72. https://doi.org/10.1080/08927014.2011.651717

Thomson, D. J. M., & Barclay, D. R. (2020). Real-time observations of the impact of COVID-19 on underwater noise. *The Journal of the Acoustical Society of America*, *147*(5), 3390–3396. https://doi.org/10.1121/10.0001271

Tollefsen, D., & Dosso, S. E. (2020). Ship source level estimation and uncertainty quantification in shallow water via Bayesian marginalization. *The Journal of the Acoustical Society of America*, *147*(4), EL339–EL344. https://doi.org/10.1121/10.0001096

Traverso, F., Gaggero, T., Rizzuto, E., & Trucco, A. (2015). Spectral analysis of the underwater acoustic noise radiated by ships with controllable pitch propellers. *MTS/IEEE OCEANS 2015 - Genova: Discovering Sustainable Ocean Energy for a New World*. https://doi.org/10.1109/OCEANS-Genova.2015.7271483

UNCLOS. (1982). United Nations convention on the law of the sea. *International Journal of Marine and Coastal Law*, *12*(7).

Vakili, S. V., Ölcer, A. I., & Ballini, F. (2020). The trade-off analysis for the mitigation of underwater noise pollution from commercial vessels: Case study – Trans Mountain project, Port of Vancouver, Canada. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, 234(2), 599–617. https://doi.org/10.1177/1475090219886397

Vakili, S. V., Ölcer, A. I., & Ballini, F. (2020a). The development of a policy framework to mitigate underwater noise pollution from commercial vessels. *Marine Policy*, 118. https://doi.org/10.1016/j.marpol.2020.104004

Vakili, S. V., Ölçer, A. I., & Ballini, F. (2020b). The development of a policy framework to mitigate underwater noise pollution from commercial vessels: The role of ports. *Marine Policy*, 120. https://doi.org/10.1016/j.marpol.2020.104132

Vancouver Fraser Port Authority. (2016). ECHO Program 2015 Annual Report. https://www.portvancouver.com/wp-content/uploads/2016/05/ECHO-Program-Annual-Report-2015-FINAL.pdf

Vancouver Fraser Port Authority. (2017). ECHO Program 2016 Annual Report. https://www.portvancouver.com/wp-content/uploads/2017/01/ECHO-Program-Annual-Report-2016-FINAL.pdf

Vancouver Fraser Port Authority. (2021). ECHO Program 2020 Annual Report. https://www.portvancouver.com/wp-content/uploads/2021/04/2021-04-05-ECHO-2020-Annual-report_Final-1.pdf

Veirs, S., Veirs, V., & Wood, J. D. (2016). Ship noise extends to frequencies used for echolocation by endangered killer whales. *PeerJ*, *2016*(2). https://doi.org/10.7717/peerj.1657

Veirs, S., Veirs, V., Williams, R., Jasny, M., & Wood, J. (2018). A key to quieter seas: half of ship noise comes from 15% of the fleet. *PeerJ Preprints*. https://doi.org/10.7287/peerj.preprints.26525

Velasquez Jimenez, L., Fakan, E. P., & McCormick, M. I. (2020). Vessel noise affects routine swimming and escape response of a coral reef fish. *PloS One*, *15*(7), e0235742. https://doi.org/10.1371/journal.pone.0235742

Vermeij, M. J. A., Marhaver, K. L., Huijbers, C. M., Nagelkerken, I., & Simpson, S. D. (2010). Coral larvae move toward reef sounds. *PLoS ONE*, *5*(5), 3–6. https://doi.org/10.1371/journal.pone.0010660

Viola, S., Grammauta, R., Sciacca, V., Bellia, G., Beranzoli, L., Buscaino, G., Caruso, F., Chierici, F., Cuttone, G., D'Amico, A., De Luca, V., Embriaco, D., Favali, P., Giovanetti, G., Marinaro, G., Mazzola, S., Filiciotto, F., Pavan, G., Pellegrino, C., … Riccobene, G. (2017). Continuous monitoring of noise levels in the Gulf of Catania (Ionian Sea). Study of correlation with ship traffic. *Marine Pollution Bulletin*, *121*(1–2), 97–103. https://doi.org/10.1016/j.marpolbul.2017.05.040

Wale, M. A., Simpson, S. D., & Radford, A. N. (2013a). Noise negatively affects foraging and antipredator behaviour in shore crabs. *Animal Behaviour*, *86*(1), 111–118. https://doi.org/10.1016/j.anbehav.2013.05.001

Wale, M. A., Simpson, S. D., & Radford, A. N. (2013b). Size-dependent physiological responses of shore crabs to single and repeated playback of ship noise. *Biology Letters*, *9*(2), 20121194. https://doi.org/10.1098/rsbl.2012.1194

Wales, S. C., & Heitmeyer, R. M. (2002). An ensemble source spectra model for merchant ship-radiated noise. *The Journal of the Acoustical Society of America*, *111*(3), 1211–1231. https://doi.org/10.1121/1.1427355

Wall, C. C., Haver, S. M., Hatch, L. T., Miksis-Olds, J., Bochenek, R., Dziak, R. P. and Gedamke, J. (2021) The next wave of passive acoustic data management: how centralized access can enhance science. Frontiers in Marine Science, **8**, 703682. https://doi.org/10.3389/fmars.2021.703682

Walsh, E. P., Arnott, G., & Kunc, H. P. (2017). Noise affects resource assessment in an invertebrate. *Biology Letters*, *13*(4). https://doi.org/10.1098/rsbl.2017.0098

Wang, L., Heaney, K., Pangerc, T., Theobald, P., Robinson, S., & Ainslie, M. (2014). Review of underwater acoustic propagation models. In *NPL Report AC 12*.

Weilgart, L. (2018). *The impact of ocean noise pollution on fish and invertebrates*.

Weir, C. R., Frantzis, A., Alexiadou, P., & Goold, J. C. (2007). The burst-pulse nature of 'squeal' sounds emitted by sperm whales (Physeter macrocephalus). *Journal of the Marine Biological Association of the UK*, *87*(01), 39. https://doi.org/10.1017/S0025315407054549

Williams, R., Veirs, S., Veirs, V., Ashe, E., & Mastick, N. (2019). Approaches to reduce noise from ships operating in important killer whale habitats. *Marine Pollution Bulletin*, **139**, 459–469. https://doi.org/10.1016/j.marpolbul.2018.05.015

Wittekind, D. K. (2014). A simple model for the underwater noise source level of ships. *Journal of Ship Production and Design*, *30*(1), 7–14. https://doi.org/10.5957/JSPD.30.1.120052

Appendix A Database field definitions

Table 8 – Description of database fields for the category Noise Sources.

Field	Unit	Description
Ship type	N/A	The ship type, as defined in the original study from which the data was extracted.
Ship name	N/A	The name of the vessel, if the measurements concern a specific ship.
Number of vessels	#	The number of ships of a certain type over which the reported source levels are averaged.
Length 1/min	metres	Ship length overall. Depending on the study, this can be the length of a specific ship, the average length of all ships of a certain type, or the minimum length for a group of vessels of a certain type.
Length 2/max	metres	Ship length overall, indicating the maximum length for a group of vessels of a certain type.
Draught	metres	Ship draught. This may be the draught reported during the measurements, or the design draught, depending on the study (if applicable).
Gross tonnage	tonnes	The gross tonnage reported in the study. Note that this quantity is more commonly reported than displacement.
Speed 1/min	knots	Ship speed, most commonly speed over ground. Depending on the study, this can be the speed of a specific ship, the average speed of all ships of a certain type, or the minimum speed for a group of vessels of a certain type.
Speed 2/max	knots	Ship speed, indicating the maximum speed for a group of vessels of a certain type (if applicable).
Engine power	kilowatts	The reported engine power in SI units. Values given in horsepower have been converted using a multiplication factor of 1.341.
Power plant	N/A	Description of the propulsion machinery (main engine).
Propulsor type	N/A	Description of the propulsor type.
Source level	decibels	The broadband source level reported in the study. The values should be interpreted using the fields 'Source level type' and 'Frequency range'.
Source level type	reference units of source level	The source level definition and associated units: • Monopole source level [dB re. 1 μPa^2 m^2]: corrected for propagation loss including interference pattern from sea surface, and integrated over a certain frequency range. • Radiated noise level [dB re. 1 μPa^2 m^2]: corrected for propagation loss excluding interference pattern from sea surface, and integrated over a certain frequency range. • Spectral source level [dB re. 1 μPa^2 m^2/Hz]: the source level associated with a particular frequency (band).
Frequency 1/lower limit	Hertz	The lower limit of the frequency range over which broadband source levels are reported, or the frequency at which spectral source levels are reported.
Frequency 2/upper limit	Hertz	The upper limit of the frequency range over which broadband source levels are reported.
Estimation procedure	N/A	Description of how the sound was measured and how source levels were derived.
Reference	N/A	A citation of the study e.g. Smith et al. (2000).
Link	N/A	The hyperlink to the source.
Comments	N/A	Additional remarks or relevant details extracted from the study.

Table 9 – Description of database fields for the category Classification Societies.

Field	Unit	Description
Classification Society	N/A	The name of the Classification Society
Name	N/A	The name of the class notation
Year	N/A	Year of publication
Type	N/A	Voluntary or mandatory
Drive	N/A	The motivation to develop the class notation
Applicable to	N/A	Identification of the type of the ship where the class notation can be obtained
Link	N/A	Link to the document

Table 10 – Description of database fields for the category Policy

Field	Description
Title	The name of the instrument
Type of instrument	Indicate whether it is a Guideline, a Decision, Agreement or Convention
Binding	Indicate if it is binding or not
Mention to URN	If there is any mention to underwater noise
Mention to shipping	If there is any mention specific to URN from shipping
Link	Indicate if it is linked to any other instrument
Year	Year of establishment/ release

Table 11 – Description of database fields for the category Mitigation Measures.

Field	Unit	Description
Measure	N/A	The name of mitigation measure
Category	N/A	The category to which the measure belongs: propeller design, propulsor selection, wake flow improvement, propulsive efficiency improvement, blade treatments, machinery selection, machinery treatments, fuel selection, hull treatments, hull design, matural propulsion, and operational.
Physical mechanism	N/A	Description of the way in which it reduces sound
Effectiveness	N/A	Evaluation of how effective the measure is in reducing sound, using a grading: low (< 5 dB), medium (5-10 dB), high (> 10 dB), following Kendrick & Terweij (2019). Either taken from literature or derived by comparison.
Verifiability	N/A	The ease of verifying the noise reduction , based on Chmelnitsky and Gilbert (2016), using a grading: easy, moderate, difficult.
Min frequency	Hertz	The lower limit of the frequency range in which the measure is reported to be effective.
Max frequency	Hertz	The upper limit of the frequency range in which the measure is reported to be effective.
Cost metric	N/A	Available metric for cost evaluation: percentage increase compared to conventional solution, expenditure, payback period and description.
Cost score	N/A	Evaluation of how costly the measure is to implement, following the appropriate cost metric.
Additional maintenance	N/A	Whether or not additional the measure would require additional maintenance during the ship's life. Only applies to technical measures.
Impact on efficiency	N/A	Assessment of the measure's effect on fuel efficiency, using a grading: negative, neutral, positive.
Co-benefits	N/A	Additional (unintentional) benefits of applying the measure.
TRL	N/A	The Technology Readiness Level of the measure, either obtained from literature or estimated.
Ship category	N/A	Types of ships for which the measure can be applied, using the categorisation from Kendrick and Terweij (2019): faster/slower, and larger/smaller.
Applicability	N/A	Whether the measure can be applied to newbuild, as a retrofit, or both.
Reference	N/A	A citation of the study e.g. Smith et al. (2000).
Link	N/A	The hyperlink to the source.
Comments	N/A	Additional remarks or relevant details extracted from the study.

Table 12 – Description of database fields for the category Impact on species

Field	Unit	Description
Common name	N/A	The name common name of the species
Scientific name	N/A	The scientific name of the species
Development stage of species	N/A	When available, the development stage of the species (e.g. larvae, juvenile, adult)
Type of study	N/A	Identification of the type of study: laboratory, field
Study location	N/A	Geographic location
Location lat	N/A	Latitude of the location
Location long	N/A	Longitude of the location
Acoustic source	N/A	Type of the acoustic source
Ship type	N/A	When available, the type of ship indicated in the study
Vessel speed	knot	When available, the vessel speed during the study
Experiment duration	Hours	When available, the duration of the experiment
Min freq playback	Hz	The minimum frequency of the playback signal
Min freq playback	Hz	The maximum frequency of the playback signal
Min highest portion of total noise	Hz	The minimum frequency of the highest portion of total noise
Min highest portion of total noise	Hz	The maximum frequency of the highest portion of total noise
SPL acoustic stimulus	dB rms 1µPa	The Sound Pressure Level of the acoustic stimulus
Objectives	N/A	The objectives of the study
Observed impact	N/A	The impact observed during the study
Category of impact	N/A	The category of impact: behavioural; morphologic; physiologic
Reference	N/A	Bibliographic reference
Year	N/A	Year of publication of the study
Remark	N/A	Additional notes
Maximum RL	dB rms 1µPa	Maximum Received Level at the receptor
Min freq	Hz	Minimum frequency analysed in the study
Max freq	Hz	Maximum frequency analysed in the study
Methodology	N/A	Type of methodology to collect data or analyse the impacts
Remaining fields according to the reference (Erbe,2019)		

Appendix B Questionnaire

Introductory text:

ABOUT THE “SOUNDS” PROJECT

Underwater radiated noise (URN) from shipping is now recognised as a significant environmental issue with regional and global impact. However, to date, there have been relatively few in-depth studies done on its effects in Europe.

To help fill the research gap, and to contribute to international work on this issue, the European Maritime Safety Agency (EMSA) is conducting a study, focusing on a number of key aspects related to URN: the existing policy in the area, the current understanding about sources of continuous URN from different types of ships, its impacts on the marine environment, and mitigation actions.

The study is being carried out by WavEC Offshore Renewables and Maritime Research Institute Netherlands (MARIN) on behalf of EMSA.

YOUR PARTICIPATION

We welcome your views and experience on this issue, which will be instrumental to the study, and which will contribute to the final report. Once the report is finalised, it will be made publicly available by EMSA, and you will be sent a copy by e-mail upon providing your e-mail address when responding . The questionnaire will be open until 07/05/2021, and should not take more than 10 minutes to complete.

RIGHTS

You can respond anonymously (respondent details are optional). Your responses will be saved in electronic format and personal information is not collected unless you decide to provide your details. Published responses to the questionnaire will be aggregated and not individually attributable.

CONTACT INFORMATION

If you have any questions about the questionnaire, please contact the project manager Erica Cruz: erica.cruz@wavec.org.

☐ I agree with the terms and conditions and consent to participate in this survey. (Mandatory box to continue with the questionnaire)

Section 1 - Contact details and experience		
Aim	Question	Who is the question aimed at (all respondents may answer all questions)
To get contact details of key individuals to invite them to Linkedin group and round-tables if invited/applicable	Respondent details (optional) – (To all answering the survey) Name E-mail Organisation Position Country	Al

Aim is to categorise the type of stakeholder who is answering the questionnaire.	Which one of the following best describes you or the organisation you work for? Shipbuilder Marine supplier Classification society Naval architect Engine manufacturer Ship owner Ship manager Ship operator Ship's Master Crew Maritime administration Environmental Administration Regulator Policy advisor Research organisation Noise consultant Navy Port State Control authority Other: ________ If Research Organisation: Please indicate the research field in which you personally work.	All
Aim to quantify the level of expertise of the respondent.	Please rank your involvement and experience in the field of URN from shipping: No experience Minor experience (rarely/ slightly aware; 1-2 times/ year) Moderate/reasonable experience (3-4 times/ year) Major experience/High level of experience (often/very aware; More than 5 times/ year or 1 to 2 times/month) Expert (always/ extremely aware; weekly – daily)	All
Gauge the general level of engagement of industry/researchers with non-mandatory and existing guidelines.	As part of your URN-related work, have you been participated in, consulted, or complied with any of the following guidelines? Please select ALL relevant answers: IMO "Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life" (MEPC.1/Circ.833) EU Marine Strategy Framework Directive on marine environmental policy (2008/56/EC) Classification society "quiet" class notations URN performance indicators e.g. Green Marine Financial incentives e.g. reduced harbour dues, such as EcoAction® programme from Vancouver Fraser Port Authority CMS "Family Guidelines on Environmental Impact Assessment for Marine Noise-generating Activities"?	All

	Other: ___________________	
Section 2 – Relationships between the stakeholders		
To find out who is seen as the main expert, authority or point of contact, by the various stakeholders.	Should you require assistance with URN-related work, who would you first contact?: (Drop down list – select 3 options by preference) Shipbuilder Marine supplier Classification society Naval architect Engine manufacturer Ship owner Ship manager Ship operator Ship's Master Crew Maritime administration Environmental Administration Regulator Policy advisor Research organisation Noise consultant Navy Port State Control authority Other: _________	All
To help establish links between the various stakeholders when it comes to URN issues.	Please select all of the stakeholders from the list below with whom you have had direct contact regarding URN-related work. Shipbuilder Marine supplier Classification society Naval architect Engine manufacturer Ship owner Ship manager Ship operator Ship's Master Crew Maritime administration Environmental Administration Regulator Policy advisor Research organisation Noise consultant Navy Port State Control authority Other: _________	All
Section 3 – Mitigation		
Canvass the motivation behind potential mitigation actions, given that there are currently no mandatory regulations.	Which one of the following options motivates you the most to address the reduction of URN from shipping? Policy e.g. IMO, EU, national legislation/guidelines Financial e.g. reduced harbour dues Environmental awareness of stakeholders	All
Quantifying awareness and knowledge of various mitigation measures.	Numerous mitigation measures for reducing URN from shipping have been proposed. Please rank each of the	Shipbuilders, marine suppliers, classification societies,

	following measures based on effectiveness at reducing URN, where 1 is ineffective, 2 is somewhat effective, 3 is moderately effective, 4 is quite effective and 5 is highly effective. Slow steaming: [1-5] Traffic routing: [1-5] Hull and propeller cleaning: [1-5] Propeller design: [1-5] Wake improvement devices: [1-5] Alternative propulsion machinery e.g. diesel-electric: [1-5] Optimising combinator curve for URN (for controllable pitch propellers) : [1-5] Air injection systems i.e. bubble curtain or "Masker" system: [1-5] Resilient mounting of machinery: [1-5] Noise isolation materials: [1-5; do not have an opinion] Other: ____________	naval architects, engine manufacturers, ship operators
This question tries to find out how various stakeholders judge the diverse mitigation measures, taking factors other than noise reduction into account.	Numerous mitigation measures for reducing URN from shipping have been proposed. Please rank each of the following measures based on how realistic it is that they are adopted, where 1 is unrealistic, 2 is somewhat realistic, 3 is moderately realistic, 4 is quite realistic, and 5 is highly realistic. In your ranking, please take into account factors such as cost, influence on vessel design and/or operation, and applicability to different vessel types. Slow steaming: [1-5] Traffic routing: [1-5] Hull and propeller cleaning: [1-5] Propeller design: [1-5] Wake improvement devices: [1-5] Alternative propulsion machinery e.g. diesel-electric: [1-5] Optimising combinator curve for URN (for controllable pitch propellers) : [1-5] Air injection systems i.e. bubble curtain or "Masker" system: [1-5] Resilient mounting of machinery: [1-5] Noise isolation materials: [1-5] Other: ____________	Shipbuilders, marine suppliers, classification societies, naval architects, engine manufacturers, ship operators
One of the few open and specific questions, aiming to understand how designers view and intend to deal with the potentially conflicting requirements of reducing fuel and noise emissions.	Energy efficiency is subject to mandatory regulation, i.e. EEDI and SEEMP, while currently no such equivalent exists for URN. A trade-off is often described between vessel URN and energy efficiency. Please rank the following in order of their suitability for making ship designs both more efficient and quieter, where 1 is the highest ranking, and 5 is the lowest ranking: Lower power requirement by reducing (design) speed Lower power requirement by utilising energy saving devices	Shipbuilders, marine suppliers, naval architects, classification societies, ship operators

	Hullform optimisation for reduced resistance and improved wake field Advanced propeller design techniques e.g. optimisation Novel propulsor designs I don't have an opinion.	
Section 4 – Data access		
Aim: to understand if AIS data is relevant	AIS data are being widely used to assess underwater noise impact from shipping. Do you use AIS data in your work? Yes No If yes, do you consider current information is enough to support your work? Yes, I have enough data Yes, but I would like to have access to more data No, I would like to have access to more data If you selected b or c, please indicate what type of data would be relevant? ________ Would it be beneficial to your work that vessels with less than 300GT, have AIS or another tracking system? Yes No	Researchers, PSC authorities (?)
	Would your work benefit if shipping noise measurements would be available on a data sharing platform (e.g. EMODnet)? Yes No Do you use any platform for acoustic data sharing? Yes No If Yes, please state: __________	Researchers, PSC authorities (?)
Section 5 – Readiness and future focus		
A general question to gauge industry readiness for possible future regulation.	How prepared do you think the European maritime sector is for the potential introduction of a mandatory regulation on URN? Very unprepared Unprepared Neither unprepared or well prepared Somewhat prepared Very prepared	All
Aims to find out where stakeholders think future work/research should be focused. The options provided are largely based on the recommendations from the SONIC-AQUO joint guidelines report.	Which of the following do you consider to be most critical for reducing URN from shipping? A standardised method for performing and evaluating ship noise measurements at sea. A standardised system of "noise labelling", to be used in design specifications and vessel URN performance assessment Design tools for assessing URN at an early design stage Cost-benefit analyses for evaluation of mitigation measures	All

	Further research on URN environmental impact, and mitigation Improve the regulatory framework Other: _____________	
This question is designed to gauge awareness of work outside the EU, and gain additional recommendations.	In your opinion, what is the most important thing the EU maritime sector can learn from progress on the subject of URN from shipping outside the EU?	All
Scope the potential for further engagement.	Are you willing to participate in further discussions on this subject? No Yes, interview Yes, round-table discussion Yes, both interview and round-table discussion	All

[Click submit] Thank you for contributing to this study and the potential development of future strategy on this subject!

Appendix C List of interviews

Table 13 – List of interviews carried out.

Organisation	Name	Position	Stakeholder group
Bureau Veritas	Eric Baudin	Head of section, Tests and Measurements	Classification societies, researchers
DG Environment	Maud Casier	Seconded National Expert	Regulators
ECHO Program	Orla Robinson and Krista Trounce	Program manager, Research manager	Research organisations
European Marine Board	Paula Kellett	Science officer	Policy advisors
Freire shipyard	Luis Santos	Production and project manager	Shipbuilders
Green Marine Europe	Emma Lelong and Antidia Citores	Project assistant and project manager	Environmental organisations
HELCOM EN-Noise	Jakob Tougaard	Chair	Regional Conventions
ICES	Cathryn Murray, Ida-Maja Hassellöv and Nathan Merchant	Chair, chair, Researcher	Research organisations
IFAW	Aurore Morin, Sahron Livermore	Marine & International Policy Campaigner	Environmental organisations
IQOE	Peter Tyack, Jennifer, Miksis-Olds, Ed Urban, Sophie Seeyave	Members	Research organisation
IMO	Andrew Birchenough	Technical Officer	Regulators
JOMOPANS	Niels Kinneging	Project manager	Research organisations
Maersk	Lee Kindberg and Anne Norderud-Poulsen	Head of environment & sustainability (North America), and Senior regulatory manager - marine	Ship owners and operators
Oceancare	Nadia Deckert, Lindy Weilgart, Carlos Bravo	Policy Advisor	Environmental organisations
Royal Association of Netherlands Shipowners	Nick Lurkin	Senior adviser, Climate & Environment	Associations of ship owners
Royal Belgian Shipowners' Association	Gudrun Janssens and Wilfried Lemmens	Head of environmental & technical affairs, and Managing director	Associations of ship owners
Transport Canada	Michelle Sanders	Director	Regulators

Appendix D Summary of members represented in the ECHO Program

Table 14 - List of members of the Advisory Working Group, Vessel Operators Committee and Acoustic Technical Committee.

Institution	Role of the organisation	Advisory working group	Vessel operators committee	Acoustic technical committee	Conservation Agreement management committee
BC Coast Pilots	Mandated to board and guide any foreign ship coming in or out of BC's ports for safety, efficiency and environmental protection.	x	x	x	
BC Ferries	Ferry company	x	x	x	
Canadian Coast Guard	Special operating agency within Fisheries and Oceans Canada. Manages traffic.	x	x		
Chamber of Shipping	Shipping association representing ship owners, operators and agents.	x	x		x
Council of Marine Carriers	Representing tug and barge operators.		x		x
Cruise Lines International Association – North West & Canada	Non-profit association representing the major cruise lines that operate in Canada and the Pacific Northwest including Washington State, Alaska and Hawaii.	x	x		
Department of National Defence	Supports the Canadian Armed Forces who serve on the sea, on land, and in the air with the Navy, Army, Air Force and Special Forces to defend Canadians' interests	x		x	
Ship Classification Societies	DNV, Loyd's Register			x	
Naval architecture, engineering and underwater noise consulting companies	DHI Group, DW Ship Consult, JASCO Applied Sciences, Robert Allan Ltd., Sea to Shore Systems			x	
Fisheries and Oceans Canada	Federal institution responsible for safeguarding our waters and managing Canada's fisheries and oceans resources.	x		x	x
Indigenous advisors	Sharing Indigenous perspectives and liaison with Indigenous communities	x			

Institution	Role of the organisation	Advisory working group	Vessel operators committee	Acoustic technical committee	Conservation Agreement management committee
International Ship-Owners Alliance of Canada (ISAC)	Representing Ship owners		x		x
National Oceanic and Atmospheric Administration (NOAA)	U.S. Federal Agency dedicated to climate monitoring to fisheries management, coastal restoration and supporting marine commerce.	x		x	
Natural Resources Defense Council, Inc.	Organisation that works to safeguard the earth—its people, its plants and animals, and the natural systems.	x			
Noise Control Engineering				x	
Ocean Wise	Conservation organisation to protect and restore the world's oceans.	x		x	
Oceans Networks Canada	Network of ocean observatories to continuously deliver data in real-time for scientific research.			x	
Pacific Pilotage Authority	The principal mandate of the Authority is to provide safe, reliable and efficient marine pilotage and related services in the coastal waters of British Columbia including the Fraser River.	x	x		x
Royal Canadian Navy	Canada's naval force	x	x	x	
Robert Allan Naval Architects	Company of Naval Architects			x	
Sea Mammal Research Unit (SMRU) Consulting Canada	Marine mammal consulting and research	x		x	
Shipping Federation of Canada	Represents the owners, operators and agents of ships involved in Canada's world trade.	x	x		x
Transport Canada	Federal institution responsible for transportation policies and programmes.	x	x	x	x
Academic Institutions	University of British Columbia; University of St. Andrews; University of Victoria			x	
Vancouver Fraser Port Authority	Responsible for the stewardship of federal port lands at the Port of Vancouver.	x	x		x
Washington State Ferries	US Washington State Department of Transportation	x	x		

Institution	Role of the organisation	Advisory working group	Vessel operators committee	Acoustic technical committee	Conservation Agreement management committee
	agency responsible for the state ferry system.				
WWF-Canada	Conservation organisation	x			
Hapag-Lloyd (Canada) Inc.	Liner shipping company		x		
Holland America Group	Cruise line		x		
Marine Exchange of Puget Sound	US operating association providing communications and information to the marine transportation industry		x		
Pacific Merchant Shipping Association	Shipping Association advocating on behalf of marine terminal operators, ocean-going vessels, and maritime industry stakeholders doing business at U.S West Coast ports.		x		
Pacific Northwest Ship & Cargo Services	Shipping and cargo solutions		x		
U.S. Coast Guard	Federal agency responsible for maritime safety, security, and environmental stewardship in U.S. ports and inland waterways		x		

Appendix E Glossary of acoustic terminology

There is a large body of literature regarding the definition and adoption of standard terminology for underwater noise e.g. Baudin & Mumm (2015); ISO (2017); ITTC (2017). The main terms are summarised here, focussing on those referred to in this study.

Table 15 – Description of acoustic terminology related to URN from shipping.

Term	Abbreviation, Acronym or Symbol	Description
Far field		The region in which the acoustic pressure (in an equivalent free field environment) is inversely proportional to the distance from the source.
Lloyd's mirror effect	LM	The interference pattern caused by the sea surface, which is a function of frequency, source depth, and receiver inclination angle.
(Monopole) source level	(M)SL	The level of an equivalent monopole source in a free field environment.
Noise	-	Unwanted sound which interferes with the normal functioning of a system.
Propagation loss	PL	Any change in acoustic pressure between the source and receiver. The difference between Sound Pressure Level and Monopole Source Level.
Radiated noise level	RNL	The source level determined only by accounting for spreading loss.
Reference distance	r_0	The distance used to normalise spreading loss corrections.
Reference pressure	p_0	The pressure used to normalise underwater noise: 1 micro-Pascal (µPa).
Sound exposure level	SEL	The decibel level of the integral of the square of the sound pressure over time, using a reference value of 1 $\mu Pa^2 s$.
Sound pressure level	SPL	The decibel level of the acoustic pressure normalised using the reference pressure. Broadband level if computed using the root mean square acoustic pressure, or spectral density if acoustic pressure spectrum used.
Spectral source level	SSL	The source level spectral density.
Transmission loss	TL	The difference in SPL between two positions. Commonly used to refer to Propagation Loss, despite the difference in definition.
Underwater radiated noise	URN	The sound radiated underwater by an anthropogenic source. In the context of a ship, this can be differentiated from the inboard sound, or the sound radiated to the air. The word "noise" is used as standard, although strictly speaking the term refers to sound.

Appendix F Summary of EU projects on URN

Table 16 – Overview of completed and ongoing European Union projects on ship URN.

Project name	Project focus	Period	Funding body	Geographic region of interest	Website
AQUO	Reduction of ship noise	2012-2015	EU FP 7 Transport	N/A	http://www.aquo.eu/
BIAS	Underwater noise monitoring; sound mapping	2012-2016	EU LIFE+	Baltic Sea	https://biasproject.wordpress.com/
Hydro Testing Alliance (HTA)	Improving hydrodynamic model testing, including propeller cavitation noise	2006-2011	EU FP6 Transport	N/A	https://trimis.ec.europa.eu/project/hydro-testing-alliance-alliance-enhance-maritime-testing-infrastructure-eu
JOMOPANS	Underwater noise monitoring; sound mapping	2018-2021	EU Interreg North Sea region	North Sea	https://northsearegion.eu/jomopans/
JONAS	Underwater noise monitoring; sound mapping	2018-2022	EU Interreg Atlantic Area	Atlantic	https://www.jonasproject.eu/
PIAQUO	Reduction of ship noise	2019-2022	EU LIFE	Mediterranean	https://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=7204
NAVAIS	Improving ship design and building processes. Reducing ship emissions, including URN.	2018-2022	EU Horizon 2020	N/A	https://www.navais.eu
QUIETMED	Underwater noise monitoring	2018-2021	EU DG Environment	Mediterranean Sea	http://www.quietmed-project.eu/
SATURN	Developing solutions for reducing the impact of ship URN.	2021-2025	EU Horizon 2020	N/A	https://www.marei.ie/project/saturn-solutions-at-underwater-radiated-noise/
SHEBA	Sustainable shipping in the Baltic region	2015-2018	BONUS	Baltic Sea	https://www.sheba-project.eu/index.php.en
SILENV	Reduction of ship noise	2009-2012	EU FP7 Transport	N/A	https://cordis.europa.eu/project/id/234182/reporting
SONIC	Characterisation of ship propeller cavitation noise	2012-2015	EU FP 7 Transport	N/A	https://cordis.europa.eu/docs/results/314/314394/final1-sonic-final-reporting-v9-19112015.pdf
STEERER	Zero emission waterborne transport	2021-2023	EU Horizon 2020	N/A	https://www.waterborne.eu/projects/coordination-projects/steerer/

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