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MANAGEMENT MEASURES TO REDUCE CONTINUOUS UNDERWATER NOISE FROM SHIPPING

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PREFACE

This report, which was commissioned and financed by the Swedish Agency for Marine and Water Management (SwAM), is devoted to the analyses of measures to mitigate underwater radiated noise (URN) from ships.

Underwater noise is one of the least explored types of environmental impacts of shipping. Until recently, it has been ignored and neither authorities nor ship designers, shipowners, or crews have shown any inclination to prioritize reduction of underwater noise. However, ships are a significant source of elevated noise levels in the oceans, which can have a negative impact on marine wildlife.

A crucial question is which measures can be implemented to effectively reduce URN on a scale that leads to noticeable impact on the noise levels in the marine environment. The primary aim of this project was to investigate whether URN can be reduced through policy measures that would mandate a reduction in ship speeds in waters around Sweden. This project also served to gather researchers and form a knowledge base for further interdisciplinary analysis of management measures related to ship noise.

This report has been produced by a group of researchers with expertise in a wide range of areas and was coordinated by the Shipping Group at the Institute of Marine Environment. The report was written by Mathias Andersson (FOI), Rickard Bensow (Chalmers University of Technology), Dag Glebe (IVL), Ida-Maja Hassellöv (Chalmers University of Technology), Emilia Lalander (FOI), David Langlet (Uppsala University), Kjell Larsson (Linnaeus University), Lars-Göran Malmberg, (University of Gothenburg), Eva-Lotta Sundblad (Swedish Institute for the Marine Environment), and Mikael Svedendahl (FOI). The authors are responsible for the report's contents and conclusions.

The report was written primarily for those working within marine management. We hope that it will also inspire researchers, experts, and research funders who are responsible for interdisciplinary knowledge that spans multiple sectors.

This report is organised to cover the main narrative in chapters 1-6, while many of the explanatory figures and methodological and technical details can be found in the Appendices.

We would also like to thank the anonymous reviewers who helped improve the report through their critical and constructive comments.

August, 2023.

SUMMARY

Underwater radiated noise (URN) from commercial ships is a significant source of elevated noise levels in the oceans and can have a negative impact on marine wildlife. Noise from commercial shipping places additional stress on the oceans, but is one of the least studied environmental pollutants, and there is an urgent need to reduce the aggregate stress levels.

Until recently, reduction of underwater noise has not been prioritised by ship designers, shipowners, or crews. Even within the field of marine management, noise has received limited interest. However, the International Maritime organization (IMO) has adopted global guidelines on URN reduction, which are currently being updated. Within the EU, the Marine Strategy Framework Directive (MSFD 2008/56/EC) Descriptor 11 criteria 11.2, now provides a framework for marine administrators to manage noise by establishing threshold values.

Marine management focuses on the total noise load on the marine environment. Management entails several considerations before recommendations can be made. As a first step, interdisciplinary teams need to assess the aggregated noise levels and determine acceptable thresholds based on the local ecosystem, then assess which existing mandates and management tools can be used, and finally assess how effective these mandates have been in improving the environment. These activities must also be managed in a way that is acceptable to various relevant stakeholders, who would need to follow the decisions. The URN from a ship can be affected by the vessel's design, either during its construction or during upgrades, and balances a trade-off against fuel efficiency. However, the URN can also depend on how the ship is operated. Regulating ship speed is one potential management tool, and its effectiveness needs to be assessed. Other management measures include how shipping lanes are drawn, areas to avoid, financial support, information, etc.

This report focuses on possible policy measures that the Swedish authorities could adopt to lower URN by regulating the speed of ships. The report presents an interdisciplinary analysis, using a case study of an area in the southern Kattegat that covered several maritime zones, different national jurisdictions, intensive traffic, and high natural values. An important part of the work was to assess whether existing source models for ship noise could be used for the type of ships that are common in waters around Sweden. In this study, the JOMOPANS-ECHO (J-E) model was used.

The J-E model was validated by comparing measurement data from a hydrophone station at Vinga on the Swedish coast that collected data from ships (254 passages) that used the port of Gothenburg. The analysis showed some deviation between the J-E model and measurement data, which could be due to differences in the length and speed of ships in waters around Sweden compared to the ships used in the development of the J-E model. However, this was likely to have negligible impact on the outcome of the case study.

Analyses of ship traffic in 2021 showed that 4,511 unique vessels visited the study area at least once. Most ships followed the main routes, but no part of the study area was completely free from ship traffic. About 68% of the ships visited the study area for 1-4 days, while about 32% visited the area more regularly. The most common ship types were General Cargo Ships, Dry Bulk Ships, and Tankers. The ships that on average travelled at highest speeds were RoPax Ships, RoRo Ships, Vehicle Carriers, and Container Ships. The ships were registered in 64 countries. About two percent of the ships were registered in Sweden and about four percent in Denmark.

Legal analysis showed that Sweden has the right and the responsibility to take measures to reduce underwater noise from ships to the extent that the noise can be deemed to pollute the marine environment. However, this mainly applies to Sweden's territorial seas, which cover roughly half the area being studied for this report. In the portion that constitutes Danish territorial sea, Denmark has comparable opportunities for managing URN. In areas that are Swedish or Danish exclusive economic zones (EEZs), the ability to introduce mandatory speed limits is significantly limited. There, the most realistic option would be to request the IMO to establish speed limits, or alternatively to issue a recommendation to navigate at lower speeds, although such guidance could not be enforced on ships that do not voluntarily reduce their speed.

It was estimated that lowering the ships' speeds to a hypothetical limit of 11 kn would reduce the average URN levels by 4.4 ± 2 dB, as registered by local receivers in the study area. This speed limit would affect approximately 44% of the ships in the area. A maximum speed of 13 kn would instead reduce the level by 1.9 ± 0.5 dB and would affect 11% of the ships on average. The reduction in noise levels may temporarily be much higher in the immediate vicinity of individual fast ships, and there might be a high degree of variation between different ships.

The study and report make it clear that it is a complex task to assess the feasibility and benefit of introducing a specific marine management tool, in this case an enforceable local speed limit. But it is also clear that there are reliable methods to make the preliminary assessments, and that it requires interdisciplinary analyses and competence.

SAMMANFATTNING

Undervattensbuller från kommersiella fartyg är en betydande källa till förhöjda ljudnivåer i haven vilket bedöms ha negativ påverkan på det marina djurlivet. Buller är alltså en ytterligare belastningstyp som haven utsätts för och en av de minst studerade, och det finns ett akut behov att reducera den aggregerade belastningsnivån.

Reduktion av buller har fram till relativt nyligen inte uppmärksammats och prioriterats i någon hög grad av fartygsdesigner, redare och besättningar. Även i den marina förvaltningen har buller tidigare rönt ett begränsat intresse. Dock finns på global nivå sedan länge en guide som IMO antagit avseende undervattensbuller och hur man kan minska det. Denna guide uppdateras just nu. Inom EU ger marina direktivet (MSFD 2008/56/EC) nya förutsättningar för marina förvaltningen att hantera buller genom att gränsvärden etableras.

Den marina förvaltningen ser till den totala belastningen på havsmiljön. Detta för med sig ett behov av att bedöma såväl den aggregerade bullernivån, inklusive vad som är acceptabel nivå utifrån ekosystemets förutsättningar i ett område, som att bedöma förvaltningens mandat att agera. Därutöver görs en bedömning av vilka förvaltningsverktyg som kan användas, samt hur effektiva dessa är för att påverka miljön. Det är även viktigt att skapa en acceptans hos de olika aktörer som ska följa de beslut som tas gällande det aktuella geografiska området.

Bullernivån från ett fartyg kan påverkas främst under designfasen, vid nybyggnation och modernisering, och kan då bli en avvägning mot bränsleeffektivitet. Bullernivån beror även på hur fartyget framförs. Reglering av fartygens hastighet är ett av de möjliga förvaltningsverktyg som är aktuella och dess effektivitet behöver bedömas. Andra exempel på verktyg är hur farleder dras, områden att undvika, ekonomiskt stöd, information m.m.

Rapporten belyser möjligheten för berörda svenska myndigheter att sänka nivån på undervattensbuller genom att reducera fartygens hastighet. För att studera denna åtgärd, genomfördes en tvärvetenskaplig fallstudie avseende ett område i södra Kattegatt med flera maritima zoner, olika nationella jurisdiktioner, intensiv trafik samt höga naturvärden. En viktig del i arbetet var att bedöma om existerande modeller av fartyg som bullerkällor kan användas för de typer av fartyg som är vanliga i vatten runt Sverige. I studien har JOMOPANS-ECHO (J-E) modellen använts.

Modellens resultat validerades genom att jämföra med mätdata från en hydrofonstation vid Vinga på den svenska västkusten som samlat in bullerdata från fartyg (254 passager) som trafikerat Göteborgs hamn. Analysen visar på en viss avvikelse mellan J-E modellen och mätdata som kunde härledas till bland annat skillnad i längd och hastighet hos fartyg i haven kring Sverige jämfört med de fartyg som används vid framtagandet av J-E modellen. Det är dock troligt att dessa avvikelser inte påverkar slutsatserna från studien.

Analyser av fartygstrafiken år 2021 visade att 4511 unika fartyg besökte fallstudiens område åtminstone en gång. De flesta fartygen följde de huvudsakliga fartygsrutterna till och från Öresund, men ingen del av studieområdet var helt fritt från trafik. Cirka 68% av fartygen besökte området endast under 1-4 dagar medan cirka 32% var där mer regelbundet. De vanligaste fartygen var lastfartyg (general cargo), torrbulkfartyg och tankfartyg. De fartyg som i genomsnitt färdades med högst hastighet var RoPax-fartyg, RoRo-fartyg, biltransportfartyg och containerfartyg. Fartygen var registrerade i 64 länder. Cirka två procent av fartygen var registrerade i Sverige och cirka fyra procent i Danmark.

Juridiska analyser visade att Sverige har såväl möjlighet som ansvar att ta initiativ för att reducera undervattensbuller i den mån bullret utgör förorening av den marina miljön. Dock gäller detta främst i Sveriges territorialhav, vilket täcker ungefär hälften av området som omfattas av fallstudien. I den del som utgör danskt territorialhav har Danmark motsvarande möjligheter. I de delar av området som utgörs av svensk eller dansk ekonomisk zon är förutsättningarna för att på nationell nivå införa obligatoriska hastighetsbegränsningar betydligt sämre. Där är det mest realistiska alternativet att försöka få till stånd ett beslut om hastighetsbegränsningar från Internationella Sjöfartsorganisationen, IMO, eller möjligen att utfärda en rekommendation om lägre hastighet som dock inte kan påtvingas fartyg som inte frivilligt sänker hastigheten.

Beräkningar av effekterna på undervattensbuller av en hypotetisk sänkning av fartygens hastighet visade att en gräns på max 11 kn har möjlighet att sänka den genomsnittliga ljudnivån med 4,4 ±2 dB i de undersökta mottagarpunkterna i studieområdet. Denna hastighetsgräns skulle påverka cirka 44% av fartygen i området. En maxhastighet på 13 kn skulle istället reducera nivån med 1,9 ± 0.5 dB och påverka 11% av fartygen. I den omedelbara närheten av enstaka snabbgående fartyg kan förstås bullerreduktionen bli betydande samtidigt som den kommer att variera mycket mellan olika fartyg.

Studien och rapporten tydliggör att det är en komplex uppgift att bedöma möjligheten och nyttan av att införa ett specifikt marint förvaltningsverktyg, i detta fall en lokal hastighetsbegränsning. Men det tydliggör också att det finns metoder att göra preliminära bedömningar men att det kräver tvärvetenskapliga analyser och kompetens.

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ABBREVIATIONS

AIS - Automatic Identification System

APM – Associated Protective Measures, are adopted by IMO

CIS - Cavitation Inception Speed

CPP - Controllable Pitch Propeller

CSI - Clean Shipping Index

ECHO - Enhancing Cetacean Habitat and Observation program

EEZ - Exclusive Economic Zone

EU - European Union

FPP - Fixed Pitch Propeller

HELCOM - Helsinki Commission, the Baltic Marine Environment Protection Commission

IMO - International Maritime Organization

ITLOS - International Tribunal for the Law of the Sea

JIT - Just In Time

J-E model - JOMOPANS-ECHO model

JOMOPANS - Joint Monitoring Programme for Ambient Noise North Sea

MARPOL – International Convention for the Prevention of Pollution from Ship

MEPC - Marine Environment Protection Committee within IMO

MSFD - Marine Strategy Framework Directive

OSPAR - Oslo-Paris Convention, the Convention for the Protection of the Marine Environment of the North-East Atlantic

PCTC / Vehicle carriers - Pure Car and Truck Carriers. Vessels specially designed for efficient transport of (often new) cars and trucks as cargo

PL - Propagation Loss

PSSA – Particularly Sensitive Sea Area, are designated by IMO

RANDI - Research Ambient Noise Directionality (a model)

RoPax - Ships that carry passengers and their vehicles or cargo-carrying trucks

RoRo - Roll-on Roll-off ships. Cargo ships designed to carry wheeled cargo, such as cargo-carrying trucks and trailers

SL - Source Level

SVP - Sound Velocity Profile

TSS - Traffic Separation Scheme

UNCLOS - United Nations Law of the Sea Convention

1. INTRODUCTION

Underwater radiated noise (URN) from commercial ships is one of the sound sources that has increased ambient noise levels in the oceans (Hildebrand, 2009, Larsson-Nordström et al., 2022), and it has been shown to have a negative impact on marine animals (see for example the review by Duarte et al., 2021). Therefore, there is strong global consensus on minimising negative anthropogenic impacts on the marine environment, and mitigation of URN from commercial ships has been included in the UN Sustainable Development Goal 14 and the UN Ocean Decade framework[1]. As with most other shipping-related pollutants, there is a need to bridge the gap between addressing the topic from the perspective of marine environmental management versus that of the shipping industry. Currently, the IMO's recommendations for noise reduction from shipping is the only policy that exclusively targets the shipping industry's perspective (Cruz et al., 2021).

Several policies have been developed, or are under development, with marine environmental management as the starting point, e.g., action plans stemming from regional conventions such as HELCOM and OSPAR (HELCOM, 2021; OSPAR, 2021) and the EU-level Marine Strategy Framework Directive (MSFD) (2008 /56/EC). Energy input to the ocean, which includes sound, was acknowledged as a pollutant by the EU in 2008, and the MSFD is the only regulatory instrument that can implement binding actions at the European level. Recently, an assessment framework that included threshold values for anthropogenic noise was adopted by the EU, forming a basis for future regional and national regulations (Borsani et al., 2023). However, its current status and whether it can achieve meaningful environmental outcomes with respect to continuous underwater noise, such as URN from shipping, is not entirely clear. While there is need for further study, there is no doubt that noise reduction is needed to improve environmental outcomes. Hence, there are strong incentives to investigate policy options that could target how ships operate without requiring major technical changes.

There are three major types of operational measures: 1) ship routing that could either focus or dilute traffic (see for example Lalander et al., 2022), or utilizing natural environmental features like trenches or islands to change or block sound propagation, 2) limiting speed, either by setting a maximum allowable speed for all vessels, or through setting limits on the percentage of intrinsic speeds for individual vessels, and 3) using noise labels that would restrict the loudest vessels by limiting their operation to certain areas (Cruz et al., 2021). Experience has shown that changing ship routes to protect certain areas can be a time-consuming and cumbersome process. The use of noise labelling for ships has also been deemed ineffective for this study for two reasons. The first is because most ships pass through the area infrequently, and thus a prohibitively large numbers of ships would need to undergo individual assessments. The second is because the local ocean environment greatly influences perceived noise levels, and the

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[1] The *Ocean Decade is a 10-year framework initiative to identify, generate and use critical ocean knowledge to manage the ocean sustainably.*

assigned noise-level label would only be relevant in a localized area. Therefore, it was determined that setting general speed limits for all vessels would be the most feasible approach for this study, as it has been successfully tested on a smaller scale in the ocean and through modelling (e.g. de Jong & Hulskotte, 2021; MacGillivray et al., 2019). However, it is not clear whether speed limits are effective at reducing URN from a majority of vessels, and it is uncertain as to what the best approaches are to develop and implement these regulations. In addition, changing the speed of the vessel might affect other emissions from ships in both positive and negative ways, e.g., by reducing air pollutants, or through leakage of toxic substances from antifouling paint (de Jong & Hulskotte, 2021). Noise reduction from ships is a complex subject and there are no technical solutions/measures that ensure universal reduction in shipping-related URN without the risk of increasing other shipping pollutants such as CO2 emissions. The effect for each ship must be assessed for each individual case.

Two major projects have led to major breakthroughs in estimating URN from commercial ships and how this noise can be modelled into regional soundscape maps. The first project is the Vancouver Fraser Port Authority-led Enhancing Cetacean Habitat and Observation (ECHO) Program, which recorded a high volume of passages of commercial ships. Several hydrophone stations were placed in the transit area close to the route into port. In total, 2,765 of these opportune measurements (MacGillivray et al. 2019) captured ships passing the station in any direction. Data were collected both during regular operation and while ships implemented a voluntary speed reduction to 11 kn during the passage. A significantly lower level of URN was recorded while the ships operated at reduced speeds. A portion of this dataset (called ECHO data) was later used in the EU Interreg Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS). A new set of reference values were generated by combining the ECHO dataset with a widely used reference model of the ship’s source-level spectrum. The new reference values for the source level were based on the ship’s speed and length and can be applied to different classes of ships in the ECHO dataset. This model has been named the JOMOPANS-ECHO (J-E) model (MacGillivray & de Jong, 2021).

1.1 AIM

The aim of this study was to investigate whether implementing a policy to reduce ship speed could reduce URN in waters around Sweden. Assessment considerations included legal/regulatory aspects, ship technological/operational prerequisites, methods to simulate the effectiveness, and local/regional environmental conditions. An important part of this study was to evaluate whether current models for predicting ship noise source levels could be applied to the types of ships that are commonly found in Swedish waters.

State-of-the-art scientific methodology was employed for this cross-disciplinary case study, which covered a geographical area that spanned several maritime zones and national jurisdictions and experienced extensive commercial shipping traffic throughout the year. Portions of the area have high biological significance, including cod spawning grounds and Natura 2000 sites for harbour porpoises and seabirds. The cross-disciplinary assessment will also serve to educate managers on the potential to reduce URN from commercial ships by imposing operational speed limits in specified areas around Sweden.

1.2 LIMITATION

This study focuses on URN only, while it is known that altering the cruising speed of ships might also affect emissions of other pollutants. This study covers policy measures to reduce URN that emerge from commercial ships. Further, no experts in economics or logistics were represented in this work, explaining why those analyses and perspectives were not covered in this study.

1.3 APPROACH AND DISPOSITION

This study was conducted by a cross-disciplinary team with expertise in the following fields:

Mathias Andersson, senior scientist at the Swedish Defence Research Agency (FOI), PhD in Marine Ecology with a focus on environmental impact of underwater sound on marine life.

Rickard Bensow, professor in hydrodynamics at Chalmers University of Technology with a focus on marine propulsion systems and cavitation nuisance.

Dag Glebe, expert in acoustics at IVL Swedish Environmental Research Institute, PhD in Engineering Acoustics with a focus on soundscape and computational hydroacoustics.

Ida-Maja Hassellöv, professor in maritime environmental science at Chalmers University of Technology with a focus on holistic assessments of the impact of shipping on the marine environment.

Emilia Lalander, PhD in Oceanography and scientist at the Swedish Defence Research Agency (FOI) with a focus on hydroacoustic measurements and analysis.

David Langlet, professor of Environmental law at Uppsala University, and former professor of Ocean Governance Law at University of Gothenburg.

Kjell Larsson, professor emeritus of Maritime Science at Linneaus University, with a focus on the impacts of shipping on the marine environment and AIS-analyses.

Lars Göran Malmberg, professor emeritus of Maritime and Transportation Law at University of Gothenburg.

Eva-Lotta Sundblad, scientific coordinator at the Swedish Institute for the Marine Environment, chair of the SIME Shipping Group.

Mikael Svedendahl, PhD in Applied Physics, and scientist at the Swedish Defence Research Agency (FOI) with a focus on hydroacoustic measurements, analysis, and hardware.

The report is organised as follows: The next three chapters (2, 3 and 4) present important foundational information: First we cover international regulations regarding URN in the different maritime zones. Second, we cover the main technical principles underlying the generation of ship noise. Third, we provide an introduction and an evaluation of the JOMOPANS-ECHO source-level model that was used in the case study. Chapter 5 covers current ship traffic in the study area, an analysis of legal options for regulating ship speed in that area, and the predicted change in noise levels by reducing speed. The results are discussed at the end of chapter 5 followed by conclusions in chapter 6. Technical details on the methods used and detailed explanatory figures and graphs are presented in the Appendices.

2. LEGAL ASPECTS OF UNDERWATER NOISE FROM SHIPPING

This chapter explores the legal preconditions for imposing speed limits on ships in order to reduce underwater marine noise. Before we cover the legal tools available to Sweden in this regard, the characterisation of noise as a form of marine pollution and the legal obligations pertaining to such pollution are briefly analysed.

2.1 NOISE AS POLLUTION

Although there are no international rules specifically targeting noise from ships, there should be no doubt that underwater noise can qualify as “marine pollution” for the purpose of international law. The United Nations Convention on the Law of the Sea (UNCLOS), which provides the overall legal framework for the utilization as well as the protection of the world’s seas, defines pollution of the marine environment as:

> “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” (UNCLOS, Art. 1).

Sound is a form of energy, and although more research is needed on the impacts of specific noise on specific species, it is well established that noise can harm marine life (see Duarte et al., 2021). That underwater noise from ships may have negative consequences on marine life, both in the short and long term, has also been recognized by the IMO (MEPC 2014). Such noise can therefore, at least above certain levels, be considered a form of marine pollution and is subject to international rules on such pollution. It should also be mentioned that the concept of marine pollution has been construed broadly in recent international case laws such as the South China Sea

Arbitration, in which the arbitration panel found the use of explosives for fishing to constitute a form of pollution (PCA 2016, para 970).

Under international law, states are under a general obligation to prevent pollution of the marine environment. More specifically, UNCLOS requires states to take “all measures consistent with [the] Convention that are necessary to prevent, reduce and control pollution of the marine environment from any source” (UNCLOS, Art. 194). In doing so, they shall endeavour to harmonize their policies. The obligation to prevent pollution is further elaborated, for example, in the regional Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area, which also requires the application of the precautionary principle in this regard (Art. 3).

This, however, does not automatically translate into a right to prescribe and enforce rules on noise from ships, including speed limits. To determine when a state has such rights, the preconditions for exercising jurisdiction must be analysed in the relevant context.

2.2 JURISDICTIONAL PRECONDITIONS

First, it must be noted that a state may exercise jurisdiction over a ship in different capacities: as a flag state, as a coastal state, and as a port state. Since port states have little say over ships’ speed outside ports this form of jurisdiction will not be discussed further. The flag state – i.e., the state where the ship is registered as reflected by the flag flying on the ship – has the primary responsibility and authority to regulate and enforce rules pertaining to the ship (UNCLOS, Art. 94). This right applies irrespective of where the ship is located, although such rules cannot typically be enforced in areas under the jurisdiction of another state. Sweden can thus, in principle, require that ships flying the Swedish flag reduce their speed in any area provided it doesn’t pose a threat to safe navigation. The EU could likewise establish rules that would be applicable to all ships registered in an EU member state. This becomes particularly pertinent in the light of the fact that the EU’s marine strategy framework directive (MSFD) provides for the establishment of threshold values for underwater noise consistent with the achievement of good environmental status in the marine environment (MSFD 2008/56/EC).

However, given that our focus is on whether Sweden has the right to enforce speed limits in order to generally reduce noise pollution within its waters, the reach of flag state jurisdiction also has limited potential. Therefore, we will assess to what extent a state can regulate ships’ speeds in its capacity as coastal state.

The jurisdictional rights of a coastal state extend up to a maximum of 200 nautical miles from the coast. Areas beyond the 200 nautical mile zone are referred to as high seas and are almost exclusively under flag state jurisdiction. However, there are no high seas areas in the Baltic Sea, the Skagerrak, or the Kattegat. These are all covered by the coastal states’ maritime zones. The zones of primary interest here are the territorial sea and the exclusive economic zone (EEZ). There is also a zone called internal waters that will be covered only briefly because it is of limited relevance to ships passing through Swedish waters. (See Figure 1 for an overview of different zones along the Swedish coast.)

Before delving deeper into maritime zones, we note that all such zones are measured from the so-called baseline. In fact, there are two kinds of baselines: normal and straight. The normal baseline is the low-water line, "as marked on large-scale charts officially recognized by the coastal State" (UNCLOS, Art. 5). Straight baselines, which may be used "where the coastline is deeply indented and cut into or, if there is a fringe of islands along the coast in its immediate vicinity", are instead formed by linking appropriate points on islands and certain low-tide elevations along the coast (UNCLOS, Art. 7).

Internal waters, which is any water on the landward side of the baseline, can be found in harbours, river mouths, and archipelagos. Internal waters are in most respects subject to the coastal state's full sovereignty in the same way as land territories are.[2] Here the coastal state is essentially free to set the rules it chooses for ships, including speed limits. However, because internal waters only cover a negligible part of the sea it is more relevant to discuss the zones on the seaward side of the baseline.

Figure 1. Different zones along the Swedish coast. The black line shows the border for the Swedish territorial sea. The red line shows the border for the Swedish Exclusive Economic Zone (EEZ).

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[2] An exception to this rule is applicable in case the establishment of a straight baseline has the effect of enclosing as internal waters areas which had not previously been considered as such. In such cases a right of innocent passage exists in those waters. (UNCLOS, Art 8).

The territorial sea stretches from the baseline to a maximum of 12 nautical miles seaward. While the sovereignty of the coastal state extends over its territorial sea, this zone is subject to an important exception to its ability to regulate shipping: the right of so-called innocent passage. This is the right of all foreign ships to pass through the territorial sea provided that the passage is “continuous and expeditious” and not “prejudicial to the peace, good order or security” of the coastal state (UNCLOS, Arts. 17-19).[3] However, the coastal state may adopt laws and regulations related to innocent passage through its territorial sea. Such laws and regulations may cover, for example, the preservation of the environment of the coastal state and the prevention, reduction, and control of pollution thereof. The rules and regulations must conform to UNCLOS and other relevant rules of international law. They may not apply to the construction, design, equipment, or manning (so-called “CDEM standards”) of foreign ships unless they give effect to generally accepted international rules or standards (UNCLOS, Art. 21). That is not a problem for speed limits because they relate to how the ship is operated, not to its construction, design, equipment, or manning.

Laws and regulations adopted by the coastal state must not hamper the innocent passage of foreign ships (UNCLOS, Art. 211). Whether speed limits could be considered to hamper innocent passage may be assessed by looking at which restrictions are generally accepted. A coastal state is explicitly authorised to prescribe sea lanes and traffic separation schemes to be used by ships claiming the right to innocent passage (UNCLOS, Art. 22). It is also widely recognized that this may be done not only for safety but also for purely environmental reasons (Jakobsen, 2016) Reasonably, speed limits often pose significantly lower impediments to innocent passage than requiring ships to use a specific sea lane. There are also examples of speed limits being imposed by individual states for environmental reasons, not least for protecting cetaceans from ship-strikes (Gillespie, 2016).

The EEZ differs significantly from the territorial sea in terms of coastal state jurisdiction. In this zone the coastal state does not exercise general sovereignty. Instead, other states enjoy to a large extent the same rights in the EEZ as they would in the high seas, including the right to freedom of navigation (UNCLOS, Art. 58). However, unlike in the high seas, in its EEZ the coastal state enjoys certain sovereign rights or jurisdiction over specific activities (UNCLOS, Art. 56). Of relevance to this analysis is the coastal state’s “jurisdiction … with regard to … the protection and preservation of the marine environment”. But this is not an all-encompassing jurisdiction covering all situations concerning protection of the environment. Instead, it is only applicable to specific situations as stipulated in UNCLOS. To what extent it allows the coastal state to take unilateral measures – as opposed to measures adopted within the framework of the IMO – is a matter of interpretation and contention. It is clear, though, that a coastal state’s right to set rules of navigation is much more limited in its EEZ than in its territorial sea

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[3] A list of passage activities that qualify as prejudicial to the peace, good order or security of the coastal State is found in UNCLOS Article 19.

(Jakobsen, 2016). For instance, in the M/V Virginia G Case (Panama/Guinea-Bissau), the International Tribunal for the Law of the Sea (ITLOS) held that a coastal state does not have a general right to regulate the bunkering of foreign vessels operating in its EEZ (ITLOS 2014) although this is an activity associated with risks for the marine environment within that zone.

It is also widely acknowledged that environmental measures taken by the coastal state in its EEZ should normally not go beyond giving effect to generally accepted international rules and standards (Andreone 2015; Jakobsen, 2016). Although there are no set criteria for determining what is an internationally accepted rule or standard, there is little to support the view that speed limits imposed for environmental reasons would qualify.

In addition to this rather limited jurisdiction regarding environmental protection, the coastal state also has "sovereign rights for the purpose of … conserving and managing the natural resources" of its EEZ (UNCLOS, Art. 56). It could be argued that these rights allow the coastal state to take measures to protect marine living resources, such as fish, from impacts that could harm the resource. However, if these rights were to be extended to such diffuse stressors as underwater noise from ships it would effectively blur the line between conservation of living resources and protection of the environment. The UNCLOS makes a clear distinction between "conserving and managing the natural resources", for which the coastal state enjoys sovereign rights, and "protection and preservation of the marine environment" for which coastal states only have limited jurisdiction.

Even if the coastal state were to be considered competent to impose speed limits on ships within its EEZ, there is "a clear preference" for flag state jurisdiction when it comes to enforcement of rules on pollution in the EEZ (Andreone, 2015). Only when there are clear grounds for believing that a ship navigating in the EEZ has violated applicable international rules on pollution from ships or national rules giving effect to such international rules and standards may the coastal state even require the ship to provide information needed to establish whether a violation has occurred. Also, proceedings for such violations may in principle only be instituted when a "discharge causing major damage or threat of major damage" to the coastline or related interests of the coastal state or to any resources of its territorial sea or EEZ has occurred (UNCLOS, Art. 220).

2.3 LEGAL CONCLUSIONS

In conclusion, international law supports the imposition of speed limits by a coastal state like Sweden on ships navigating its territorial sea, provided that the measures are non-discriminatory and do not impede innocent passage. As for the EEZ, it could be argued that there is a corresponding right to impose speed limits if needed to protect the living resources of the EEZ from the harmful effects of underwater noise. However, this would challenge the structure and logic of UNCLOS relating to how pollution and natural resources management are regulated and would likely meet with protests. Because there are not yet any international standards for underwater noise that the coastal state can rely on, imposing speed limits based on its jurisdiction over pollution is unlikely to be generally accepted by flag states. Moreover, there might be significant challenges in enforcing such standards on ships that do not respect them.

3. CAVITATION NOISE GENERATION AND ITS IMPACT ON SHIP PROPULSION DESIGN AND OPERATION

There is a growing number of studies investigating how technical or operational characteristics of ships contribute to URN. Some of these studies collected dedicated measurements from single or multiple ships, e.g. the study on the effect of controllable pitch propellers (CPP) or fixed pitch propellers (FPP) on coastal ferries by McIntyre et al. (2021). There are also some review papers on possible solutions to mitigate noise, e.g. Smith and Rigby (2022). Other literature covers statistical analyses of larger datasets of measurements on vessels of opportunity; examples here are the outcome of the ECHO slowdown trial in Vancouver (MacGilllivray et al., 2019), but also attempts at correlating URN with ship parameters (Chion et al. 2019; MacGillivray et al, 2022). Apart from the ECHO trial, which found a significant reduction in URN by slowing down large commercial ships with FPP, results have been inconclusive. While it can be expected that reducing speed will lead to reduced URN for most vessels, there seems to be no other solution, neither technical nor operational, that would work for all vessels.

Here, we provide a brief description of the origins to cavitation noise from ships in order to better understand the reasons behind the lack of generalisable solutions, provide some background on the modelling and analysis described in this report, and interpret the data and the reliability/uncertainties in the results. For brevity, we will limit the discussion to cavitation noise because this is the main source of noise when cavitation is present, which is typically the case for ships that travel at speeds of 11 kn or higher.

When the propeller starts to cavitate, it has been established that the noise generated by this cavitation will dominate all other sources of noise, such as machinery. Some tonal noise can often be detected and is related to engine generators, gears, or similar, but the energy emitted by these sources is lower than that from cavitation, e.g. see Ross (1964) for some basic explanations and comparisons. At transit speeds, a basic principle for good propeller design is that the propeller cavitates, otherwise it is not efficient enough. There are many aspects behind this principle, but the basic one is that cavitation can be avoided by increasing the blade area, which then leads to increased losses and reduced efficiency. At present, propeller manufacturers are forced to compete on efficiency. From a propeller design perspective, reduction of cavitation noise is thus typically in conflict with achieving low fuel consumption. There are exceptions to the generalisation that all vessels operate with cavitating propellers, e.g., for military vessels and research vessels where silent operation is more important than efficiency, contracts prioritise the highest speed of cavitation-free speed, or Cavitation Inception Speed (CIS).

Cavitation on the propeller blade arises from low pressure levels that occur when loading the blade, which generates the forward thrust. This occurs on the suction side, or the front side of the blade. Higher thrust requirements typically yield lower pressure and more cavitation; this can be reduced by increasing the blade area, which would distribute the pressure over a larger area, but at the cost of friction-related losses and reduced efficiency. The blade experiences different loading conditions during one complete revolution because it operates in the wake of a ship. Cavitation thus grows and shrinks regularly with the periodicity of the passing blades. In addition, there are unstable phenomena in the ship's wake and cavity development. This set of conditions only applies to a ship at constant speed with well-developed cavitation on the propeller. If the ship operates at speeds close to CIS, cavitation may start to occur more intermittently leading to more erratic behaviour. Further, if the propeller operates in conditions it is not designed for, the low-pressure zone may move to the other side of the blade, the pressure or back side, yielding highly transient cavitation behaviour.

For a single cavitation bubble, the level of radiated noise is related to the rate of change in the volume of the bubble. Thus, rapid growth or violent collapse of a bubble would yield higher levels of noise than a bubble that underwent slower variation in size. Remarkably, this relation applies to cavities of almost any shape. One additional factor to consider for propeller cavitation is that the cavity is moving in the water with the propeller blade. Thus, the size of the cavity is also important, as a larger cavity is noisier than a smaller one. This factor, however, has less impact on noise levels than the rapid growth or collapse of the cavity. Thus, the regular dynamics of cavitation on the blade produce tonal noise that increases in proportion with both the cavity size and the dynamics of collapsing bubbles. Further, rapid collapse or intermittent occurrence leads to high frequency noise within the broadband range.

Thus, cavitation noise can be reduced without sacrificing efficiency by either reducing the power requirements to allow for a lighter load on the propeller or by reducing wake variations, which would allow for less variation in cavity volume; in many cases often also leading to improved efficiency. This can be partially achieved through technical solutions, e.g. by designing a wake-equalising duct to improve the propeller inflow, or through energy-saving solutions such as wind assistance, etc. However, there is no universal device that works for all vessels, and a solution that improves the wake on one ship might worsen it on another. Further, predictive tools are not yet advanced enough to be able to reliably predict changes in URN.

Reduced speeds lead to reduced power consumption, which in turn makes noise reduction a reasonable and expected. However, this might not be the case for ships that are equipped with a CPP. The CPP traditionally operates at a constant shaft rotation rate due to constraints in the machinery, e.g. a shaft generator can only operate at a fixed frequency. Ship speed is controlled by changing the pitch of the propeller. This may lead to cavitation on the pressure side, which, as described above, typically leads to highly dynamic and disruptive cavitation performance. However, there are ships with CPP where changes in shaft rotation and propeller pitch are integrated to extend the range of efficient operation of the propulsion system. To accurately predict the level of radiated noise from ships with CPP, one must know which mode of operation is under use. This information was not available in the traffic data accessed for this study by the Automatic Identification System (AIS). In general, CPP-equipped ships operating at constant shaft rates (the type of operation that generates high URN) are not very common, but can affect the outcomes of a speed limit mandate when they are in service, e.g. a ferry might negatively impact URN outcomes.

To conclude this chapter, we provide a comprehensive description of how ship speed affects emitted noise levels. For those interested, detailed plots and explanations are given, e.g., in the book by Ross (1964). Typically, noise from the machinery dominates at speeds under CIS, before cavitation starts, and this noise is speed-independent. Generally, CIS is only determined for specialised vessels (e.g., silent operation vessels) and not for commercial vessels, but it is reasonable to expect it to be in the range of 8-10 kn. At CIS or just above, intermittent cavitation can lead to a sharp increase in noise levels of approximately 10-30 dB, often resulting in a broadband hump at higher frequencies of approximately 1-5 kHz. At speeds that allow cavitation to develop, the dynamics created by the blade passing the ship's wake generate tonal sound in the lower frequencies, either at blade-pass frequency or at harmonics below ~100 Hz, that typically dominate over the broadband hump. Increasing the speed any further would normally lead to a more loaded propeller and increased levels of radiated noise. There are some indications that lower frequencies are more affected than higher ones, which is a reasonable assumption from a physical point of view, but would need further studies and might not be generalisable for all vessels.

4. MODELLING OF SHIPS AS POINT SOURCES OF NOISE

Detailed predictions of URN from individual ships are impeded by high degrees of uncertainties. Measurements at model scale of the same set-up performed by different test institutes can differ by almost 20 dB, and methods for computational assessment are not yet established (Tane et al, 2020). This is an active area of research, e.g., the PUB (Prediktionsmetoder för utstrålat fartygsbuller) project within the Lighthouse Sustainable Shipping program in Sweden. However, there are several statistical models developed by analysing large-scale data on the contribution of shipping-generated URN to the underwater soundscape. A technical review of these models is provided in Liefvendahl et al. (2015); here we include a brief overview of available models to indicate their limitations and reliability.

One of the first models of ship URN was developed by Ross (1976), which was based on theoretical arguments and dedicated measurements of URN on both isolated propellers and on ships. The model was parametrized by reference values for ship speed and length. Most of the measurements concerned vessels from World War II and were later extended to some vessels from the 1950s and 1960s. In general, all vessels were small (below 150 meters in length) and had low design speed (10-12 kn).

One of the more commonly used models is RANDI3.1 (Breeding et al., 1996). It is based on the model by Ross, but was further extended to ship types that appeared in the 1980s, e.g., Supertankers. The framework in RANDI3.1 also includes more elaborate propagation modelling that considers hydrography and hydrology.

Recently, an effort was made in the JOMOPANS project to further update the RANDI3.1 model (MacGillivray and de Jong, 2021). Using the measurements from the ECHO project, new reference values were developed for ship speed and length for the different classes of ships in the ECHO dataset by minimizing the residual error in URN between the model and the set of measurements. This model has been named the JOMOPANS-ECHO (J-E) model. More information on this model is given below and in the Appendix.

The Wittekind model (Wittekind, 2014) is worth mentioning as well because it takes a different approach. Here, the three different contributions from machinery noise, low-frequency cavitation noise, and broadband cavitation noise are modelled separately based on detailed technical information, including engine type and size and propeller diameter, that is not available in AIS data.

In this study we chose to use the J-E model because it is based on modern measurements from a large number of modern ships and thus deemed to be the most accurate considering the ship information available to us for the analysis.

4.1 THE JOMOPANS-ECHO MODEL – BACKGROUND AND LIMITATIONS

In this study the J-E model is used for ship noise source modelling. This model for monitoring ambient noise in the North Sea expanded on a prior framework developed through the JOMOPANS project and was supported by the European North Sea countries (https://northsearegion.eu/jomopans/; accessed on 26 March 2021). One of the outcomes of the JOMOPANS project was this model, which can be used to generate regional maps of shipping-related noise in the North Sea. The effort is described in MacGillivray and de Jong (2021). Their review of prior modelling efforts led to their decision to base this model on the existing RANDI3.1 while updating reference values and parameters to a more appropriate and contemporary set of measurements of ship URN.

The data they chose to work with were originally collected through the ECHO program. This refers to the two-month trial where the Vancouver Fraser Port Authority requested voluntary compliance with a speed limit of 11 kn from all ships passing through the Haro Strait outside Vancouver. Several hydrophone stations collected the radiated noise data before and during the trial. These measurements from ships of opportunity, i.e., ships that happened to pass by the measurement stations as opposed to studies where ships were specifically requested to run on a specific route, have been documented by MacGillivray et al. (2019).

Next, MacGillivray and de Jong (2021) reanalysed the measured data and compared them with the RANDI3.1 model. The ships in the dataset were categorised into different classes, and new parameters were determined for each class, which minimised any residual differences between the model and the measurements spanning the whole range of frequencies for all ships in every class.

The regression analysis performed in the JOMOPANS project demonstrated good agreement between the developed model and the data in the ECHO dataset. When applying the model to other sets of vessels there are several considerations that can affect the applicability and reliability of the model:

- This model cannot be used to model URN from a single ship, and only average levels from several ships can be estimated.
- The statistical uncertainty was estimated to be ± 6 dB in the frequency range of 20 Hz-20 kHz.
- There are no data supporting the accuracy of the model for ships that were not included in the ECHO dataset. This relates to type, size, and speed of the ships.
- The voluntary speed limit was set at 11 kn, so there are no data below this speed. Based on this and physical arguments, this model should not be applied for speeds under this limit.
- The speed function in the model is based on only two speeds for each vessel in the dataset, and the behaviour of URN for intermediate speeds is not verified although the complete statistics cover this range.

4.2 SHIP CLASSES IN THE JOMOPANS-ECHO MODEL

The ships that were measured in the ECHO project were categorised into different classes of ships. The J-E model gives further recommendations on how this classification of ships translates to different AIS ship types. We describe here the different ship classes in the ECHO dataset and additional ship types that can be found in areas around the Swedish coast to better understand the applicability of the J-E model for areas and traffic that fall outside the range of the original data. We will limit the description to regular commercial vessels, and exclude other types e.g., Fishing Boats, Tugs, Dredgers, and Work Boats (some of which are distinct classes in the ECHO dataset while others are classified as *Miscellaneous*).

The following major ship classes are included in the J-E model:

- Tankers are vessels with a full hull form and a large block coefficient that operate at relatively low design speeds in the range of 12-15 kn. Often, tankers are single screw, i.e., are equipped with one propeller. In the ECHO dataset all tankers are relatively large, around 170-200 m in length.
- Bulkers are comparable to tankers in terms of the hydrodynamics for the purposes of this study. Also, the bulk ships in the ECHO dataset are of similar size as the tankers.
- Container Ships are designed with a slender hull and operate at medium to high speeds in the range of 16-20 kn. They are generally equipped with one propeller. The container ships in the ECHO dataset are large, around 300 m.
- Vehicle Carriers are somewhat more ambiguous in definition. We interpret this class as Pure Car or Truck Carriers (PCTC), i.e., used to ship cars or trucks as cargo, as opposed to the broader classification of RoRo ships (Roll on-Roll off) where the shipped trucks themselves are carrying the cargo. These vessels are comparable to container ships in that they have slender hulls and a single propeller, but they are designed to operate at lower speeds in the range of 16-18 kn.
- Cruise Ships are slender and possess a flat barge-type aft, often with two or more pods as propulsion systems. Care is taken to ensure smooth operation with high constraints on vibrations, with passengers' comfort in mind.
- Passenger Ships are also an imprecise ship class. It is noted that they are smaller, <100 m in length, but no other details are available.

The following classes of ships were not included in the original ECHO dataset but would need to be considered when the model is applied to traffic around Sweden:

- Smaller coastal or liner vessels of Tankers, Bulkers, and Container Ships, with lengths in the range of 75-150 m.
- RoPax and RoRo Ships, carrying passengers and their vehicles, or cargo-carrying trucks. These ships are often slender with twin shaft lines and propellers, and thus differ in design from the vehicle carriers that were included in ECHO.
- Some ferries that may differ from RoPax, mentioned above. Such ships can be classified under the ECHO Passenger class.

In addition to this, Fishing Vessels are difficult to classify because they typically operate under two modes: in transit or towing/trawling. This classification is included in the ECHO dataset, and it is reasonable to believe that these data were measured in transit mode. However, if we were to only use AIS data it would not be possible to uniquely determine if a ship was in transit or trawling. Thus, if noise from fishing is in focus, special analysis methods are needed.

4.3 COMPARISON OF THE JOMOPANS-ECHO SOURCE-LEVEL MODEL DATA TO MEASUREMENTS OF SHIPS FROM WATERS AROUND SWEDEN

Source-level models such as the J-E model are used to produce soundscape maps, which are later used to study the environmental pressure that URN places on the marine environment. It is therefore necessary to evaluate the models in terms of their agreement with measured data, even though source levels from individual ships will deviate. This is especially important when applying the J-E model to a different composition of ship classes, sizes, and speeds than what it was originally developed for. Thus, data from opportunistic measurements of commercial ships passing a cabled real-time hydrophone station on the Swedish west coast were used to test the agreement of the J-E source-level models for commercial ships in waters around Sweden. The scope of this analysis was to evaluate whether, and to what extent, the J-E model could be used in this case study even though it was based on data from a different region and vessel type. This was done by studying the difference between the estimated source level from the measurements and the calculated source level for the various ship classes from the J-E model. In addition, we studied the relationship between speed and source level in both the models and the measurements in order to estimate the accuracy of the model.

The measured data were collected from the Vinga hydrophone station, which was in operation from November 2021 to June 2022. The station was located in the ocean outside the entrance to the port of Gothenburg on the west coast of Sweden. The station was operated under the JOMOPANS project. Initially, there was a cabled hydrophone system in place, which was later succeeded by an autonomous hydrophone logger (Soundtrap 500HF from Ocean Instrument NZ) that collected data from April to June 2022. The station was designed to record the local ambient noise and obtain opportunistic measurements from several commercial vessels passing in relatively shallow, 46 m, waters. Details of the hydrophone station and the EU project can be found in Andersson et al. (2023).

When commercial ships travelled to and from the port, they would pass the hydrophone station, resulting in opportunistic source-level measurements. Ship passage was detected using AIS data recorded locally, and suitable time periods in the recorded acoustical data were selected based on the closest approach distance, as well as the distance to other vessels. Details about this analysis method can be found in Appendix 1 and in Lalander et al. (2022).

4.4 SHIP TYPE COMPARISON

Ships can be categorized according to information transmitted in the AIS messages. However, many times there are discrepancies in the AIS message regarding the ship type and the actual ship itself. Therefore, ship IMO numbers were used to verify the ship type from the Vessel Finder database. Thereafter, the ships used in this analysis were divided as per the classification used by MacGillivray et al. (2019), which was also used in the

J-E model. Hereafter, we refer to the different categories of ships as classes.

The Vinga dataset contains source-level estimations of 254 opportunistic commercial ship passages. Many ships belonged to the ship classes of Tankers, Bulkers, and Container Ships. However, the most common ship type in the Vinga data, in terms of number of passages, was the RoRo Ship, which does not exist as a class in the J-E model (Appendix 1, Table A1.1). This type of ship is also common in other parts of European waters. Therefore, we conducted an analysis of these ships to determine how to classify RoRo ships by J-E vessel classes for future use in the case study. Out of the unique ships in the Vinga dataset, 60 also traversed the area covered by the case study.

There were many passages by RoRo Ships, but only eight unique ships were identified. These ships were the largest and fastest in the whole dataset. For instance, one RoRo Ship passed the Vinga station 33 times with an average speed of 20 kn. Of the General Cargo Ships, only a few appeared more than once. For Tankers, only one ship appeared more than 4 times, and it passed the station 8 times with an average speed of 8 kn. Initial analysis showed some limitations in the Vinga dataset, which are described below:

- The classes of Vehicle Carriers, Container Ships, and Miscellaneous had very few passages during the measurement and thus were excluded from subsequent analysis.
- A few estimated source levels were unrealistic and therefore were removed from this analysis. Most likely, the underlying measurements forming the basis of those source-level estimations contained interference of either hydroacoustic or electrical nature.
- Only data from November 2021 to May 2022 were included because the sound/speed profile changed in May, affecting the propagation loss estimations in the following month.

The classes in the J-E model are tuned to a reference speed and length, and the models might deviate for ships outside this reference range. Compared to the ECHO-dataset, the General Cargo Ships (J-E class Bulkers) and Tankers passing by the Vinga station were generally shorter (Appendix1, Figure A1.2). For instance, the Tanker class of ships appeared 33 times in this analysis and had an average length of 94 m. For the ships analysed in the ECHO dataset, the average length was 186 m. Most General Cargo Ships (J-E class Bulkers) were less than 100 m, while the J-E Bulker had an average length of more than 200 m. The RoRo Ship is not considered a class under the J-E model; however, RoRo Ships passing Vinga were longer than Vehicle Carriers class from than ECHO J-E, but were within the length range of the Container class in J-E.

Regarding ship speed, on average Tankers and Bulkers travelled faster in the ECHO dataset compared to the Vinga dataset (Appendix 1, Figure A1.2). The opposite was true for the RoRo Ships that operated at higher average speeds than Vehicle Carriers and Container Ships, although there was some overlap in operating speeds.

To summarize, in terms of ship length and speed RoRo ships in the Vinga dataset could potentially be categorized either as Vehicle Carriers or Containers in the J-E model in terms of length and speed, although as noted above the ship design could be different. However, it is not clear if the Tanker and Bulker ship J-E models were comparable to the Tankers and General Cargo Ships that passed the Vinga station, given the differences in length and speed. This is further analysed below.

4.5 SOURCE-LEVEL COMPARISON BETWEEN MEASUREMENT DATA AND THE J-E MODEL

The estimated source levels of the ships in the Vinga dataset were compared to the ship classes used in the J-E model, which were calculated using information on ship speed and length from AIS data. One example of this comparison is shown in Figure 2, where the source level estimated from a RoRo Ship passage is compared to the J-E model for different classes using the same length and speed as the passing ship. It can be noted that the estimated source level for this RoRo Ship matched data from both Vehicle Carriers and Container Ship classes. However, the propagation loss was not measured below 160 Hz, and therefore the calculated levels show some instances of larger uncertainties that are not seen at higher frequencies. The J-E model originates from RANDI3.1 with the difference that the source level is dependent on the classes of the ships from the ECHO dataset. The RANDI3.1 model is thus only dependent on the length and speed of the vessels, and the source level estimated from RANDI3.1 is included in the analysis for comparison. In this case, the J-E model has better accuracy than the RANDI3.1 model.

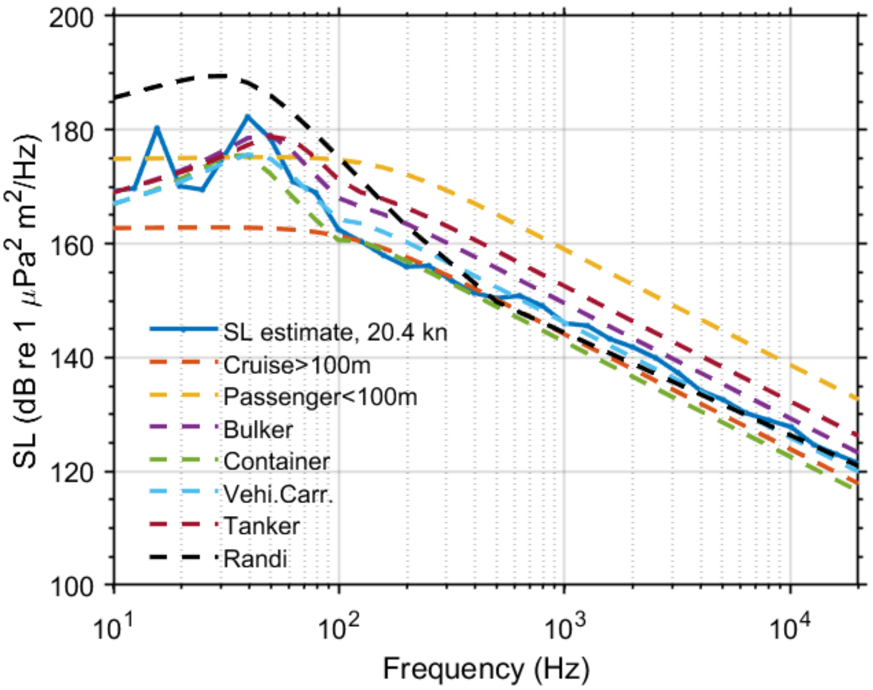

Figure 2. Source-level (SL) estimates from a RoRo Ship passage near the Vinga station in winter 2021. The solid blue line is the source-level estimate from the measurement, and the dashed lines are from the J-E model using different ship categories and the same length (234 m) and speed (20.4 kn) as the measured ship. The RANDI3.1 model result is included for reference. Note that the propagation loss was not measured below 160 Hz, and therefore the calculated levels have larger uncertainties at lower frequencies than at higher frequencies.

For a more detailed analysis of all 103 RoRo Ship passages, the broadband source level (20 Hz to 32 kHz) was calculated and compared with the J-E models of various ship classes, and the RANDI3.1 model is included in the analysis for comparison (Figure 3a). The source level of each class was subtracted from the estimated source level resulting in a residual. This was done for all ships falling under the classes of Tanker, General cargo/Bulker, and RoRo.

For RoRo Ships, the lowest broadband (20 Hz–32 kHz) mean of the residuals was noticed for the Container Ships (+1 dB) or Vehicle Carrier (–2 dB) classes (Figure 3b). In the spectral domain, upon comparing the two classes with lowest residual difference (Appendix 1, Figure A1.3), the Vehicle Carrier class was found to have a smaller residual difference throughout the spectrum (especially above 20 Hz), while the Container Ship class showed a predominantly negative residual difference below 400 Hz and a positive residual difference above 400 Hz, resulting in a smaller total residual difference. This indicates that the RoRo Ship can be categorized as either one of these two classes, corresponding to the categories of actual length and speed as seen in the previous section, and this holds true for the vessels passing Vinga.

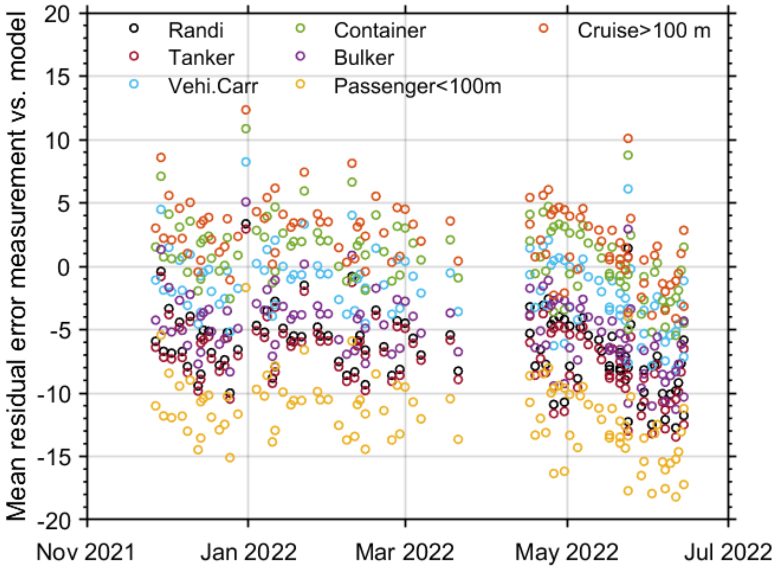

Figure 3a. The mean source-level error between measurement data and the model (20 Hz–32 kHz) for the RoRo Ships compared to the J-E ship classes as well as the RANDI3.1 model.

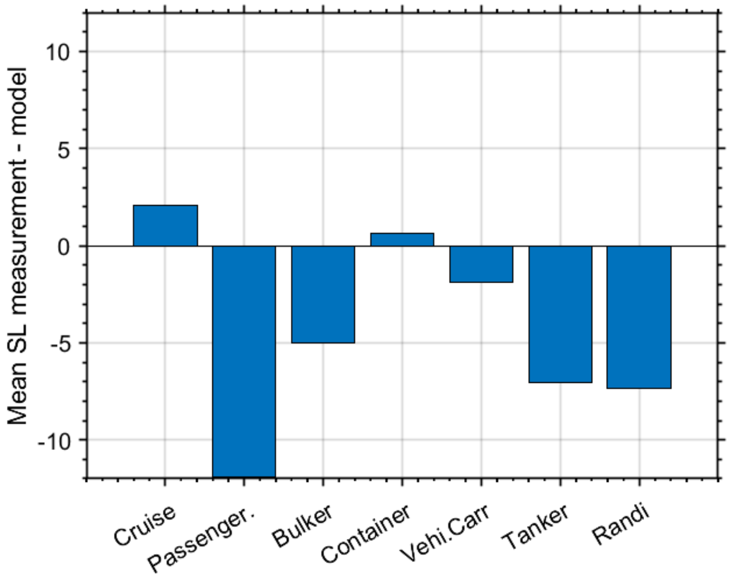

Figure 3b. The mean residual difference of all the passages in Figure 3a combined to a single broadband (20 Hz–32 kHz) value.

The residual source level for all RoRo Ships passing the Vinga station deviated in May 2022, which is believed to be an effect of the changes in sound propagation conditions in the area. This deviation could not be adjusted for because the measured propagation loss measurements were performed in March and June 2022. The water temperature and salinity profile changed in the middle of May. Due to this, only data between November 2021 and 15th of May 2022 were used in the analysis. More details regarding propagation loss measurements are available in Appendix I.

We performed the same analysis as described above for General Cargo Ships and Tankers. Briefly, for General Cargo (J-E class Bulker), 32 source-level estimations were used. The residual error between the measured broadband source level (20 Hz to 32 kHz) and the J-E Bulker model was 10 dB. For Tankers (J-E class Tanker), 22 source-level estimations were used, and the analysis showed a residual error between the measured broadband source level (20 Hz to 32 kHz) and J-E Tanker model of 8 dB.

4.6 SOURCE-LEVEL DEPENDENCE ON SHIP LENGTH AND SPEED

To further evaluate the J-E model regarding the length and speed of the ships passing the Vinga station, the estimated broadband (20 Hz to 32 kHz) source level was compared with the J-E and RANDI3.1 models (shown in Figure 4). The source level for the classes of Tanker and General Cargo (J-E class Bulker) was slightly underestimated by the J-E model as related to speed. This was especially true for ships traveling at low speeds (<10 kn), which is a speed outside the range of the model. This is exemplified by the fact that none of the measured source levels are below ~170 dB re 1 µPa, while the model consistently shows lower levels with lower speed. However, MacGillivray and de Jong (2019), also highlight the limitation of their model at speeds under 10 kn. Nevertheless, ships do travel at speeds below 10 kn, and some estimations of these speeds are needed.

Regarding the length dependency, both the RANDI3.1 and the J-E model estimate the source level at a lower level for both the Tankers and the Bulkers in comparison to the measured source level. This could be due to the shorter length of Tankers and Bulker ships at Vinga compared to ships in the ECHO-data set. For RoRo Ships, the J-E model Container class better predicts the average source level for both speed and length, whereas the RANDI3.1 model overestimates the source levels, especially for speed.

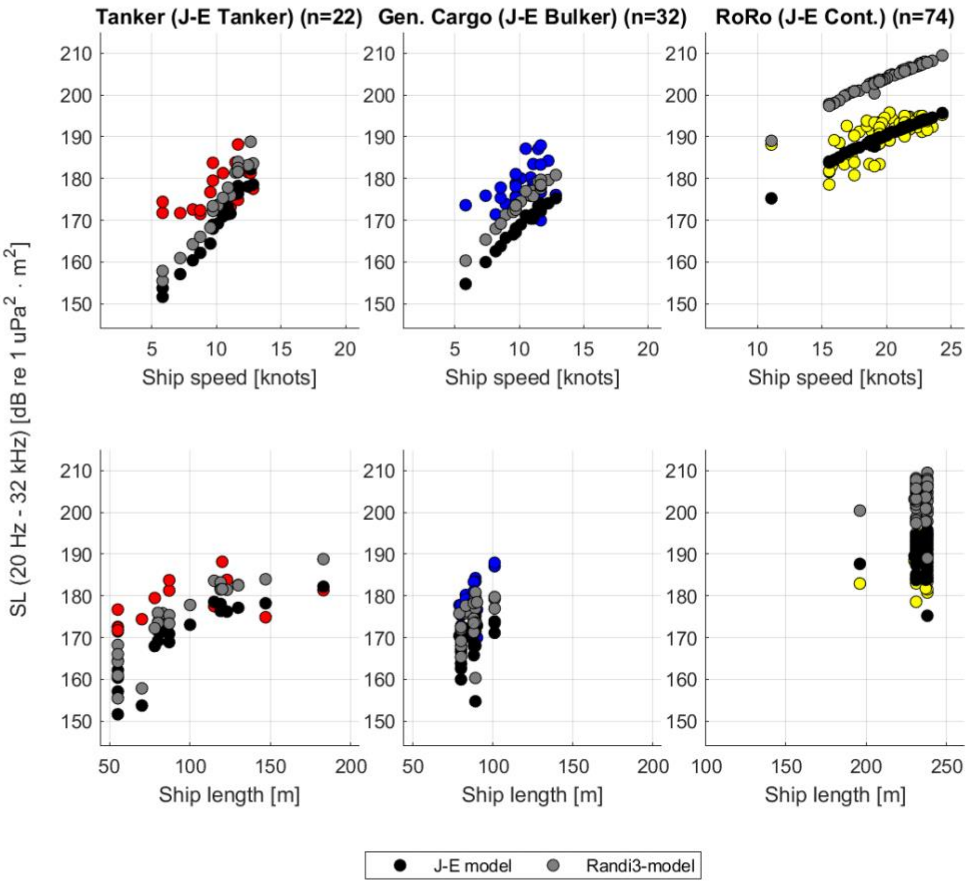

Figure 4. Broadband source level (SL) estimated from measurements and model data (J-E black, RANDI3.1 grey), respectively, compared with ship speed and length for ship classes Tankers (red), General Cargo (blue) and RoRo Ships (yellow) passing the Vinga station.

To summarize, the J-E model can be used for shipping traffic in waters around Sweden, although there are some discrepancies between measured and modelled source levels. The RoRo Ships can be classified as either Container Ships or Vehicle Carriers under the J-E model. There is a substantial difference between the J-E model and the estimated source level for Tankers and Bulkers, especially at low speeds. The source level is dependent on speed, but the Vinga dataset does not contain enough ship passages at different speeds for a detailed statistical comparison. There are uncertainties in the source level estimations that could explain some of the differences noted in the J-E model comparisons, such as the estimated propagation loss, which is complex in this relatively shallow depth (46 m). This is further elaborated on in Appendix 1.

5. CASE STUDY – RESTRICTING SHIP SPEED

In this chapter, we present some preconditions for restricting the speed in an area. Several factors were considered in selecting an appropriate area for this case study, which included various speed reduction strategies, legal options, potential measures, and their impact on maritime traffic and noise levels. The selected area should also contain sensitive habitats and species and be relevant to Swedish conditions. Based on this, a rectangular area was chosen in Kattegat north of the sound between Sweden and Denmark, Öresund, shown in Figure 5a and 5b. This area is partly within the Swedish jurisdiction, the traffic is quite dense as most ships will pass through the area *en route* to the central Baltic Sea, and it harbours sensitive habitats, including a spawning ground for cod and several Natura 2000 sites for the harbour porpoise and seabirds.

To analyse available legal options and their effects on maritime traffic, we simulated the potential reduction in URN under two operational scenarios that set maximum speed limits of 11 kn and 13 kn for all ship types. The lower limit of 11 kn was based on two factors – it had been successfully applied for the voluntary speed reduction trials in Vancouver and it was also deemed to be reasonable in waters around Sweden – and thus it was applied to the models used here. To balance the study, a higher speed (13 kn) was also chosen, and while we expected this to result in a lower level of noise reduction, it would substantially reduce the number of affected ships.

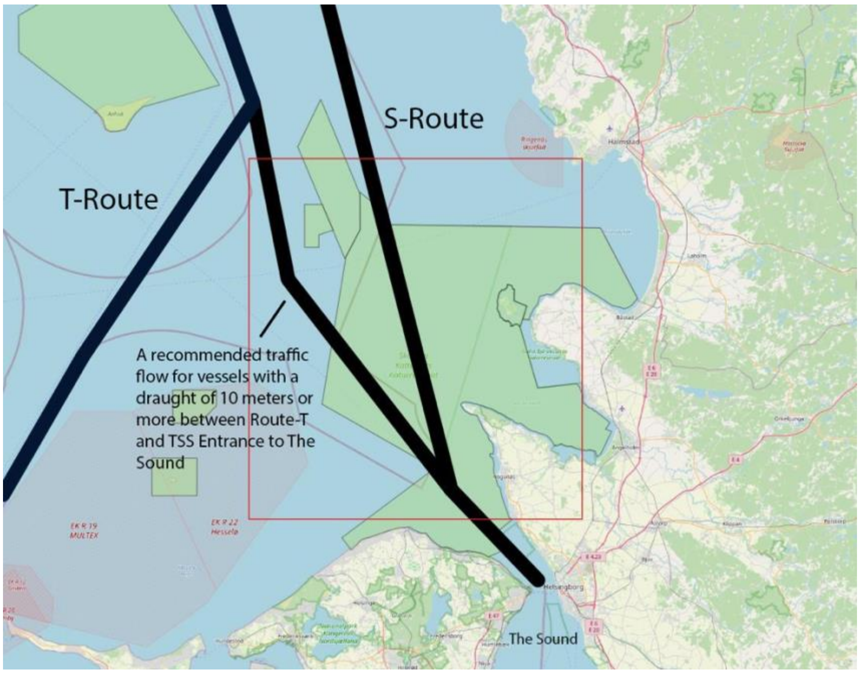

Figure 5a. The study area in southern Kattegat is marked by a red line. Black lines show the main ship routes. Green areas show Natura 2000 sites in Swedish and Danish waters (background map from QGIS).

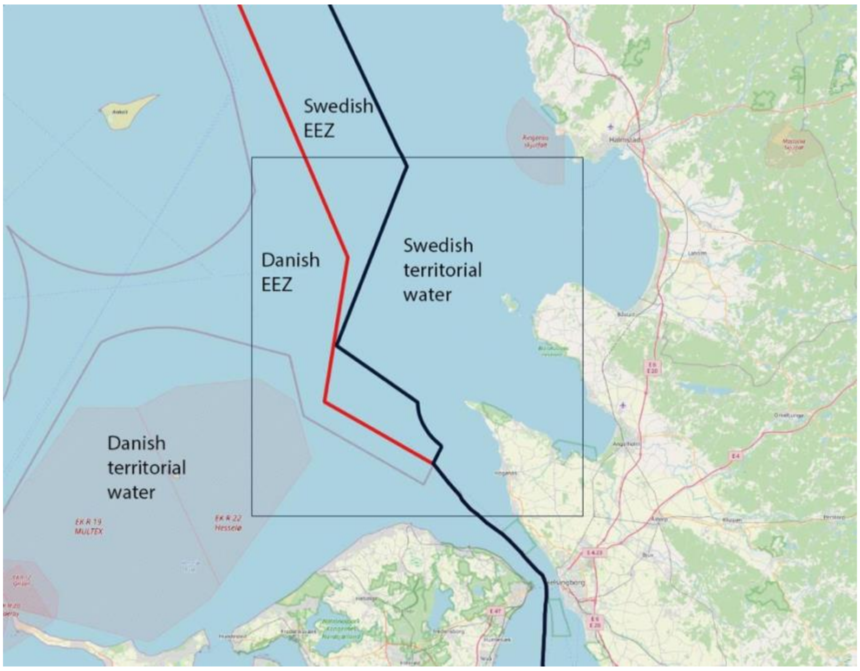

Figure 5b. Different zones in southern Kattegat. The waters east of the black line are Swedish territorial waters. The area between the black and red lines is the Swedish EEZ. The zones west of the Swedish EEZ and territorial waters are the Danish EEZ and Danish territorial waters. The Danish zones are separated with a thin greyish line. The study area is marked with a thin black line.

5.1 ANALYSIS OF SHIP TRAFFIC IN THE STUDY AREA IN SOUTHERN KATTEGAT

Southern Kattegat, north of Öresund has some of the heaviest traffic in the Baltic Sea (Figure 5 a and b). Approximately 4,511 unique ships passed through the area at least once during calendar year 2021—this estimate does not include fishing ships and smaller fishing and recreational boats. Most ships followed the major routes, but no part of the study area was completely free from traffic. Most ships observed in the study area also passed through Öresund. Very large ships, such as fully loaded large tankers and dry bulk ships with draughts exceeding 7.7 meters, cannot pass through the shallow southern waters of Öresund and thus, were rarely observed in the study area, which was situated directly north of Öresund. Very large ships instead use the T-route through the Danish Great Belt when travelling to and from the Baltic Proper. Large ships with draughts exceeding 7.7 meters coming from the north may call on the ports of Halmstad or ports in Öresund such as Helsingborg, Landskrona, Malmö, and Copenhagen. The ships that travelled through the study area in 2021 were registered in 64 countries (flag states). Approximately 2 percent of the ships were registered in Sweden and about 4 percent in Denmark (Appendix 5). The number of days that different ships, and different ship classes, were present in the study area differed greatly. Analyses of AIS data showed that as many as 68 percent of the ships that passed through the study area at least once were only observed in the area for 1 to 4 days in 2021. About 30 percent of the ships were observed in the area more frequently, that is, for 5 to 40 days. About 2 percent of the ships were observed in the area for more than 40 days (Figure 6 and 7).

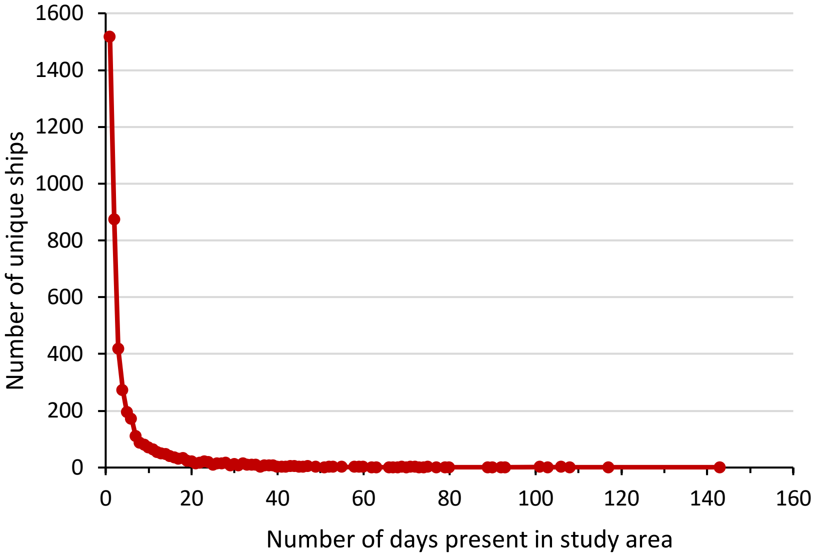

Figure 6. The temporal distribution of ships´ presence in the study area. Most ships passed through the study area only a few times in 2021. Two ships, one RoPax Ship, and one Pilot, which were present in the study area for 290 days and 251 days, respectively, are not included in the figure.

One day of presence of a ship, that is, one shipday, represents in most cases one transit through the study area. In total, the 4,511 unique ships travelling through the area added up to 28,247 shipdays. The number of shipdays was calculated as the overall sum of the number of days each ship was observed in the area. A minority of the ships, about 32 percent, that were observed in the area for five days or more resulted in 80 percent of the total number of shipdays (Figure 7). Further, the 76 ships that were observed for 41 days or more resulted in approximately the same number of shipdays as the 3,081 ships that were only observed in the area for 1 to 4 days.

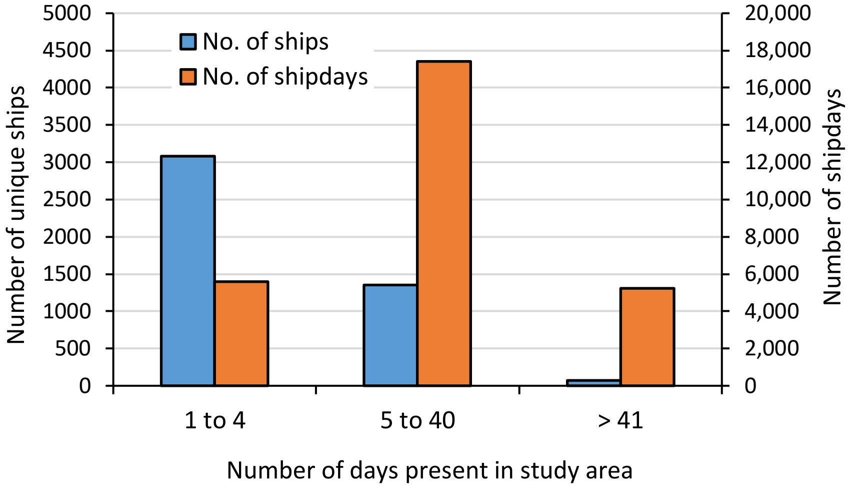

Figure 7. Relationships between the number of unique ships and the number of shipdays in 2021.

Table 1. Number of ships travelling in the study area and the number of shipdays in 2021.

SHIP CLASS/TYPE	NUMBER OF UNIQUE SHIPS	PRESENT DURING 1-4 DAYS	PRESENT DURING 5-40 DAYS	PRESENT DURING 41+ DAYS	TOTAL NUMBER OF SHIPDAYS
Tankers	989	672	301	16	5759
Dry bulk ships	1274	1202	66	6	3056
General cargo	1555	783	753	19	12677
Container ships	115	58	47	10	1592
Reefers	85	51	33	1	675
RoRo	66	21	35	10	1266
Vehicle carriers	58	33	18	7	689
RoPax	27	23	1	3	531
Cruise ships	30	22	8	0	122
Miscellaneous	312	216	92	4	1880
Sum	**4511**	**3081**	**1354**	**76**	**28247**

The most common ship types in southern Kattegat were General Cargo, Tankers, and Dry Bulk (Table 1). These three classes made up 85 percent of the ships. However, the mean number of shipdays per ship was higher for RoPax, RoRo, Container Ships, and Vehicle Carriers than for General Cargo, Tankers, and Dry Bulk ships (Figure 8). High values per ship imply that those ships transited through the area at higher frequencies. Thus, in general terms, the mean number of shipdays per ship, or transits per ship, was higher for ship classes that follow a timetable (e.g. RoRo, RoPax, Container Ships, and Vehicle Carriers) than for other classes of ships.

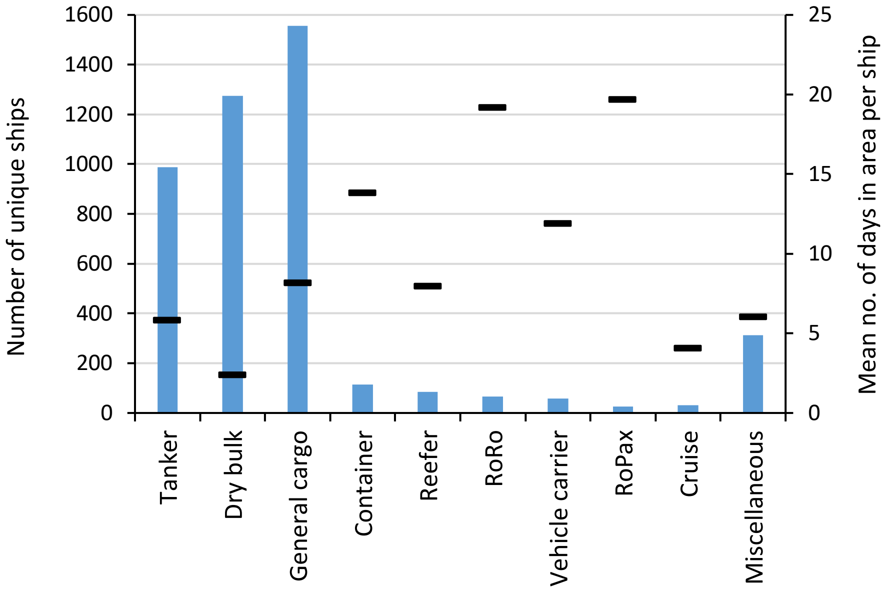

Figure 8. The number of unique ships for each class of ships and the mean number of days in the study area per ship (black lines).

The distribution of ship classes in the study area in Kattegat was compared to the distribution of ship classes navigating the main shipping route east of Öland in the central Baltic Sea, that is, through the TSS southeast of Öland or through the adjacent deep-water route. The distributions were similar, and thus the traffic in southern Kattegat can be equated to the heavier traffic seen in other routes in the central Baltic Sea (Figure 9). Fewer Tankers were observed in southern Kattegat than southeast of Öland, likely because large fully loaded Tankers with a large draught are required to use the T-route through the Great Belt instead of travelling through Öresund.

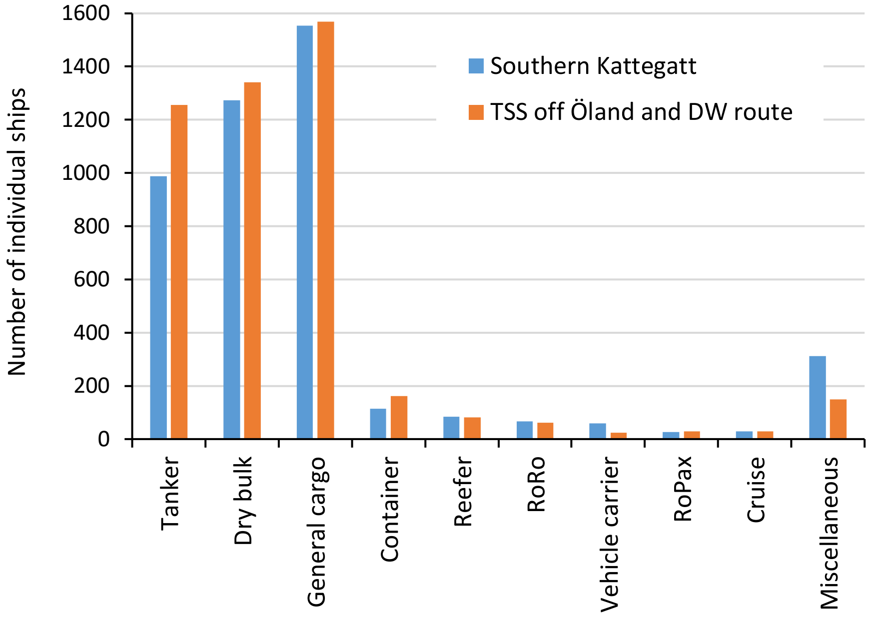

Figure 9. Comparison of ship traffic through the study area in southern Kattegat and east of Öland in the central Baltic Sea.

5.1.1 Ship speed

AIS-data were used to estimate the mean speed at which ships generally travel in the study area in southern Kattegat. The mean speed of a specific ship in the study area was calculated as the mean of all the speed information collected from AIS messages from that ship. The mean value for each ship was in most cases based on information in several hundred or several thousand AIS messages. The mean speed for ships of a specific class were thereafter calculated as an overall mean derived from individual mean values for each distinct ship within that class. This measure can be used to describe the general speeds for ships of different classes in the study area.

On average, General Cargo Ships, Tankers, and Dry Bulk Ships travelled at slower speeds than Container Ships, Reefers, RoRo Ships, Vehicle Carriers, RoPax Ships, and Cruise Ships (Figure 10 and 11). We compared speeds for ships in southern Kattegat with those in the main shipping route off Öland in order to determine whether ships in southern Kattegat travelled at slower speeds because of heavier traffic (Appendix 4, Table A4.1). On average, the ships travelled about one knot slower in southern Kattegat than off Öland. Table 2 shows the proportion of ships that travelled faster than 11 and 13 kn as they navigated the study area in southern Kattegat. Most Container Ships, Reefers, RoRo Ships, Vehicle Carriers, and RoPax Ships travelled with a mean speed exceeding 11 kn.

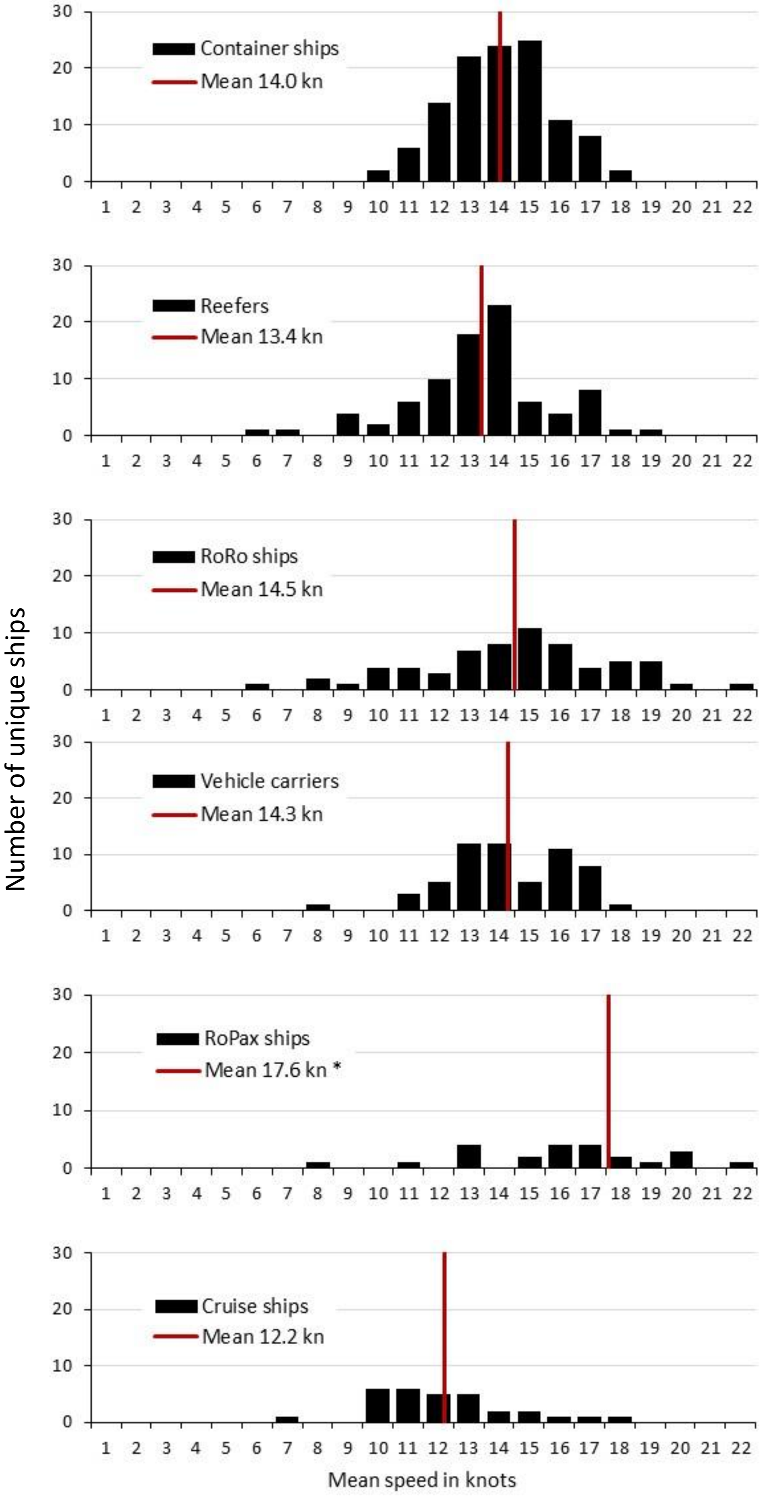

*Figure 10. Mean speeds of Container Ships, Reefers, RoRo Ships, Vehicle Carriers, RoPax Ships, and Cruise Ships in the study area in 2021. *The mean speed of three high speed crafts (RoPax Ships) exceeded 22 knots, but these data are not shown in the figure. Note that the scale at the y-axis differs in Figure 10 and Figure 11.*

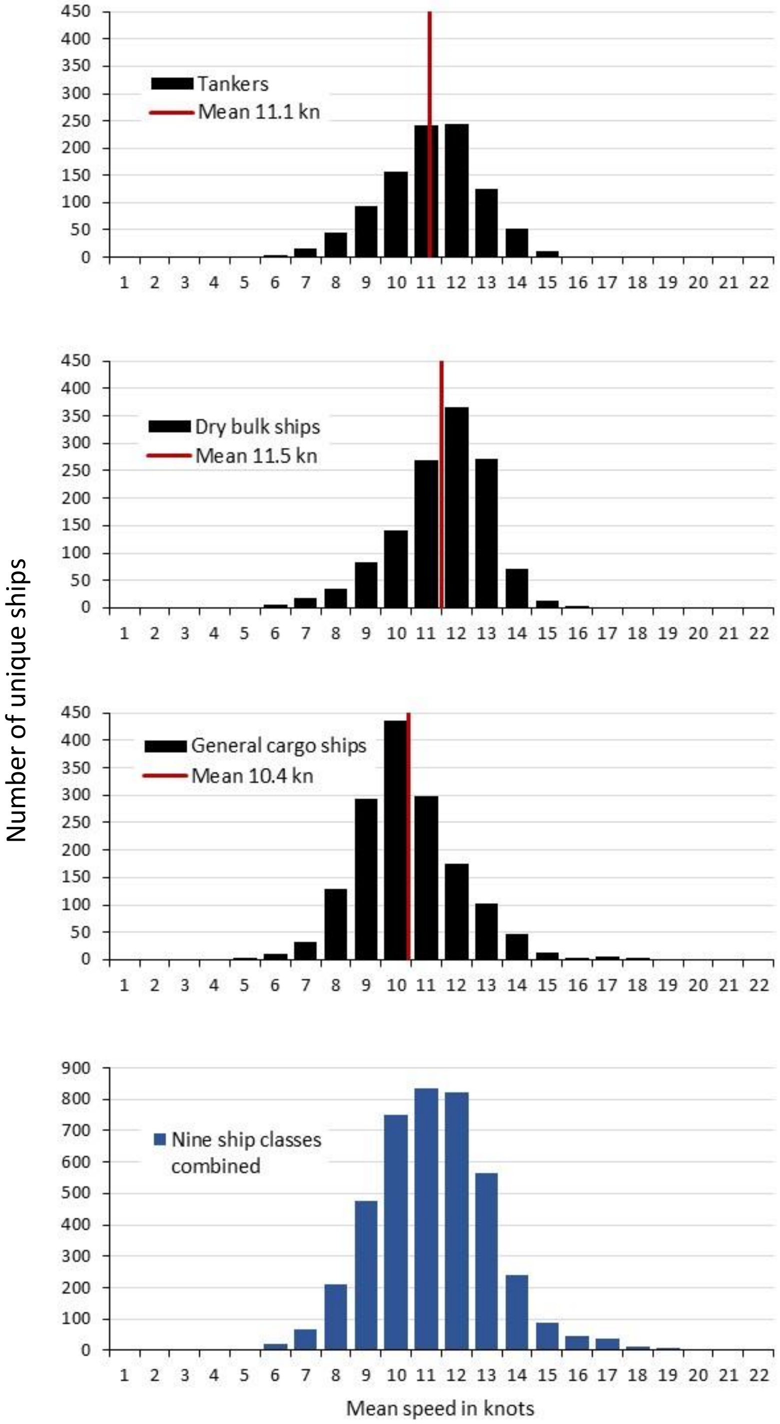

Figure 11. Mean speed of Tankers, Dry Bulk Ships, and General Cargo Ships in the study area in 2021. The mean speed of all ships in the nine ship classes included in Figures 10 and 11 is also shown. Of all ships in the nine classes, 43.6 percent and 10.5 percent travelled with a mean speed faster than 11 kn, and 13 kn, respectively.

Table 2. The percentage of ships navigating the study area in southern Kattegat with mean speeds of over 11 kn and 13 kn.

	PERCENTAGE OF SHIPS WITH A MEAN SPEED FASTER THAN 11 KNOTS	PERCENTAGE OF SHIPS WITH A MEAN SPEED FASTER THAN 13 KNOTS
Tankers	44	7
Dry bulk ships	57	7
General cargo	23	5
Container ships	93	61
Reefers	84	51
RoRo ships	82	66
Vehicle carriers	93	64
RoPax ships	92	77
Cruise ships	57	23
Total combined	44	11

5.1.2 Traffic intensity in different parts of the study area

Most ships in the study areas followed the S-route or the recommended traffic flow west of the S-route. The latter is recommended for vessels with a draught of 10 meters or more travelling between Route T and TSS Entrance to the Sound. However, many ships also travelled in other directions, for example to and from the port of Halmstad, as well as westward from the entrance of Öresund. Thus, no part of the study area was completely free from ship traffic (Figure 12). The flow of traffic differed among ship classes. Figures showing how different ship classes travelled in the study area are presented in Appendix 4. Figure 4.2).

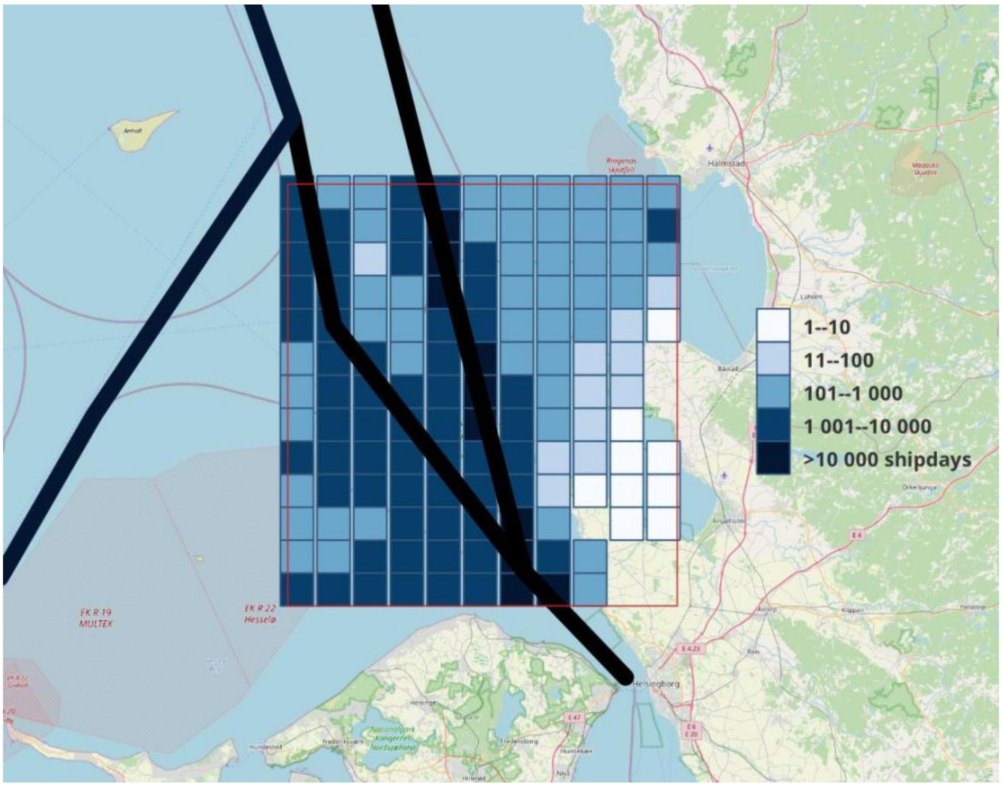

Figure 12. Traffic intensity expressed as shipdays per pixel in the study area in 2021. Each pixel is 0.04 degrees x 0.08 degrees, that is, approximately 4.4 km x 4.8 km, in size. Black lines show the main routes, that is, the S-route, T-route, and the recommended direction of traffic flow established for vessels with a draught of 10 meters or more, between Route T and TSS Entrance to the Sound. The figure is based on AIS-messages from 4,511 unique ships with IMO numbers. Fishing ships and smaller fishing and recreational boats are not included. Corresponding figures for different ship classes are presented in Appendix IV. Note that pixels are coloured according to a logarithmic scale.

5.2 LEGAL ANALYSIS OF REGULATING SHIPPING SPEED

In legal terms, approximately half of the selected study area in the Kattegat north of Öresund is composed of Swedish territorial waters. Further, smaller portions also represent Danish territorial seas and Swedish and Danish EEZ. Had the case study also covered (portions of) Öresund, it would have added an additional level of complexity. Öresund is widely considered to qualify as a strait “in which passage is regulated in whole or in part by long-standing international conventions in force specifically relating to such straits” according to UNCLOS, Article 35 (c). This necessitates, in the case of Öresund, an analysis of a treaty from 1857 (the Sound Treaty, 1857) and subsequent state practice (Mahmoudi, 2014). But that is not necessary for the selected study area.

As concluded in Chapter 2, it is widely accepted that coastal states, such as Sweden or Denmark, can set rules for ships that navigate their territorial seas for the purpose of protecting the marine environment. Instituting sea lanes and reasonable speed limits should be considered acceptable methods of exercising coastal state jurisdiction for protecting the marine environment. However, this assumes that such rules do not pose any threats to maritime safety, are non-discriminatory, and do not prevent foreign ships from exercising their right of innocent passage.

Further, within areas that constitute the EEZ, there is limited legal support for imposing restrictions on foreign ships. Although an argument could be made for the right to impose speed limits to protect the marine living resources of the EEZ, it would challenge the structure and logic of UNCLOS and would quite likely meet with protests. An alternative strategy would be for Sweden and Denmark to request the adoption of such measures by the IMO. It can even be argued that Denmark and Sweden are obligated under EU law to make such a request at the IMO, if that is needed to achieve URN levels consistent with good environmental status according to the MSFD.

While they mostly focus on ship design and construction, the IMO’s guidelines on underwater noise, which were adopted in 2014, acknowledge that “reducing ship speed can be a very effective operational measure for reducing underwater noise” (MEPC 2014). In this regard, it is also helpful that the IMO has already designated the Baltic Sea, including the Skagerrak, as a particularly sensitive sea area (PSSA). While the designation of an area as a PSSA does not grant additional jurisdictional powers to the coastal states or impose new obligations on ships navigating the EEZ, it can support the adoption of ‘associated protective measures’ (APMs) by the IMO. APMs may be adopted based on relevant international agreements, such as the International Convention for the Prevention of Pollution from Ships (MARPOL), and could include measures such as sea lanes, areas to be avoided, and speed limits. In practice, however, IMO member states have shown considerable resistance toward adoption of mandatory APMs as they are seen to pose an obstacle to free navigation (Langlet, 2022). If Sweden does not want to wait for approval by the IMO, or if such approval is not granted, the adoption of voluntary measures could be considered. Such measures may have a positive impact even if they cannot be enforced on those who choose not to comply (Huntington, 2015).

Finally, it should be noted that the presence of protected areas in the form of Natura 2000 sites in the study area, including in the Swedish EEZ, does not change the above analysis. Although the natural values that are protected by the Natura 2000 designation could potentially support the adoption of APMs by the IMO, the designation itself is purely a matter of national and EU law and does not affect the right of navigation under international law.

5.3 CALCULATION OF SOUND REDUCTION WITH SPEED LIMITS

In this section, we calculate the impacts of hypothetical limits on ship speed on the underwater noise levels that can be detected at some receiver (immission) points. The JOMOPANS-ECHO (J-E) model will be used for these calculations. Above, we noted some discrepancies stemming from differences in the ship classes for this case study, but those considerations are unlikely to be important in using this model to calculate relative speed limits in this section. In the two-month trial of the ECHO study, the effect of setting speed limits at 11 kn was studied. As there is a greater uncertainty in extrapolating this model to speeds below those set by the trial, 11 kn was adopted as a lowest speed limit for these calculations. Details of the model are outlined in Appendix 2.

5.3.1 General considerations

To give some context for the calculations in this section, some important general relationships (not specific to the study area) are discussed below. In particular, these include the relationships between adjustable parameters, such as speed and number of ships, and the resulting effects such as radiated noise and the time the ships spend in a certain area. The key elements are summarised below and discussed further in the discussion section of this chapter.

- Speed affects the noise level but not the spectrum in the model.
- The model gives the effect of a speed reduction directly in the vicinity of individual ships.
- The net effect of reduced speed is a reduction of noise level in the affected area. In comparison, there is negligible impact on the resulting level reduction from any extra time that ships spend in the area due to speed reduction.
- Halving the number of ships will on average reduce the resulting noise level in the affected area by 3 dB, which according to the model corresponds to a 12 % speed reduction, e.g. applying a speed of limit of 11 kn to a ship travelling at 12.4 kn.
- The background noise levels from the passing ships will be fairly constant over time, in a remote distance from a route with heavy traffic.
- On the other hand, in areas adjacent to or within shipping lanes the impact of a speed limit will fluctuate over time, experiencing strong peaks in noise levels with the passage of individual ships.

Speed vs. radiated noise levels of individual ships

The relationship between speed and predicted radiated noise levels for a ship can be directly imputed from the equations defined in the model. Since the sound pressure level (in dB) is a function of the logarithm of the speed, *the difference in sound when a certain ship is moving at different speeds will experience parallel shifts of the noise spectrum* (i.e. the only difference is in level). We present an example of such parallel sound pressure level spectra at various speeds for the model ship class, Container Ships, in Figure 13.

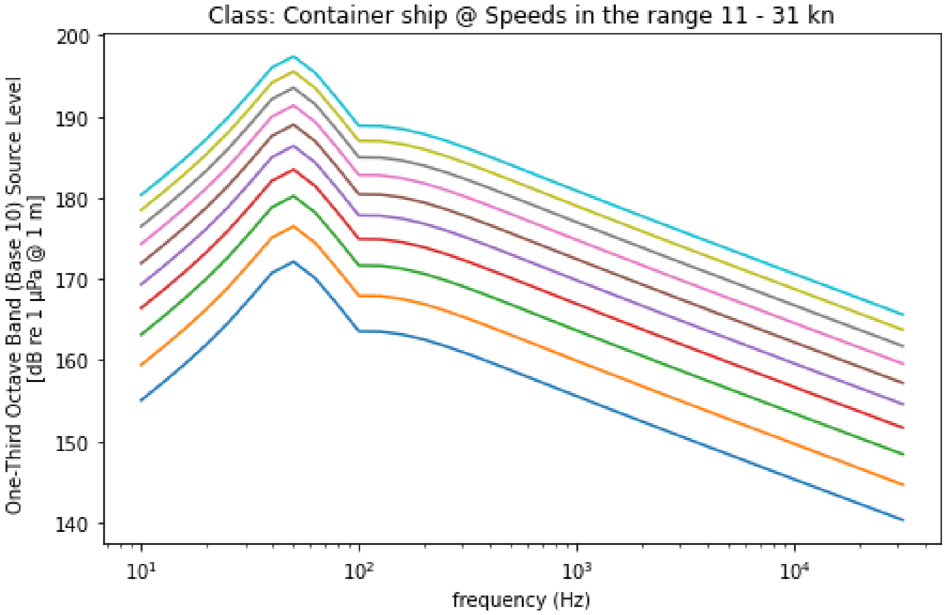

Figure 13. Noise spectra of various speeds of the ship class Container Ship. From top: 31 kn down to 11 kn in increments of two knots. The ship length in this example is 200 m. The one-third octave bands are calculated with base 10 (decidecade) according to the J-E model.

Calculations of radiated noise levels at various speeds with the J-E model provide reasonable estimates of the resulting effect in the direct vicinity of a single ship that is sharing a shipping lane with various ship types. As noted above, the modelled relationship between the sound levels and the ship's speed is only valid above the threshold of cavitation speed (and only in a statistical sense). Below this speed, machinery noise might dominate the emitted noise from the ship and the model can underpredict the URN.

If a ship slows down, there will be an increase in duration of audible noise as the ship is passing through. Reducing speed by half, from 22 kn to 11 kn (the lower speed limit in the Vancouver study), will result in a doubling of the time that the ship spends emitting noise in the area and thus will result in *an increase of noise levels by approximately +3 dB*. At the same time, however, the reduction of speed will inherently lead to decreased levels of radiated noise, which is estimated to be at least 18 dB according to the model, resulting in a total reduction in net noise levels by approximately 18 - 3 = 15 dB as captured at a stationary listening position. That is, extended time in the area due to a speed reduction will have negligible impact on the resulting noise levels relative to the change in emitted noise levels.

Effect of the number of ships versus ship speeds on the noise level

The effects of the number of ships and of ship speeds can be illustrated with an example: halving the number of ships would result in an average reduction in noise levels by ~3 dB if most ships in the area were of the same type. On the other hand, if these ships were travelling at 13 kn then limiting their speed by two knots, to 11 kn, would reduce radiated noise levels by 4 dB (due to the logarithmic relationship between the radiated sound pressure levels and the ship speed). As shown in the calculations, as well as in data from areas where most ships would be unaffected by a mandated speed limit, these reductions in noise can still be appreciable. In conclusion, the same levels of noise reduction can be achieved either through a substantial reduction in the number of ships in an area or through a relatively moderate reduction in speed.

Effects of distance from source and the effects of high density of ship traffic

Close passages of single ships result in greater noise level variations because each halving of the distance between two individual sound sources can result in an approximately 5 dB (±1 dB) increase in the sound levels. Thus, the actual distance from a shipping lane to an immission point (i.e. the point of a hypothetical listener for whom the resulting noise level is calculated) is very important. As an example, moving a shipping lane that was 1 km from an immission point to 2 km from the immission point (i.e. 1 km farther out) may result in a noise reduction of approximately 5 dB. Then again, moving a lane 50 m away from an immission point to 500 m farther out (i.e. moving it by 450 m) would result in reduction of ~17 dB under the same conditions because it is 10 times further away.

A representative scenario is presented in Figure 14, which shows the distribution of ships in the study area at one point in time. If all ships in the figure were to radiate equally loud noise, the resulting level at the immission point denoted “within the S-route” would be almost the same as if no other ships were present in the area except for the nearest ship, Selin D. The difference would be approximately 1 dB, which is considered as a just-noticeable sound change under ideal conditions for humans (Zwicker & Fastl, 1999).

However, if Selin D were removed the noise level would be 6.5 dB lower. The nearest ship, Selin D, is almost a nautical mile (1.852 km) away from the immission point, but it would still sound 10 dB louder than the second nearest ship, Narew, if the radiated noise levels were the same.

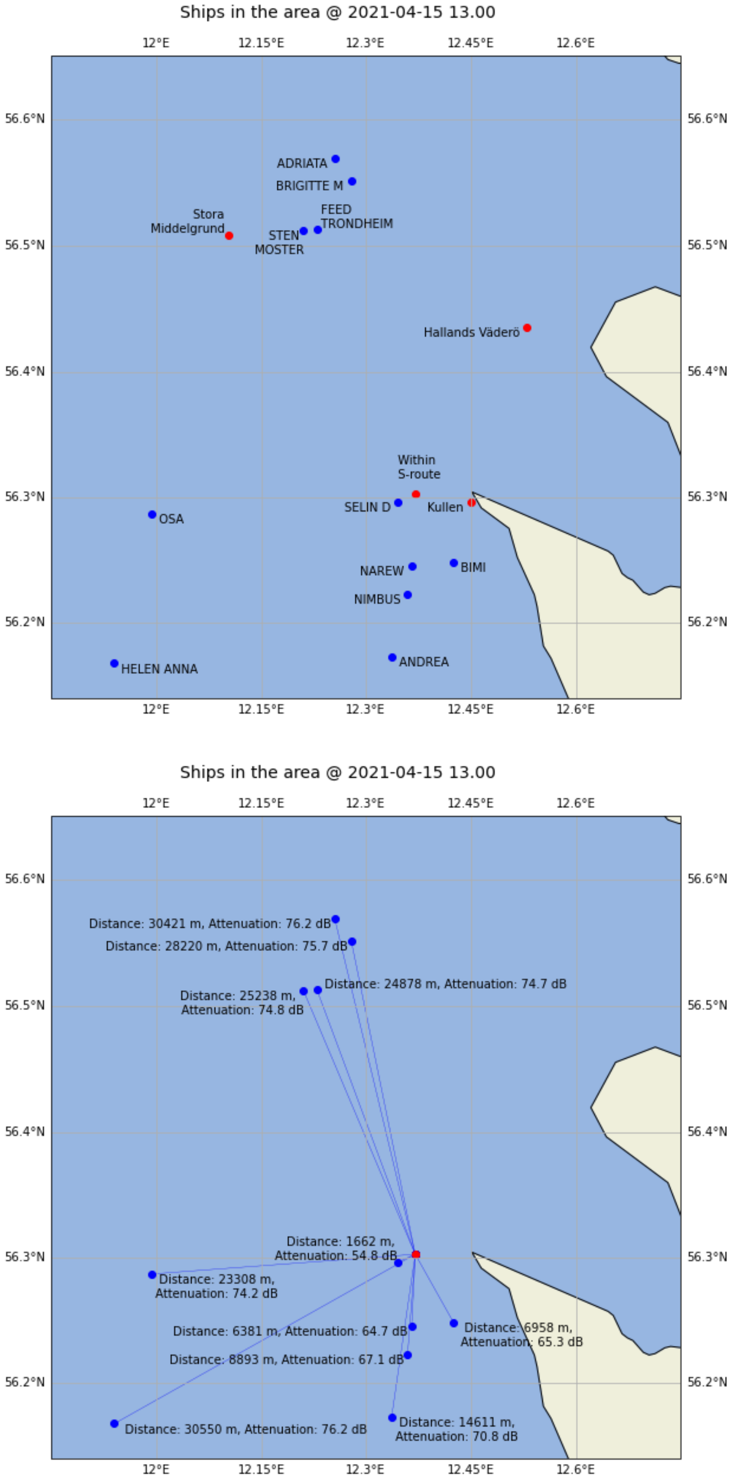

*Figure 14. Top: The position of the ships (blue dots) in the sampled time slot 2021-04-15 at 13:00. The red dots show the immission points used in the calculations. Bottom: At the immission point (red), the contributions from each ship (blue) were calculated as the radiated noise minus the distance attenuation (here 17 * $\log_{10}(R)$, discussed below) and summarized.*

The significance of the discussion in the top paragraph in this section is that the distance attenuation of noise from different ships in a shipping lane a few kilometres away will remain in the same order of magnitude. If the ship traffic density is high, the resulting underwater noise level at distant listening positions, the immission points, will remain almost constant over time, reflecting the average sound energy emitted by many ships present in the area at the same time. The term “immission point” will hereafter be used to denote an assumed listening, receiving, or measurement position, i.e., a position at which a resulting noise level can be calculated.

On the other hand, at an immission point close to a single fast ship, reduction of speed for that particular ship would inherently lead to a significant reduction in the noise levels. For instance, if a container ship at a distance of 100 m travels at 13 kn instead of at 23 kn, the resulting noise reduction would be ~16 dB, i.e. there will be considerable reduction in local noise at the time of the passage. In conclusion, the effects may differ substantially over time and place depending on the absolute distance to the ships and on the traffic density, particularly with respect to the average noise levels in relation to the strong peak levels of noise from individual ships.

Potential noise reduction from imposing speed limits in the study area

A more complex question is how much noise reduction can be expected in a realistic scenario. In the selected area in Kattegat, we have used the J-E model to calculate how much reduction can be achieved under various scenarios. The immission points include both positions within the S-route, which pick up the impact of single ship passages, and at greater distances close to the coast, which in turn reflects the general reduction of emitted sound energy in the area. These calculations were based on AIS-data samples from twelve days distributed over the year and were drawn from the dataset described above. Traffic from the whole area was analysed, that is, the analysis assumed that a speed restriction was applied over the complete study area.

Because the detailed conditions (e.g., seabed structure, temperatures, currents at the time, etc.) were not available for this study and would only affect the absolute levels of the noise from the heavy traffic (present 24/7 all year) in the area, we have assumed a simple distance attenuation of $17 \log_{10}(r)$, where r denotes the distance. This is a common modification of the $20 \log_{10}(r)$ attenuation of spherical wave propagation to compensate for the slightly higher noise levels often found in actual measurement results when compared to predicted levels as based on previous FOI experiences (Bergström et al., 2013; Andersson et al., 2015). Note that the calculations are very robust in capturing variations in expressions and boundary conditions, and other simplified expressions; for example, $18 \log_{10}(r)$ in ANSI 2009 gave similar results. Furthermore, the inherent uncertainties and randomness of the sea bottom can result in considerable uncertainty in the predicted distance attenuation at longer ranges (James 2009). Thus, the simplified approach works well for the purposes of estimating the reduction in noise levels and other relative parameters in comparison to more advanced models based on the uncertain boundary parameters. Absolute levels are beyond the scope for this study and would in any case be encumbered with too high an uncertainty to be used for drawing conclusions.

The calculated noise reduction of a speed limit at 11 kn

A detailed description and a flow chart of the calculations can be found in the Appendix. The initial calculations indicated that entire days, sampled each month over a year, would yield a representative average value of the overall noise impacts (although the AIS data contain numerous errors that had to be corrected). All AIS data of the ships in the selected area were collected from complete 24-hour periods of the 10th day of each month. The sound pressure levels, averaged over 5-minute intervals during the 24-hour periods for each of these days, were calculated at the four immission points shown in Figure 17, namely "Stora Middelgrund", "Hallands Väderö", "within the S-route", and "Kullen". Sound pressure level is from here on denoted as equivalent level, L_{eq}, to indicate that it is the average value over time. Values of L_{eq} were calculated both for the actual speed, according to the AIS data (speed and time/position), and for a scenario in which all ships travelling at speeds higher than 11 kn reduced their speed to 11 kn. All the frequency bands of the J-E model were summed in the calculations to a single value entity.

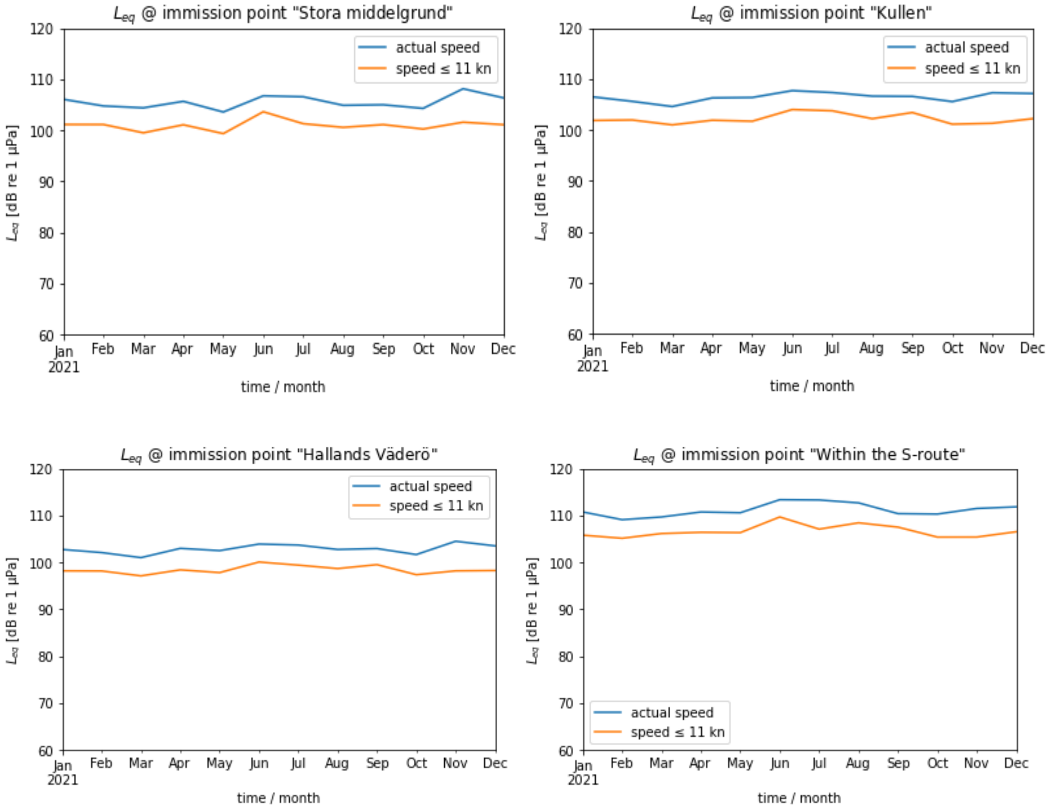

Figure 15. Calculated average levels, L_{eq}, at the four immission points from sampled days in 2021.

As shown in Figure 15, the three immission points that are situated outside the shipping lanes show very similar trends and overall levels, whereas the immission point within the S-route show higher levels. However, as shown in Table 3, the reduction in noise levels achieved at a speed limit of $v \leq 11$ kn is almost equally large in all four cases, i.e. independently of the absolute levels and of the choice of immission point. Assuming that the J-E model is valid, the predicted average effect of a speed limit at $v \leq 11$ kn is approximately $\Delta L_{eq} = 4.4 \pm 2$ dB (it should be noted that the indicated uncertainty is based on the standard deviation in the calculations, see also the discussion in Appendix, and that there is also an uncertainty of 6 dB between the model and measurements for individual ships according to MacGillivray and Jong 2021).

However, the absolute values are less likely to be accurate because the propagation attenuation values cannot be calculated with sufficient precision (as discussed above) and because the spectra and levels of the ships in Kattegat are not entirely similar to those of the ships in the Vancouver study. Except for ship lengths, no individual differences within the ship classes are included in the model.

Table 3. Total calculated levels and level differences at the four selected immission points averaged over all sampled days of the year.

IMMISSION POINT	COORDINATES (DECIMAL FORM)	L_{EQ} [DB RE 1 µPA] ACTUAL SPEED	L_{EQ} [DB RE 1 µPA] MAX SPEED 11 KN	ΔL_{EQ} [DB]
Kullen	56.29648 N, 12.45075 E	107	102	4.3
Hallands Väderö	56.43510 N, 12.53045 E	103	99	4.5
Within the S-route	56.30276 N, 12.37045 E	112	107	4.6
Stora Middelgrund	56.50863 N, 12.10285 E	106	101	4.6
Average excl. route (incl. route)		106 (108)	101 (103)	4.4 (4.5)[4]

5.3.2 Distribution of average noise levels over the 5-minute intervals

An estimation of how much variation in noise and noise reduction can be expected over a day can be achieved by calculating the statistical distribution of noise levels of the 5-minute time intervals. If the noise level at the immission point at Stora Middelgrund is calculated for ships at their actual speeds, the difference between the 10th percentile (the value that is higher than 10% of the 5-minute intervals) and the 90th percentile (the value that is higher than 90% of the 5-minute intervals) is 11 dB (Table 4). The difference between the average value and the 90th percentile is merely 3 dB, which is less than the corresponding standard deviation of $\sigma = 4.6$ dB, which indicates a parabolic (non-symmetrical) distribution. However, such a skewed distribution is to be expected because the model is likely to result in a normal distribution with respect to the sound pressure (Pa), but the output parameters are expressed in sound pressure level (dB).

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4 The average values are excluding those from the immission point “within the S-route”, while the average values in parentheses include this value.

It should be noted that the difference between the 10th percentile and the 90th percentile is 2 dB lower in the case of a speed reduction. This is, however, a consequence of the fact that noise from distant ships and natural sources of underwater noise are always present, and that a speed reduction does not affect all ships. This is also the reason that although there is a 6 dB difference within the 90th percentiles, there is only little more than 1 dB difference between the 10th percentiles.

Table 4. Some statistical distribution parameters of L_{eq} over time (5-minute periods)

STORA MIDDELGRUND	AVERAGE L_{EQ}, DB RE 1 µPA	90-PERCENTILE, DB RE 1 µPA	10-PERCENTILE, DB RE 1 µPA	STANDARD DEVIATION, DB
Actual speed	106	109	98	4.6
Reduced speed	101	104	95	3.7
Differences of 5-minute intervals	4.6	6.4	1,3	2.1

5.3.3 The calculated noise reduction at a speed limit of 13 kn

To complement our case study of a speed limit of 11 kn, the noise reduction was also calculated for a scenario with a speed limit set at $v \leq 13$ kn. On average, only 11% of the ships would need to reduce their speed under this scenario, as opposed to 44% of the ships that would be affected in case the speed limits were set at $v \leq 11$ kn. However, the reduction in noise levels that could be attained by setting speed limits to $v \leq 13$ kn would be limited to $\Delta L_{eq} = 1.9 \pm 0.5$ dB. However, this level of reduction in speed would still yield a significant reduction in noise levels in the immediate vicinities of individual fast ships, as discussed earlier.

5.3.4 Calculations for subsets of shipping classes

The overall noise levels generated by specific ship classes can be compared against their respective proportional representation within the total traffic. As was shown in Section 5.1.1, a high percentage of RoPax Ships, Roro Ships, Vehicle Carriers, Container Ships, and Reefers travelled at mean speeds higher than 13 kn. The percentage of ships from these five classes was only about 8% of total traffic, but they constituted about 48% of all ships that would need to reduce their speed if a hypothetical speed limit were set at $v \leq 13$ kn. Therefore, the hypothetical noise reduction that could be achieved if only these ship types were to reduce their speed (corresponding to the all-year average calculations above), would be $\Delta L_{eq} = 1.6 \pm 2$ dB (cf. Figure 16). In this case the outcome would fluctuate over time between no noise reduction and 3–4 dB reduction, but the noise reduction near the fastest ships in these ship classes can be quite substantial: over $\Delta L_{eq} >$ 15 dB in some cases according to the model (to which may be added an additional model uncertainty of 6 dB for individual ships).

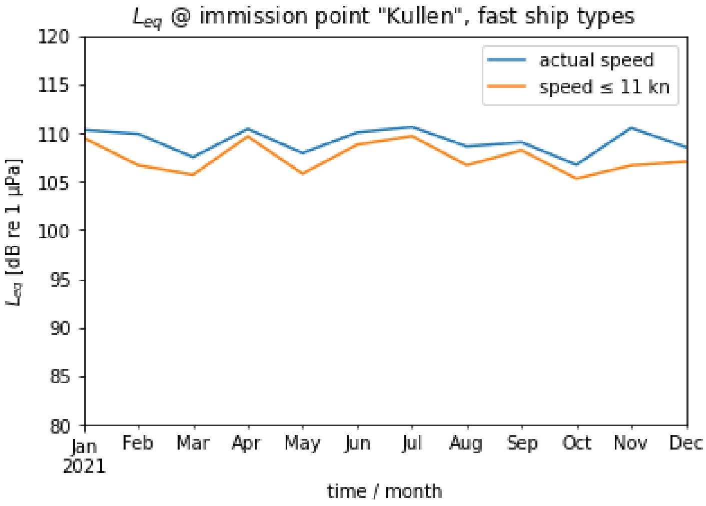


Figure 16. The difference of L_{eq} *at "Kullen" calculated for a hypothetical speed limit of 11 kn only affecting shipping classes with a high percentage of fast ship types (i.e., Container Ships, Reefers, RoPax Ships, Roro Ships, and Vehicle Carriers).*

5.3.5 Comparisons with non-anthropogenic ambient noise

Although calculation of absolute levels is not within the scope of this study, it is worthwhile to make a comparison between calculated underwater ship noise and the contribution of non-anthropogenic ambient noise sources. These are primarily of geophonic origin, typically caused by wind/waves and rain. It is quite clear that even during heavy weather conditions ship noise will generally dominate the underwater soundscape (cf. Figure 17 a and b) regardless of the uncertainties in the calculations of absolute levels. Typically, the ship's noise will dominate in the low frequency range below approximately f = 1 kHz, and during inclement weather the generated ambient noise will be dominating above that frequency. Nonetheless, the resulting total sound levels will undoubtedly be determined by the radiated ship noise. Therefore, any reduction of the URN levels will also result in a reduction of the total underwater ambient noise levels in the area.

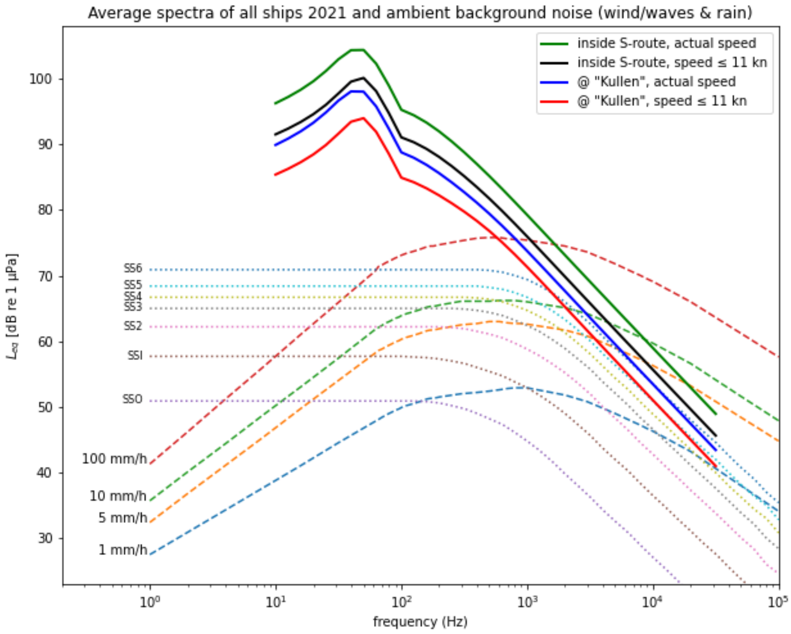


Figure 17a. Average spectra of all ships in the area and ambient noise spectra of weather (sea state 0 - 6) and rain (1, 5, 10, and 100 mm/h). Ambient noise spectra from Hodges 2010.

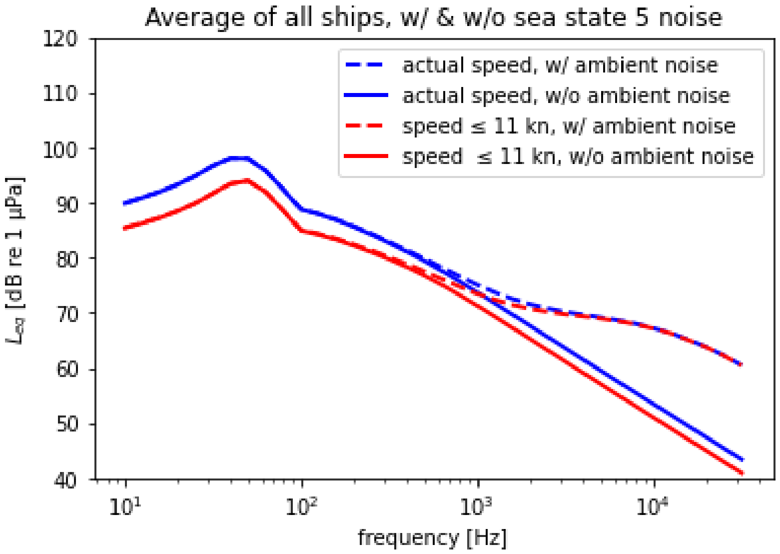


Figure 17b. Resulting average noise spectra of all ships in the area, with and without inclusion of ambient noise from medium wind and rain. Sea state 5, i.e., wind 8.0-10.7 m/s and "Medium" rain (5 mm/h). Ambient noise spectra from Hodges 2010.

5.4 DISCUSSION OF THE CASE STUDY

The MSFD (directive 2008/56/EC) imposes an obligation on EU member states to cooperate on measures to achieve good environmental status in the marine environment, including by reducing URN to be consistent with the limit values developed under the directive.

Regarding the right to take relevant measures, international law enables a coastal state like Sweden to require ships to reduce their speed for environmental reasons when navigating in its territorial seas. The requirement must be implemented in a non-discriminatory manner and cannot make it impossible or exceedingly hard to exercise the right to innocent passage. It would be legally challenging to justify a mandatory speed limit imposed by a coastal state in areas that are comprised of EEZ. Instead, the most viable options would be to request that the IMO adopt measures or to issue a non-binding recommendation for ships to lower their speed when navigating the area.

The protocol to calculate predicted levels of URN in a studied area are not reliable for absolute noise levels, primarily because the propagation modelling is simplified and does not account for the physical properties of the ocean and seabed in the area. Further, there are uncertainties in the modelled noise source levels for the ships present in the study area compared with the dataset that was used to derive the J-E model. In addition, there is already a statistical uncertainty of ±6 dB in the model related to the actual ships included in the ECHO dataset. However, the relative change in URN resulting from the reduction in speed is more reliable.

While there were a few ships that were frequently navigating the area, most ships only passed through on a limited number of days during the study period. Thus, in order to reduce the average noise level in the studied area it would be ineffective to mandate measures for specific ships with the exception of ships that were frequently navigating the area.

A speed limit at 11 kn would on average yield a noise reduction of $\Delta L_{\mathrm{eq}} = 4.4 \pm 2$ dB at the immission points. Such a limit would, based on AIS data from 2021, affect approximately 44% of the ships in the studied area. A speed limit set at 13 kn would instead yield a noise reduction of $\Delta L_{\mathrm{eq}} = 1.9 \pm 0.5$ dB dB and affect approximately 11% of the ships.

Farther from the shipping lanes, the URN is relatively constant over time and is less affected by individual ships. If a ship passes close to an immission point, URN from that ship will dominate the soundscape and determine the resulting total levels of noise. It should be noted that none of the studied segments of the area were completely free from ship passage during 2021.

From the perspective of potential impacts on biological habitats, we note that the EU assessment work deals in part with habitat quality. The quality in this case could mean the communication range for marine animals under water, i.e., at what range can an animal detect an important signal such as a cod mating call. When URN from ships raises the ambient noise levels, the animal's communication range is lowered and the signal they are trying to detect is masked by the ship's noise. Some, but not all, animals can increase their own sound levels when they try to communicate or they may be forced to swim closer to each other. As an example, a 6 dB increase in noise levels due to shipping would decrease the communication range of animals by 50%. In the area being studied, shipping-related noise levels are already high due to the intense shipping, and the communication range has already been affected (Lalander et al., 2022). Correlating these aspects with the results from the case study, one can expect that the noise level reduction of ~4–5 dB would allow the communication range to improve if speed limits were to be enacted.

6. CONCLUSIONS AND RECOMMENDATIONS

Enforcing a reduction in ship speed is likely to reduce the average levels of URN in an area and thus increase the quality of marine animal habitats. There can be exceptions for certain types of traffic, e.g., ferries operating with CPPs at constant shaft rate or some types of work boats, but details for these are beyond the scope of this study. Peak levels of noise at a specific immission point are strongly affected if a ship is passing close by. Thus, if strict limits on URN are required it may be necessary to shield certain areas from ship traffic altogether, e.g., within Marine Protected Areas.

The case study presented herein covers a local area, but still involves two nations, Sweden and Denmark. As such, this type of analysis can naturally be extended to regional or international perspectives. However, there are several complications involved in investigating measures to reduce noise pollution from shipping. The legal preconditions for taking action look different in different maritime zones. Whereas a coastal state like Sweden can, in principle, impose speed limits in its territorial seas for environmental reasons, action through the IMO would likely be needed for such measures to be adopted in the EEZ, at least if the measures were to go beyond mere recommendations. Few details are available on noise emitted from ships, and the generation of sound depends on local environmental conditions for which information is lacking in many locations. Moreover, there are likely economic and logistic implications that might affect the situation but have not been included in this study. Further cross-disciplinary studies and considerations will be necessary.

Other policy measures on shipping noise were not studied in detail, but some were discussed within the research group and some reflections from these discussions are included in the following paragraphs for further follow up. Putting a cap on the noise emitted from all vessels instead of enforcing a speed limit is speculated to have a similar or smaller effect than a scenario where speed is limited to 13 kn. However, enforcing such a noise cap will be difficult as all passing ships would need to be assessed for emitted noise in the area. The class notations of silent vessels for environmental reasons could be a tool for this but are still extremely rare. Further, these notations are not harmonized between the different classification societies; however, this work is in progress (Ainslie et al., 2022). Economic measures directed at individual ships, like the ones at the Vancouver port, that offer reduced port fees for quieter ships are not believed to be effective in the studied area or in other areas with similar types of traffic. This is because most ships are just passing through the area and only a few can be considered as regular traffic. However, this economic approach might be effective in local areas where a certain type of traffic is dominant, e.g. support vessels for wind farms or aquaculture, or in areas serviced by ferry lines or tourist or public transportation. Measures applied through Corporate Social Responsibility within such areas could contribute to a reduction in noise levels, or could at least limit increases in URN. One initiative enabling this is the Clean Shipping Index (CSI) (IVL, 2023) that promotes rebates on fairway dues to ships that demonstrate high environmental performance. Recently, the possibilities of including a URN-related criteria in the CSI framework were investigated in a research project led by IVL (Johansson et al, 2023)). Another framework aiming to steer the shipping industry towards sustainable development is Poseidon Principles, which connects banks and insurance companies operating in the shipping industry (https://www.poseidonprinciples.org/). As with the CSI, Poseidon Principles has set up conditions for transparent reporting and a structure that allows for future stepwise and stricter limits with respect to ships' carbon emissions, in line with the decarbonization strategy of shipping as outlined by the IMO (2018). Ships need to meet established criteria to be eligible for loans and insurance from the banks and insurance companies committed to the Poseidon Principles. According to the Poseidon Principles, they currently cover ~70% of the total loan volumes within the global shipping industry. Although the focus of the Poseidon Principles is decarbonisation, the signatories state that they will consider future expansion of the framework. Hypothetically, the framework could also be used to condition ships (especially newbuilds) to promote the construction of vessels that produce lower URN. However, for both for Poseidon Principles and CSI, there is the remaining issue of how to verify whether a vessel is built or operated to be more silent. Class notation is not yet applicable at an acceptable noise index, nor is there a priori knowledge on technical installations.

REFERENCES

Andersson, M. H., Lalander, E., Linné, M., Svedendahl, M., & Östberg, M. (2023). *Slutrapport för EU projektet JOMOPANS – Joint Monitoring Programme for Ambient Noise North Sea.* FOI rapport FOI-R--5411--SE. https://www.foi.se/rest-api/report/FOI-R--5411--SE

Andreone, G. (2015). The Exclusive Economic Zone. In Rothwell, D. et al. (eds). *The Oxford Handbook of the Law of the Sea.* Oxford University Press, 2015, 159–180. https://doi.org/10.1093/law/9780198715481.003.0008

Borsani, J.F., Andersson M., André M., Azzellino A., Bou M., Castellote M., Ceyrac L., Dellong D., Folegot T., Hedgeland D., Juretzek C., Klauson A., Leaper R., Le Courtois F., Liebschner A., Maglio A., Mueller A., Norro A., Novellino A., Outinen O., Popit A., Prospathopoulos A., Sigray P., Thomsen F., Tougaard J., Vukadin P., and Weilgart L. (2023). *Setting EU Threshold Values for continuous underwater sound, Technical Group on Underwater Noise (TG NOISE), MSFD Common Implementation Strategy*, Edited by Druon J.N., Hanke G. and Casier, M. Publications Office of the European Union, Luxembourg. doi:10.2760/690123, JRC133476. https://dx.doi.org/10.2760/690123

Breeding Jr, J.E., Bradley, M., Hebert Walrod, M., McBride, W. (1996). *Research Ambient Noise Directionality (RANDI) 3.1 Physics Description*. Technical Report, NRL/FR/7176--95-9628. https://apps.dtic.mil/sti/pdfs/ADA316034.pdf

Bureau Veritas. (2018). *Underwater Radiated Noise (URN).* Rule Note NR 614 DT R00. https://erules.veristar.com/dy/data/bv/pdf/614-NR_2018-07.pdf

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,* 6:714. https://doi.org/10.3389/fmars.2019.00714

Cruz, E. Lloyd, T., Bosschers, J., Lafeber, F.H., Vinagre, P. Vaz, G., (2021). *Study on inventory of existing policy, research and impacts of continuous underwater noise in Europe*. EMSA report EMSA/NEG/21/2020. WavEC Offshore Renewables and Maritime Research Institute Netherlands. https://www.emsa.europa.eu/newsroom/latest-news/item/4569-sounds.html

de Jong, C. A. F., & Hulskotte, J. H. J. (2021). *Reduction of ship traffic emissions and underwater radiated noise - Part 2.* TNO 2021 R10560. https://www.health.belgium.be/sites/default/files/uploads/fields/fpshealth_theme_file/a_slow_steaming_scenario_in_the_north_sea_region.pdf

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A. C., Halpern, B. S., Harding, H. R., Havlik, M. N., Meekan, M., Merchant, N. D., Miksis-Olds, J. L., Parsons, M., Predragovic, M., Radford, A. N., Radford, C. A., Simpson, S. D., … Juanes, F. (2021). The soundscape of the Anthropocene ocean. *Science*, *371*(6529), eaba4658. https://doi.org/doi:10.1126/science.aba4658

The EU Marine Strategy Framework Directive. (2008). Directive 2008/56/EC of the European Parliament and of the Council establishing a framework for community action in the field of marine environmental policy, *Off. J. Eur. Union L164,* 19-40. https://eur-lex.europa.eu/eli/dir/2008/56/oj

Faber, J., Huigen, T., & Nelissen, D. (2017). *Regulating speed: a short-term measure to reduce maritime GHG emissions.* https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_7L90_Regulating_speed_DEF.pdf

Finnsgård, C., Kalantari, J., Roso, V., & Woxenius, J. (2020). The Shipper's perspective on slow steaming - Study of Six Swedish companies. *Transport Policy, 86*, 44-49. https://doi.org/10.1016/j.tranpol.2019.10.005

Gillespie, A. (2016). Vulnerability and Response to the Risk of International Shipping: The Case of the Salish Sea. *RECIEL, 25*, 317-332. https://doi.org/10.1111/reel.12174

HELCOM (2021). *Regional action plan on underwater noise (RAP NOISE).* HELCOM Recommendation 42-43/1., 12pp (2021). https://helcom.fi/wp-content/uploads/2021/08/Rec-42_43-1.pdf

Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series*, *395*, 5-20. https://www.int-res.com/abstracts/meps/v395/p5-20/

Hodges, R.P. (2010). *Underwater Acoustics: Analysis, Design and Performance of Sonar.* John Wiley & Sons; Chichester, UK: 2010. ISBN: 978-0-470-68875-5

Huntington, H. P., Daniel, R., Hartsig, A., Harun, K., Heiman, M., Meehan, R., Noongwook, G., Pearson, L., Prior-Parks, M., Robards, M., Stetson, G. (2015). Vessels, risks, and rules: Planning for safe shipping in Bering Strait. *Marine Policy, 51*, 119-127. https://doi.org/10.1016/j.marpol.2014.07.027

IMO (2018). Resolution mepc.304(72). Initial IMO strategy on reduction of GHG emissions from ships. International Maritime Organization. 27pp. https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf

ITLOS (2014). M/V Virginia G Case (Panama/Guinea-Bissau) Case No. 19. 53 ILM 1164 (2014). *International Tribunal for the Law of the Sea*, April 14, 2014.

IVL (2023) Clean Shipping Index. Retrieved from https://www.ivl.se/projektwebbar/clean-shipping-index.html [2023-08-16]

Jakobsen, I. U. (2016). *Marine Protected Areas in International Law: An Arctic Perspective.* Brill 2016. ISBN: 978-90-04-25472-5.

James K. R. (2009). *Uncertainty in Underwater Acoustic Field Prediction.* Dissertations & Theses - Gradworks 2009. https://deepblue.lib.umich.edu/bitstream/handle/2027.42/62232/krjames_1.pdf?sequence=1&isAllowed=y

Johansson, T., Skold, S., Andersson, C., Krång, A.-S., Winnes, H., Andersson C. & Hoppe, S. (2023). *Underwater noise from fairways – policies, incentives and measures to reduce the environmental impact.* IVL Swedish Environmental Research Institute, Report number C 743. ISBN 978-91-7883-477-8. Retrieved from https://urn.kb.se/resolve?urn=urn:nbn:se:ivl:diva-4161

Lalander, E., Svedendahl, M., Nordström-Larsson, R., Johansson, T., & Andersson, M. H. (2021). *The underwater soundscape in the port of Gothenburg and estimations of the underwater radiated noise from ships.* FOI-R--5156--SE. https://www.foi.se/rest-api/report/FOI-R--5156--SE

Lalander, E., Nordström-Larsson, R., Andersson, M.H. (2022). *Changes in the underwater soundscape in Kattegat due to shipping re-routing.* FOI-R--5334--SE. https://www.foi.se/rest-api/report/FOI-R--5334--SE

Langlet, D. (2022). Shipping and the Ecosystem Approach. In Basu Bal, A., Rajput, T., Argüello G. Langlet, D. (eds). *Regulation of Risk - Transport, Trade and Environment in Perspective.* Brill, 2022, 419-451. https://doi.org/10.1163/9789004518681_015

Larsson Nordström, R., Lalander, E., Skog, I., Andersson M. (2022). Maximum likelihood separation of anthropogenic and wind-generated underwater noise. *The Journal of the Acoustical Society of America,* 152(3), pp. 1292–1299. https://doi.org/10.1121/10.0013887

Liefvendahl, M., Feymark, A., Bensow, R.E. (2015). *Methodology for noise source modelling and its application to Baltic Sea shipping - Deliverable D4.1 of the BONUS SHEBA project.* https://research.chalmers.se/publication/232045

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

MacGillivray, A.O., 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://www.mdpi.com/2077-1312/9/4/369

MacGillivray, A. O., Ainsworth, L. M., Zhao, J. N., Dolman, J. N., Hannay, D. E., Frouin-Mouy, H., Trounce, K. B., & White, D. A. (2022). A functional regression analysis of vessel source level measurements from the Enhancing Cetacean Habitat and Observation (ECHO) database [Article]. *Journal of the Acoustical Society of America, 152*(3), 1547-1563. https://doi.org/10.1121/10.0013747

Mahmoudi, S. (2014). The Baltic Straits. In Caron, D. D. and Oral, N. (eds), *Navigating Straits: Challenges for International Law.* Brill, 2014, 125-137. https://doi.org/10.1163/9789004266377_007

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*, 13, Article 109075. https://doi.org/10.1016/j.oceaneng.2021.109075

MEPC (2014). Marine Environment Protection Committee, International Maritime Organization. MEPC.1/Circ.833 7 April 2014. *Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life.* 8pp. https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/833%20Guidance%20on%20reducing%20underwater%20noise%20from%20commercial%20shipping%2c.pdf

Nordström, R. L., Lalander, E., Skog, I., & Andersson, M. (2022). Maximum likelihood separation of anthropogenic and wind-generated underwater noise. *Journal of the Acoustical Society of America, 152*(3), 1292-1299. https://doi.org/10.1121/10.0013887

OSPAR. (2021). *Strategy of the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic 2030.* https://www.ospar.org/site/assets/files/1200/north-east_atlantic_environement_strategy_compiled.pdf

PCA (2016) South China Sea Arbitration, Philippines v China, Award, PCA Case No 2013-19, ICGJ 495, 12th July 2016, Permanent Court of Arbitration.

Ross, D., F. F. Alvarez, Radiated underwater noise of surface ships. *U.S. Navy J. Underw.* 566 *Acoust.* **14** (1964)

Ross, D. (1976) *Mechanics of Underwater Noise*. xiv, 375 pages. ISBN: 978-1-4831-6046-7. https://www.sciencedirect.com/book/9780080211824/mechanics-of-underwater-noise

Smith, T. A., & Rigby, J. (2022). Underwater radiated noise from marine vessels: A review of noise reduction methods and technology. *Ocean Engineering, 266*, 15, Article 112863. https://doi.org/10.1016/j.oceaneng.2022.112863

Svedendahl M, Lalander E, Sigray P, Östberg M, Andersson MH. (2021). *Underwater acoustic source signatures from recreation boats - Field measurements and guidelines.* FOI report FOI-R--5115--SE. https://www.foi.se/rest-api/report/FOI-R--5115--SE

SOLAS - International Convention for the Safety of Life at Sea (adopted 1 November 1974, entered into force 25 May 1980) 1184 UNTS 2. (1974). https://treaties.un.org/doc/Publication/UNTS/Volume%201184/volume-1184-I-18961-English.pdf

Tani G, Viviani M, Felli M, Lafeber FH, Lloyd T, Aktas B, Atlar M, Turkmen S, Seol H, Hallander J, Sakamoto N. (2020). Noise measurements of a cavitating propeller in different facilities: Results of the round robin test programme. *Ocean Engineering.* 2020;213(March):107599. https://doi.org/10.1016/j.oceaneng.2020.107599

The Sound Treaty (1857). Treaty for the Redemption of the Sound Dues between Denmark and Austria, Belgium, France, Great Britain, Hanover, The Hansa Towns, Mecklenburg-Schwerin, the Netherlands, Oldenburg, Prussia, Russia, and Sweden-Norway, signed at Copenhagen on 14 March 1857.

United Nations Convention on the Law of the Sea (UNCLOS), 1-202 (1982). https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf

Wittekind, D. (2014). A Simple Model for the Underwater Noise Source Level of Ships. *Journal of ship production and design*, 30, 7-14.

Zwicker, E., & Fastl, H. (1999). *Psychoacoustics - Facts and Models* (2nd 1999. ed.). XII, 417 pp. ISBN: 9783662095621. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-09562-1

APPENDIX 1: UNDERWATER RADIATED NOISE MEASUREMENTS

There are international standards and class notations that describe how to measure the underwater radiated noise (URN) from commercial ships (ISO 17208-1:2016; Bureau Veritas, 2018; ISO 17208-2:2019). However, the method used to calculate the URN or source level differs, and the accuracy varies between the standards due to their different requirements regarding, for example, the measurement set-up and estimation of the propagation loss (PL). Additionally, most of these standards and notations are not designed to work in shallow water (<150 m) (Ainslie et al., 2022; MacGillivray et al., 2023). However, the Bureau Veritas (2018) notation covers both shallow and deep waters. Further, there is currently a new ISO standard being developed that specifies the requirements for shallow water measurements. This standard is planned to be published in 2024.

VINGA STATION DESCRIPTION AND PROPAGATION LOSS MEASUREMENTS

The Vinga hydrophone station, located outside Gothenburg (Figure A1.1), was developed by the Swedish Defence Research Agency (FOI) and consists of three main parts. First is a sea unit located at the sea floor, consisting of two hydrophones and a transmitter, a data collection system and a network switch that sends the recorded data to shore. Second is a hybrid fibre optic cable that connects the sea unit with the third part, a land unit that supplies power to the sea unit and receives data and stores it on a hard drive. The hydrophones, mounted in a PVC structure 1.5 m above the seabed with a 0.75 m separation, had a sensitivity of -153 dB re 1 V/µPa below 10 kHz. From 10 kHz up to 25 kHz the sensitivity dropped monotonically to -157 dB re 1 V/µPa. The system was programmed to collect data with a 51.2 kHz frequency. The selected sample rate allows for analysis up to approximately 20 kHz, including radiated noise from most ships and sound from wind and waves as well as biological sound from fish, seals, and some cetaceans. More details of the hydrophone station can be found in Andersson et al. (2023).

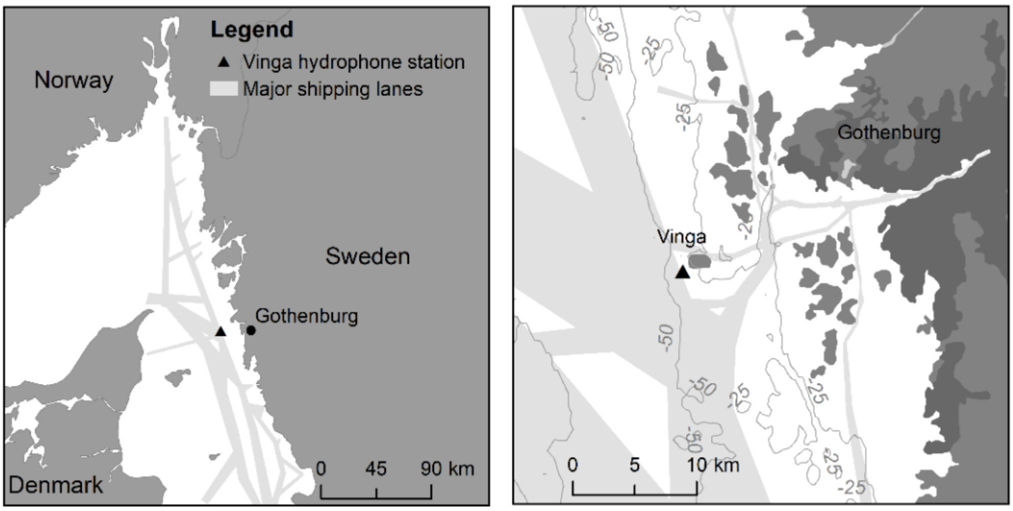


Figure A1.1. Location of the Vinga hydrophone station (▲) close to the Port of Gothenburg (●) on the Swedish west coast. Map source: GSD-Sverigekartor © Lantmäteriet (2020), bathymetry: GEBCO_2021.

The hydrophone station was deployed at 46 m depth, ~2 km outside the island of Vinga where many ships pass within 1 km on their way to or from the Port of Gothenburg on the Swedish west coast. The number of possible opportunistic passages of commercial ships with an active AIS transponder was about 30 ships every day within 5 km from the station. However, not all passages could be used in the analysis due to noise disturbances from other ships in the area. There are also smaller vessels without AIS transponders, which will add noise to the area that can be detected at the hydrophone station. The sea bottom in the area consists mainly of mud with patches of hard rock. However, the hydrophones are located on a similar bottom type (mud) as the passing ships.

Propagation loss measurements were conducted in March and June 2022 by towing an underwater acoustic transducer (Lubell Labs 1424HP) at a depth of approximately 5 m from the position of the hydrophone station and 4 km towards southwest. Seven tones, ranging from 160 Hz to 1060 Hz, were continuously played throughout the measurement. As the hydrophone station was online during the March measurement, the decay of the signals could be monitored in real time and the measurements were conducted until the signals decreased to background levels. The received levels were compared to the received levels from a reference hydrophone located on a ship about 7 m from the transducer. The sound velocity profile (SVP) was measured with a Swift Sound Velocity Profiler from Valeport Instruments, both in March and June 2022.

SOURCE LEVEL ESTIMATION

The subsequent steps were followed to extract time periods suitable for opportunistic source level estimates.

- Decode AIS data within a suitable area and time period.
- For each ship with a unique identification number (MMSI) within the area, detect time periods where the distance from the ship to the hydrophone station is below 1000 m and the ship speed is greater than 1 m/s.
- Keep only passages with time periods longer than 30 s.
- Keep only time periods where all other moving ships (ship speed > 0.2 m/s) are at least 1200 m away from the hydrophone station.
- Keep only time periods where the closest point of approach (CPA) is below 650 m.
- Keep only time periods where the longest duration between AIS messages is less than 20 s.

Data from the hydrophones were processed in several sequential steps to calculate the source level of a passing ship, based on the guidelines from Bureau Veritas (Bureau Veritas 2018). In accordance with the guideline, the Sound Pressure Levels (SPLs) measured in different directions from a ship are treated equally and averaged to form the final URN from the ship. The signal processing steps are given in detail in Svedendahl et al. (2021).

VINGA DATA SHIP STATISTICS

*Table A1.1. Statistics of ship passages near the Vinga station during the measurement period, November 2022 to June 2023, according to *Ship type in the AIS, Vessel finder and JOMOPANS-ECHO (J-E) ship class.*

SHIP TYPE*	INFORMATION FROM VESSEL FINDER	J-E SHIP CLASS	NO OF UNIQUE SHIPS	NO OF PASSAGES	MEAN SPEED [KN]	MEAN LENGTH [M]
Tanker	Tanker: chemical and oil product tankers and LNG	Tanker	17	33	10.3	94
General cargo	General cargo ships	Bulker	34	48	10.2	88
Miscellaneous	Miscellaneous, e.g., tug, utility vessel, search and rescue vessel	Miscellaneous	3	3	7.8	49
Container	Container ship	Container ship	3	4	13.2	130
RoRo	Ro-ro cargo ship	Container/ Vehicle carrier	8	102	19.9	233
Dry Bulk	Dry bulk carrier: Cement carrier	Bulker	1	1	12.4	90
Vehicles carrier	Vehicles carrier	Vehicles carrier	1	1	12.5	148

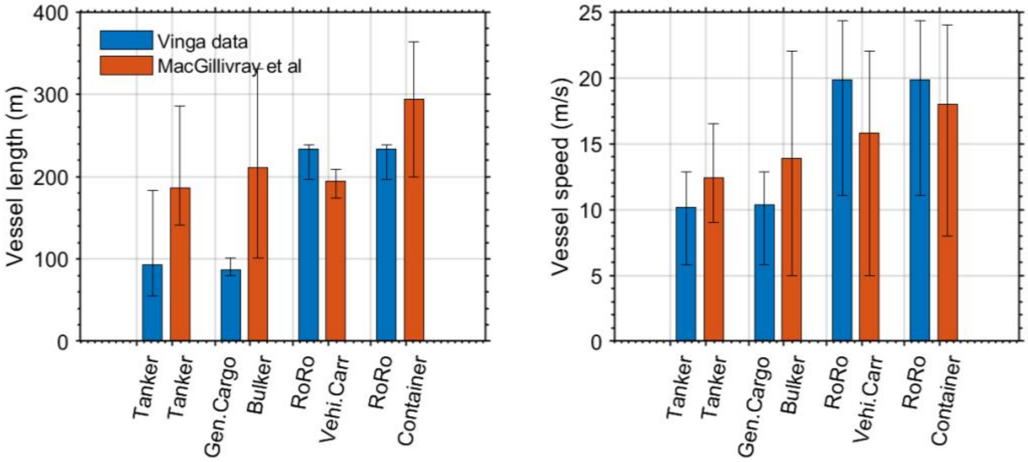


Figure A1.2. Comparison of average vessel length and speed of the analysed ships in the Vinga dataset (blue) compared with ECHO-dataset (red). Error bars denote max and min values. There were few passages of Vehicle Carriers and Containers in the Vinga data for this statistical comparison and therefore not included here.

SPECTRAL DIFFERENCE BETWEEN THE RORO MEASUREMENT AND J-E MODEL

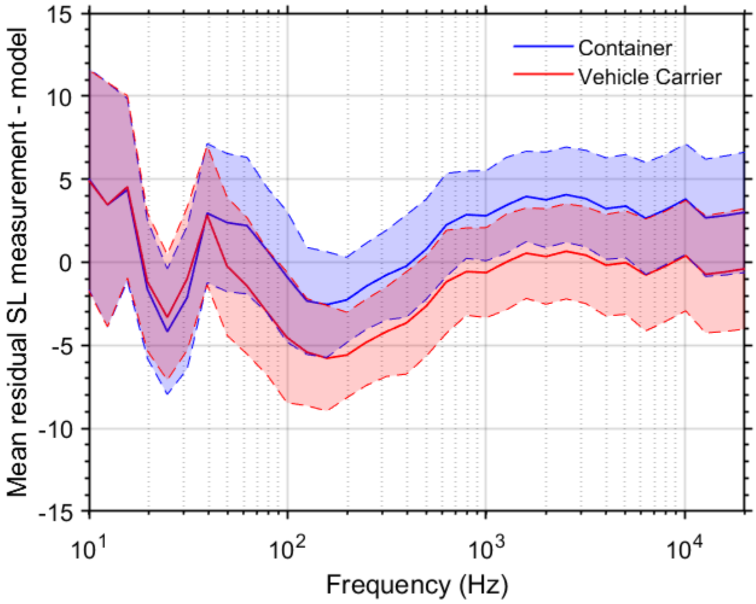


Figure A1.3. Mean residual over frequency, subtracting the modelled source level from the source level estimated from measurements for the J-E classes "Container" (blue) and "Vehicle Carrier" (red) as a function of frequency. Positive residuals mean that the ship SL is higher than the model. Note that the propagation loss was not measured below 160 Hz and therefore the calculated levels show larger uncertainties than higher frequencies.

UNCERTAINTIES IN THE J-E MODEL EVALUATION

The estimation of the source levels from the measurements near Vinga contain several uncertainties. The main issue is the propagation loss (PL), which was measured twice during the measurement campaign. The PL measurements were conducted in March and June 2022. The measurements were conducted by transmitting seven continuous tones (160-1060 Hz) while driving away from the Vinga station position. It was not possible to transmit lower frequencies with the available equipment, and the lowest frequencies (160 and 210 Hz) had a relatively low source levels, resulting in larger uncertainties for these low frequency estimation of the PL.

The PL is closely related to the sound velocity profile (SVP). The SVP taken during the PL measurements was compared with modelled data from the Swedish Meteorological and Hydrological Institute (SMHI), indicating that the measurements in March were relevant for measurements during the winter and that the SVP significantly changes during May and June. However, the SVP is not constant during winter either and may very well change the PL slightly from one day to another depending on the weather. Therefore, although the measurement yields a good average PL, there will be an error in the PL used for a specific passage.

Furthermore, the same PL was used in all directions, which is not necessarily the case, as differences in the actual PL, for instance, depend on the local seabed, depth etc.

Although the PL uncertainty is likely the most significant error in the measurements used to estimate the source level of a ship, the estimation of the PL uncertainty and how it impacts a particular source level estimation is a large undertaking that falls outside of the current work.

Finally, some AIS speed data are only sent with integer precision, which has a large impact on how well the estimated source level compares to the J-E model. This is especially true for low speeds, where a large discrepancy between the estimated source levels and the model was apparent for the J-E Tanker and Bulker classes. The slowest passage, at 3 m/s (6.8 knots), could therefore be wrong by as much as 17%.

REFERENCES APPENDIX 1

Ainslie, M. A., Martin, S. B., Trounce, K. B., Hannay, D. E., Eickmeier, J. M., Deveau, T. J., Lucke, K., MacGillivray, A. O., Nolet, V., & Borys, P. (2022). International harmonization of procedures for measuring and analyzing of vessel underwater radiated noise. *Marine Pollution Bulletin*, 174, 13, Article 113124. https://doi.org/10.1016/j.marpolbul.2021.113124

Bureau Veritas. (2018). *Underwater Radiated Noise (URN).* Rule Note NR 614 DT R00. https://erules.veristar.com/dy/data/bv/pdf/614-NR_2018-07.pdf

ISO 17208-1:2016. (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. https://www.iso.org/standard/62408.html

ISO 17208-2:2019. (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. https://www.iso.org/standard/62409.html

MacGillivray A.O., Martin S.B., Ainslie M.A., Dolman J.N., Li Z., Warner G.A. (2023). Measuring vessel underwater radiated noise in shallow water. *J Acoust Soc Am.* Mar;153(3):1506. doi: 10.1121/10.0017433. PMID: 37002101. https://doi.org/10.1121/10.0017433

Svedendahl M, Lalander E, Sigray P, Östberg M, Andersson MH. (2021). *Underwater acoustic source signatures from recreation boats - Field measurements and guidelines.* FOI report FOI-R--5115--SE. https://www.foi.se/rest-api/report/FOI-R--5115--SE

APPENDIX 2: THE JOMOPANS-ECHO MODEL

The JOMOPANS- ECHO source level model (MacGillivray & de Jong, 2021) defines a spectrum for each shipping class, expressed as spectral density levels:

$$L_{S_f,0}\left(\hat{f},\mathrm{C}\right) = K - 20\log_{10}\left(\hat{f}_1\right)\ \mathrm{dB} - 10\log_{10}\left(\left(1-\frac{\hat{f}}{\hat{f}_1}\right)^2 + D^2\right)\ \mathrm{dB}$$

where $\hat{f} = \frac{f}{f_{\mathrm{ref}}}$, C denotes the vessel class, $\hat{f}_1$ = 480 Hz × $\left(\frac{V_{\mathrm{ref}}}{V_C}\right)$, f_{ref} = 1 Hz and V_{ref} = 1 kn, and K = 191 dB, D = 3 for all classes, except $D_{\text{cruise vessel}}$ = 4.

For cargo vessels (Container Ships, Vehicle Carriers, Bulkers, and Tankers) the model includes an additional low-frequency bump in the spectrum below 100 Hz

$$\begin{aligned} L_{S_f,0}&\left(\hat{f} < 100, \mathrm{Cargo}\right) \\ &= K^{LF} - 40\log_{10}\left(\hat{f}_1^{LF}\right)\mathrm{dB} + 10\log_{10}\left(\hat{f}_1\right)\mathrm{dB} \\ &\quad - 10\log_{10}\left(\left(1-\left(\frac{\hat{f}}{\hat{f}_1^{LF}}\right)^2\right)^2 + \left(D^{LF}\right)^2\right)\mathrm{dB} \end{aligned}$$

where K^{LF} = 208 dB and $\hat{f}_1^{LF}$ = 600 Hz × $\left(\frac{V_{\mathrm{ref}}}{V_C}\right)$, and D^{LF} = 0.8 for Container Ships and Bulkers or D^{LF} = 1.0 for Vehicle Carriers and Tankers.

The spectra are then used in a model of source levels based on the speed and length dependencies of the corresponding RANDI 3.1 model:

$$L_{S_f,J-E}(f,V,i,\mathrm{C}) = L_{S_f,0}\left(\hat{f},\mathrm{C}\right) + 60\log_{10}(V/V_C)\ \mathrm{dB} + 20\ \log_{10}(l/l_0)\ \mathrm{dB}$$

In calculations the expressions are converted to source levels in decidecade frequency bands by adding the factor:

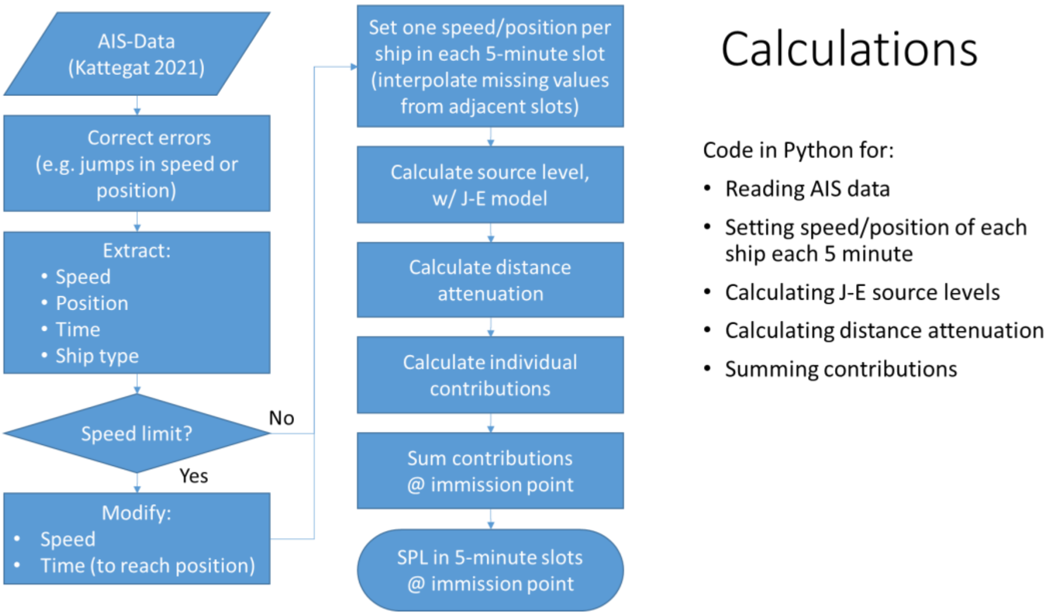
$$10\log_{10}\left(0.231\hat{f}_1\right)\ \mathrm{dB}.$$

CLASSIFICATION OF RORO SHIPS IN THE CALCULATIONS

The RoRo Ships of this study were classified in the calculations as both “Container Ship” and “Vehicle Carriers”, respectively, because these ships did not completely match the ship types that were measured in the Vancouver study. According to the conclusions of the Vinga study, in Section 3.3, either of these spectra may match RoRo Ships. This was in line with the results of the calculations, which showed overall differences within a 0.1 dB margin between both cases.

INITIAL CALCULATIONS TO EVALUATE THE DATA VARIATION

Initial calculations were done using data covering four full days and sampled from different seasons in 2021. A flow chart of the calculations is shown below. The purpose of these calculations was to check if any strong systematic variations were to be found, either between the seasons or during 24-hour periods split into 5-minute intervals. The sample days were selected based on the traffic flow study presented in Chapter 5. The immission point of these calculations was located far from the routes, near Kullen, cf. Figure 16. The reason for choosing a remote calculation point was that close passages of single ships result in greater noise level variations (as discussed above), which would be hard to interpret on the small data set.



Calculations

Code in Python for:

- Reading AIS data
- Setting speed/position of each ship each 5 minute
- Calculating J-E source levels
- Calculating distance attenuation
- Summing contributions

Figure A2.1 A flow chart of the calculations done to check if systematic variations were to be found.

The calculated noise levels of the sampled days showed surprisingly low variation, both in the long and the short time frame. This is probably because traffic is generally quite dense in the area, with several ships present 24 hours a day during the entire year, making the variations in sound level less than it would be in case of sparse and intermittent traffic. As can be seen in table A2.1, the difference in equivalent noise levels, ΔL_{eq}, between the four sample days was less than one decibel in both cases, “actual speed according to AIS-data” and “speed reduced to 11 kn” (the calculation of the noise levels in the latter case will be elaborated below). The equivalent noise level is an average over the considered time interval, which can refer to a pass-by, a measurement period, etc. In the calculations, this is an average either over 5-minute or 24-hour intervals.

Table A2.1. The equivalent noise level, L_{eq}, at the immission point Kullen, calculated at four dates for actual speeds according to AIS data and for a hypothetical speed limit at 11 kn.

DATE	L_{EQ24H} @ ACTUAL SPEED	L_{EQ24H} @ SPEED ≤ 11 KN
2021-01-15	106 dB re 1 µPa	102 dB re 1 µPa
2021-04-15	106 dB re 1 µPa	102 dB re 1 µPa
2021-07-15	107 dB re 1 µPa	102 dB re 1 µPa
2021-10-15	106 dB re 1 µPa	103 dB re 1 µPa

The equivalent noise levels, L_{eq}, taken over 5-minute intervals during the 24-hour periods of the four sample days is shown in Figure 24. It is interesting that the trends of significant daily variations in traffic flow are hardly discernible in the figure. Some indications can be seen in the diagram of July 15, which probably is due to slightly lower general traffic intensity combined with the fast RoPax Ships in peak traffic. But the variations in noise level that day are still considerably lower than those of traffic intensity - probably for the same reason as discussed above (dense traffic in an area will generally make the noise variations smaller).

If the immission point is moved into the route, passages of nearby ships will yield noise peaks with levels determined by individual ships' radiated noise level and the corresponding closest distance between these ships and the immission point. The resulting noise level for the immission point "within the S-route" (marked with a red dot in Figure 17) is shown in Figure 25 together with those of the immission point "Kullen". As can be seen, the peaks from passing ships are considerably higher at the immission point closest to the passage, and so the equivalent noise level is higher. However, the differences between the calculated noise levels at actual speed and at reduced speed, respectively, are almost the same in both cases (ΔL_{eq} = 4.3 dB vs. ΔL_{eq} = 4.5 dB). The difference between the calculated values is quite robust and may only differ appreciably in cases where a single ship happens to come very close to the immission point, as discussed above. In such a case, the actual speed of that ship determines what noise reduction will be achieved by reducing its speed. Such random events are not very interesting since the outcome is erratic. A much better strategy is to use either distanced immission points, that will give robust and representative estimates of the overall impact of the ships in the region, or to use values of single ships to find the maximum impacts (which will result from close passages).

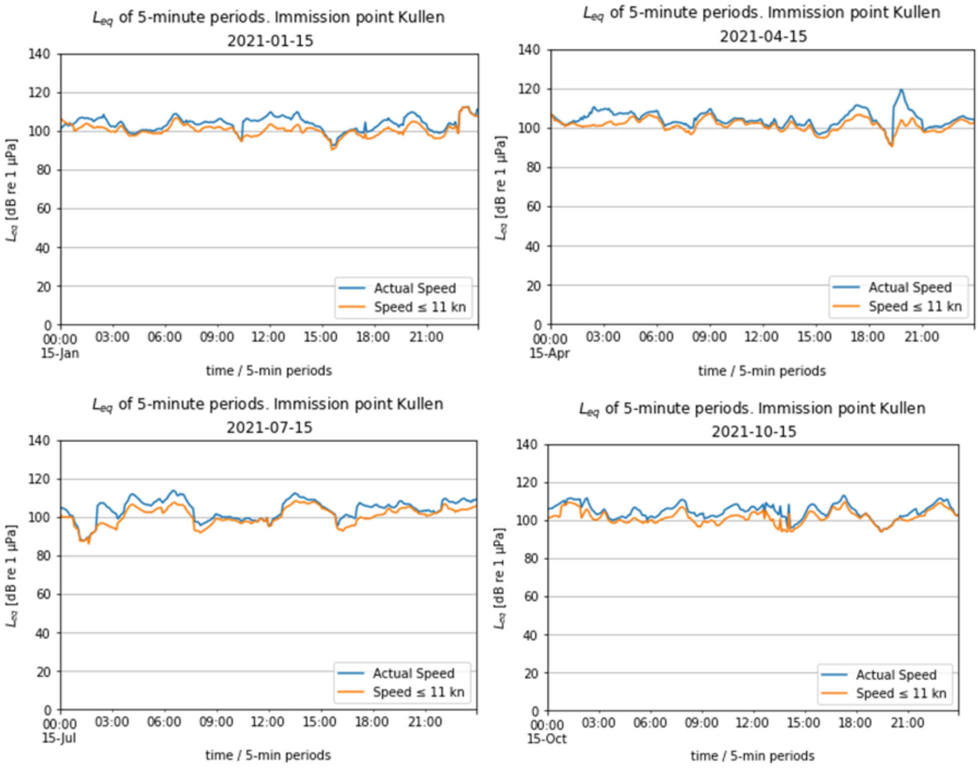


Figure A2.1. Equivalent noise levels L_{eq} taken over 5-minute intervals during the 24-hour periods of the four sample days.

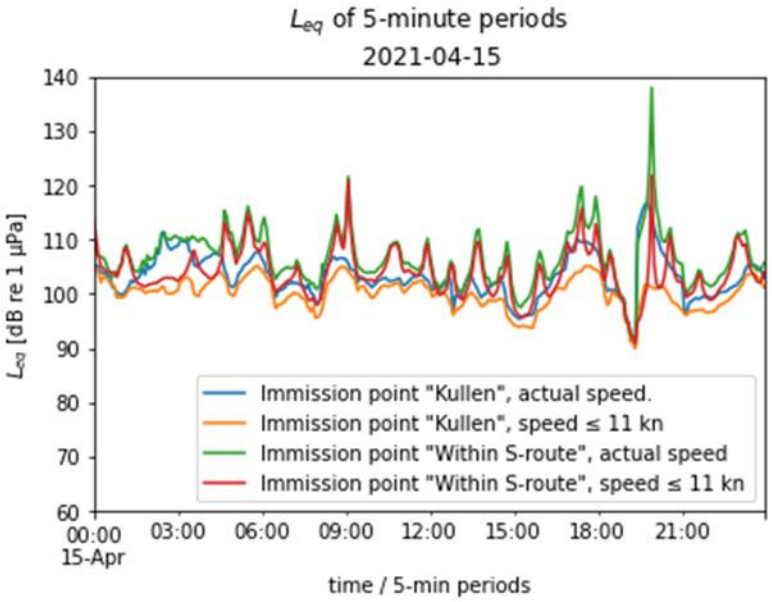


Figure A2.2. Equivalent noise levels L_{eq}, at the immission point "within the S-route", and at the the immission point "Kullen". As expected, the noise peaks "within the S-route" are much higher than near Kullen, far away from the shipping lane, due to closely passing ships.

STANDARD DEVIATION CALCULATION

The method by which the standard deviation values were calculated needs to be discussed. The standard strategy when calculating noise impact is to use energy considerations, as using logarithmic dB numbers regularly results in skewed distributions (it is more common that the sound pressure has a normal distribution compared to the sound pressure level). However, there is no correct or generally accepted way to calculate the standard deviation of sound pressure level (although a few formulas have been suggested). Here, we have used the sound pressure level values in dB because this is the most common way to do it and because any differences will be small.

APPENDIX 3: AIS ANALYSES

The ship traffic in the study area in southern Kattegat was analysed using historical AIS data covering the year 2021. AIS data files were received from the Swedish Maritime Administration under an agreement with the Swedish Institute for the Marine Environment. The AIS files included information of the IMO and MMSI number, date and time, position, ship type, ship length (m), and ship speed (kn). More detailed information on ship types was obtained from Vesselfinder. By using data from Vesselfinder, and in a few cases data from other open data sources, ships were categorised into ten categories: Tankers (TANK), Dry bulk ships (DRYB), General cargo ships (GENE), Container ships (CONT), Reefers (REEF), RoPax ships (ROPA), Cruise ships (CRUI), RoRo-ships (RORO), Vehicle carriers (VEHI), and Others / Miscellaneous (MISC) (Table A3.1). The category Miscellaneous is very heterogeneous and includes ship types that were not included in the other nine categories, for example, tugs, supply ships, and various other specialised ships. Only ships with IMO numbers are included in the analyses in this report. Unique IMO numbers are assigned to sea-going merchant ships according to an IMO regulation, and this applies to all passenger ships and to all cargo ships of 300 gross tonnage and upwards. Although some fishing boats and fishing ships have been assigned IMO numbers, these vessel types are not included in the analyses in this report.

The AIS data were used to calculate the number of unique ships of different categories that travelled through the study area in 2021. To also obtain a measure of traffic intensity in the whole study area as well as in parts of the area, i.e. in different “pixels”, the variable “number of shipdays” was calculated. The number of shipdays was calculated as the overall sum of the number of days each ship was observed in the study area or in the different pixels. The variable “number of shipdays” can together with other information be used to estimate the environmental stress different ships or ship categories may exert on different parts the study area.

The variable “number of shipdays per ship” was also calculated and can be used to analyse how often different ships pass through the area. High values of the number of shipdays per ship mean that ships navigated through the area repeatedly. Most ship traffic in the study area was transit traffic.

Subsamples of AIS data covering representative days in 2021 were used to estimate underwater radiated noise from ships in the study area (details on subsamples are given in Chapter 5).

Table A3.1 Classification of ship types.

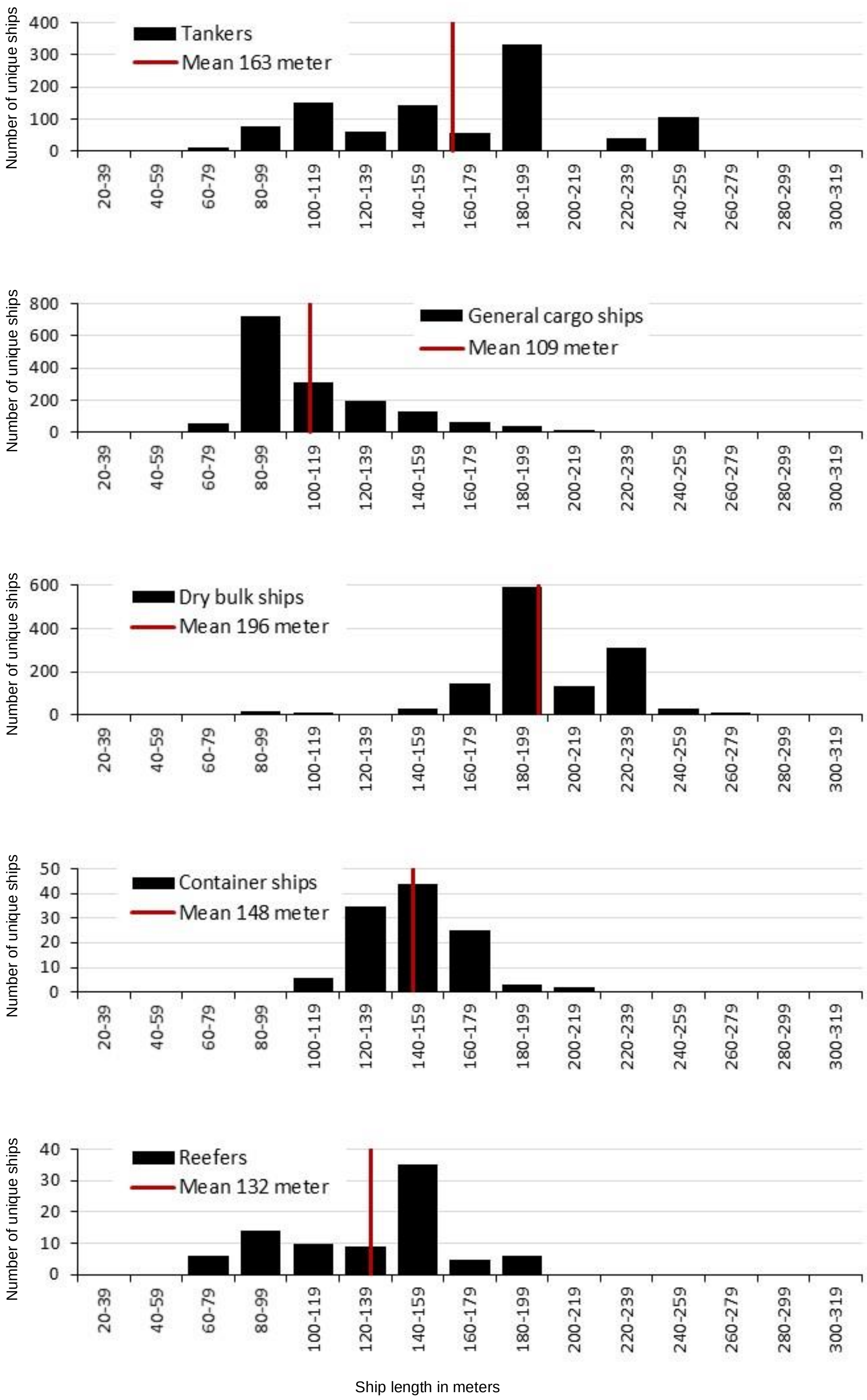
VESSELFINDER TYPE NAME	THIS REPORT
Liquefied Gas	TANK
LNG Tanker	TANK
LPG Tanker	TANK
CO2 Tanker	TANK
Chemical Tanker	TANK
Chemical/Oil Products Tanker	TANK
Vegetable Oil Tanker	TANK
Crude Oil Tanker	TANK
Oil Products Tanker	TANK
Bitumen Tanker	TANK
Asphalt/Bitumen Tanker	TANK
Molasses Tanker	TANK
Bulk Carrier	DRYB
Self Discharging Bulk Carrier	DRYB
Cement Carrier	DRYB
Limestone Carrier	DRYB
General Cargo Ship	GENE
Palletised Cargo Ship	GENE
Deck Cargo Ship	GENE
Passenger/General Cargo Ship	GENE
Heavy Load Carrier	GENE
Nuclear Fuel Carrier	GENE
Refrigerated Cargo Ship	REEF
Container Ship	CONT
Ro-Ro Cargo Ship	RORO
Vehicles Carrier	VEHI
Passenger/Ro-Ro Cargo Ship	ROPA
Passenger (Cruise) Ship	CRUI
Fishing Support Vessel	MISC
Supply vessel	MISC
Offshore Tug/Supply Ship	MISC
Offshore Support Vessel	MISC

Drilling Ship	MISC
Pipe Layer	MISC
Standby Safety Vessel	MISC
Pipe Burying Vessel	MISC
Research Vessel	MISC
Tug	MISC
Pusher Tug	MISC
Dredger	MISC
Hopper dredger	MISC
Motor Hopper	MISC
Crane Ship	MISC
Icebreaker	MISC
Cable layer	MISC
Pollution Control Vessel	MISC
Patrol Vessel	MISC
Crew Boat	MISC
Training Ship	MISC
Utility Vessel	MISC
Search & Rescue Vessel	MISC
Pilot vessel	MISC
Salvage Ship	MISC
Buoy/Lighthouse Vessel	MISC
Supply Tender	MISC
Work/Repair Vessel	MISC
Anchor Hoy	MISC
Exhibition Vessel	MISC
Bunkering Tanker	MISC
Vessel (function unknown)	MISC
Sailing Vessel	MISC
Yacht	MISC
Naval/Naval Auxiliary	MISC
Non Propelled Barge	MISC
Pontoon	MISC

APPENDIX 4: SHIP SPEED, SHIP LENGTH, AND TRAFFIC INTENSITY

Table A4.1. Comparison of the mean speed of ships (in knots) in southern Kattegat and in the main shipping route off Öland in the central Baltic Sea.

SHIP TYPE	MEAN SPEED OFF ÖLAND	MEAN SPEED IN SOUTHERN KATTEGAT	DIFFERENCE
Tankers	11.8	11.1	0.7
Dry bulk ships	12.4	11.5	0.9
General cargo ships	10.5	10.4	0.1
Container ships	14.9	14.0	0.9
Reefers	15.6	13.4	2.2
RoRo ships	15.6	14.5	1.1
Vehicle carriers	15.1	14.3	0.8
RoPax ships	19.1	17.6	1.5
Cruise ships	14.0	12.2	1.8


Number of unique ships
400
300
200
100
0
Tankers
Mean 163 meter
Number of unique ships
800
600
400
200
0
General cargo ships
Mean 109 meter
Number of unique ships
600
400
200
0
Dry bulk ships
Mean 196 meter
Number of unique ships
50
40
30
20
10
0
Container ships
Mean 148 meter
Number of unique ships
40
30
20
10
0
Reefers
Mean 132 meter
20-39
40-59
60-79
80-99
100-119
120-139
140-159
160-179
180-199
200-219
220-239
240-259
260-279
280-299
300-319
Ship length in meters

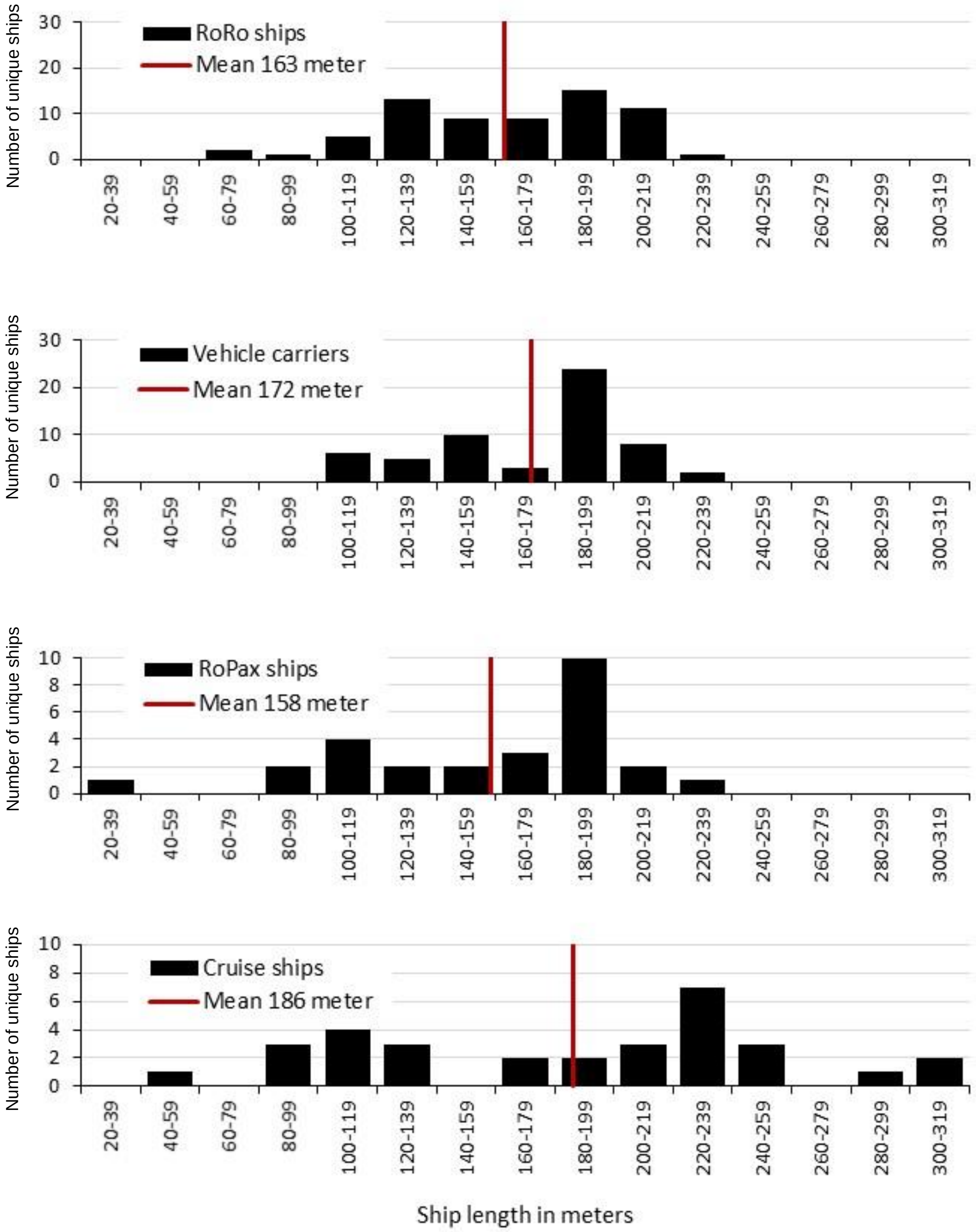
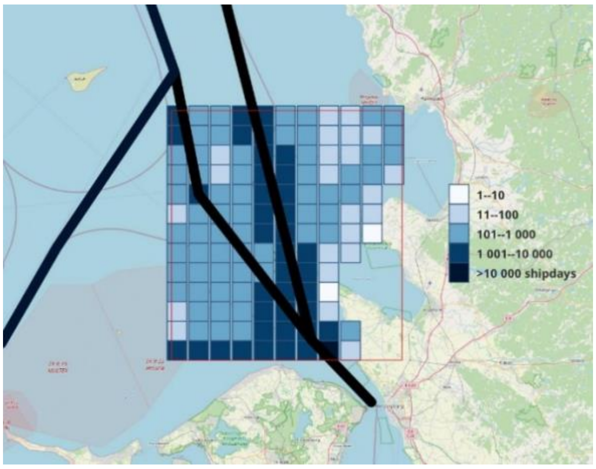
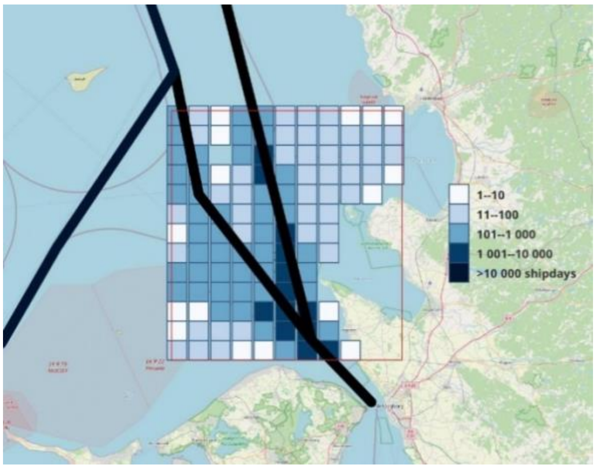


Figure A4.1. Lengths of different ship classes that travelled through the study area in 2021. Note different scales on the y-axis.

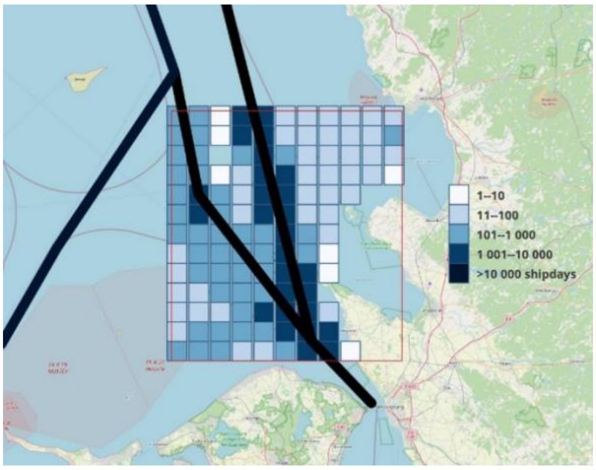
The ten figures below (Figure A4.2) show the traffic intensity expressed as ship-days per pixel of different ship classes in the study area in 2021. Each pixel is 0.04 degrees x 0.08 degrees, that is, approximately 4.4 km x 4.8 km, in size. Black lines show the main routes; the S-route, T-route, and the recommended direction of traffic flow established for vessels with a draught of 10 meters or more between “Route T” and “TSS Entrance to The Sound”.



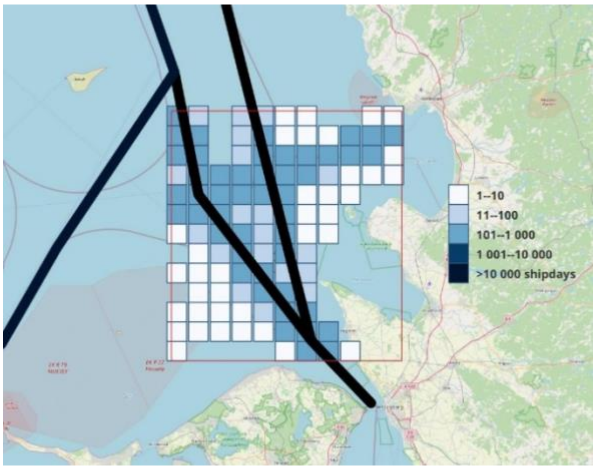
General cargo ships



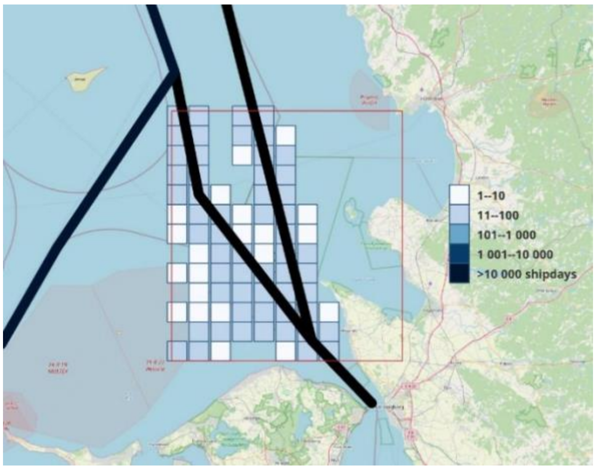
Dry bulk ships



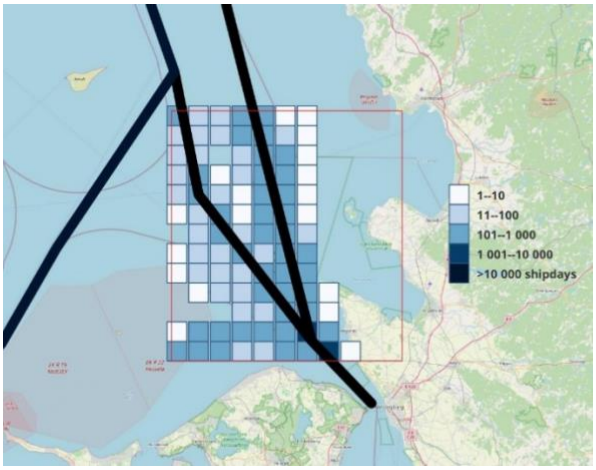
Tankers



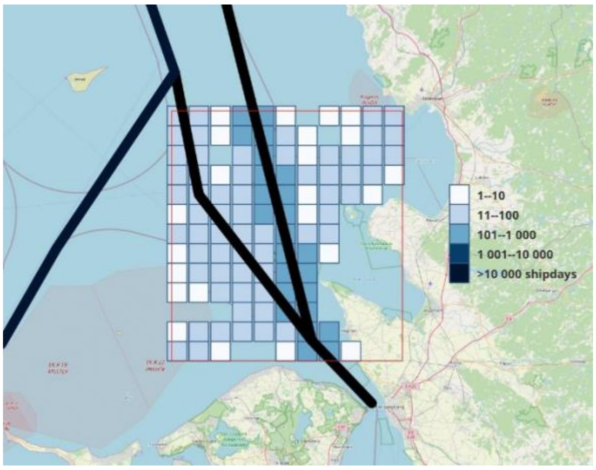
RoPax ships



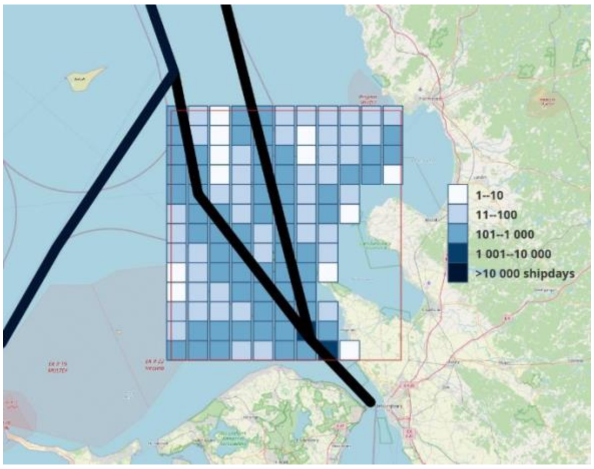
Cruise ships



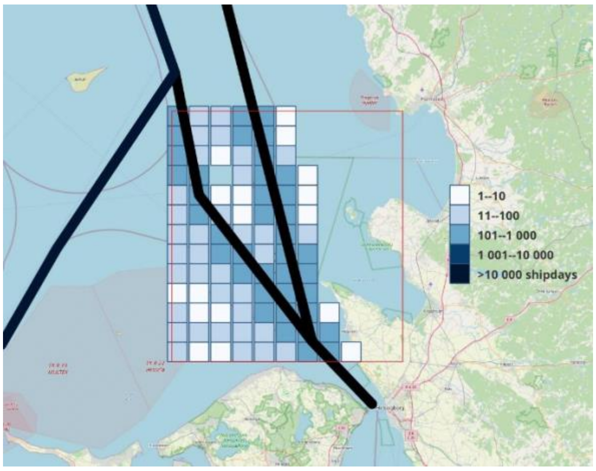
RoRo ships



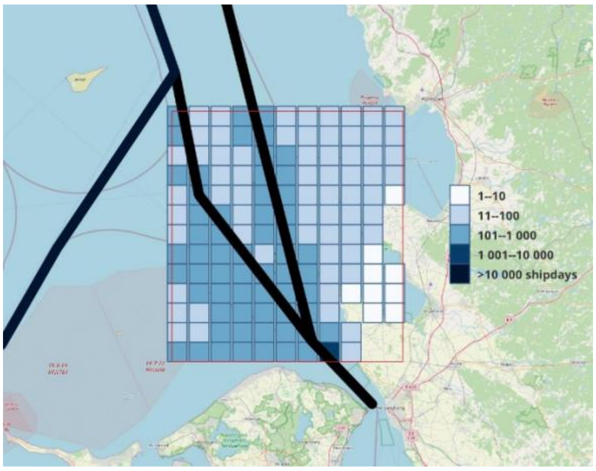
Vehicle carriers



Container ships



Reefers



Miscellaneous ships

Figure A4.2. Traffic intensity per ship type.

APPENDIX 5: FLAG STATES FOR THE SHIPS

The ships that travelled through the study area in 2021 were registered in 64 countries (flag states). About two percent of the ships were registered in Sweden and about four percent in Denmark.

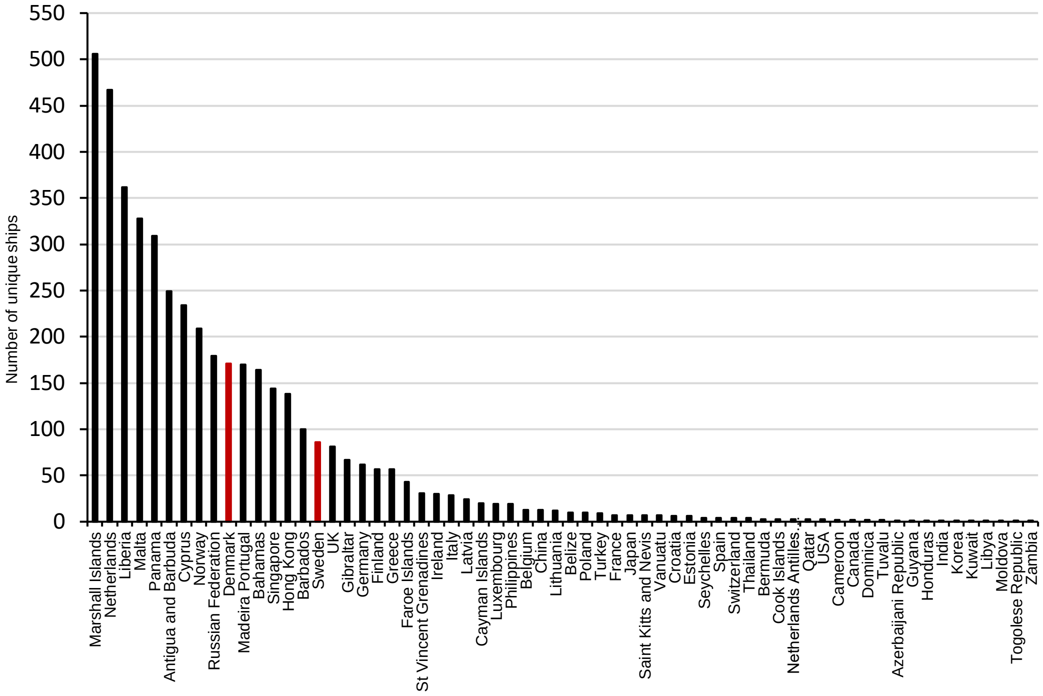


Figure A5.1. Flag states of ships that travelled through the study area in southern Kattegat in 2021.

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