TP15478E

Study of Quiet-Ship Certifications

Analysis using the ECHO Ship Noise Database

By:

David Hannay

Alex MacGillivray

Héloïse Frouin-Mouy

Zizheng Li

Federica Pace

Jennifer Wladichuk

Zahra Alavizadeh

JASCO Report: 01737

Final Report Version 1.0:

JASCO Applied Sciences (Canada) Ltd.

29 March 2019

Document Version Control

Version	Date	Name	Change
1.0	2019 Mar 29	D. Hannay	Addressed comments on draught report. Added Exec Summary and Discussion

Notices

This report reflects the views of JASCO Applied Sciences and not necessarily those of the Innovation Centre of Transport Canada.

The results presented herein are relevant within the specific context described in this report. They could be misinterpreted if not considered in the light of all the information contained in this report. Accordingly, if information from this report is used in documents released to the public or to regulatory bodies, such documents must clearly cite the original report, which shall be made readily available to the recipients in integral and unedited form.

Suggested citation:

Hannay, D.E. A.O. MacGillivray, H. Frouin-Mouy, Z. Li, F. Pace, J. Wladichuk and Z. Alavizadeh. 2018. *Study of Quiet Ship Certifications*: *Analysis using ECHO Ship Noise Database.* JASCO Document 01737, Final Report Version 1.0. Technical report by JASCO Applied Sciences for Transport Canada.

Un sommaire français se trouve avant la table des matières.

Transport Canada / Transports Canada

PUBLICATION DATA FORM

1. Transport Canada Publication No. TP 15478E	2. Project No. TA 002	3. Recipient's Catalogue No.
4. Title and Subtitle Study of Quiet-Ship Certifications: Analysis using ECHO Ship Noise Database		5. Publication Date 2019-03-29 6. Performing Organization Document No. 01737
7. Author(s) Hannay, D.E., A.O. MacGillivray H. Frouin-Mouy, Z. Li, F. Pace, J. Wladichuk, and Z. Alavizadeh		8. Transport Canada File No. -
9. Performing Organization Name and Address JASCO Applied Sciences (Canada) Ltd. 2305-4464 Markham Street Victoria, BC V8Z 7X8 Canada		10. PWGSC File No. - 11. PWGSC or Transport Canada Contract No. T8156-17-0001/001/VAN
12. Sponsoring Agency Name and Address Transport Canada, Innovation Centre Place de Ville, Tower C 330 Sparks Street, Ottawa ON K1A 0N5		13. Type of Publication and Period Covered Technical Report, 2015-2019 14. Project Officer Veronique Nolet

15. Supplementary Notes (Funding programs, titles of related publications, etc.)

Results of this study were presented in two papers at International Maritime Organization, London UK. Presentation 1, January 31, 2019: Modelling noise exposure reductions from vessels meeting prescribed emission thresholds, and Presentation 2, February 1, 2019: Comparison of Class Society Quiet Notation maximum noise levels with ECHO program measurements. The results are also included in a scientific manuscript.

16. Abstract

This study uses the large ship noise database, acquired by the Vancouver Fraser Port Authority's Enhancing Cetacean Habitat Observation (ECHO) program, to assess the conservativeness of five vessel noise certification societies. A multi-variate linear regression analysis of the database produced a powerful vessel noise model that can predict ship noise based on ship type and operating conditions. The model accounts for ship category (e.g. containership or tanker), ship length, dead-weight-tonnage, and year-built. It also accounts for vessel speed, effective wind speed and direction, and static draught. The model was used to scale ECHO measurements to a common reference vessel type for each category. Scaled measurements were compared with maximum noise emission limits of five certification societies. The general findings are that the society limits are conservative for faster categories (e.g. container ship) but not for slower vessels such as tankers. Harmonizing the certification society thresholds and developing category-dependent thresholds would be useful. A final study examined noise savings in Haro Strait due to vessels meeting an optimal set of noise emissions thresholds. The study found important noise savings at key southern resident killer whale feeding areas if 90% of vessels conformed with thresholds based on median noise emission levels of ECHO measurements.

17. Key Words Vessel noise, underwater acoustics, noise measurements, Enhancing Cetacean Habitat Observation, multivariate analysis, certification society		18. Distribution Statement Digital Copy		
19. Security Classification (of this publication) Unclassified	20. Security Classification (of this page) Unclassified	21. Declassification (date) —	22. No. of Pages 96	23. Price

CDT/TDC 79-005
Rev. 96

Transports Canada | Transport Canada

FORMULE DE DONNÉES POUR PUBLICATION

1. Nº de la publication de Transports Canada TP 15478E	2. Nº de l'étude TA002	3. Nº de catalogue du destinataire
4. Titre et sous-titre Étude des certificats de navires silencieux: Analyse utilisant la base de données ECHO sur le bruit des navires		5. Date de la publication 2019-03-29
		6. Nº de document de l'organisme exécutant 01737
7. Auteur(s) Hannay, D.E., A.O. MacGillivray H. Frouin-Mouy, Z. Li, F. Pace, J. Wladichuk, et Z. Alavizadeh		8. Nº de dossier - Transports Canada -
9. Nom et adresse de l'organisme exécutant JASCO Applied Sciences (Canada) Ltd. 2305–4464 Markham Street Victoria, BC V8Z 7X8 Canada		10. Nº de dossier - TPSGC -
		11. Nº de contrat - TPSGC ou Transports Canada T8156-17-0001/001/VAN
12. Nom et adresse de l'organisme parrain Centre d'innovation (IC) Place de Ville, tour C 330 rue Sparks Ottawa (Ontario) K1A 0N5		13. Genre de publication et période visée Rapport technique, 2015-2019
		14. Agent de projet Veronique Nolet

15. Remarques additionnelles (programmes de financement, titres de publications connexes, etc.)

Les résultats de cette étude ont été présentés en deux papiers à l'organisation maritime international a Londres (UK). Première présentation, le 31 janvier 2019: Modélisation des réductions de l'exposition au bruit par les navires répondant aux seuils d'émission prescits. Seconde présentation, le 1er février 2019: Comparaison des niveaux de bruit maximum selon les organisations de notation pour les navires silencieux avec les mesures du programme ECHO. Les résultats sont également inclus dans un manuscript scientifique.

16. Résumé

Cette étude utilise une large base de données de bruit de navires, acquise par le programme ECHO (Enhancing Cetacean Habitat Observation) initié par le Port de Vancouver (Vancouver Fraser Port Authority), en vue d'estimer l'approche conservatrice de cinq organisations de certification pour le bruit des navires. Une analyse de régression multivariée de la base de données a produit un modèle performant du bruit de navires qui peut prédire le bruit du navire basé sur le type de navires et les conditions de fonctionnement. Le modèle tient compte de la catégorie du navire (par exemple: porte-conteneur ou pétrolier), la longueur du navire, le tonnage de port en lourd, et l'année de construction. Il tient compte également de la vitesse du navire, de la vitesse et direction du vent, et du tirant d'eau statique. Le modèle était utilisé pour mettre a l'échelle les mesures du project ECHO en utilisant un type de navire comme référence commune pour chaque catégorie. Les mesures mises a l'échelle étaient alors comparées avec les limites maximales d'émission de bruit selon les cinq organisations de certification. Les conclusions générales sont que les limites des organisations sont conservatrices pour les catégories les plus rapides (par exemple: porte-conteneur) mais pas pour les navires plus lents tels que les pétroliers. L'harmonisation entre les seuils des organisations de certification et le développement de seuils dépendants de la catégorie seraient utiles. Une dernière étude examinait la réduction du bruit dans les zones d'alimentation les plus importantes pour les épaulards résidents du Sud si 90% des navires se conformaient avec les seuils basés sur les niveaux médians des émissions sonores des mesures du projet ECHO.

17. Mots clés	18. Diffusion Copie numérique

19. Classification de sécurité (de cette publication) Non classifiée	20. Classification de sécurité (de cette page) Non classifiée	21. Déclassification (date) —	22. Nombre de pages 96	23. Prix

CDT/TDC 79-005
Rev. 96

ACKNOWLEDGEMENTS

The authors would like to recognize the managers of the Enhancing Cetacean Habitat Observation (ECHO) program, and specifically Krista Trounce and Orla Robinson for their dedication and vision to implement a clearly world-leading vessel noise measurement study. We would also like to recognize that the acoustic data collection under ECHO was jointly sponsored by Vancouver Fraser Port Authority, Transport Canada, Fisheries and Oceans Canada. ECHO collaborators Ocean Networks Canada and JASCO Applied Sciences provided additional contributions in time and specialized equipment, and the BC Pilot's association participation and support of the study was instrumental.

EXECUTIVE SUMMARY

This report describes several related studies that make use of the large database of several thousand systematic commercial ship noise measurements acquired between September 2015 and April 2017 by the Vancouver Fraser Port Authority's ECHO program. The ECHO database comprises the largest set of systematic vessel noise measurements ever compiled. Its measurements were performed to conform approximately with vessel measurement standard ANSI S12.64 (Grade-C) and it contains a large amount of associated metadata, including meteorological, ocean current and accurate vessel navigation information for each measurement. Further, the database includes many vessel parameters, including AIS type category and sub-category, dimensions, tonnage, flag, year-built, static draught, and others.

The base study under this project was a multi-variate linear regression of the ECHO database's monopole source levels (MSL) and radiated noise levels (RNL) against several parameters that describe vessels and their measurement conditions. The purpose of this analysis was to develop a method to scale ship noise measurements to account for differences between individual ships (e.g. of different categories and sizes) and under different measurement conditions (e.g. for different transit speeds and wind conditions). The multivariate analysis produced a powerful ship noise model that can predict 1/3-octave band MSL and RNL based on ship category, ship length, dead-weight-tonnage, static draught, effective wind speed magnitude and direction, ship speed, and surface angle. This noise model is likely the best available presently, worldwide. It is already very useful for understanding noise emissions variations with ship characteristics and under different operating conditions.

The second study of this project used the ship noise model to scale the ECHO database measurements to account for differences in vessel characteristics within each vessel category. The categories included container ships, bulkers, tankers, vehicle carriers, cruise ships and tugs. The model also accounted for differences in measurement conditions, including transit speed, static draught and wind conditions. The purpose of scaling the ECHO measurements was to create a modified dataset to compare with existing vessel noise certification society noise thresholds. The five vessel certification societies considered were:

- Det Norske Veritas: *Rules for Classification of Ships*. Part 6 Chapter 24. Newbuildings Special Equipment and Systems – Additional Class, Silent Class Notation (2010)
- Bureau Veritas: *Underwater Radiated Noise (URN)*. Rule Note NR 614 DT R00 E (2014)
- American Bureau of Shipping: *Guide for the Classification Notation: Underwater Noise* (2018)
- RINA: *Rules for the Classification of Ships: Amendments to Part F. Additional Class Notations. Introduction of the new additional class notations "dolphin quiet" and "dolphin transit"* (2016)
- Lloyd's Register: *ShipRight Design and Construction: Additional Design Procedures. Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise* (2018)

It was found that the certification systems using MSL had better matches with measurement data than the approaches using RNL. The conservativeness of the certification society thresholds was found to vary with vessel category. Container ships produce the highest noise levels on average and consequently their conformance with all societies was lowest. Only 13 percent of container ships fully conformed with the least conservative society thresholds. None of the container ships conformed with the most conservative society thresholds. Other vessel categories faired better but the lack of category-dependent thresholds led to substantial differences in conservativeness of the certifications across vessel categories.

While the classification society measurement methods were found to be well-designed, their lack of harmonization precludes direct comparisons of the measurements between the societies. Therefore, measurements obtained using the protocol of one certification society are generally not comparable with measurements of a different society or with measurements under ANSI S12.64, upon which the ECHO database was acquired.

None of the certification societies accounts for differences of vessels within a vessel category. Therefore, small ships are currently evaluated against the same threshold criteria as large ships. The scaling system

developed here using the ECHO dataset could be used to scale measurements (or thresholds) to account for different vessel sizes and operating conditions.

The last study examined real-world noise savings that could be achieved by having vessels conform with “optimal” noise emission thresholds, similar to those of the certification societies but defined separately for each vessel category (i.e. different thresholds for containerships and tankers). Optimal thresholds were defined by the medians of the scaled ECHO MSL measurements for each vessel category. Noise savings were evaluated near shipping lanes in Haro Strait, British Columbia under the assumption that 90% of future commercial shipping traffic conformed with these thresholds. While a 90% participation rate is relatively high, the thresholds themselves are not aggressive and are easily met by existing vessel construction using standard quiet engineering methods. In fact, almost half of existing vessels are already conformant. A real-time ship noise model calculated noise levels at several receiver stations in Haro Strait using existing noise emission levels (baseline) and reduced levels representing conformance with the defined thresholds (mitigated). Noise savings were calculated by subtracting the mitigated noise levels from the baseline noise levels. This study found that broadband monthly mean noise level savings near key SRKW feeding sites in Haro Strait ranged from 1.3 to 3.8 dB, depending on location. Noise levels were also calculated by accounting for the frequency-dependent hearing sensitivity of killer whales. The killer whale hearing-adjusted levels were 0.1 to 3.9 dB below baseline. As expected, stations more distant from shipping lanes experienced less reductions than closer stations. This analysis also found that mean unweighted noise levels were at least 3 dB lower over a 10 km swath centred approximately between shipping lanes in Haro Strait (themselves separated by 2.8 km). Mitigated killer whale hearing-weighted levels were at least 3 dB lower than baseline levels over a swath about 5 km wide, also centred between the lanes. These results indicate that a non-aggressive vessel noise certification approach could produce important noise savings near and within several kilometers from shipping lanes.

SOMMAIRE

Ce rapport décrit plusieurs études reliées qui font usage de la large base de données de plusieurs milliers de mesures systématiques du bruit de navires commerciaux acquises entre septembre 2015 et avril 2017 par le programme ECHO mené par le port de Vancouver. La base de données ECHO comprend le plus grand nombre de mesures systématiques de bruit de navires jamais compilés. Les mesures étaient réalisées presque conformément au standard ANSI S12.64 (Grade-C) de mesure de navires et contient une large quantité de métadonnées associées, incluant des informations météorologiques, de courants océaniques et des informations précises sur la navigation du navire. De plus, la base de données inclut de nombreux paramètres du navire, incluant la catégorie et sous-catégorie AIS, les dimensions, le tonnage, le pavillon, l'année de construction, le tirant d'eau statique, et autres.

L'étude de base pour ce projet était une régression lineaire multivariée des niveaux de bruit de source monopole et rayonné, provenant de la base de données ECHO, contre plusieurs paramètres qui décrivent les navires et leurs conditions de mesures. Le but de cette analyse était de développer une méthode pour mettre à l'échelle les mesures de bruit des navires pour tenir compte des différences entre les navires individuels (par exemple, pour différentes catégories et tailles) et sous différentes conditions de mesures (par exemple pour différentes vitesses de transit et conditions de vent). L'analyse multivariée a produit un modèle performant de bruit de navire qui peut prédire les tiers d'octaves des niveaux de bruit de source monopole et rayonné sur la base de la catégorie du navire, sa longueur, et l'angle de surface. Ce modèle de bruit est probablement le meilleur présentement disponible mondialement. C'est déja très utile pour comprendre les variations des émissions sonores avec les caractéristiques du navire et sous différentes conditions d'utilisation.

La seconde étude de ce projet utilisait le modèle de bruit du navire pour mettre à l'échelle les mesures de la base de données ECHO pour tenir compte des différences dans les caractéristiques du navires avec chaque catégorie de navire. Les catégories incluaient les porte-conteneurs, les vraquiers, les pétroliers, les transporteurs de véhicules, les bateaux de croisières et les remorqueurs. Le modèle prenait également compte des différences dans les conditions de mesures, incluant la vitesse de transit, le tirant d'eau statique et les conditions de vent. Le but de la mise a l'échelle des mesures ECHO était de créer un set de données modifiées pour comparer avec des seuils de bruit existants d'organisations de certifications de bruit de navire. Les cinq organisations de certification navale considérées étaient:

- Det Norske Veritas: Règles pour la Classification des Navires. Partie 6 Chapitre 24. Equipment Speciaux et Systèmes pour Nouvelles constructions – Classe Additionnelle, Notation Classe Silencieuse (2010)
- Bureau Veritas: Bruit Rayonné Sous-marin. Rule Note NR 614 DT R00 E (2014)
- American Bureau of Shipping: Guide pour la Notation de Classification: Bruit Sous-marin (2018)
- RINA: Règles pour la Classification des Navires: Amendements à la Partie F. Notations pour la Classe Additionnelle. Introduction aux notations des Nouvelles classes "dolphin quiet" et "dolphin transit" (2016)
- Lloyd's Register: Design et Construction ShipRight: Procèdures pour le Design Additionnel. Design Additionnel et Procèdure de Construction pour la Détermination du Bruit Sous-marin Rayonné d'un Navire (2018)

Il a été trouvé que les systèmes de certifications utilisant le bruit de source monopole avaient un meilleur appariement avec les données de mesures que les approches utilisant le bruit rayonné. L'approche conservatrice des seuils des organisations de certifications était variable avec les catégories de navire. Les porte-conteneurs produisent les niveaux de bruit les plus élevés en moyenne et par consequent, leur conformité avec toutes les organisations était la plus faible. Seulement 13% des porte-conteneurs se conformait totalement avec les seuils de l'organisation la moins conservatrice. Aucun des porte-conteneurs ne se conformait avec les seuils de l'organisation la plus conservatrice. Les autres catégories de navires réussissaient mieux mais le manque de seuils dépendants de la catégorie conduit à des différences substentielles dans l'approche conservatrice des certifications à travers les catégories de navires.

Tandis que les méthodes de mesures des organisations de classification étaient trouvées être bien désignées, leur manque d'harmonisation empêche des comparaisons directes des mesures entre les organisations. Donc, les mesures obtenues en utilisant le protocole d'une organisation de certification ne sont généralement pas comparables avec les mesures d'une organization différente ou avec les mesures conformes au ANSI S12.64, suivant lequel la base de données ECHO était acquise.

Aucune des organisations de certification ne tient compte des différences des navires au sein d'une même catégorie de navire. Donc, les petits navires sont actuellement évalués suivant les mêmes critères pour le seuil que les larges navires. Le système d'échelle développait ici en utilisant la base de données ECHO pourrait être utilisé pour mettre à l'échelle les mesures (ou les seuils) afin de tenir compte des différentes tailles de navires et conditions d'opérations.

La dernière étude examinait les réductions du bruit réel qui pourraient être accomplies en ayant des navires conformes aux seuils d'émissions sonores "optimaux", similaires à ceux des organisations de certifications mais définis séparement pour chaque catégorie de navire (par exemple: différents seuils pour des porte-conteneurs et des pétroliers). Les seuils optimaux étaient définis par les médianes des mesures de bruit de source monopole de la base données ECHO mise à l'échelle pour chaque catégorie de navire. Les réductions du bruit étaient évaluées près des voies navigables dans Haro Strait, Colombie-Britannique, en partant du principe que 90% du futur trafic de navigation commerciale se conformait à ces seuils. Tandis qu'un taux de participation de 90% est relativement élevé, les seuils eux-mêmes ne sont pas agressifs et sont facilement atteints par la construction navale existente en utilisant des pratiques d'ingénierie standard pour minimiser le bruit. En fait, presque la moitié des navires existants sont déja conformes. Un modèle de bruit de navire en temps réel calculait les niveaux de bruit à plusieurs stations de réception dans Haro Strait en utilisant les niveaux d'émissions sonores existants (point de comparaison) et les niveaux réduits représentants la conformité avec les seuils définis (atténués). Les réductions du bruit étaient calculés en soustrayant les niveaux de bruit atténués aux niveaux de bruits utilisés pour comparaison. Cette étude trouvait que les réductions des niveaux de bruit à large bande sur une moyenne mensuelle près des zones d'alimentation des épaulards résidents du Sud dans Haro Strait allaient de 1.3 a 3.8 dB, dépendamment de la location. Les niveaux de bruit étaient aussi calculés en tenant compte de la sensibilité auditive dépendante de la fréquence des épaulards. Les niveaux ajustés selon l'audition de l'épaulard étaient de 0.1 a 3.9 dB sous le point de comparaison. Comme prévu, les stations les plus distantes des voies navigables avaient moins de reductions que les stations plus proches. Cette analyse trouvait également que les niveaux de bruit moyens non pondérés étaient au moins 3 dB plus faible sur une bande large de 10 km centrée approximativement entre les voies navigables dans Haro Strait (elles-mêmes distantes de 2.8 km). Les niveaux atténués pondérés avec l'audition de l'epaulard étaient au moins 3 dB plus faible que les niveaux de comparaison sur une bande large de 5 km, également centrée entre les voies. Les résultats indiquent que l'approche non-agressive de certification du bruit des navires pourrait produire d'importantes réductions du bruit près et a plusieurs kilometres des voies navigables.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

1/3-octave-band
Non-overlapping frequency passbands that are one-third of an octave wide (where an octave is a doubling of frequency). Three adjacent 1/3-octave-bands comprise one octave-band. 1/3-octave-bands become wider with increasing frequency. Also see octave.

Acoustic Doppler Current Profiler (ADCP)
A device that uses the doppler shift of acoustic backscatter to measure water current speed and direction over a range of depths.

Automatic Identification System (AIS)
A system deployed on most large commercial vessels that broadcasts, via VHF or Satellite radio, the identification information, position, speed and operating conditions of the ship. The AIS generally broadcasts the position and speed read from an on-board Geographical Positioning System (GPS) device.

broadband sound level
The total sound pressure level measured over a specified frequency range. If the frequency range is unspecified, it refers to the entire measured frequency range.

closest point of approach (CPA)
The point at which the distance between two objects, of which at least one is in motion, reaches its minimum value. For a fixed underwater system measuring noise produced by a transiting vessel, the CPA occurs when the vessel is at the shortest distance from the measurement system.

dead-weight-tonnage (DWT)
A measure of the maximum weight a vessel can carry. It does not include the weight of the ship empty of all fuels and supplies.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power.

Enhancing Cetacean Habitat Observations (ECHO)
An environmental program managed by the Vancouver Fraser Port Authority, and having a large number of collaborators including government, industry and environmental organizations. Information about the program and its collaborators, and results from its initiatives, are available at https://www.portvancouver.com/echo

frequency
The rate of oscillation of a periodic function measured in cycles-per-unit-time. The reciprocal of the period. Unit: hertz (Hz). Symbol: f. 1 Hz is equal to 1 cycle per second.

hertz (Hz)
A unit of frequency defined as one cycle per second.

hydrophone
An underwater sound pressure transducer. A passive electronic device for recording or listening to underwater sound.

Maximum Continuous Rating (MCR)
The MCR is the maximum continuous rated power that a marine engine can produce. MCR is usually listed on the engine nameplate. The term is also used to represent the corresponding vessel speed when the engine is operating at this level of power under typical cargo loading.

monopole source level (MSL)
A source level that has been calculated using an acoustic model that accounts for the effect of the sea-surface and seabed on sound propagation, assuming a point-like (monopole) sound source. See related term: radiated noise level.

octave
The interval between a sound and another sound with double or half the frequency. For example, one octave above 200 Hz is 400 Hz, and one octave below 200 Hz is 100 Hz.

pressure, acoustic
The deviation from the ambient hydrostatic pressure caused by a sound wave. Also called overpressure. Unit: pascal (Pa). Symbol: *p*.

radiated noise level (RNL)
A source level that has been calculated assuming sound pressure decays geometrically with distance *r* from the source in metres according to 20 log *r*, with no influence of the sea-surface and seabed. See related term: monopole source level.

received level
The sound level measured at a receiver.

Southern Resident Killer Whale (SRKW)
A population of the resident killer whale ecotype that ranges from southern California to the southern Salish Sea. Its numbers have fallen over recent years to approximately 74 individuals as of February 2019. There is concern about the survivability of this population that has important foraging habitat that overlaps with commercial shipping routes in the Salish Sea.

sound
A time-varying pressure disturbance generated by mechanical vibration waves travelling through a fluid medium such as air or water.

sound pressure level (SPL)
The decibel ratio of the time-mean-square sound pressure, in a stated frequency band, to the square of the reference sound pressure (ANSI S1.1-1994 R2004).

For sound in water, the reference sound pressure is one micropascal (p_0 = 1 µPa) and the unit for SPL is dB re 1 µPa:

$$\mathrm{SPL} = 10\log_{10}\left(p^2/p_0^2\right) = 20\log_{10}\left(p/p_0\right)$$

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level. See also 90% sound pressure level and fast-average sound pressure level.

source level (SL)
The sound level measured in the far-field and scaled back using propagation loss to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 µPa m.

spectrum
An acoustic signal represented in terms of its power (or energy) distribution compared with frequency.

speed through water (STW)
The speed of a ship with respect to the water, which therefore accounts for the effect of currents. This differs from speed over ground SPG.

Underwater Listening Station (ULS)
A general term that refers to a semi-permanent sound monitoring system in the ocean. ULS's can consist of a hydrophone connected to an autonomous recorder, or to hydrophones connected to subsea cables that transmit acoustic information to shore.

1. INTRODUCTION

This report presents the results of a study that compares the ship noise measurements from the Port of Vancouver's Enhancing Cetacean Habitat Observations (ECHO) program database, with the maximum permitted noise emission levels of five quiet vessel certification societies. The study was split into four parts. Part 1 was a multivariate analysis of the ECHO database to determine how vessel noise emissions vary with several important parameters, including ship speed through water, ship length, breadth, draught, dead-weight-tonnage (DWT), year built, and wind resistance during measurement. Part 2 used the relationships identified in Part 1 to scale all vessel measurements to average conditions (e.g., length, speed, DWT, and year built) in each vessel category. Part 3 compared the scaled measurements with the maximum permitted noise thresholds of five well-known class notation certification societies. This required making additional adjustments to account for measurement and analysis differences between the class notations. Part 4 scaled ECHO data were analyzed to generate a set of new thresholds, similar to those of the class notation certification societies, but based on the median of the measurements. This work also included noise modelling to determine noise savings expected in SRKW habitat in Haro Strait B.C., obtained if 90% of future vessels conformed with these proposed thresholds.

The multivariate analysis of Part 1 examined how the measured ship noise levels varied with ship length, breadth, draught, tonnage, speed and wind speed (or functions of some of these parameters). The functional forms of the parameters are referred to here as covariates. An initial analysis examined the potential relationships (correlations) between pairs of covariates, to help reduce the number of covariates needed to explain noise emission measurement variations. A set of mostly non-correlated covariates was then used in a multivariate regression analysis that also examined the statistical significance of each covariate's regression coefficient. The multivariate analysis produced a set of coefficients, one for each covariate for each frequency band. Together, these coefficients can be applied in simple equations to predict the noise for any combination of covariates (i.e. the parameters describing a vessel and its operating characteristics), thus comprising a ship noise model. This model is arguably the most powerful tool presently available for predicting noise emissions of vessels. It is of interest to ship noise researchers and modellers worldwide. However, it was developed here primarily for scaling the ECHO vessel measurements to account for vessel characteristics and dimension differences, and differences in conditions such as vessel speed, during the times of their respective acoustic measurements.

In Part 2, all vessel measurements in each category were scaled to a common set of parameters (e.g., length, speed, DWT, and year built). This was performed using the regression coefficients model developed in Task 1. The scaling step is important to account for noise differences due to vessel differences within a category. For example, a small tanker might be expected to produce less noise than a large tanker. Likewise, a tanker measured at slow speed might be expected to produce less noise than a tanker measured at high speed. To rate the emissions of different sized vessels measured at different speeds, we must first perform scaling to a common reference size and speed, and other parameters. While none of the present certification systems account for vessel size within a vessel category, or any other vessel and measurement parameters, that is a goal of future certifications. Section 3 describes the approach used to perform scaling. Results of scaling the ECHO database are presented in Sections 3.4 and 3.5.

The goal of Part 3 was to compare the ECHO measurements with the maximum permitted noise thresholds of five classification societies. These are:

- American Bureau of Shipping (ABS),
- Bureau Veritas (BV),
- Det Norske Veritas (DNV),
- Lloyd's Registrar (LR), and
- RINA.

There are differences in measurement and data analysis procedures of each of these societies and of ANSI S12.64 ANSI/ASA S12.64/Part 1 (2009), that lead to different measurement values even for the same vessel under the same operating conditions. These differences are discussed in Section 5.1. It was therefore necessary to adjust the ECHO measurements acquired with ANSI S12.64 to account for this issue. The adjustments were applied to the scaled version of the ECHO database and the adjusted results are presented in Sections 5.2 and 5.3. These adjusted levels were then compared with the class notation society thresholds and results are presented in Chapter 6.

In Part 4 of this study, we stepped back and defined a new set of potential thresholds that are similar to the class notation certification society thresholds but that are vessel category-dependent. The new thresholds are based on the median measured and scaled level in each frequency band for the respective vessel category. These thresholds are presented in Section 7.1. The expected reduction of mean noise emission levels for each vessel category were calculated under the assumption that 90% of future vessels in each vessel category meet the new thresholds. The reductions in mean emission levels are presented in Section 7.1. A sophisticated vessel noise model was applied to calculate received noise levels over a wide area of Haro Strait, B.C., for actual ship traffic from July 2015, derived from AIS vessel track data. The noise model was again run with the reduced noise emissions levels from compliance with the proposed optimal thresholds as described above. The modelled noise results are presented in noise level maps in Section 7.3, using the unweighted sum of mean sound levels across all frequencies and using a weighted sum that accounts for the frequency-dependent hearing acuity of killer whales. The spatially-varying noise reductions were calculated by subtracting the future noise levels from the baseline 2015 levels. A detailed analysis of the noise level reductions was performed along a path that crossed the shipping lanes perpendicularly, and at 8 test receiver positions located at key foraging locations in Haro Strait.

2. ECHO DATABASE

2.1. Database Overview

The ECHO vessel measurement data were obtained from a cabled Underwater Listening Station (ULS) deployed in the Strait of Georgia and from data collected with autonomous recorders deployed in Haro Strait, BC, Canada.

The cabled ULS operated from 21 Sep 2015 to 17 Apr 2018. This system used tetrahedral hydrophone arrays deployed on the seabed on the western edge of the east (inbound) shipping lane leading into Port of Vancouver (Figure 1). The processed hydrophone was either 1.5 or 2.5 m above the seabed in 170 m water depth. Acoustic data were digitally sampled at 64 kHz from 21 Sep 2015 to 4 Nov 2017 and at 512 kHz from 5 Nov 2017 to the end of the study on 17 Apr 2018. All data had 24-bit resolution with approximately 21 bits of acoustic dynamic signal range. The digitizing systems were JASCO's Autonomous Multichannel Acoustic Recorders (AMAR G3s) from the start of the study to 4 Nov 2017 and JASCO's Observer systems from 5 Nov 2017 to the end of the study. Both digitizing systems streamed raw data (and partly processed data in the case of the Observer) to shore through Ocean Network Canada's Victoria Experimental Network Under the Sea (VENUS) array.

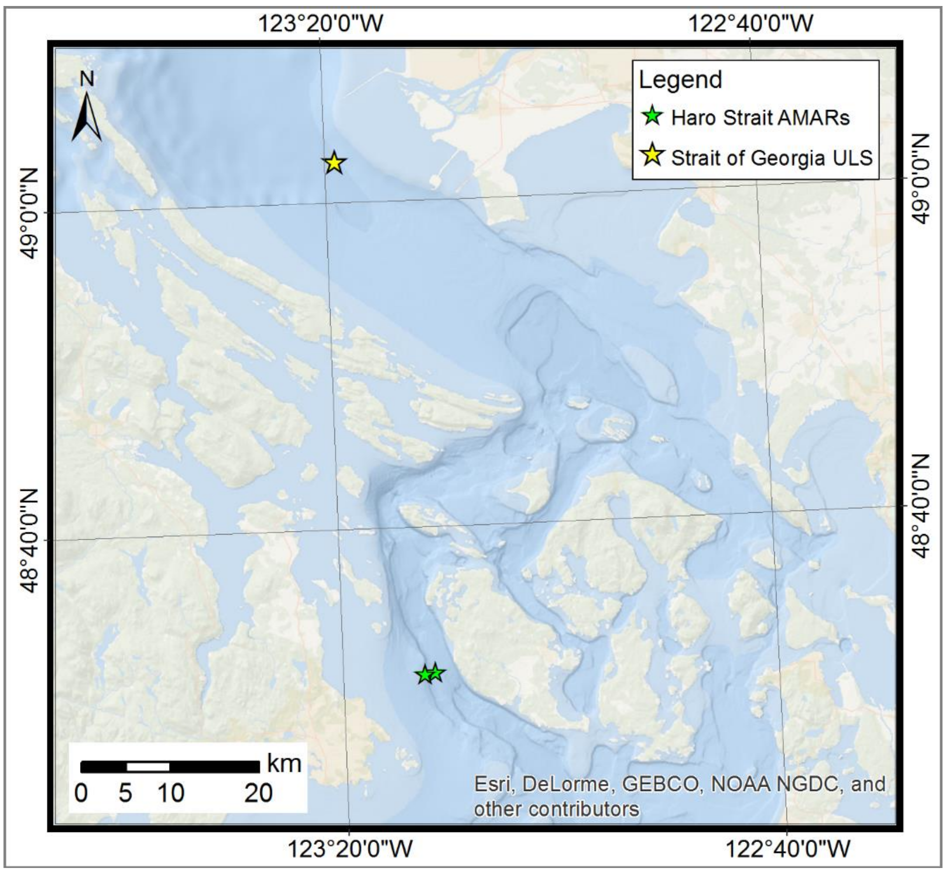


Figure 1. Map showing the location of the ECHO ULS in Strait of Georgia and the Slowdown Trial AMARs in Haro Strait.

The Haro Strait autonomous recorders were JASCO's AMAR G3, deployed from 6 Jul to 26 Oct 2017. These recorders sampled at 128 kHz with 24-bit resolution. One recorder was deployed at the edge of the east (inbound) shipping lane and the other on the west (outbound) lane.

All data were processed automatically by JASCO's ShipSound analysis system. ShipSound tracked vessels using a combination of Automatic Identification System (AIS) and acoustic methods. Near-surface water currents were tracked using an upward-looking real-time Acoustic Doppler Current Profiler (ADCP) mounted near the ULS arrays in Strait of Georgia and using a computer current model in Haro Strait. ShipSound applied the ANSI S12.64 (2009) Grade-C approach to calculate ship Radiated Noise Levels (RNL) for each vessel that passed the systems. The primary non-conformance with ANSI S12.64 (2009) was that only a single vessel pass was processed, while the standard requires averaging two port and two starboard passes. Further, while many of the vessels passed at the closest point of approach (CPA), meeting the standard's requirement for distance and surface angle, the ECHO database contains measurements at distances from 100 to 800 m. Only measurements meeting the standard's signal-to-noise ratio (SNR) requirements were retained. Measurement adjustments were made as specified by the standard when SNR was between 3 and 10 dB.

The ANSI S12.64 (2009) standard produces only RNL measurements. As the ECHO system measurements are also intended for use in noise models, the ShipSound application also calculates Monopole Source Levels (MSL). These were calculated under the approximation that all noise originates from a small depth range, defined by a Gaussian depth distribution, referenced to the depth of the vessel's acoustic centre. The MSL in decidecade bands (ISO 17208), in this report referred to as 1/3-octave frequency bands, were calculated by using a computer sound propagation model to predict propagation loss at the position of the hydrophones. The modelled propagation loss values in each 1/3-octave-band were used in place of the ANSI S12.64 (2009) RNL distance correction of 20 log(r), where r is the distance of the hydrophone from the ship's surface location. ShipSound calculates and reports both RNL and MSL. This is important for the analysis performed here, as some certification societies use RNL, while others use MSL.

2.2. Database Measurement Graphs

The ECHO database contains measurements from 13 vessel categories. In this study we analyzed only the measurements for the following six categories of vessels:

- Bulker/General Cargo,
- Container ship,
- Cruise ship,
- Tanker,
- Tug, and
- Vehicle Carrier.

Figure 2 shows the 1/3-octave-band Radiated Noise Level (RNL), and Figure 3 shows the 1/3-octave-band Monopole Source Level (MSL) of all ECHO measurements, for the six vessel categories considered here. A small random frequency offset was applied to the data displayed in these graphs, so they appear distributed slightly above the true frequency of the corresponding 1/3-octave-band centre frequency. This randomization was applied only to improve the display of these results.

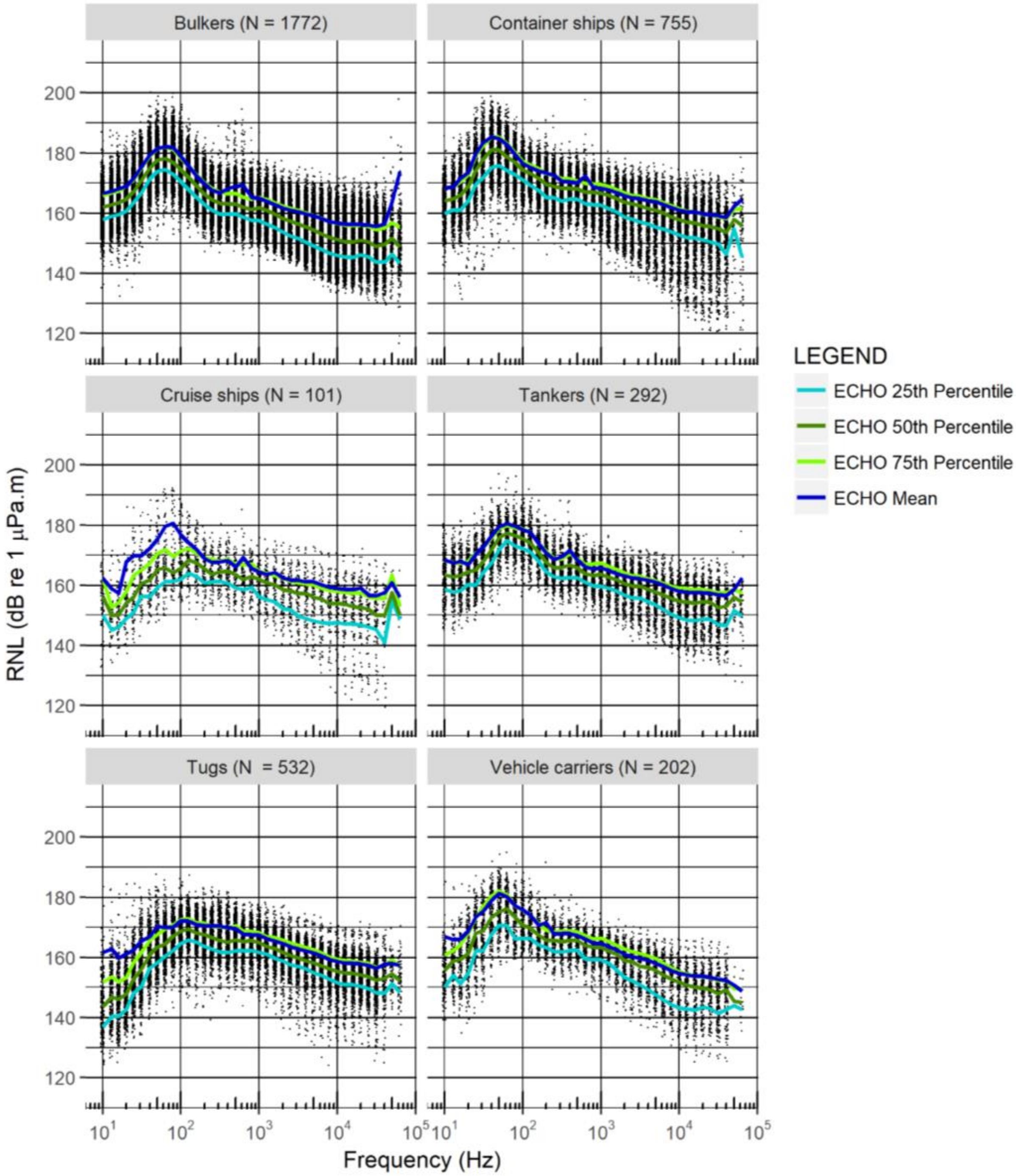


Figure 2. Radiated noise level (RNL) measurements of the ECHO database, in 1/3-octave frequency bands (black dots), with 25th (teal), 50th (dark green), and 75th (green) percentiles and mean (blue) shown as overlaid lines. The graph headers show the number of measurements included.

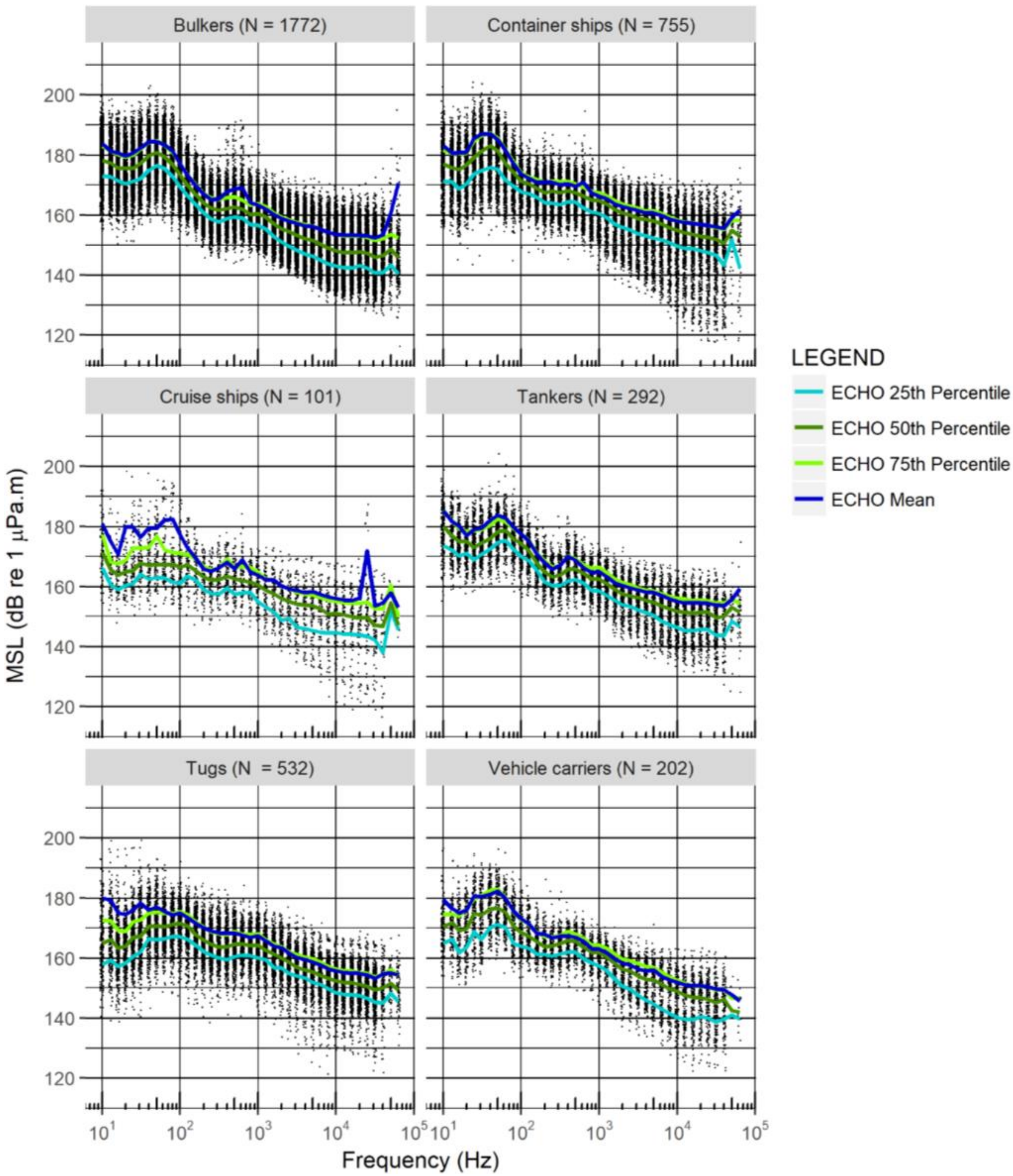


Figure 3. Monopole source level (MSL) measurements of the ECHO database, in 1/3-octave frequency bands (black dots), with 25th (teal), 50th (dark green), and 75th (green) percentiles and mean (blue) shown as overlaid lines. The graph headers show the number of measurements included.

2.3. Features of the ECHO Database

Key features of the database include the noise emission level distribution by vessel category (Figure 4 and Figure 5), measurement distribution by vessel length in each category (Figure 6), measurement distribution by dead-weight-tonnage (DWT; Figure 7), measurement distribution by year built (Figure 8), and the mean and median measured RNL and MSL (Figures 9 and 10, respectively). Note that DWT is not available for most tugs in the database, since this is a measure of a vessel's cargo capacity and is therefore not particularly relevant for vessels in the tug category.

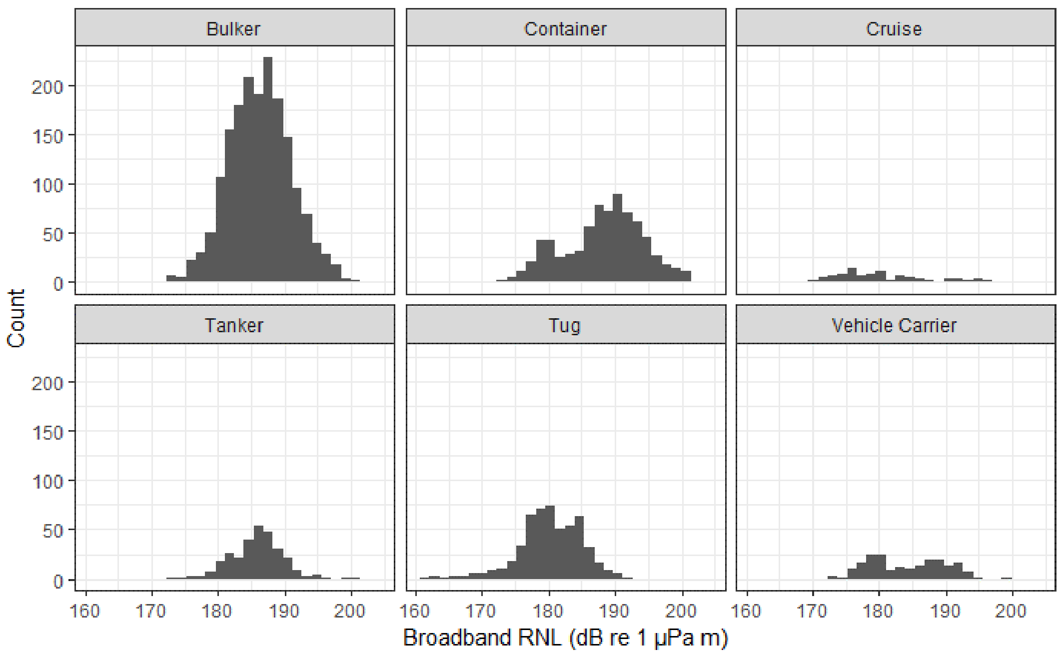


Figure 4. Histograms of measurements by broadband (20 Hz to 31.5 kHz) radiated noise level (RNL) for each vessel category.

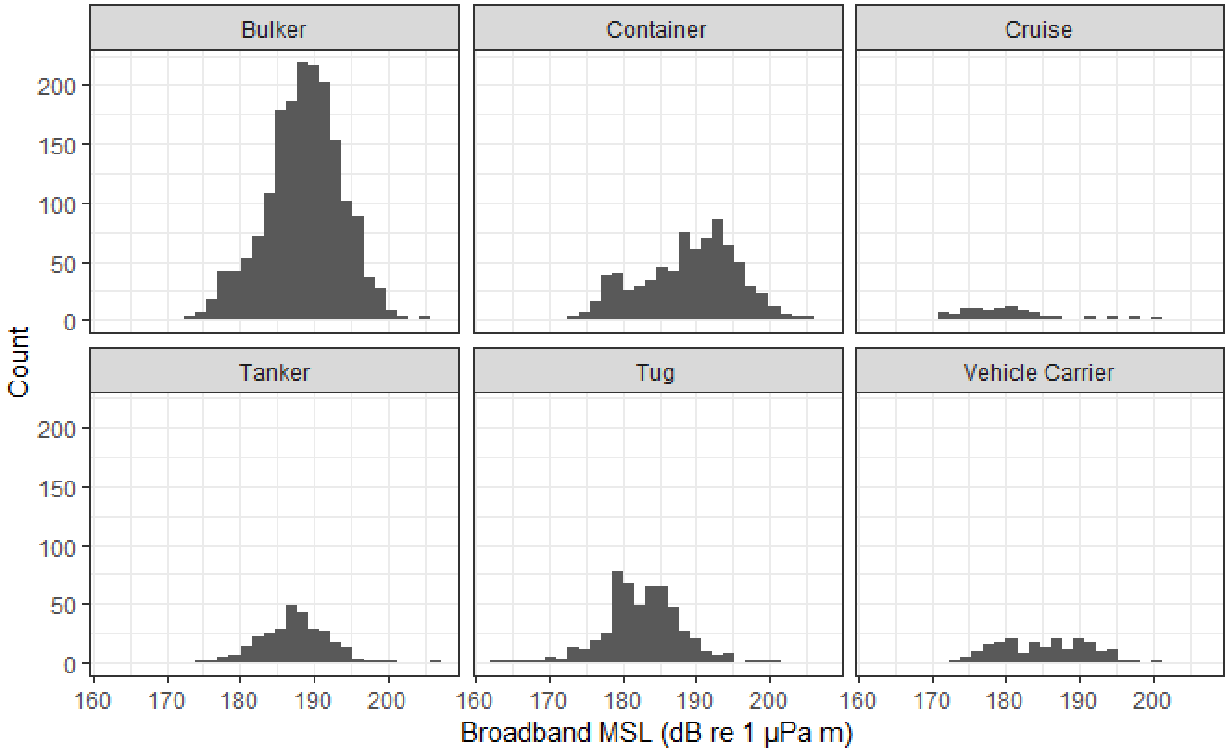


Figure 5. Histograms of measurements by broadband (20 Hz to 31.5 kHz) monopole source level (MSL) for each vessel category.

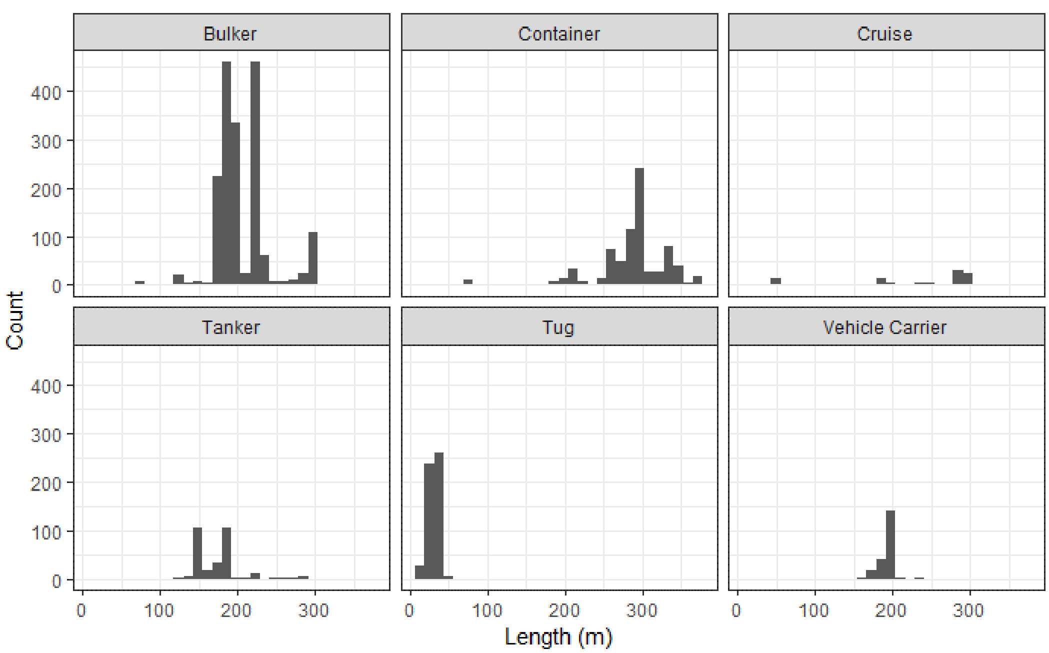


Figure 6. Histograms of vessels by length (in meters) within each vessel category.

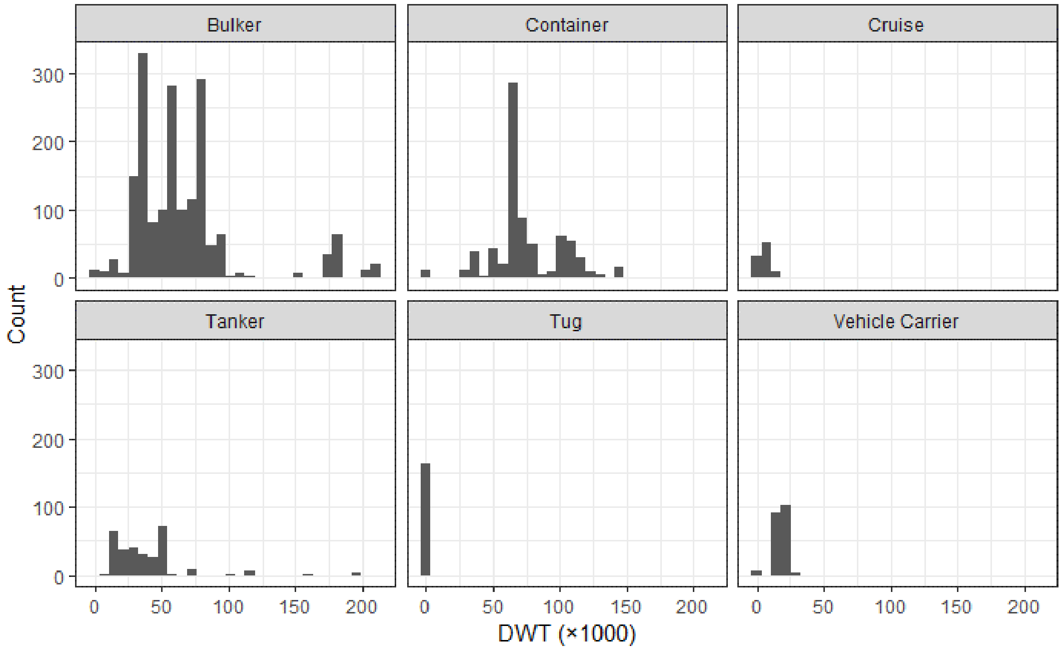


Figure 7. Histograms of vessels by Dead-Weight-Tonnage (DWT) within each vessel category.

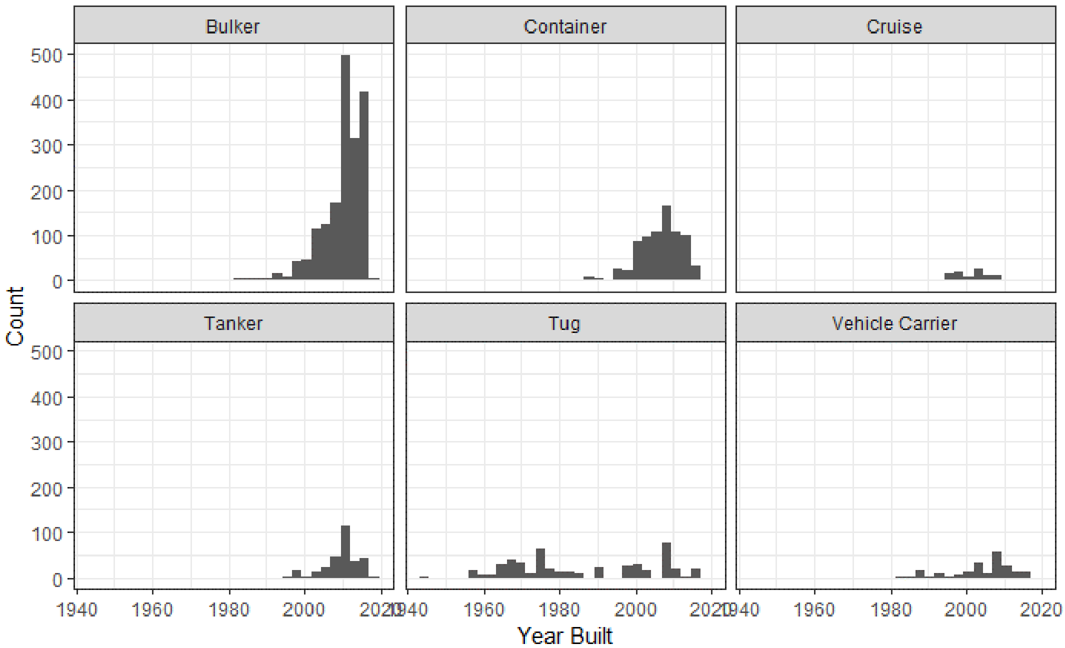


Figure 8. Histograms of vessels by year built within each vessel category.

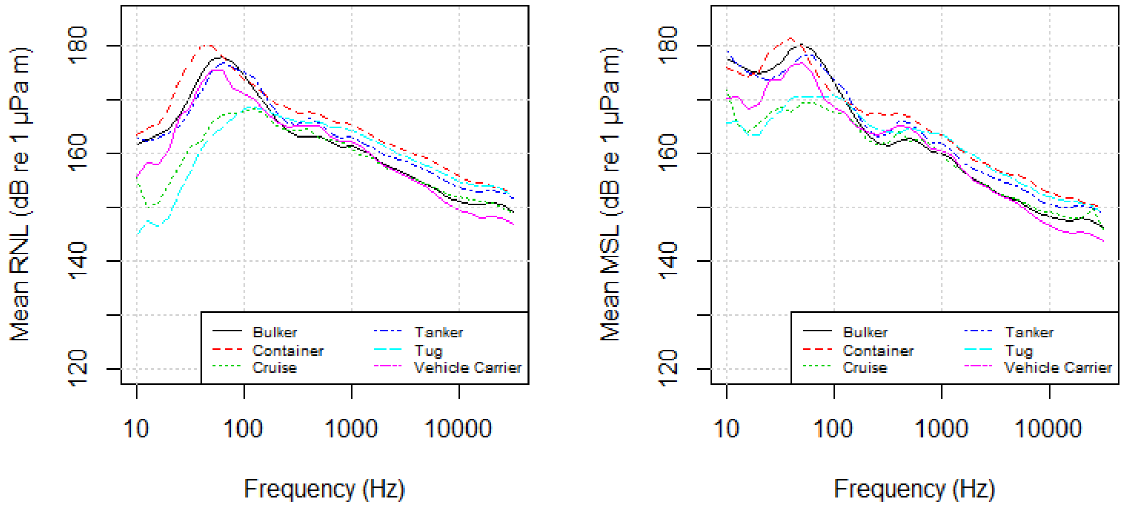


Figure 9. Mean unscaled radiated noise level (RNL; left) and monopole source level (MSL; right) by vessel category in 1/3-octave frequency bands.

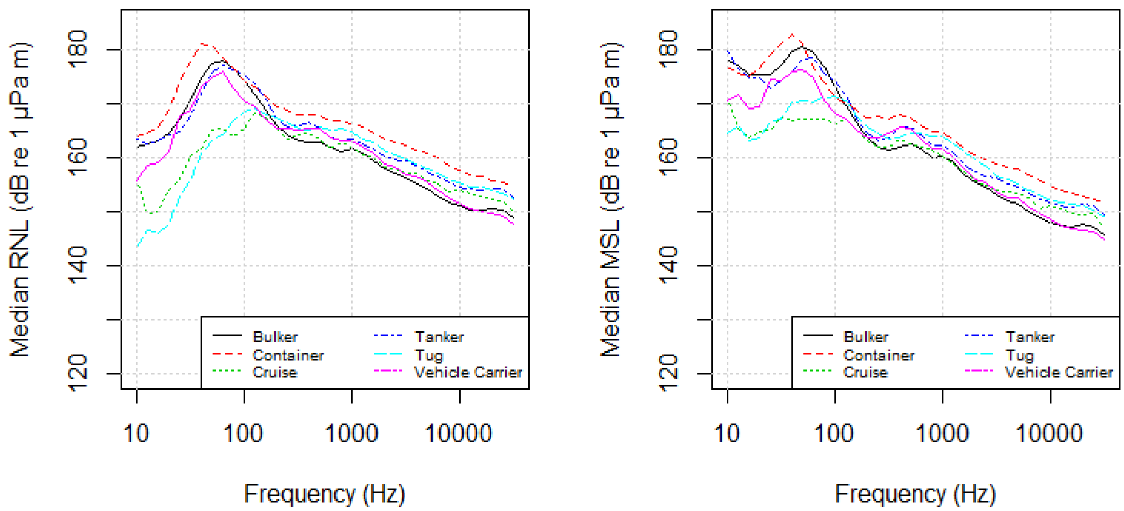


Figure 10. Median unscaled radiated noise level (RNL; left) and monopole source level (MSL; right) by vessel category in 1/3-octave frequency bands.

3. MULTIVARIATE ANALYSIS

3.1. Vessel and Measurement Parameters Considered (Covariates)

As discussed in the Introduction, an important goal of this study is to be able to scale individual measurements to account for differences in vessel dimensions and measurement parameters. The vessel characteristics and measurement conditions were parameterized by a set of covariates described below.

The multiple regression model applied here was defined separately for each 1/3-octave-band. In each band, the regressions included the following four covariates describing the vessel characteristics:

- Category offset term, in decibels: ship category dependent
- Log_{10}(Ship Length in meters): ship category dependent
- Year Built (since 2000): ship category dependent
- Log_{10}(DWT in metric tonnes): ship category dependent, excluded for tugs

and the following four measurement condition covariates:

- Log_{10}(Speed through water in m/s): ship category dependent
- Wind resistance (See Section 3.2) independent of ship category
- Static Draught in meters: independent of ship category
- Surface Angle: independent of ship category

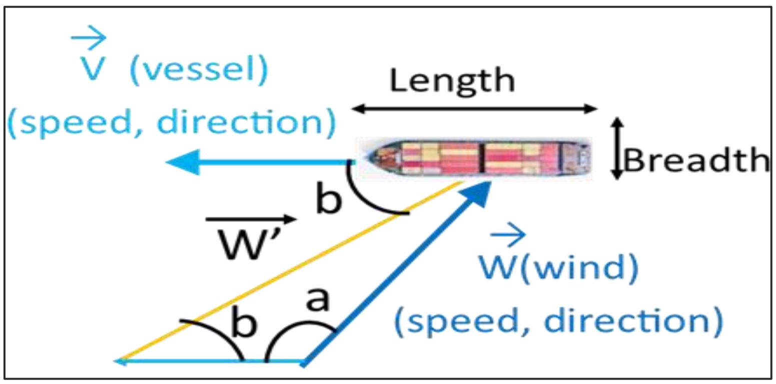
Here, Surface Angle represents the angle below horizontal, of the direct acoustic path connecting the vessel's acoustic centre at CPA with the hydrophone. It depends mainly on the CPA distance and depth of the hydrophone.

Following Ross (1976), a log-transform was applied to the speed, length, and tonnage[1] parameters as shown above, so as to reflect the expected power law relationship between these covariates and underwater noise level. Ship breadth was excluded because it is correlated quite strongly with the two other size-related parameters: ship length and DWT. Including this additional parameter was tested and it did not improve the explanatory power of the multivariate model.

[1] Ross uses displacement tonnage, but this information was not available for vessels in the ECHO dataset, therefore dead-weight tonnage (DWT) has been used here instead.

3.2. Wind Resistance

Wind was found to have a significant effect on noise emissions. Its effect was assumed to be physically related to wind resistance that required additional propulsion thrust. The physical model developed to address wind resistance was based on the effective wind vector $\overrightarrow{W'}$, calculated as the vector sum of vessel speed $\vec{V}$ and opposite of wind speed over ground $\vec{W}$, as illustrated in the top panel of Figure 11. Even in a zero-wind condition relative to ground, the effective wind speed is equal to the vessel's speed over ground and the effective wind direction is 0° (a direct head wind). In general, the effective wind speed and direction are related to the true wind speed and direction and the vessel's speed over ground and sailing heading as illustrated in the bottom panel of Figure 11 and Equation 1 (a-c).



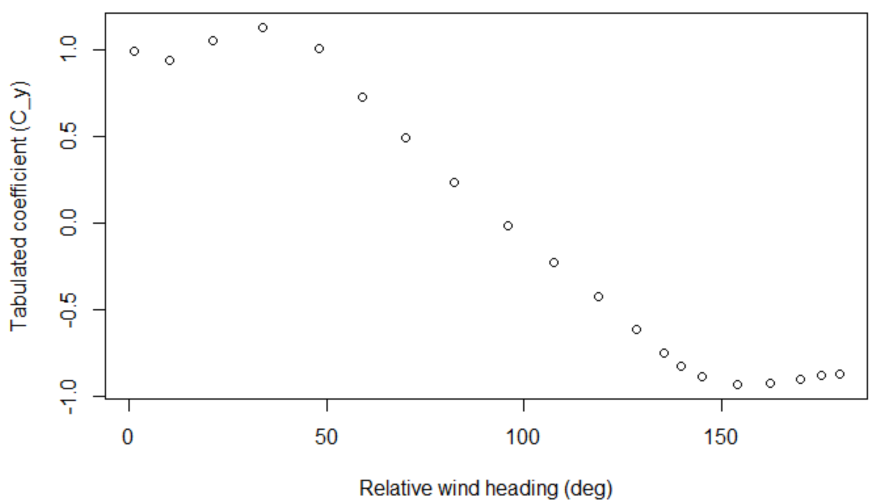


Figure 11. Top: effective wind speed vector diagram. Bottom: heading coefficient versus relative (effective) wind direction *b*. For reference, *b*=0° corresponds to a direct headwind while *b*=180° is a direct tailwind.

Vessel speed and heading vector $\vec{V}$, and wind speed and direction vector $\vec{W}$ are included in the calculation of effective wind vector $\overrightarrow{W'}$as shown in Equation1. They are used to calculate the angles *a* and *b* in Figure 11:

$$\overrightarrow{W'} = \vec{W} - \vec{V} \quad \text{(Eq. 1a)}$$

$$a = \cos^{-1}\left(\vec{V} \cdot \vec{W} / |V||W|\right) \quad \text{(1b)}$$

$$b = \sin^{-1}(|W| \sin a \,/ |W'|) \quad \text{(1c)}$$

Wind resistance force on the vessel has two components: parallel (in-line with the vessel's heading) and transverse (perpendicular to its heading). The parallel drag must be directly compensated by propulsion thrust. The transverse component may require some off-path heading adjustment "crabbing" to maintain the desired sail direction and this can also require increased propulsion thrust. Further, the wind resistance in both directions is complex and depends on the area of vessel exposed perpendicularly to the effective wind direction. That leads to maximum resistance when the effective wind direction is to the side of directly forward. The overall drag force versus wind direction has been studied for commercial vessels and characterized by the heading coefficient C_Y. The heading coefficient versus effective wind angle *b* are shown in the lower panel of Figure 11, extracted from the graph in *Principles of Naval Architecture II* (Figure 33 from Lewis 1988) for the Design Displacement condition. It is apparent that maximum wind resistance occurs for *b*~35° (i.e. effective wind arriving from approximately 35° port or starboard of directly forward). $C_Y = 0$ occurs at an angle greater than 90°, representing an arrival direction slightly aft of abeam. This is likely a result of the need for a slight tailwind component to offset the drag effect of crabbing.

We assumed the additional RNL and MSL noise emission levels in decibels, due to wind drag force, are dependent on an unknown power of the product of the heading coefficient and the absolute value of the effective wind speed magnitude. A study of residuals of the multivariate analysis against the unknown power *p* found minimum residuals for *p*=1.2, but since there was negligible difference between that and for *p*=1.0, the latter value was used in our final model. Therefore, the physical wind resistance model used in our multivariate analysis has the simple form: $RNL_{wind} \propto C_Y(b)\,|W'|$ and $MSL_{wind} \propto C_Y(b)\,|W'|$ where α represents direct proportionality. The constants of proportionality are estimated by the multivariate regression analysis described in Section 3.4.

3.3. Covariate Cross-correlation Analysis

A covariate cross-correlation analysis was performed to identify related parameters, with an end goal of removing some parameters from the final multivariate analysis. The cross-correlation analysis was limited to physical vessel parameters that are constant for a given vessel. Measurement parameters that vary with the operational conditions of a vessel, such as speed through water, static draught and wind-speed, were not included in the cross-correlation analysis. Vessel static draught varies with load, so it was also omitted from this analysis. Finally, we limited the analysis to unique vessels, as we wanted to avoid biasing results to vessels that happened to be measured multiple times.

Cross-correlations indicate the degree to which one variable varies with another. For example, if variables x and y vary linearly with each other (i.e. y = cx, where c is a constant) then the cross-correlation of x and y will be equal to 1.0 (perfect correlation). In this case it would not make sense to include both x and y in a linear regression model, because either variable can fully account for the influence of the other on the dependent variable of the model. Including correlated variables can hide real dependencies, so it is usually recommended to exclude one of each pair of strongly correlated variables. The cross-correlation analysis was consequently performed to identify possibly-correlated variables to inform decisions for excluding variables from the noise regression analysis. The results, presented in Figure 12, indicate that parameters related to the vessel size (length, breadth, and DWT) were quite strongly correlated (coefficient above 0.75) for most categories. Year-built was weakly correlated. Based on the high correlation between the vessel dimension variables, we excluded breadth from the multiple regression analysis (Section 3.4) because it was closely related to length and DWT. Tests of the regression including and excluding this parameter also did not show improved explanatory power of the final statistical model.

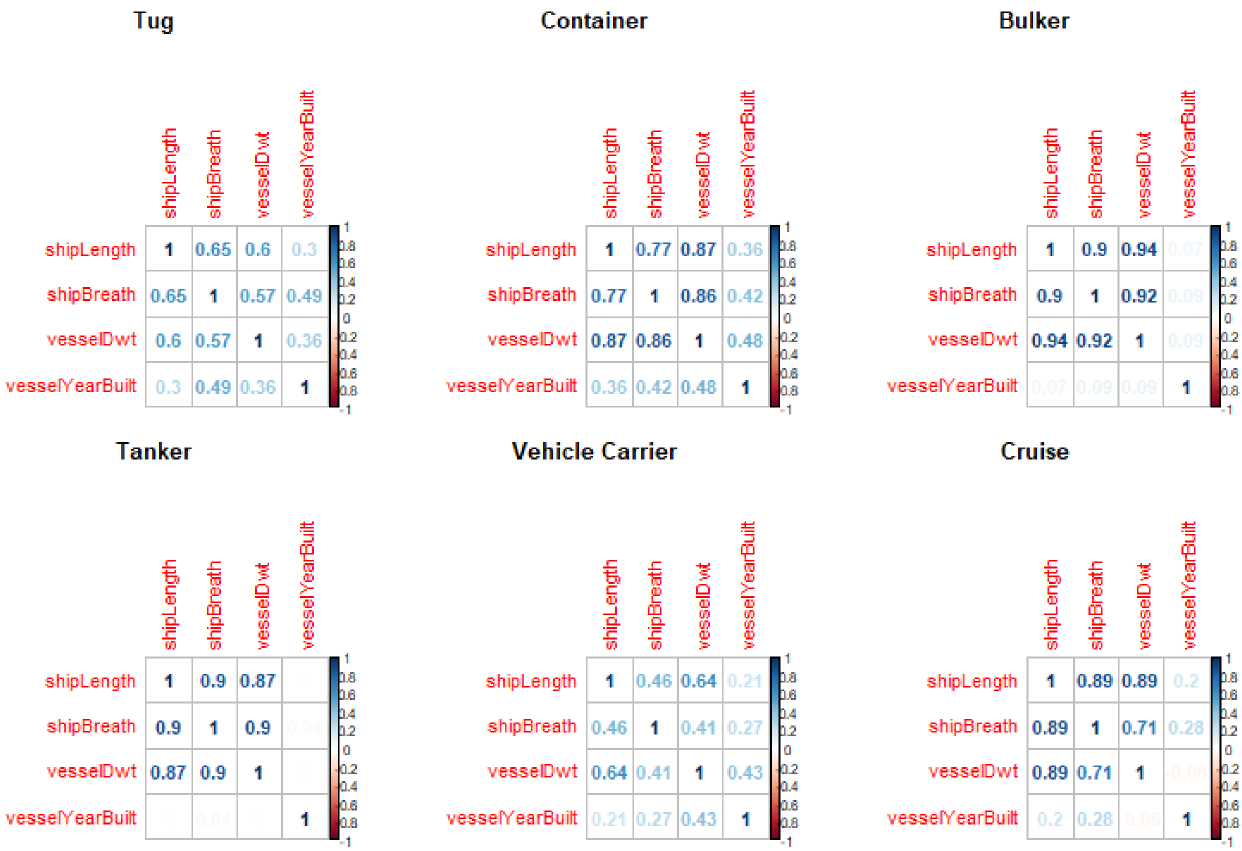


Figure 12. Vessel size parameter covariate cross-correlations for unique vessels.

3.4. Multivariate Regression Results

Multivariate regressions using the covariates presented in Section 3.1 were performed on the entire ECHO dataset separately for each 1/3-octave frequency band. Overall, there were eight covariates per vessel category for each frequency (five category-dependent covariates plus three category-independent covariates). The determination of covariate category-dependence was carried out by applying multiple linear regression analysis[2] to the RNL and MSL measurements, omitting any measurements that were missing one or more of the required covariates. Figures 13 and 14 present the best-fit linear model coefficients resulting from the regression analysis.

[2] Using the `lm` function from the `stats` package in R version 3.5.1. R Core Team (2018). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org.

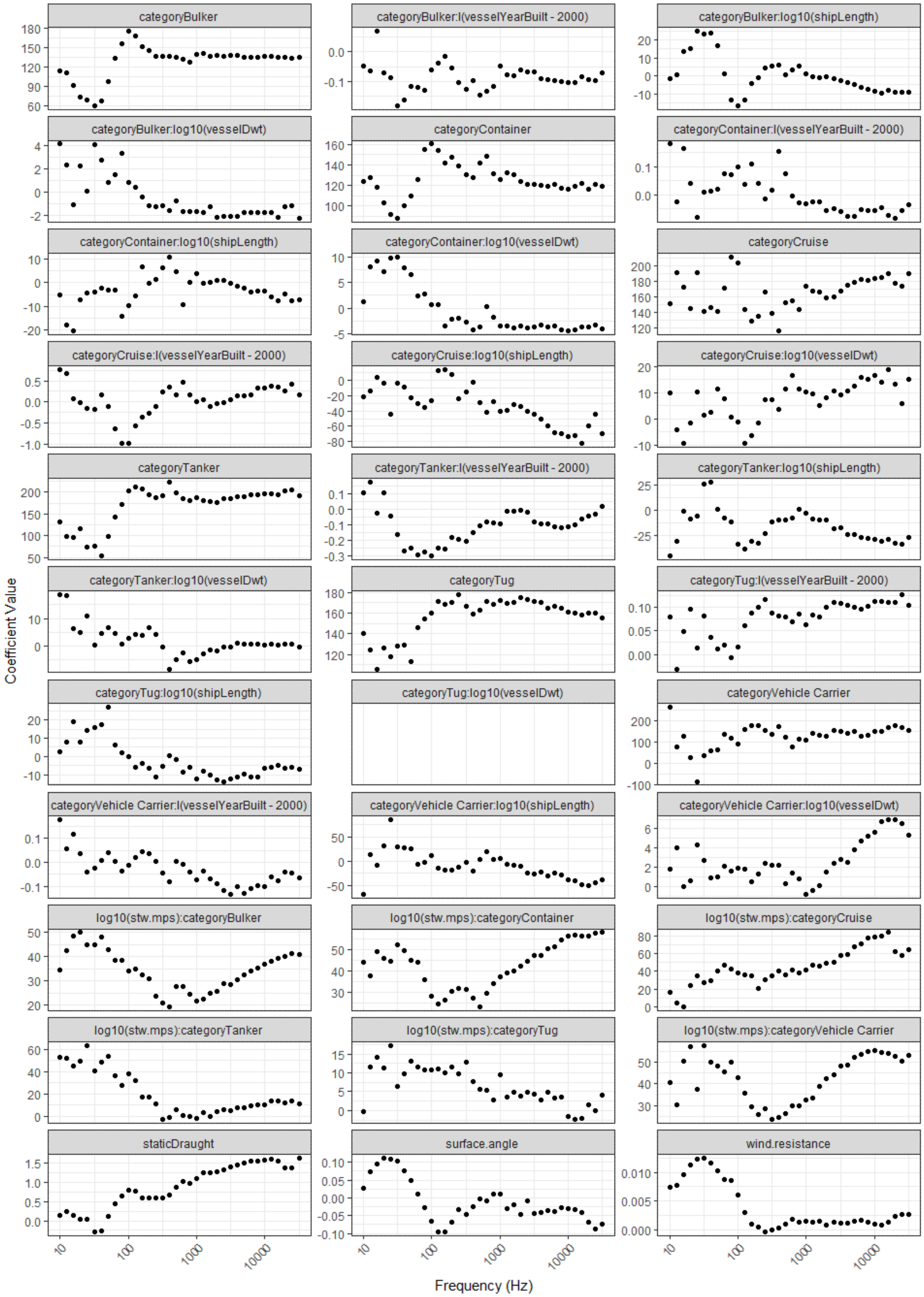


Figure 13. Multiple linear regression (MLR) model coefficients for radiated noise level (RNL), by vessel category, for each covariate across all 1/3-octave frequency bands. Dead-weight-tonnage (DWT) was excluded as a covariate for tugs, since it was unavailable for most vessels in this category.

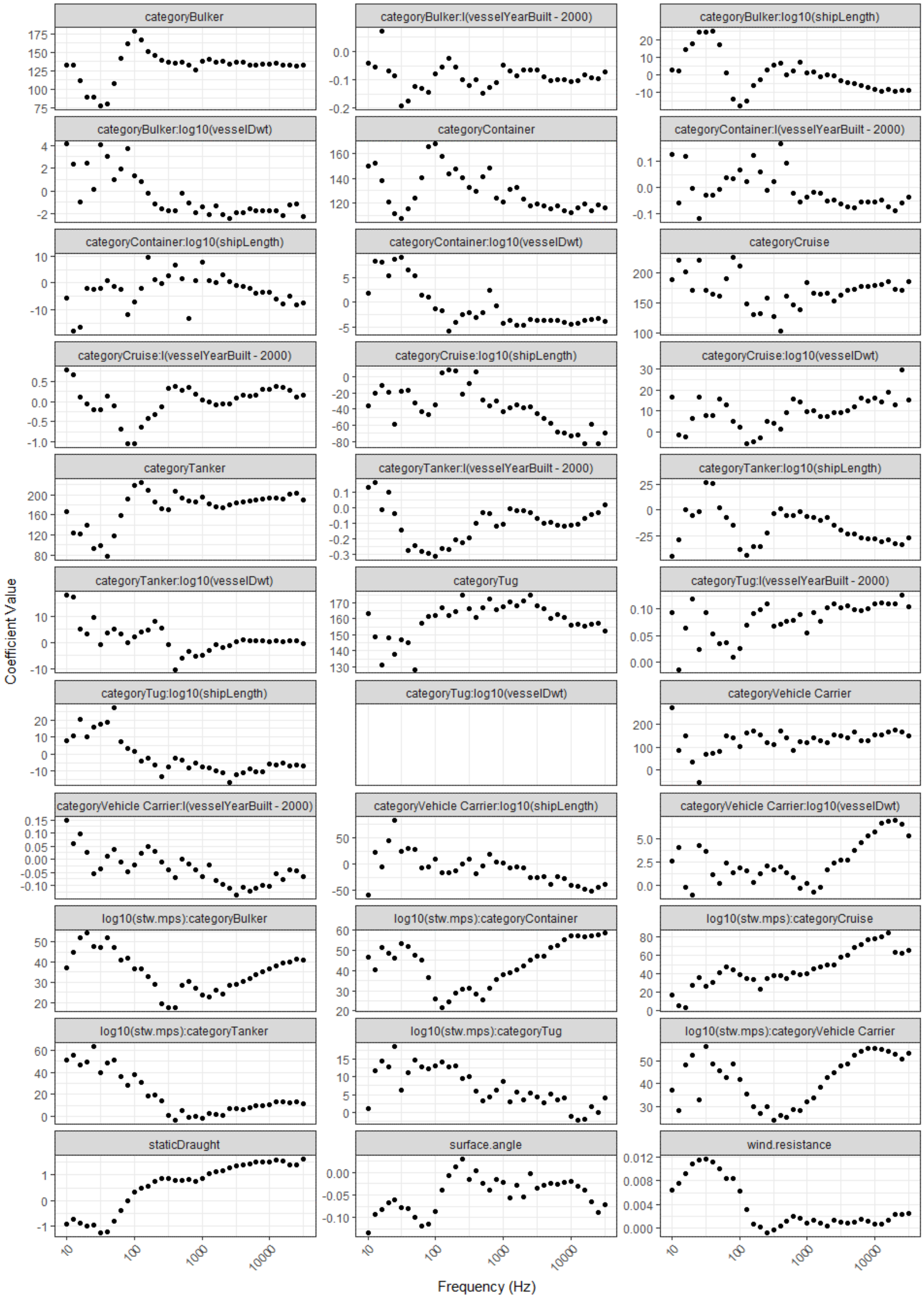


Figure 14. Multiple linear regression (MLR) model coefficients for monopole source level (MSL), by vessel category, for each covariate across all 1/3-octave frequency bands. Dead-weight-tonnage (DWT) was excluded as a covariate for tugs, since it was unavailable for most vessels in this category.

3.5. Ability of Multivariate Model to Explain Data Variation

An important outcome of the multivariate regression analysis described above, was developing a ship noise emissions model. This model can predict the 1/3-octave band RNL and MSL for any ship given its dimensions, draught, speed, angle from surface to the measurement hydrophone (dependent on the CPA), and wind conditions. Figures 15 and 16 show the broadband RNL and MSL, respectively, for all measurements of the ECHO database with a single parameter varied in each panel and the corresponding model predictions based on the vessel and measurement parameters. This shows that the model can reproduce much of the broadband variation in measured source levels (Table 1). The model includes independent regression coefficients for each 1/3-octave-band. It therefore calculates band levels that could be viewed individually in plots similar to the broadband results of Figure 15. The variance unexplained by the multivariate model reflects vessel-specific differences in noise emissions that cannot be attributed to measurement circumstances (speed, wind, draught, and CPA) or vessel characteristics (category, length, DWT, and year built).

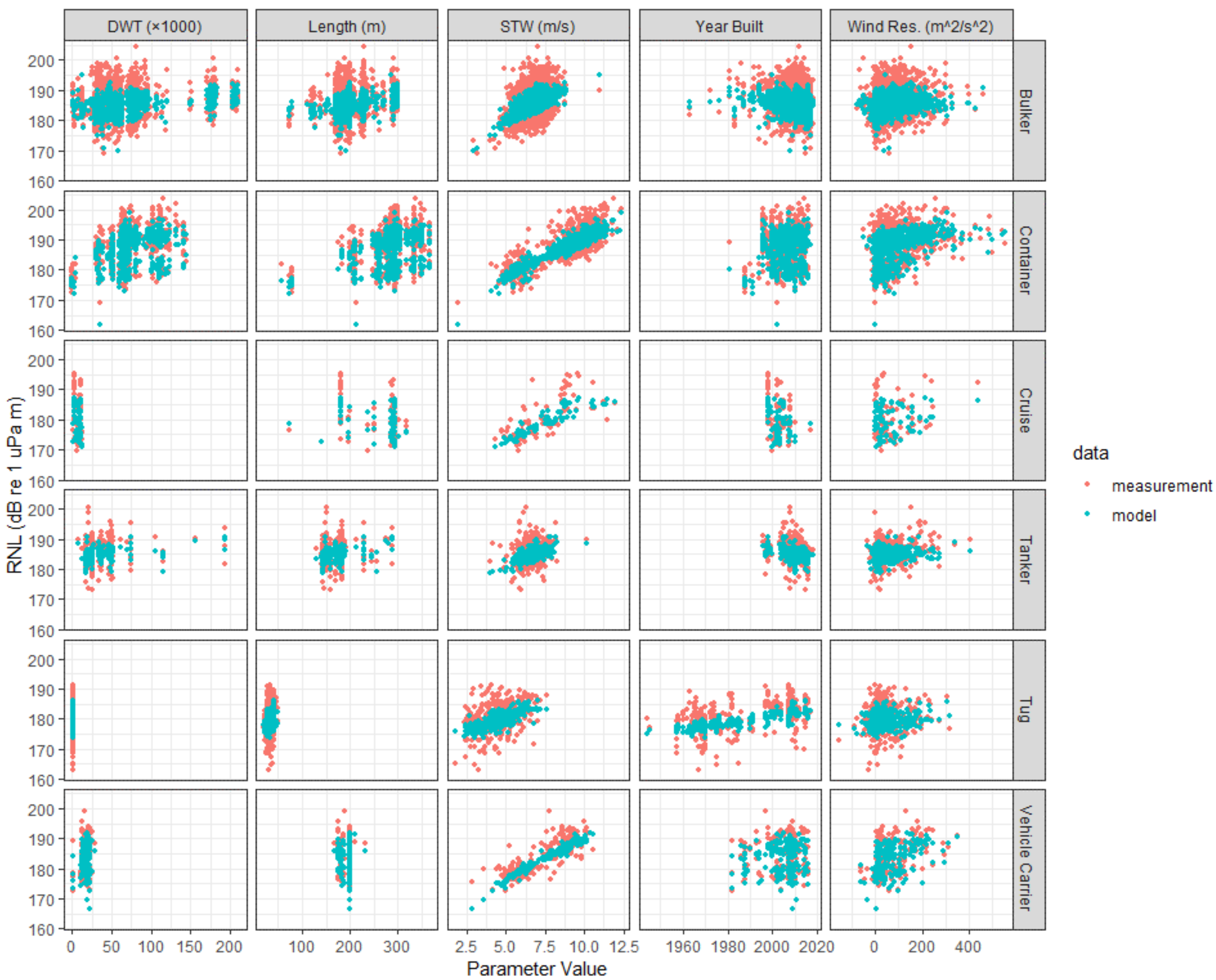


Figure 15. Use of multiple linear regression (MLR) model to explain variability in broadband (20 Hz to 31.5 kHz) radiated noise level (RNL) data for each parameter by vessel category. Each panel shows the variation of the raw measured data (red dots) with each covariate for one vessel category. The blue dots show model predictions of broadband RNL using the vessel and measurement parameters.

Figure 16. Use of multiple linear regression model to explain variability in broadband (20 Hz to 31.5 kHz) monopole source level (MSL) data for each parameter by vessel category. Each panel shows the variation of the raw measured data (red dots) with each covariate for one vessel category. The blue dots show model predictions of broadband MSL using the vessel and measurement parameters.

The multiple linear regression model produced 1/3-octave band noise emission predictions based on specific values of the covariate inputs described in Section 3.3. These include ship category, ship length, DWT, year-built, wind drag coefficient, static draught, transit speed and surface angle. By summing the predicted 1/3-octave band RNL and MSL, we can calculate broadband levels as shown in FiguresFigure 15Figure 16. A test was performed to understand how much of the ECHO program broadband measurement variance (i.e. the common statistical measure of differences of measurements from their mean value) could be explained by the model. We calculated the variance in decibels of the raw ECHO MSL and RNL results and the variance of the model-scaled results, where scaling was based on the differences of each vessel's covariates (listed above) from their mean values. The results are presented as "Data-variance explained by model." These values are the fractional reduction in variance relative to the raw data variance.

The results of Table 1 indicate a range of model effectiveness variation between ship categories. The model results for Vehicle Carrier and Container Ship categories produced the best descriptions of their noise emissions, accounting for over 70% of the raw data variance. These results are likely very good because of the strong dependence on speed, and due to larger speed variations within the measurements. Nevertheless, this is a very important result. The model explained 42-45% of MSL and 24-27% of RNL for bulkers and tankers. These MSL results are quite good, considering the measurement speed ranges for these categories is quite small. The model's higher performance for MSL than RNL is attributed to complex variations of low frequency noise emissions that are accounted for better by MSL than by RNL (i.e. the complex variations remaining in RNL generally cannot be predicted well by a regression model). The model accounted for 38% and 47% of cruise ship MSL and RNL variance respectively. These reductions in variance arose largely from differences in vessel size and speed that were accounted for by the model. Finally, the tug category data variance was least-accounted for by the model; only 24% of MSL and 28% of RNL variance reductions were observed for tugs.

Table 1. Percentage of broadband data variance (radiated noise level (RNL) and monopole source level (MSL)) explained by the multiple regression model.

Category	Data variance explained by model (MSL)	Data variance explained by model (RNL)
Bulker	45%	24%
Container	74%	70%
Cruise	38%	47%
Tanker	42%	27%
Tug	24%	28%
Vehicle Carrier	71%	76%

4. RNL AND MSL SCALING TO COMMON REFERENCE CONDITIONS

The multivariate model coefficients of Figure 13 were applied to every measurement of the ECHO database to normalize to reference vessels for each vessel category. We chose reference values for vessel dimensions based on the mean values per category. Several of the certification society measurement protocols require vessels to be transiting at 85% of their Maximum Continuous Rating (MCR) speed. As the MCR is vessel-dependent, we used the 75th percentile speeds of all vessels measured by the Haro Strait recorders, but only for non-slowed vessels, as a slow-down trial occurred during their deployment time. The use of the 75th percentile speed instead of the median speed was to compensate for vessels perhaps transiting slightly slower in Haro Strait than they would in open water. Finally, we set the effective wind speed to the actual vessel speed over ground, and effective wind direction to the ship's heading. This represents a no-wind condition. Table 2 lists the common parameters for each category.

Table 2. Reference vessel parameters for each category, used for scaling the vessel source level measurements. Reference speed through water (STW) was based on the 75th percentile speed of unslowed vessels in Haro Strait (this was assumed to be approximately equal to speed at 85% maximum continuous rating (MCR). Other vessel parameters were based on the median values for each category from the database. The reference angle from the surface was taken to be 30°, in accordance with the ANSI S12.64 (2009) Grade-C standard for ship noise measurement.

Category	STW (m/s)	Dead-weight-tonnage	Year built	Length (m)	Draught (m)
Bulker	7.4	58642	2012	199	7.8
Container	10.4	67680	2007	293	11.5
Cruise	9.3	8222	2002	287	8.1
Tanker	7.5	33674	2010	170	8.2
Tug	4.8	336	1983	32	5.0
Vehicle Carrier	9.4	18561	2007	199	8.5

Figures 17 and 18 show the density distributions of broadband RNL and MSL, respectively, of the unscaled (raw ECHO database results) and the same data scaled to match the reference dimensions and measurement parameters given in Table 2. The unit of density shown here represents the fraction of all measurements that fall within a 1 decibel range of the x-axis (RNL or MSL) value. The scaled levels had narrower and more symmetrical distributions than the unscaled data. This was expected, as the goal of scaling was to produce more consistent results between ships within each category. While the figures show only the scaled broadband distributions, the values plotted there are calculated from the scaled 1/3-octave-band levels. In Section **Error! Reference source not found.**, the scaled 1/3-octave-band l evels are compared with the certification society maximum permitted noise levels for all bands.

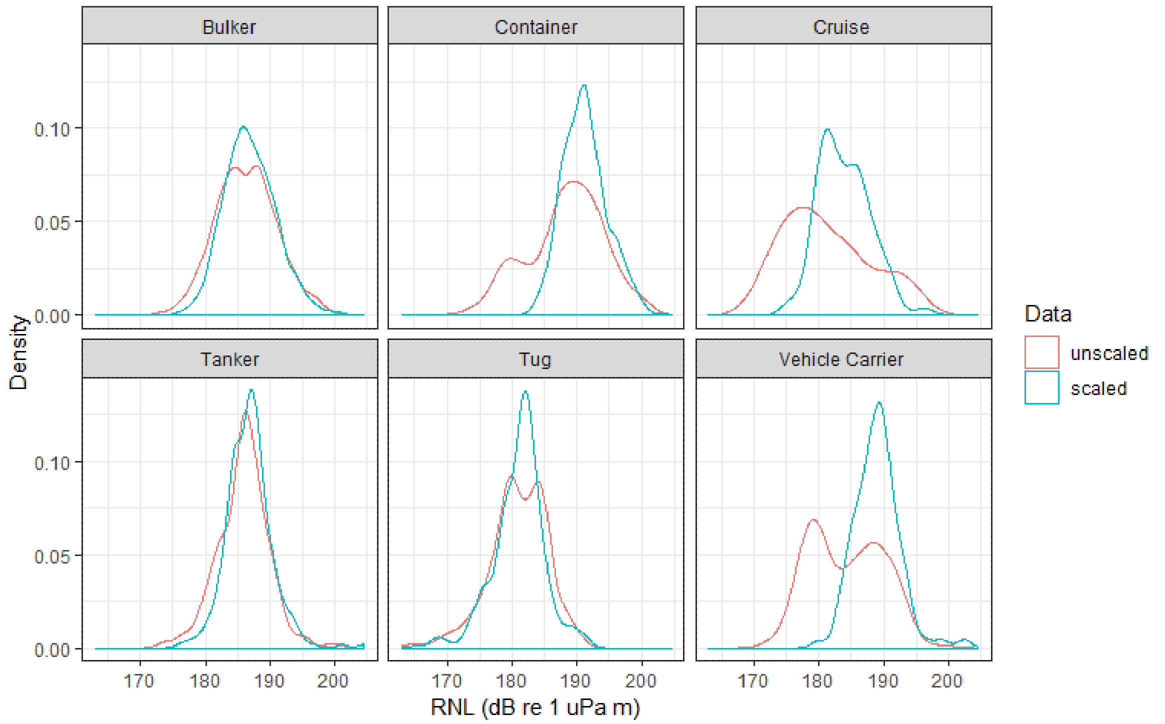


Figure 17. Density plot of radiated noise level (RNL) for unscaled (red line) and scaled (blue line) vessel noise measurements.

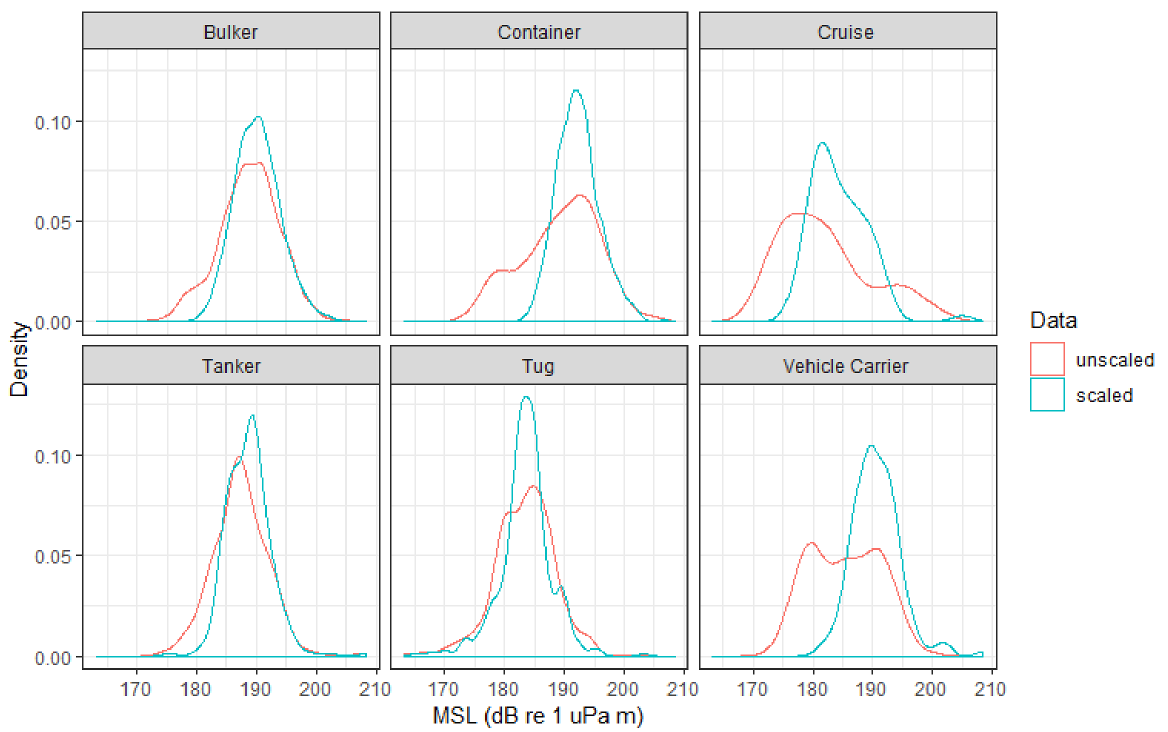


Figure 18. Density plot of monopole source level (MSL) for unscaled (red line) and scaled (blue line) vessel noise measurements.

5. ECHO MEASUREMENT ADJUSTMENTS FOR CLASS NOTATION MEASUREMENT PROCEDURES

The ECHO dataset was obtained using the measurement procedure documented in ANSI S12.64 (2009), with some relaxation of requirements for number of passes and hydrophone surface angles as identified in Section 2. Measurements of ship noise depend on the procedures used to acquire them, and there are differences between the ANSI S12.64 (2009) procedure and the procedures specified by all five of the certification societies. In this part of the study, adjustments to the ECHO dataset values are applied to account for differences between ANSI S12.64 (2009) and the procedures of the respective certification societies.

5.1. Differences in Class Notation Society Measurement Procedures

The certifications evaluated here are as follows:

- Det Norske Veritas: *Rules for Classification of Ships*. Part 6 Chapter 24. Newbuildings Special Equipment and Systems – Additional Class, Silent Class Notation (2010)
- Bureau Veritas: *Underwater Radiated Noise (URN)*. Rule Note NR 614 DT R00 E (2014)
- American Bureau of Shipping: *Guide for the Classification Notation: Underwater Noise* (2018)
- RINA: *Rules for the Classification of Ships: Amendments to Part F. Additional Class Notations. Introduction of the new additional class notations “dolphin quiet” and “dolphin transit”* (2016)
- Lloyd’s Register: *ShipRight Design and Construction: Additional Design Procedures. Additional Design and Construction Procedure for the Determination of a Vessel’s Underwater Radiated Noise* (2018)

Table 3. Differences in measurement procedures between the certification societies considered and ANSI S12.64, which was used to acquire the ECHO dataset. Pink shading indicates a method is different from ANSI S12.64 while green indicates it is the same. Yellow indicates it is the same as the method used by ECHO to calculate MSL.

Parameter	ANSI S12.64 Grade C	DNV Silent-E	BV URN	RINA Dolphin	LR ShipRight	ABS UWN
Water depth	75 m or one times(1x) the overall ship length, whichever is greater	Min 30 m under keel, and d > 0.64 v2, with sloping seabed preferred	Shallow: 60 m < d <150 m and d > 0.3 v^2 Deep: >200 m and >2 × vessel length	>200 m	Shallow: 60 m < d <150 m and d > 0.3 v2 Deep: >150 m and >1.5 × vessel length	Shallow: 60 m < d <150 m and d > 0.3 v2 Deep: >150 m and >1.5 × vessel length
Hydrophone depth(s)	1 hydrophone 20° angle ±5°	0.2 m above seabed	Shallow: 3 hydrophones at ~4, 20, and 40 m above seabed Deep: 3 hydrophones spaced at more than 30 m, with top >40 m from surface	3 hydrophones at depths for: 15°, 30°, and 45° below horizontal	Shallow: 3 hydrophones at d/10, d/2, and 5 m above seabed Deep: 3 hydrophones at depths for: 15°, 30°, and 45° below horizontal	3 hydrophones at depths for: 15°, 30°, and 45° below horizontal
Closest point of approach	100 m or 1 vessel length ±10%	150–250 m	Greater of 200 m and ship length. If background noise issues are foreseen, then CPA of 100 m is acceptable Also 400 and 500 m	Greater of 150 m and ship length	Greater of 100 m and ship length	Greater of 100 m and ship length
Averaging time	Time for passing DWP = DWL/v [s] DWL is distance in m ±30° of CPA	2 × ship length/speed	Time for passing ±45° of CPA, but divided into 5° steps	Time to travel 1.5 × ship length	Time for passing ±30° of CPA	Time for passing ±30° of CPA
Measurement type	RNL	RNL_1 (modified$_4$)	MSL_2	RNL_1	MSL_2	RNL_1(modified)
Distance adjustment factor	20 log r	18 log (r)	20log r + distcorr	20 log r	20 log r	20 log r
Weather	Wind speed limit of less than 20 knots for vessels longer than 100 m		Limit to sea state <3 Beaufort scale for bottom mounted configuration - corresponds to wind speed less than 7 knots	Wind speed less than 20 knots but advised to use wind speed less than 10 knots and sea state 3 (Douglas scale) for vessels larger than 100 m	Sea state limit to 2 but Beaufort to 4 <11 knots). sea state 3 acceptable if background noise not significantly affected	Sea state 3 with wind Beaufort 4

Parameter	ANSI S12.64 Grade C	DNV Silent-E	BV URN	RINA Dolphin	LR ShipRight	ABS UWN
Seabed reflection adjustment		−5 dB	Acoustic model	None	Shallow: measured or modelled Deep: none	−5 dB if hydrophone less than 20 cm off bottom
Number of passes	Minimum requirement1 - port + 1 starboard. Arithmetic average	1 port + 1 starboard	6 port + 6 starboard, Arithmetic average 2 at each of 3 CPAs	2 port + 2 starboard	2 port + 2 starboard	2 port + 2 starboard
Frequency range for recording	10 Hz to 50 kHz	10 Hz to 100 kHz	10 Hz to 50 kHz	10 Hz to 50 kHz	10 Hz to 100 kHz	10 Hz to 50 kHz for commercial vessels and 10 Hz to 100 kHz for research
Frequency range post-processing	50 Hz to 10 kHz in 1/3-octave-bands	all relevant frequencies in 1/3-octave-bands	10 Hz to 50 kHz in 1/3-octave-bands	10 Hz to 50 kHz in 1/3-octave-bands	10 Hz to 10 kHz	10 Hz to 50 kHz for commercial vessels and 10 Hz to 100 kHz for research
Vessel speed	Less than 50 knots	Transit: 85% MCR3 Cruise: 11 knots for vessels >50 m length	Not specified	Not specified	Transit: 85% MCR3 Quiet: max. 10 knots	Transit: 85% MCR3 Quiet: 3.1 m/s + 0.0084 × vessel length
Background noise	SNR > 10 dB no correction 3<SNR<10dB correction SNR<3 dB discard data	SNR > 10 dB no correction (3)or5 < SNR < 10 dB correction SNR < 5 dB discard	SNR > 10 dB no correction 3 < SNR < 10 dB correction SNR < 3 dB discard data	SNR > 10 dB no correction 3 < SNR < 10 dB correction SNR < 3 dB discard data	Not specified - as long as not affecting measurements	SNR > 10 dB no correction 3 < SNR < 10 dB correction SNR< 3 dB discard data
Calibration	Every 12 months according to IEC60565		According to IEC60565	According to IEC60565	According to IEC60565	According to IEC60565
Directionality	Omni-directional	Omni-directional	Omni-directional	Omni-directional	Omni-directional	Omni-directional
Allowed limit of measurement uncertainty	4 dB (but also ±3 dB for repeatability)	Not specified	Deep water ±3.5 dB		±3 dB	3 dB
Acoustic centre of vessel (taken for CPA)	Longitude - halfway between engine and propeller	At 0.7 propeller radius when blade pointing upwards	Longitude - halfway between engine and propeller	Longitude - halfway of the ship	Not specified	Longitude - halfway between engine and propeller
			Vertical - 2/3 vessel draught from water line	Vertically - halfway between water line and bottom of ship		Vertically not specified

Key differences between these certifications are summarized in Table 4. While not all differences are accounted for in the adjustments, the most important ones listed in the table are addressed.

Table 4. Summary of adjustments (in decibels) applied to ECHO measurements to allow them to be compared with the certification society measurement protocols.

Requirement adjustment compared to ECHO dataset	DNV Silent-E	BV URN	RINA Dolphin	LR ShipRight	ABS UWN
Measurement type	RNL (modified)	MSL	RNL	MSL	RNL (modified)
Distance adjustment factor	2 log r	0	0	0	0
Sea surface adjustment	0	0	0	0[1]	0
Seabed reflection adjustment	−5	0	0	0[1]	−5

[1] Dependent on difference between values calculated by models as specified in each protocol. The ECHO MSL measurements use a full-wave wavenumber integral model for seabed and sea surface reflections. LR uses a formula-based surface reflection model.
[2] MSL Monopole Source Level, as defined under Source Level in ISO 17208 (2016)

5.2. Adjusted Levels by Vessel Category

Here we present the ECHO measurements scaled to reference ship parameters from Table 2 and adjusted to account for the measurement procedure differences in Table 4. These scalings and adjustments were applied to every measurement of the ECHO database. Figures 19 to 24 present the resulting mean values in each frequency band by vessel category. The key feature of these results is that the measurements are clearly dependent on the certification society measurement methods. Therefore, it is not generally possible to compare the results from one certification measurement system with those from another, or with those from ANSI S12.64 (2009). Likewise, the maximum noise emission level thresholds from one society cannot generally be applied to measurements collected under another society's procedure. That is the underlying reason for the adjustments applied in this study, namely to scale and adjust the ECHO measurements, collected approximately according to ANSI S12.64 (2009), to be compatible with the thresholds of each of the certification societies.

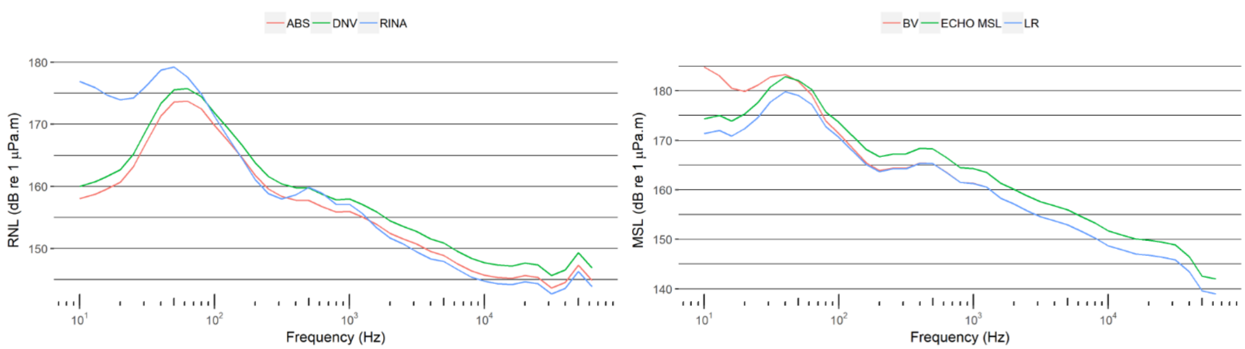


Figure 19. *Bulkers*: Median radiated noise level (RNL; left) and monopole source level (MSL; right) of scaled measurements adjusted for the measurement procedures of the different certifications

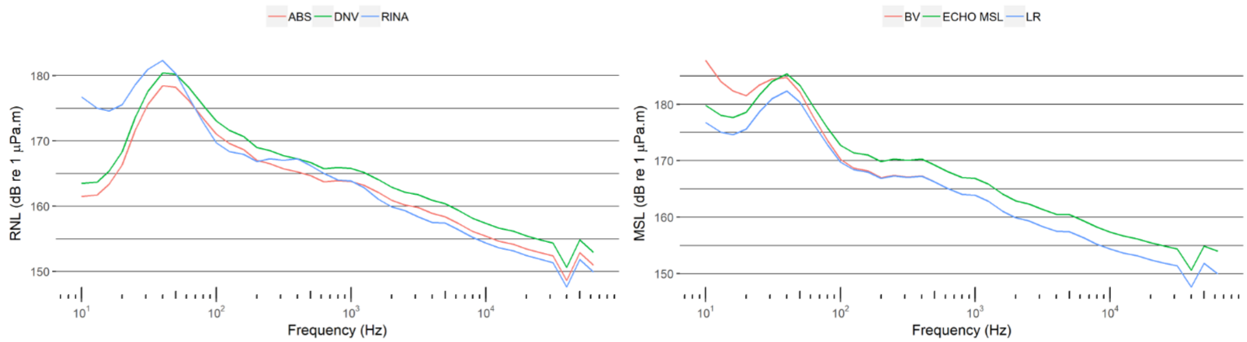


Figure 20. *Containers*: Median radiated noise level (RNL; left) and monopole source level (MSL; right) of scaled measurements adjusted for the measurement procedures of the different certifications

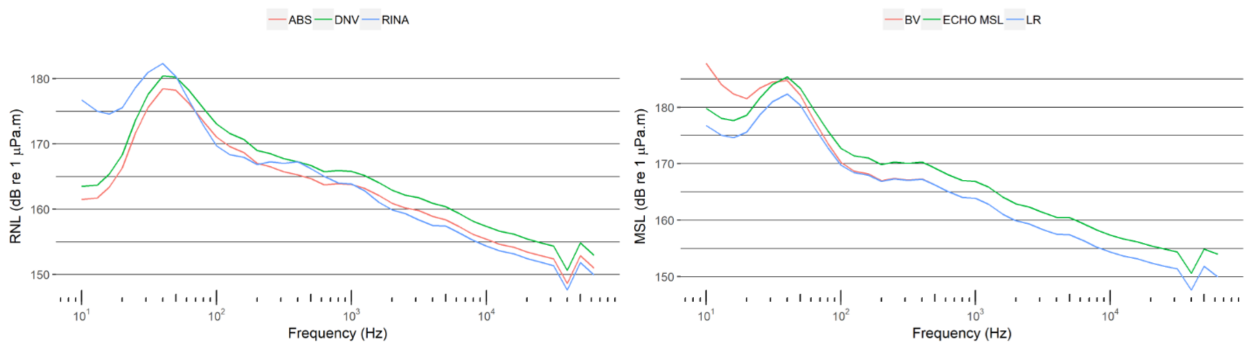


Figure 21. *Cruise ships*: Median radiated noise level (RNL; left) and monopole source level (MSL; right) of scaled measurements adjusted for the measurement procedures of the different certifications

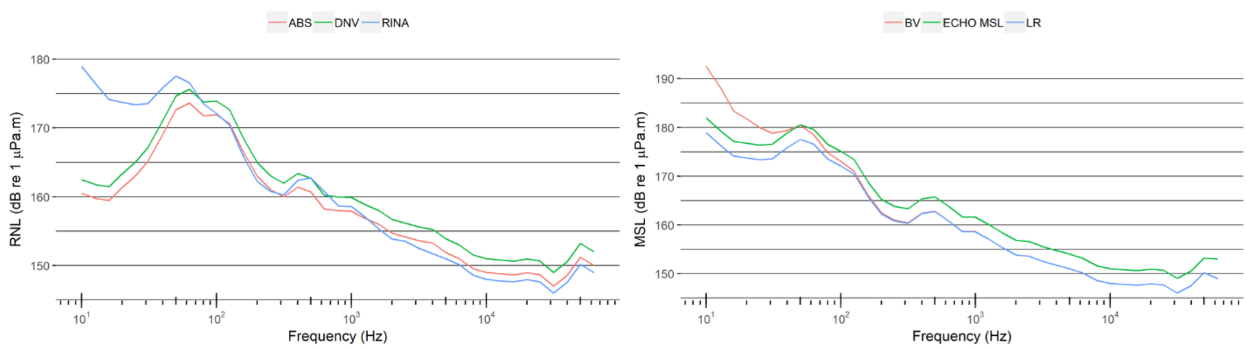


Figure 22. *Tankers*: Median radiated noise level (RNL; left) and monopole source level (MSL; right) of scaled measurements adjusted for the measurement procedures of the different certifications

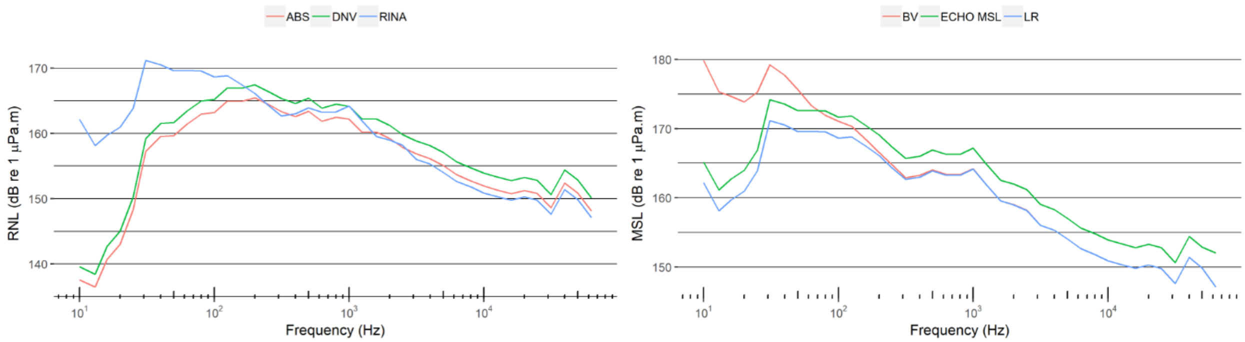


Figure 23. *Tugs*: Median radiated noise level (RNL; left) and monopole source level (MSL; right) of scaled measurements adjusted for the measurement procedures of the different certifications

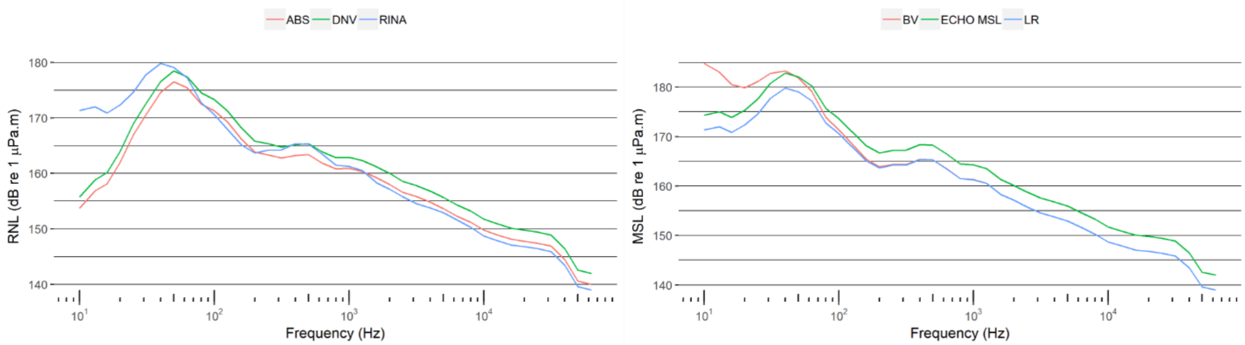


Figure 24. *Vehicle Carriers*: Median radiated noise level (RNL; left) and monopole source level (MSL; right) of scaled measurements adjusted for the measurement procedures of the different certifications

5.3. Adjusted Levels by Certification Society

It is informative to examine differences in the scaled and adjusted ECHO database measurements for each certification society across different vessel categories. This presentation format reveals a quite strong dependence of noise emissions on vessel category. Figures 25 to 29 show the variation of noise emissions by vessel category (scaled to the reference vessel for each category) for each certification society. It is apparent that container ships produce higher noise levels than all other categories in most frequencies. That is largely attributed to their higher speed. However, their average speed is only 1 m/s higher than the reference speeds for cruise ships and vehicle carriers, and the median sound emission levels of those two categories are substantially less than the median levels of container ships at most sound frequencies.

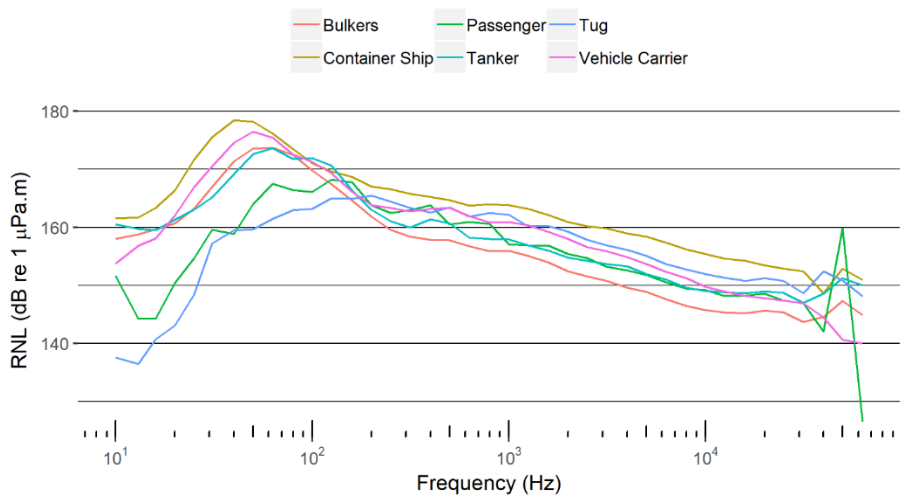


Figure 25. *American Bureau of Shipping (ABS)*: Median of scaled ECHO radiated noise level (RNL) measurements, adjusted for the measurement procedure.

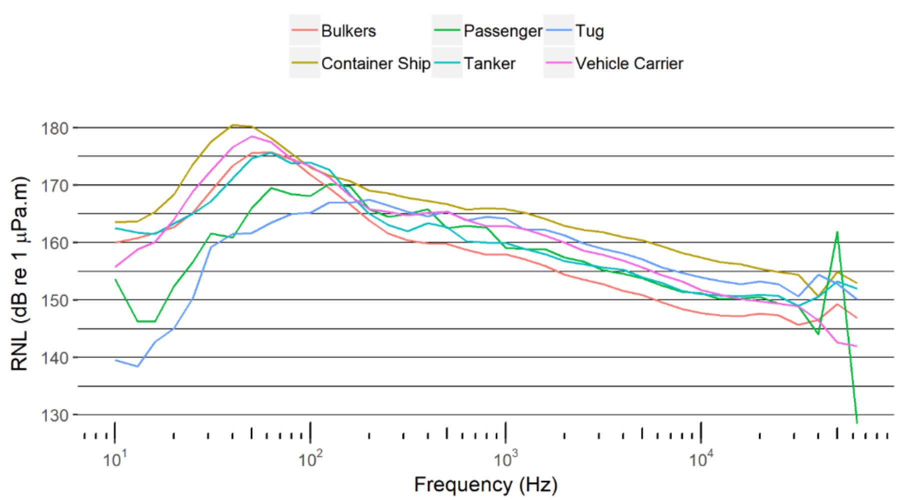


Figure 26. *Det Norske Veritas (DNV)*: Median of scaled ECHO radiated noise level (RNL) measurements, adjusted for the measurement procedure.

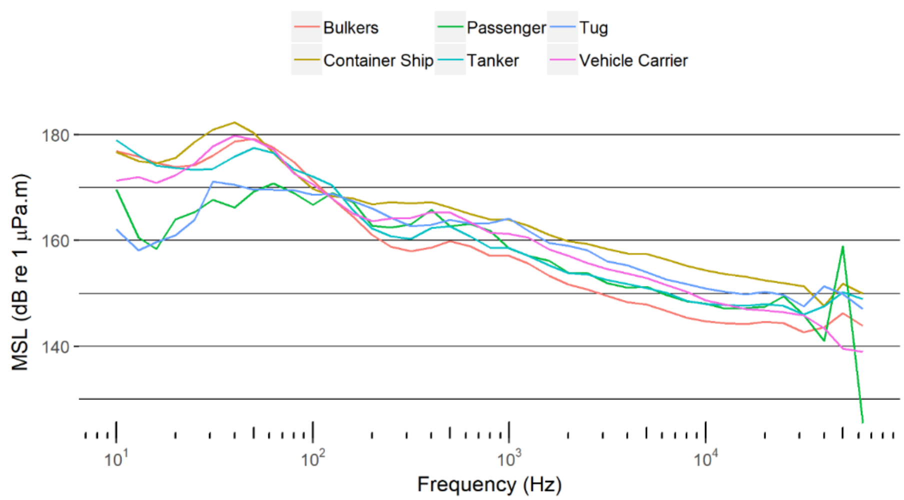


Figure 27. *Lloyd's Registrar (LR):* Median of scaled ECHO monopole source level (MSL) measurements, adjusted for the measurement procedure.

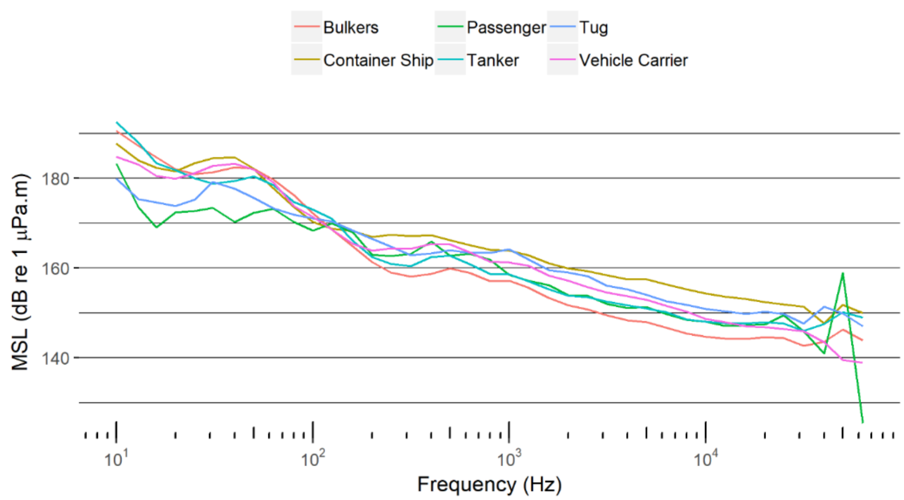


Figure 28. *Bureau Veritas (BV)*: Median of scaled ECHO MSL measurements, adjusted for the measurement procedure.

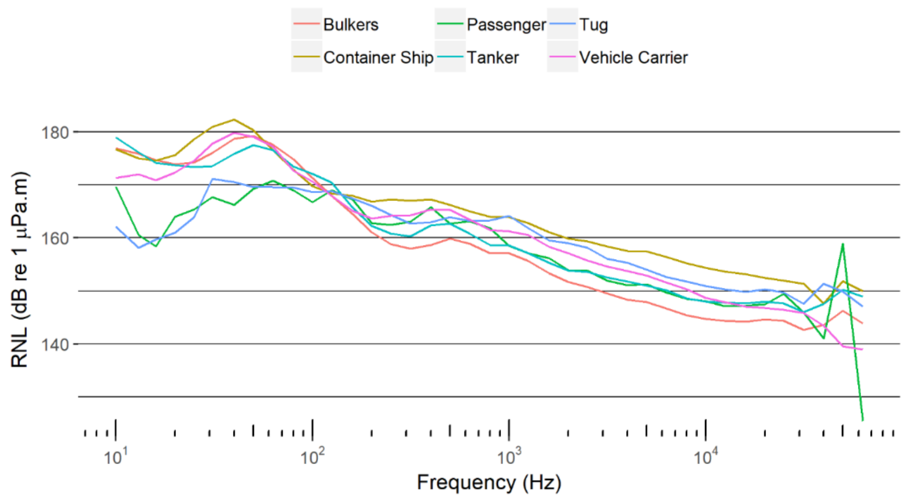


Figure 29. *RINA*: Median of scaled ECHO radiated noise level (RNL) measurements, adjusted for the measurement procedure.

6. ECHO MEASUREMENTS COMPARISON WITH CLASS NOTATION THRESHOLDS

Each of the five class notation societies considered in this study describes a set of thresholds for assessing the noise radiated from ships. Here we considered the generic notations for environmental assessment, referred to as “quiet” and “transit” in all standards except the BV, which instead refers to the equivalent notations as “controlled” and “advanced”.

6.1. Class Notation Thresholds

All certifications are based on a decomposition of vessel noise into its constituent 1/3-octave acoustic frequency bands. This approach is important for rating the noise emissions of vessels because it allows the results to be interpreted according to the frequency sensitivity of individual species. For example, killer whales are more sensitive to sound frequencies above 1000 Hz than North Pacific right whales, whereas the right whales are more sensitive than killer whales below that frequency. The definition of the relevant notations differs for each standard, as per the following:

American Bureau of Shipping UWN:

Quiet:	170.5–1.5 log(f)	for f from 10 Hz to 100 Hz
	179.5–6 log(f)	for f from 100 Hz to 1000 Hz
	191.5–10 log(f)	for f from 1000 Hz to 100 kHz
Transit:	178.5–1.5 log(f)	for f from 10 Hz to 100 Hz
	187.5–6 log(f)	for f from 100 Hz to 1000 Hz
	199.5–10 log(f)	for f from 1000 Hz to 100 kHz

Bureau Veritas URN:

Thresholds are expressed as spectral levels and not 1/3-octave-band levels like the others. A conversion of +10*Log10(0.2308 f) can be applied to calculate 1/3-octave-band levels. This conversion assumes the mean spectral level in each band is equal to the calculated spectral level at the band’s centre frequency; this is not exactly true but generally is a reasonable approximation.

Controlled:	169–2 log(f) + LFcor	for f from 10 Hz to 50 Hz
	165.6–20 log(f/50) LFcor	for f from 63 Hz to 1000 Hz
	139.6–20 log(f/1000)	for f from 1.25 kHz to 50 kHz
Advanced:	174–11 log(f) + LFcor	for f from 10 Hz to 50 Hz
	155.3–18 log(f/50)	for f from 63 Hz to 1000 Hz
	131.9–22 log(f/1000)	for f from 1.25 kHz to 50 kHz

where LFcor = $\max[0, 10 \log(0.5+(4\pi f d \sin(\theta)/c)^{-2})]$[3]

DNV Silent-E:

Quiet cruise:	171–3 log(f)	for f from 10 Hz to 1000 Hz
	162–12 log(f/1000)	for f from 1000 Hz to 100 kHz
Transit:	183–5 log(f)	for f from 10 Hz to 1000 Hz
	168–12 log(f/1000)	for f from 1000 Hz to 100 kHz

[3] For consistency with the calculations applied to obtain the adjusted measurements database, the low-frequency correction here was calculated using the same parameters, i.e. speed of sound (c) of 1480 m/s, source depth as two thirds of vessel draught and angle theta of 15 degrees (deep water).

Lloyd's Register ShipRight:

Quiet:	180–15 log(f/10)	for f from 10 Hz to 100 Hz
	165–2 log(f/100)	for f from 100 Hz to 1000 Hz
	163–13 log(f/1000)	for f from 1000 Hz to 100 kHz
Transit:	186–15 log(f/10)	for f from 10 Hz to 100 Hz
	171–2 log(f/100)	for f from 100 Hz to 1000 Hz
	169–13 log(f/1000)	for f from 1000 Hz to 100 kHz

RINA Dolphin:

Dolphin quiet:	173–4 log(f)	for f from 10 Hz to 1000 Hz
	161–12 log(f)	for f from 1000 Hz to 100 kHz
Dolphin transit:	182–5 log(f)	for f from 10 Hz to 1000 Hz
	167–12 log(f)	for f from 1000 Hz to 100 kHz

DNV and RINA split the frequency variation of their maximum noise thresholds into two frequency categories, while ABS, BV and LR use three frequency intervals. The frequency dependence of the maximum noise thresholds within each frequency interval vary linearly with logarithm of frequency. The slopes of the frequency variations differ between the certification society thresholds. Figure 30 presents the above threshold levels for all certifications through the full frequency range of 10 Hz to 100 kHz. Vessel noise levels are expected to fall below these thresholds in all or most frequency bands to be granted a certification.

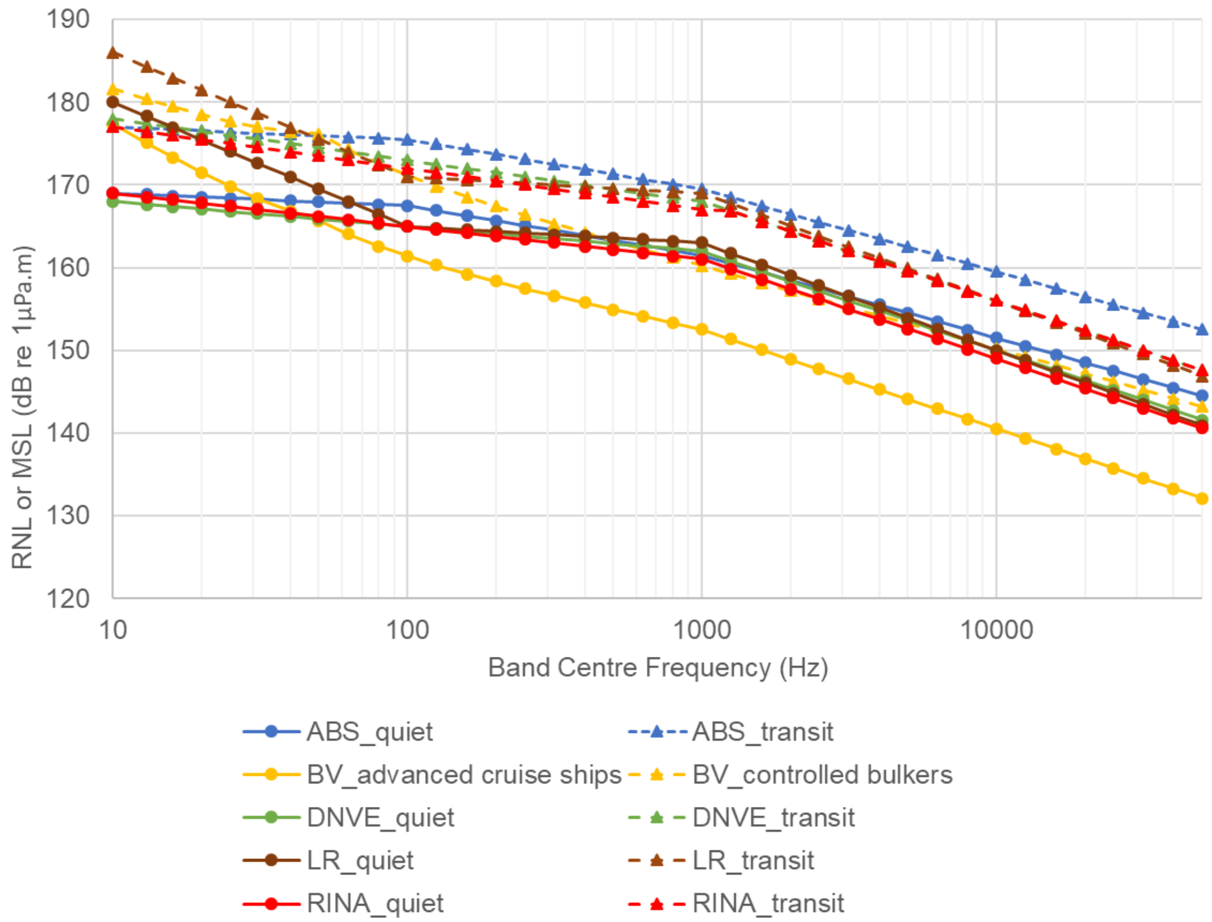


Figure 30. Threshold levels for the five certification society notations. American Bureau of Shipping (ABS), Det Norske Veritas (DNV), and RINA thresholds are in radiated noise level (RNL) units. Bureau Veritas (BV) and Lloyd's Register (LR) thresholds are in monopole source level (MSL) units.

Some of the standards are more descriptive regarding the vessel types than others. They prescribe the following threshold notations that should be indicated on a certification:

- The ABS standard only distinguishes between commercial vessels (without indicating their specific categories) and fishing (for which a separate threshold applies that has not been presented here).
- The BV and RINA standards do not refer to differences in vessel categories. The DNV standard distinguishes between environmental notations for transiting vessels (implying these are commercial vessels) and other vessel types (i.e., fishing, seismic, and research).
- The LR standard is the most descriptive of all standards with regard to vessel categories. Here, a distinction is made between commercial vessels (that mentions bulkers, containers, tankers, and tugs), cruise ships, ferries, and research, seismic, and fishing vessels. The standard specifies that transit conditions apply to commercial vessels, ferries, research (unless towing), and seismic vessels, while the quiet notation applies to cruise ships sailing at approximately 10 knots.

6.2. Scaled and Adjusted Measurement Overlays with Thresholds

Maximum permitted noise emissions thresholds for each of the class notations have been plotted overlaid with the relevant scaled and adjusted measurement data (Figure 31 to Figure 35). The “transit” notation thresholds are shown for all vessel categories except cruise ships. Cruise ship data were plotted against the “quiet” or “advanced” notation thresholds of the corresponding societies. The measurements and their respective 10th, 50th (median), and 90th percentile measured RNL or MSL levels in each frequency band are shown in these plots.

The ABS URN notation thresholds divide the frequency bands into three categories, one for low frequencies below 100 Hz, one for frequencies between 100 Hz and 1000 Hz, and one for all frequencies above 1 kHz. The thresholds have a smooth decay over the frequency range up to 100 kHz (Figure 31). The formulas for ABS thresholds do not implement corrections for the sea surface reflection interference that clearly effect RNL at low frequencies. Consequently, the ABS thresholds do not reproduce the destructive interference that lowers RNL for very low frequencies, so the thresholds lie mainly above RNL measurements for frequencies below approximately 40 Hz. The thresholds between about 50 Hz and 250 Hz follow a linear trend while the RNL for most categories peak in that frequency range. The threshold trend above 300 Hz follows that of the RNL measurements, falling at the 50th to 90th percentile of measurements depending on category.

The BV thresholds are based on MSL so do not suffer as much from the low frequency interference effects that influence RNL. However, the BV thresholds appear to follow an initial low-frequency dependent slope that is shallower than the MSL data suggest for bulkers, tankers and container ships. Interestingly, the match of their low frequency slope to MSL data for cruise ships, tugs and vehicle carriers is better at low frequencies. Above about 500 Hz the BV frequency-dependent slope matches that of all MSL measurements for all vessel categories. This standard requires implementation of a correction for the sea surface reflection to the measurements as well as to the calculation of the notation thresholds. This correction takes into account source depth, which we varied according to vessel category based on their average draughts. Therefore, a different set of notations is applied to each vessel category. The data presented in Figure 32 show that the slope of the BV “controlled” notation approximates well the slope observed in the scale and adjusted measurements up to about 32 kHz. Above 32 kHz the ECHO MSL show an increase that is not followed by any of the notation thresholds. Some of that increase is due to sounds from vessels’ navigation sonars, but those results need further examination.

The DNV certification thresholds are defined by linear trends below and above 1 kHz (Figure 33). These thresholds are in RNL units, and again (like ABS) do not map the low-frequency interference pattern of the RNL data. Their slope appears to be too shallow between about 250 Hz and 500 Hz. Above 1 kHz their slope appears slightly greater (steeper) than the RNL data suggest. The DNV threshold slope appears to fit the data quite well between 400 Hz and 1 kHz. These thresholds follow approximately the median measured RNL levels for container ships for most frequencies above 200 Hz. They follow approximately the 75th percentile levels for bulkers and tankers in that same frequency range.

The LR certification thresholds are based on MSL and follow constant slopes in three frequency intervals: below 100 Hz, 100-1000 Hz, and above 1000 Hz (Figure 34). The LR standard also requires that a sea surface correction be applied to the measurements. The slopes of these thresholds appear to follow the general slopes observed in the MSL data over these same frequency ranges. An exception is at very low frequencies, below approximately 40 Hz, where the slope of the threshold frequency variation is steeper than that of the data. These thresholds lie between the 50 and 75th percentiles of the ECHO data for containerships, and typically above the 75th percentile for other ship categories.

The RINA notations are nearly identical to the DNV-E notations and, therefore, the same observations made for that standard apply (Figure 35).

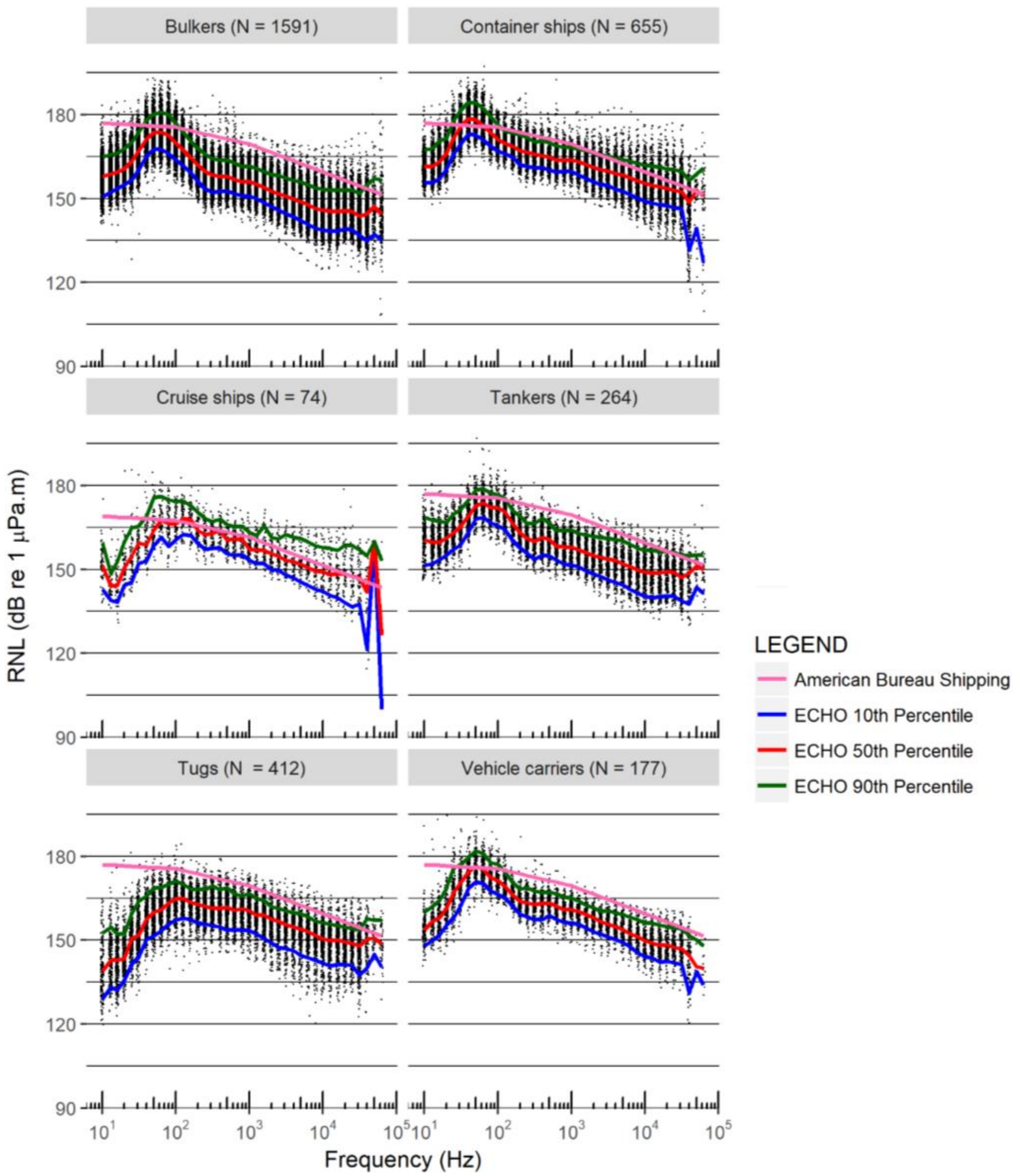


Figure 31. *American Bureau of Shipping (ABS)*: Scatter plot of the scaled and adjusted RNL measurements according to the ABS class notation protocol overlaid with the percentile distribution of the data for each centre frequency (blue=10th percentile, red = 50th percentile, dark green = 90th percentile) and the ABS notation thresholds (pink).

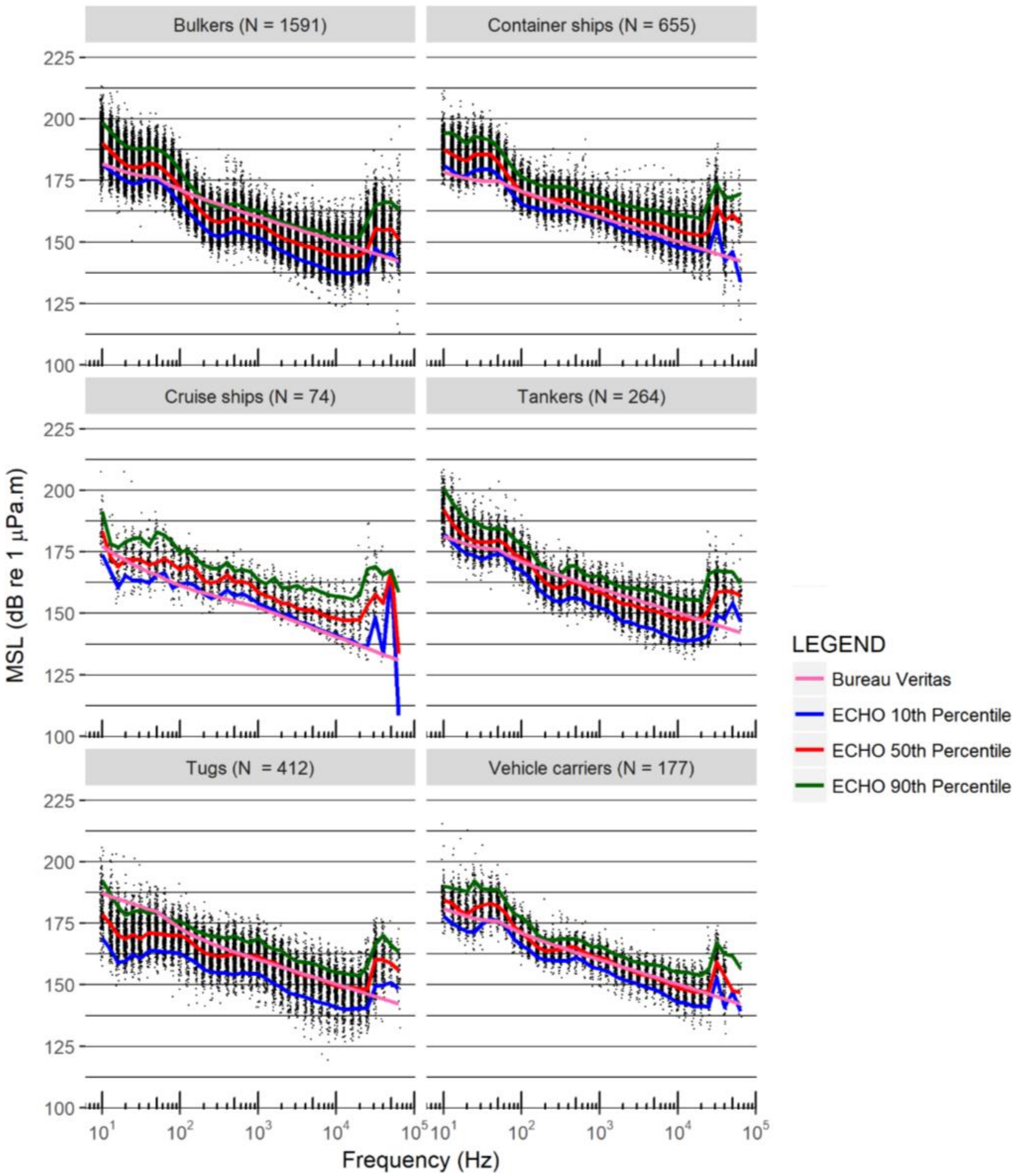


Figure 32. *Bureau Veritas (BV)*: Scatter plot of the scaled and adjusted MSL measurements according to the BV classification protocol overlaid with the percentile distribution of the data for each centre frequency (blue=10th percentile, red = 50th percentile, dark green = 90th percentile) and the relevant notation (pink).

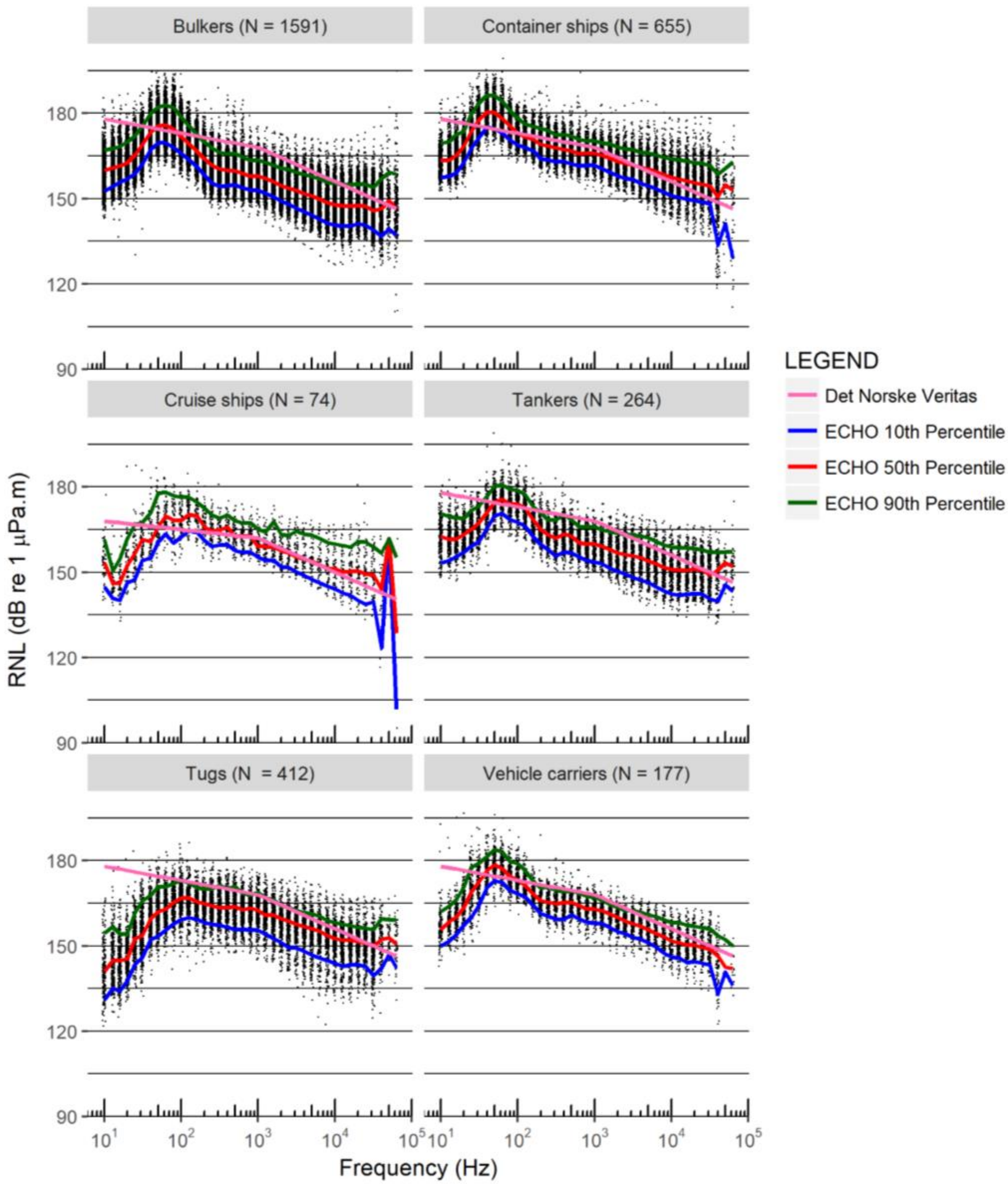


Figure 33. *Det Norske Veritas (DNV)*: Scatter plot of the scaled and adjusted measurements according to the DNV classification protocol overlaid with the percentile distribution of the data for each centre frequency (blue=10th percentile, red = 50th percentile, dark green = 90th percentile) and the relevant notation (pink).

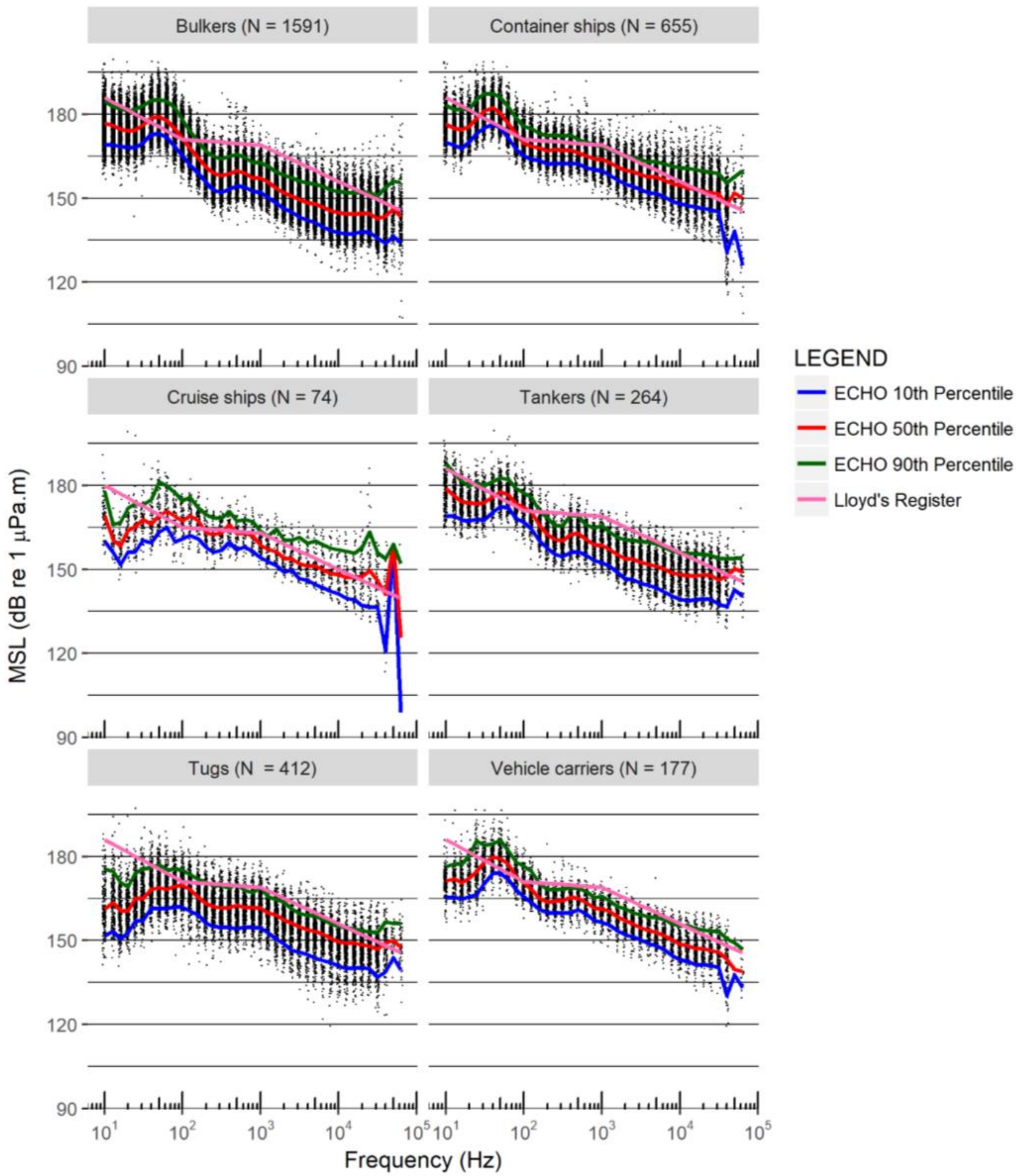


Figure 34. *Lloyd's Registrar (LR)*: Scatter plot of the scaled and adjusted measurements according to the LR classification protocol overlaid with the percentile distribution of the data for each centre frequency (blue=10th percentile, red = 50th percentile, dark green = 90th percentile) and the relevant notation (pink).

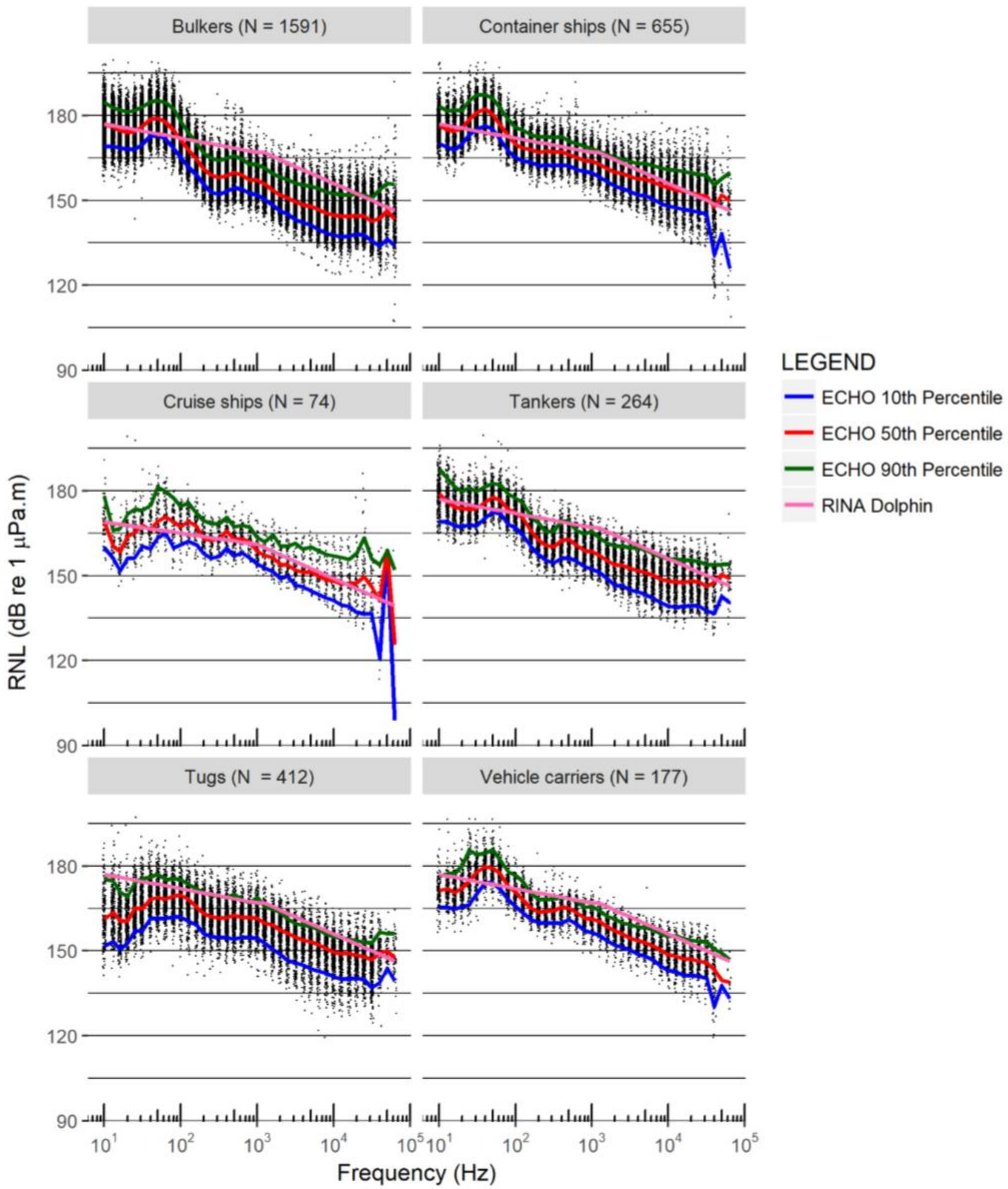


Figure 35. *RINA*: Scatter plot of the scaled and adjusted measurements according to the RINA classification protocol overlaid with the percentile distribution of the data for each centre frequency (blue=10th percentile, red = 50th percentile, dark green = 90th percentile) and the relevant notation (pink).

6.3. Conformance with Certification Society thresholds

This section compares the scaled and adjusted levels from Section 5 with the maximum noise levels permitted by the certification societies. The 1/3-octave band levels of all scaled and adjusted measurements were compared with the corresponding 1/3-octave band threshold level of each certification society (Section 6). As previously mentioned in Table 3 (Section 5), if a 1/3-octave band level of the measurement data was within 3 dB of the ambient noise level, the band was assigned a null value during the PortListen® processing. In this analysis, these null-valued bands were treated as meeting the criteria since they are assumed to have low amplitudes. That assumption is not always valid, because high background noise levels during some measurements were responsible for the failed test that resulted in the null value assignment. Nevertheless, this assumption is generally justified.

Figure 36 presents the percentage of compliant vessels in all but 5 bands in the broadband frequency range for each transit or controlled notation certification society. The American Bureau of Shipping (ABS) notation appears to be the most permissive, but it is important to keep in mind that very few vessels were conformant in all bands – which is the requirement for certification. In fact only 14 percent of container ships were fully compliant with ABS. BV (Bureau Veritas) appears to be the most conservative notation. More discussion about conservativeness in Section 6.4.

Tables 5 to 9 in Sections 6.3.1 to 6.3.5 below present the percentage of vessels in each vessel category meeting each society certification (transit or controlled), except in the specified number of frequency bands (quiet and advanced notation results are presented in Appendix A.2). The results show that ABS transit (Table 5) had the highest rate of compliance (particularly tugs at 77%) in all bands. The society with the next highest percentage of compliance is DNV transit (Table 7) (tugs at 34% in all bands, 68% in all but 5 bands), followed by LR transit (Table 8) (tugs at 29% and cruise ships at 26% in all bands). All other notations had <20% compliance in all bands for all vessel types.

Figures 37 to 41 present histograms of the cumulative percentage of bulkers potentially-complying with each certification society versus number of non-compliant frequency bands. Histograms for Bulkers are shown here since they had the highest number of measurements. Histograms for all other vessel categories are in Appendix A.1.

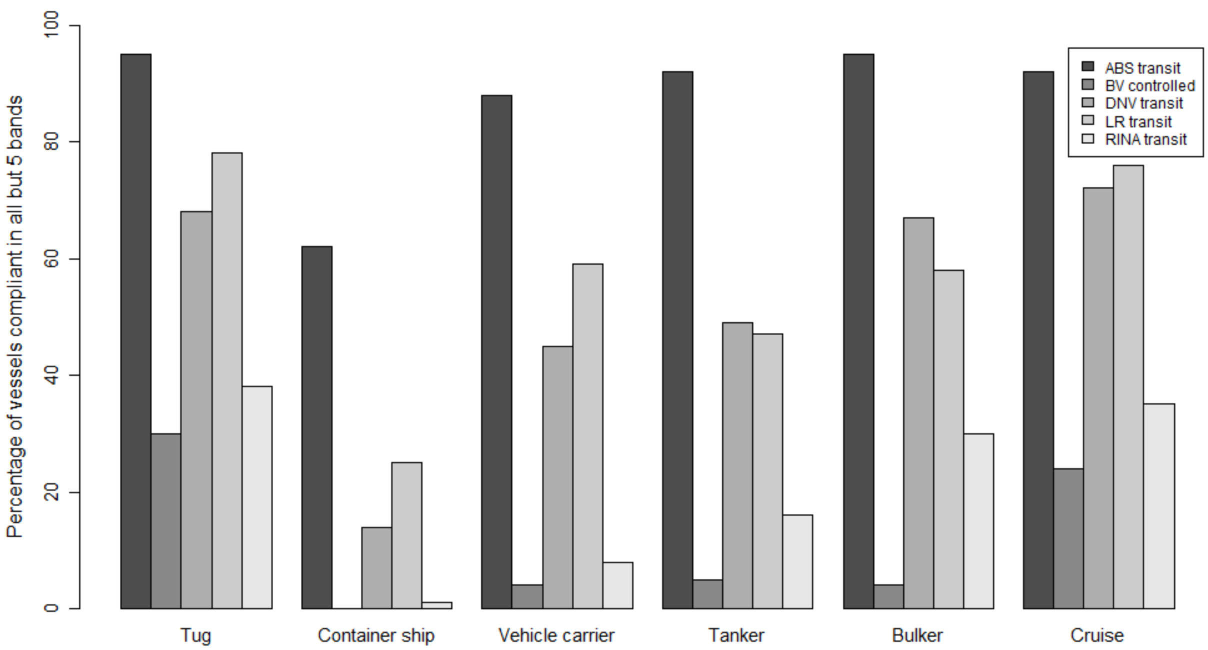


Figure 36. Histogram showing percentage of vessel compliance in all but 5 bands for transit and controlled notations. Results for full compliance (conformant in all bands) are substantially lower than shown here.

6.3.1. American Bureau of Shipping

Table 5 presents the percentage of vessels in each vessel category meeting the American Bureau of Shipping (ABS) notation standard except in the specified number of frequency bands (for the transit notation; the quiet standard results are in Appendix A.2). Figure 37 shows the corresponding histogram of the cumulative percentage of bulker compliance. All other vessel categories are in Appendix A.1.

Table 5. *American Bureau of Shipping (ABS)*: Percentage of vessels in each category meeting the transit notation except in the specified number of frequency bands.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	77	95	97	97	100	100
Container	13	62	83	88	95	98
Vehicle Carrier	22	88	98	99	100	100
Tanker	46	92	97	99	99	100
Bulker	44	95	99	99	100	100
Cruise	50	92	96	96	100	100

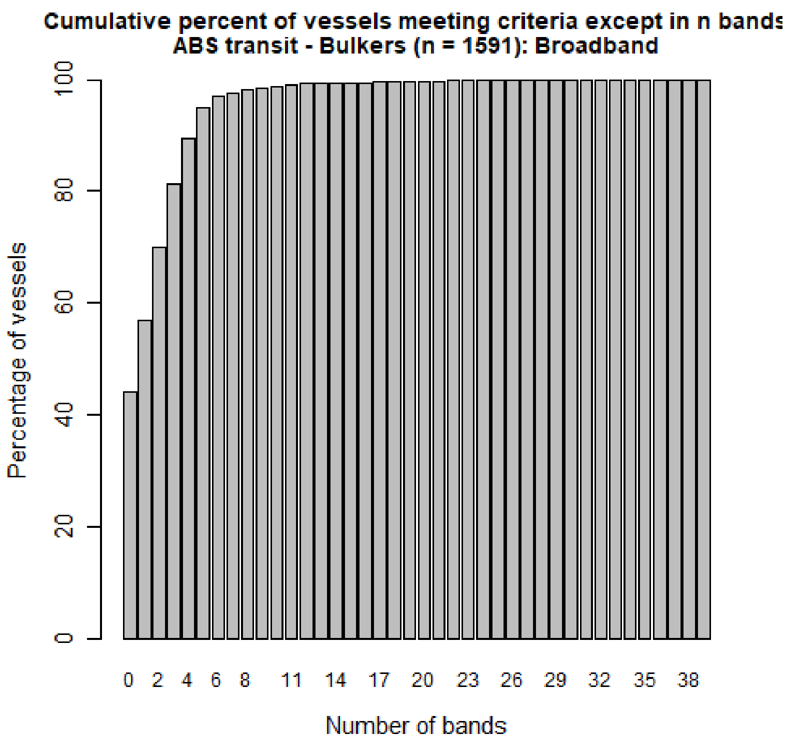


Figure 37. *American Bureau of Shipping (ABS)*: Histogram of the cumulative percentage of bulker compliance in all but the specified number of bands for the transit notation.

6.3.2. Bureau Veritas

Table 6 presents the percentage of vessels in each vessel category meeting the Bureau Veritas (BV) notation standard except in the specified number of frequency bands (for the controlled notation; the advanced standard results are in Appendix A.2). Figure 38 shows the corresponding histogram of the cumulative percentage of bulker compliance. All other vessel categories are in Appendix A.1.

Table 6. *Bureau Veritas (BV)*: Percentage of vessels in each category meeting the controlled notation except in the specified number of frequency bands. Separate threshold per vessel category.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	3	30	45	56	74	92
Container	0	0	2	9	18	27
Vehicle Carrier	0	4	18	39	55	71
Tanker	0	5	21	54	65	72
Bulker	0	4	34	73	84	90
Cruise	0	24	55	72	81	86

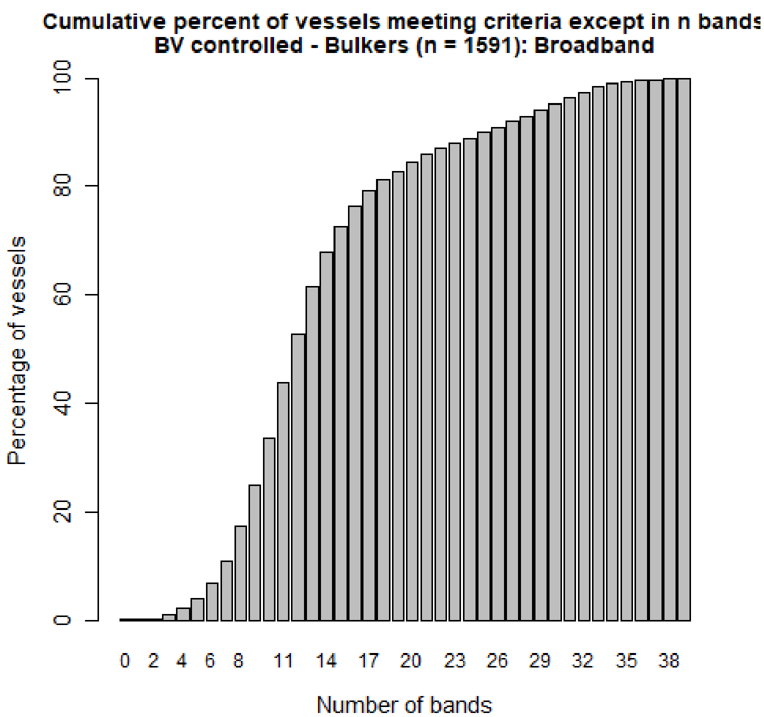


Figure 38. *Bureau Veritas (BV)*: Histogram of the cumulative percentage of bulker compliance in all but the specified number of bands for the controlled notation.

6.3.3. Det Norske Veritas

Table 7 presents the percentage of vessels in each vessel category meeting the Det Norske Veritas (DNV) notation standard except in the specified number of frequency bands (for the transit notation; the quiet standard results are in Appendix A.2). Figure 39 shows the corresponding histogram of the cumulative percentage of bulker compliance. All other vessel categories are in Appendix A.1.

Table 7. *Det Norske Veritas (DNV)*: Percentage of vessels in each category meeting the transit notation except in the specified number of frequency bands.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	34	68	82	91	96	98
Container	1	14	34	50	64	81
Vehicle Carrier	6	45	77	86	94	98
Tanker	6	49	74	88	93	98
Bulker	14	67	90	96	98	99
Cruise	20	72	85	89	93	99

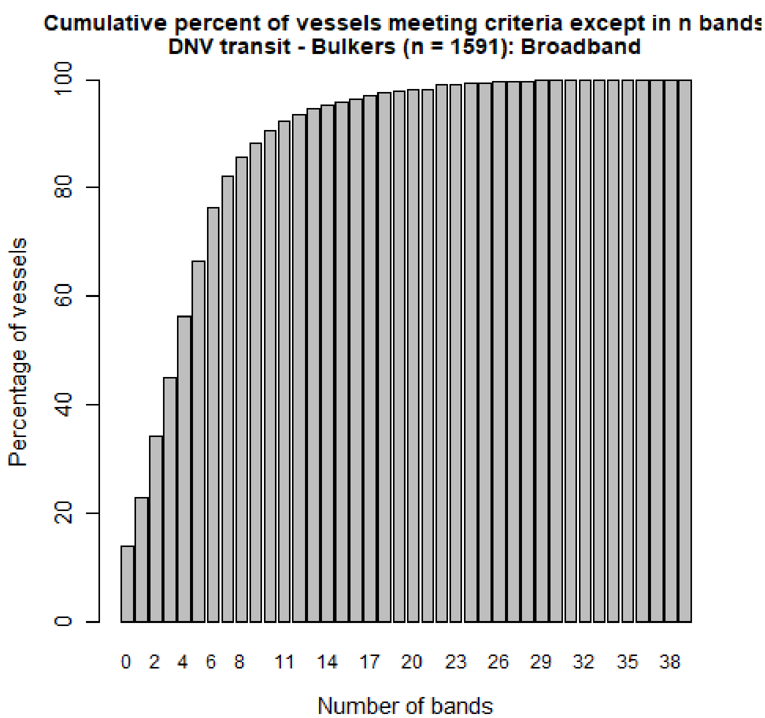


Figure 39. *Det Norske Veritas (DNV)*: Histogram of the cumulative percentage of bulker compliance in all but the specified number of bands for the transit notation.

6.3.4. Lloyd's Register

Table 8 presents the percentage of vessels in each vessel category meeting the Lloyd's Register (LR) notation standard except in the specified number of frequency bands (for the transit notation; the quiet standard results are in Appendix A.2). Figure 40 shows the corresponding histogram of the cumulative percentage of bulker compliance. All other vessel categories are in Appendix A.1.

Table 8. *Lloyd's Register (LR)*: Percentage of vessels in each category meeting the transit notation except in the specified number of frequency bands.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	29	78	90	94	96	99
Container	0	25	56	74	86	95
Vehicle Carrier	4	59	89	95	98	99
Tanker	5	47	86	94	98	99
Bulker	6	58	93	98	99	100
Cruise	26	76	86	93	97	100

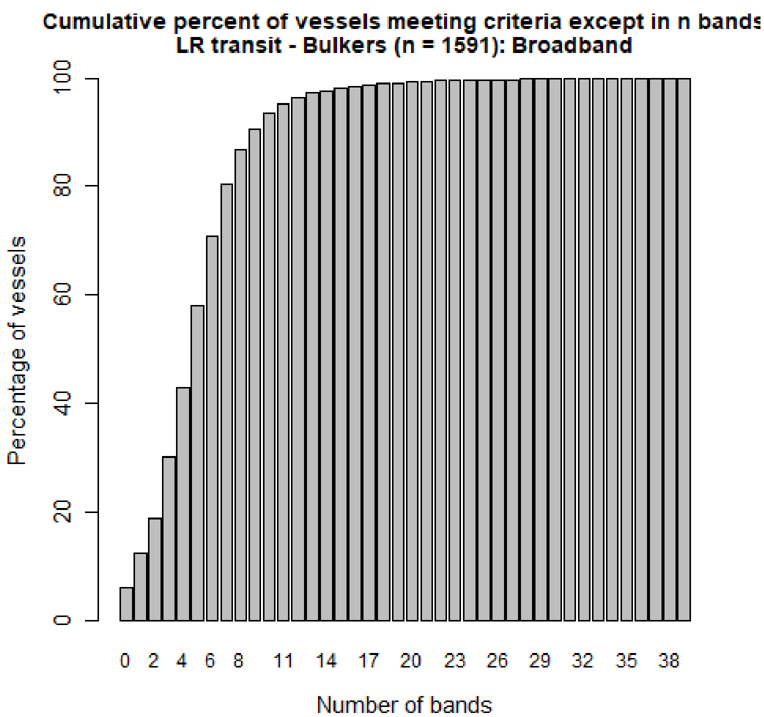


Figure 40. *Lloyd's Registrar (LR)*: Histogram of the cumulative percentage of bulker compliance in all but the specified number of bands for the transit notation.

6.3.5. RINA

Table 9 presents the percentage of vessels in each vessel category meeting the RINA notation standard except in the specified number of frequency bands (for the transit notation; the quiet standard results are in Appendix A.2). Figure 41 shows the corresponding histogram of the cumulative percentage of bulker compliance. All other vessel categories are in Appendix A.1.

Table 9. *RINA* Percentage of vessels in each category meeting the transit notation except in the specified number of frequency bands.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	14	38	52	64	79	93
Container	0	1	8	15	26	38
Vehicle Carrier	0	8	36	53	68	82
Tanker	1	16	48	66	77	86
Bulker	2	30	70	84	90	95
Cruise	1	35	66	80	85	86

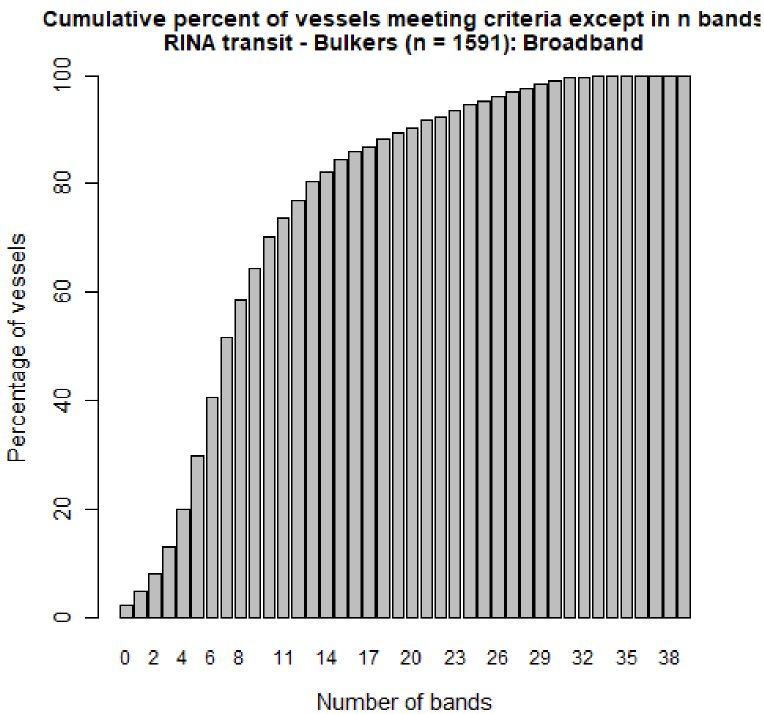


Figure 41. *RINA*: Histogram of the cumulative percentage of bulker compliance in all but the specified number of bands for the transit notation.

6.4. Conservativeness

Section 6 described each notation in terms of its shape and decay over the frequency spectrum. Here we discuss the distributions of ECHO program measurements relative to the maximum noise thresholds of each society's certification thresholds, shown in Figure 42.

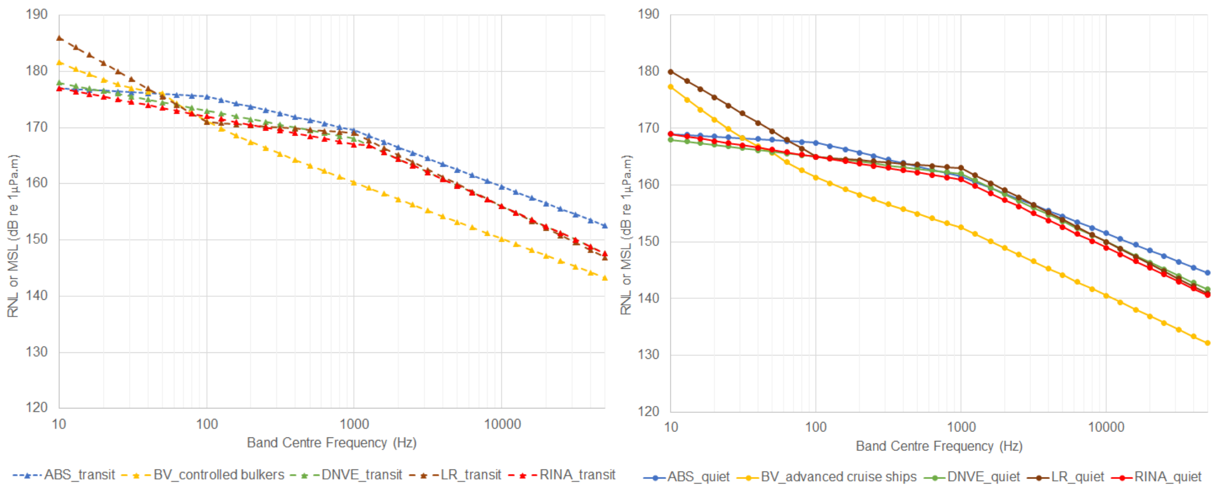


Figure 42. Transit and controlled notations (left) and quiet and advanced notations (right).

Importantly, BV and LR noise emissions criteria are based on MSL, while ABS, DNV, and RINA noise emissions criteria are based on RNL. At higher frequencies, approximately above 1 kHz, RNL approaches MSL plus 3 dB. At lower frequencies MSL is increasingly affected by sea surface reflection interference effects, and its relationship with RNL becomes complex. The end-result is that the BV and LR criteria are less comparable with the ABS, DNV, and RINA criteria at lower frequencies (<1 kHz).

First, when looking at centre frequency bands above 100 Hz (Figure 42), the BV notations are the most conservative, being always 5–10 dB lower than the equivalent notations for the other standards. Even with 3 dB added to compensate for the difference in RNL and MSL, BV has relatively low levels (lower conservativeness). Conversely, below 100Hz, the BV and the LR notations are more stringent than the standards based on the received noise level (for the cruise ship quiet notation this applies only to about 50 Hz); however, the LR notations are slightly higher (between 2.6 and 4.2 dB) in this frequency range.

For the quiet notations, the RNL-based certifications (ABS, DNV, and RINA) present a good match at the very low frequencies (<20 Hz) and between 300 Hz to 6 kHz. After that point and between 20 and 300 Hz, the ABS standard is slightly more conservative than the others[4]. Meanwhile, the LR (MSL-based) transient notation follows these RNL-based notations very well above 100 Hz. Below this frequency, it is the most conservative notation. Therefore, in terms of total number of centre frequencies considered, the ABS standard represents the least stringent, while the RINA notation is the most conservative, not considering BV.

A similar pattern is seen in the transit and controlled notations, except the ABS threshold is higher than all the others in essentially all frequency bands.

This is reflected in the ECHO measurements (Figure 43), which show the notation with the highest number of compliant vessels is ABS (in both transit/controlled and quiet/advanced notations). And the BV notation has the lowest number of compliant vessels. This is also shown in Figure 44, which presents the histograms of the percentage of container ships meeting the ABS and RINA transit notations as an example. These histograms show that approximately 80% of container ships are compliant in all but 10

[4] The ABS URN requires splitting the frequency ranges into three groups and one boundary is between the 50 and 63 Hz centre frequencies.

bands with respect to the ABS transit notation, whereas less than 10% are compliant with respect to the RINA transit notation.

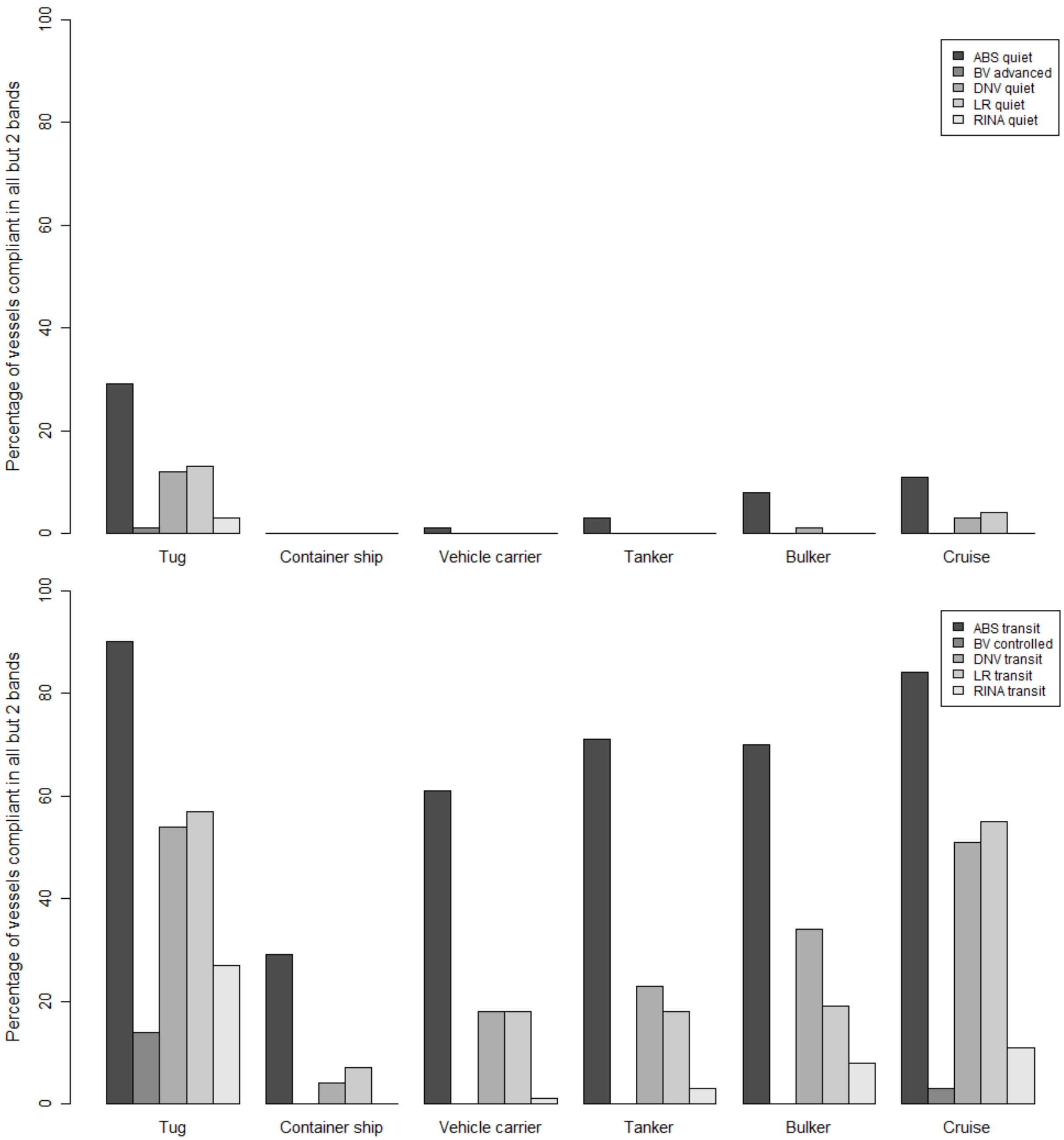


Figure 43. Percentages of compliant vessels in all but 2 frequency bands for the quiet and advanced notations (above) and transit and controlled notations (below).

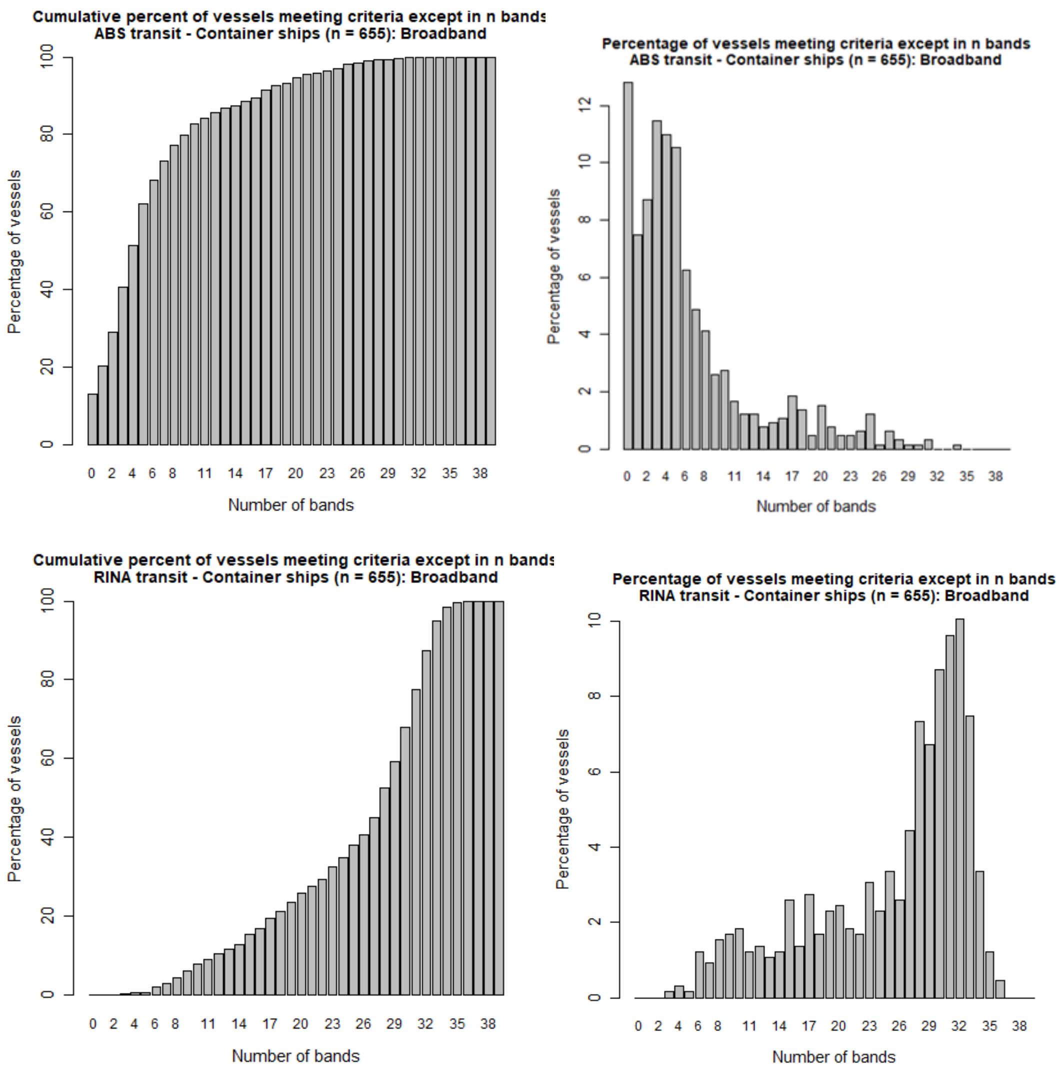


Figure 44. Percentages of container ships meeting the ABS transit notation (above) and RINA transit (below). Cumulative percent plots are on the left and the percentage of vessels being compliant in all but the specified number of bands are on the right.

7. MODELLING NOISE SAVINGS FROM VESSEL CONFORMANCE WITH OPTIMAL THRESHOLDS

7.1. Optimal Certification Thresholds

The goal of the modelling study was to evaluate the reduction of noise levels that would result from implementing mandatory noise limits for commercial vessels in the future. While several approaches to this investigation are possible, this analysis applied the following steps:

1. Define a set of “optimal” thresholds based on a chosen percentile of the 1/3-octave MSL measurements from the ECHO program database (scaled to a reference vessel for each category). The optimal thresholds were then used similarly to the maximum noise levels of each of the certification societies. A decision was made by Transport Canada and JASCO to use the median level in each band of all valid measurements for each vessel category as the “optimal” threshold. These median levels are shown in Figure 45. This approach leads to less than half of present vessels being conformant in all bands, as vessels will have some noisier bands and some quieter bands.
2. Define a participation rate for each vessel category representing what we expect will be the fraction of vessels in the future that will meet the optimal thresholds in all bands. While it would be informative to test multiple participation rates, time constraints for this analysis required choosing just one rate. The chosen participation rate for vessels meeting the optimal thresholds in the future was 90%. The final goal is that all vessels would be required to meet the thresholds, and this was a reason for using a relatively liberal percentile as the “optimal” thresholds. Therefore 90% future participation is quite realistic and should not cause undue concern to industry.
3. Find the reductions in mean MSL in each frequency band for each category, due to 90% of vessels participating at meeting the optimal thresholds. First, the mean MSL in each frequency band was calculated for the current vessel fleets based on the scaled ECHO program dataset (shown in the left panels of Figure 46). To calculate the future case MSLs, we sampled 90% of the scaled ECHO database in each category and lowered 1/3-octave-band MSL of these sampled vessels to the thresholds where those thresholds were exceeded. The reduced-level dataset is shown in the center panels of Figure 46. MSLs for the remaining 10% of the database (right panels of Figure 46), which were not adjusted based on the optimal thresholds, were then appended to the reduced dataset. The mean MSLs of this modified dataset were calculated and subtracted from the original mean MSLs to obtain the mean reductions in each 1/3-octave-band for each category. The reductions in mean levels are shown in Figure 47.

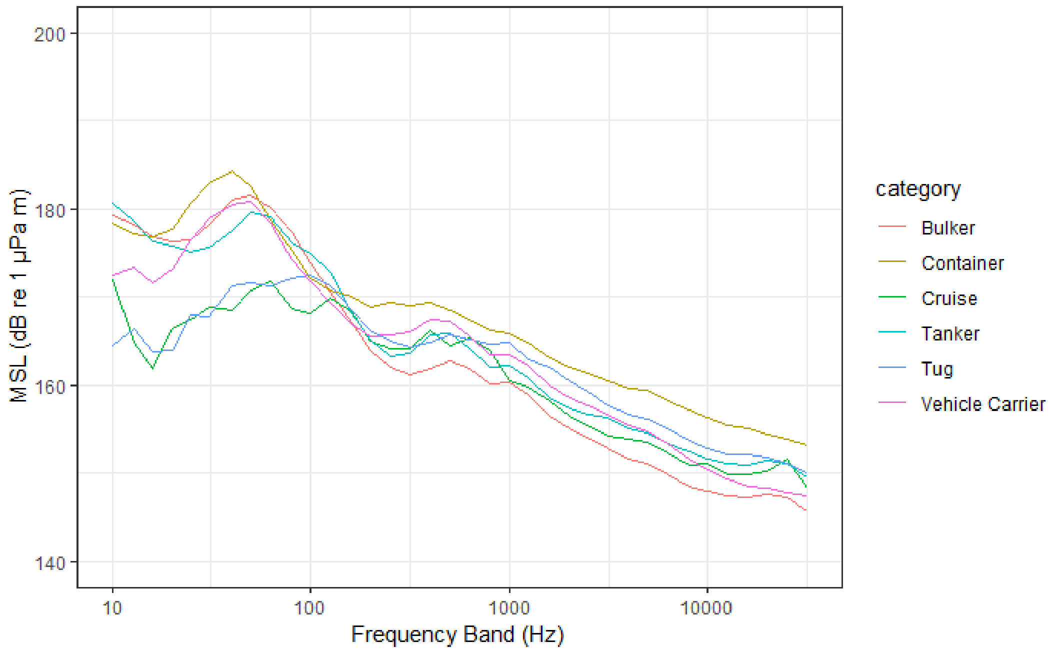


Figure 45. Median monopole source level (MSL) of the scaled ECHO database. These median levels are used as thresholds, in the noise modelling analysis, to be met by 90% of vessels in the future-case scenario.

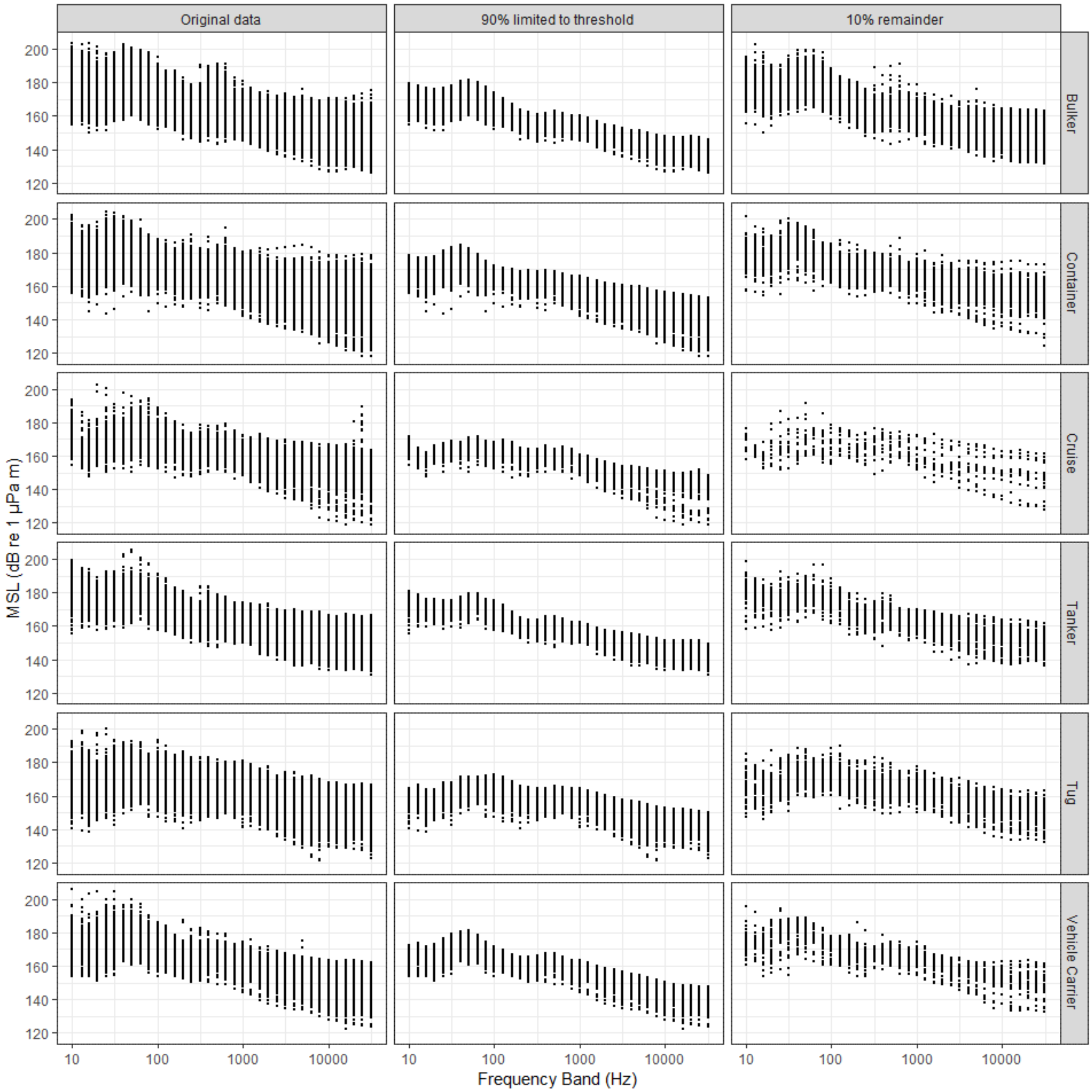


Figure 46. Interim monopole source level (MSL) for the original scaled ECHO database (left column of panels), sample of 90% of measurements with level reductions to median (center column of panels), and the remaining 10% of the original database (right column of panels). The reduced 90% results and the remaining 10% non-reduced results (centre and right columns of panels) were merged to represent the future case distribution.

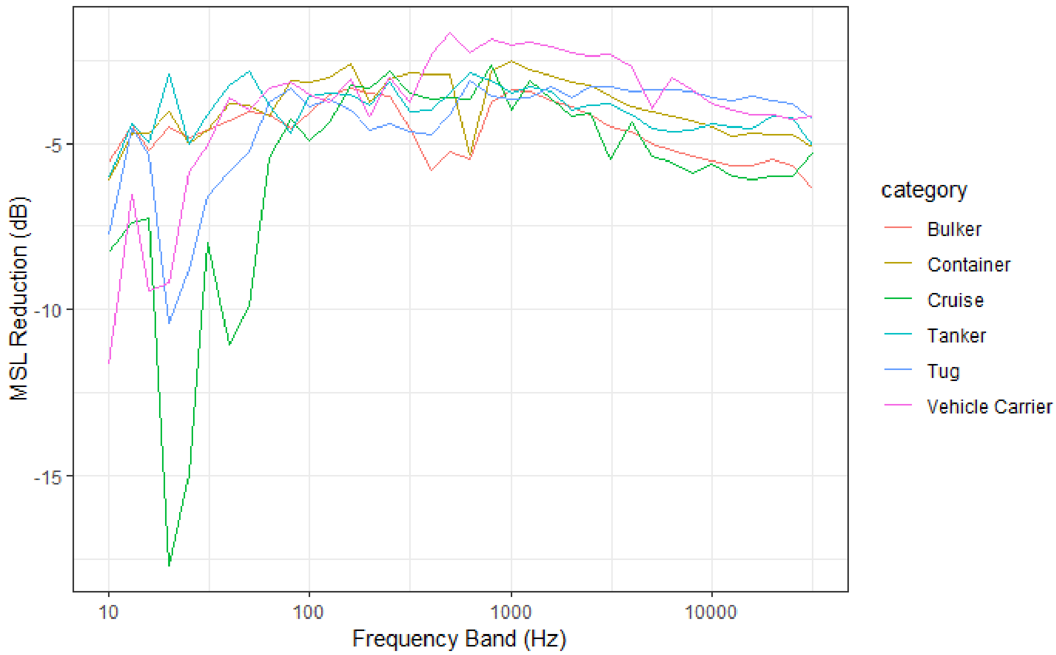


Figure 47. Reductions in mean monopole source level (MSL) produced by 90% of vessels meeting optimal noise emission thresholds based on the median of present vessel MSL.

7.2. Modelling Methods

A shipping noise model (RTM developed by JASCO) was used to calculate monthly averaged noise levels, as well as sound pressure levels (SPL) in 1-minute steps that daily noise distributions were calculated from. The model results of the mitigation approach were compared with baseline results, and the relative effectiveness of this approach was assessed according to the predicted changes in noise levels. When assessing the effectiveness of the mitigation approach, the sound frequencies of the ship noise were considered relative to the ability of killer whales and other marine animals to detect those sounds. Audiogram-weighted levels represent sound levels above an animal's hearing threshold in units of decibels relative to hearing threshold (dB re HT). In this study, results are presented in two formats: as unweighted noise levels and as Southern Resident Killer Whale (SRKW) audiogram-weighted noise levels. Audiogram-weighted equivalent continuous noise levels (L_{eq}) represent the mean noise level perceived by a SRKW over the month of July 2015 – the month that vessel tracking data were available for. It is acknowledged that vessel traffic can vary seasonally, so the results here might not be representative of different time periods. Nevertheless, those changes are likely relatively small for most commercial vessel classes.

The vessel noise model requires inputs that include the nominal vessel noise emission levels (MSL), traffic densities, and transit speeds for each vessel class. It also incorporates oceanographic data including ocean temperature profile, salinity profile, water depth variations, and seabed properties. A large range of sound frequencies (from 10 Hz to 63 kHz) was examined. This frequency range covers most of the frequencies used by killer whales for communicating and echolocating (echolocation clicks can extend weakly to frequencies up to 100 kHz). It is important to assess the frequency-dependence of noise because noise emissions from ships vary substantially across this frequency range. Although most vessel sound energy occurs below 1 kHz, killer whale hearing sensitivity is generally best between 15–30 kHz (Branstetter et al. 2017). Sound propagation in the ocean varies with frequency; lower frequencies tend to propagate with less attenuation (reduction in amplitude with propagation distance) than higher frequencies.

Sound levels were modelled over relatively large regions and tabulated at fixed sample locations in the SRKW key habitat in Haro Strait. At each fixed location we evaluated the changes between baseline and mitigated noise levels. The sample locations are shown in the map of Figure 48, with geographic coordinates listed in Table 10. We also calculated the change in noise levels along a transect that ran perpendicularly across the shipping lanes in mid Haro Strait (blue line in Figure 49). Noise results are presented as maps showing the spatial distribution of monthly equivalent continuous underwater noise levels (L_{eq}). The monthly L_{eq} are calculated similarly to the 8-hour L_{eq} used for human workplace noise assessments but with a much longer averaging time (1 month versus 8 hours). Since L_{eq} is a time average, it does not provide information about noise level variations over time within the averaging period.

Table 10. Noise field sample locations in Haro Strait.

Sample location	Description	Easting/Northing (m), BC Albers Projection		Latitude	Longitude
1	South Haro Strait/ Juan de Fuca	1218680 E	380765 N	48° 24' 06.0100" N	123° 03' 07.7198" W
2	South San Juan	1218303 E	386920 N	48° 27' 26.0500" N	123° 03' 13.5601" W
3	Central South San Juan	1213787 E	390220 N	48° 29' 19.0400" N	123° 06' 46.2100" W
4	Central San Juan	1210304 E	392842 N	48° 30' 48.5900" N	123° 09' 30.2101" W
5	North San Juan/ Henry Island	1207105 E	399437 N	48° 34' 26.4900" N	123° 11' 52.9901" W
6	Stuart Island	1203577 E	409760 N	48° 40' 05.5200" N	123° 14' 25.0598" W
7	Inbound Traffic Lane	1208303 E	392857 N	48° 30' 51.6626" N	123° 11' 07.4354" W
8	Outbound Traffic Lane	1206185 E	392843 N	48° 30' 53.9157" N	123° 12' 50.3791" W

The mitigation scenario randomly sampled 90% of the vessels and reduced their emissions to the certification thresholds. The affected vessel categories were: Container ships, Fishing vessels, Merchant ships, passenger vessels (≥100 m in length), Tankers, Tugs, and Vehicle carriers. Noise levels were then modelled using the same traffic density and speed values as for the projected levels, but with the reduced mean source levels for the affected vessel classes.

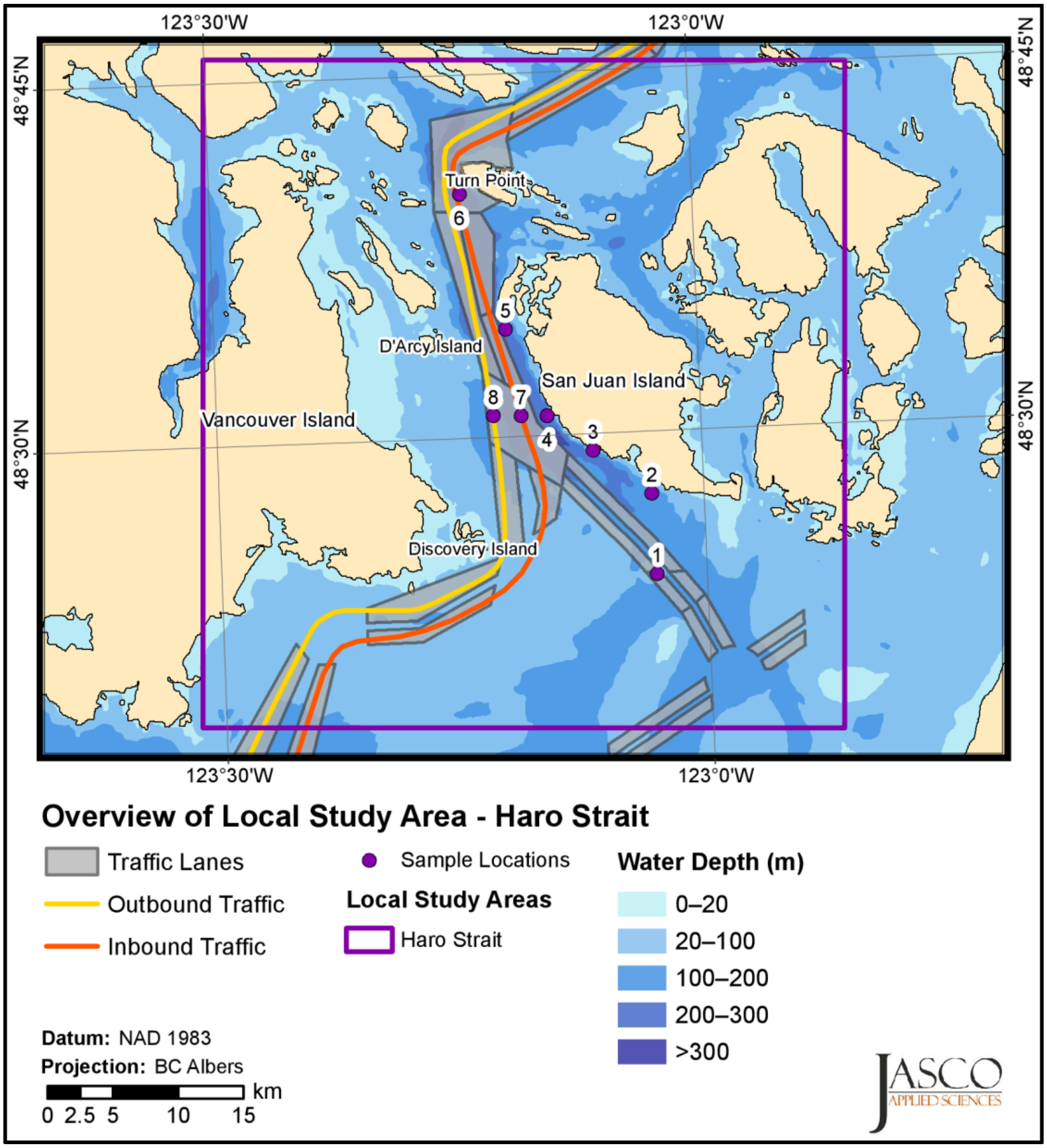


Figure 48. Noise field sample locations on Haro Strait based on the Southern Resident Killer Whale (SRKW) critical habitat, relative to shipping lanes.

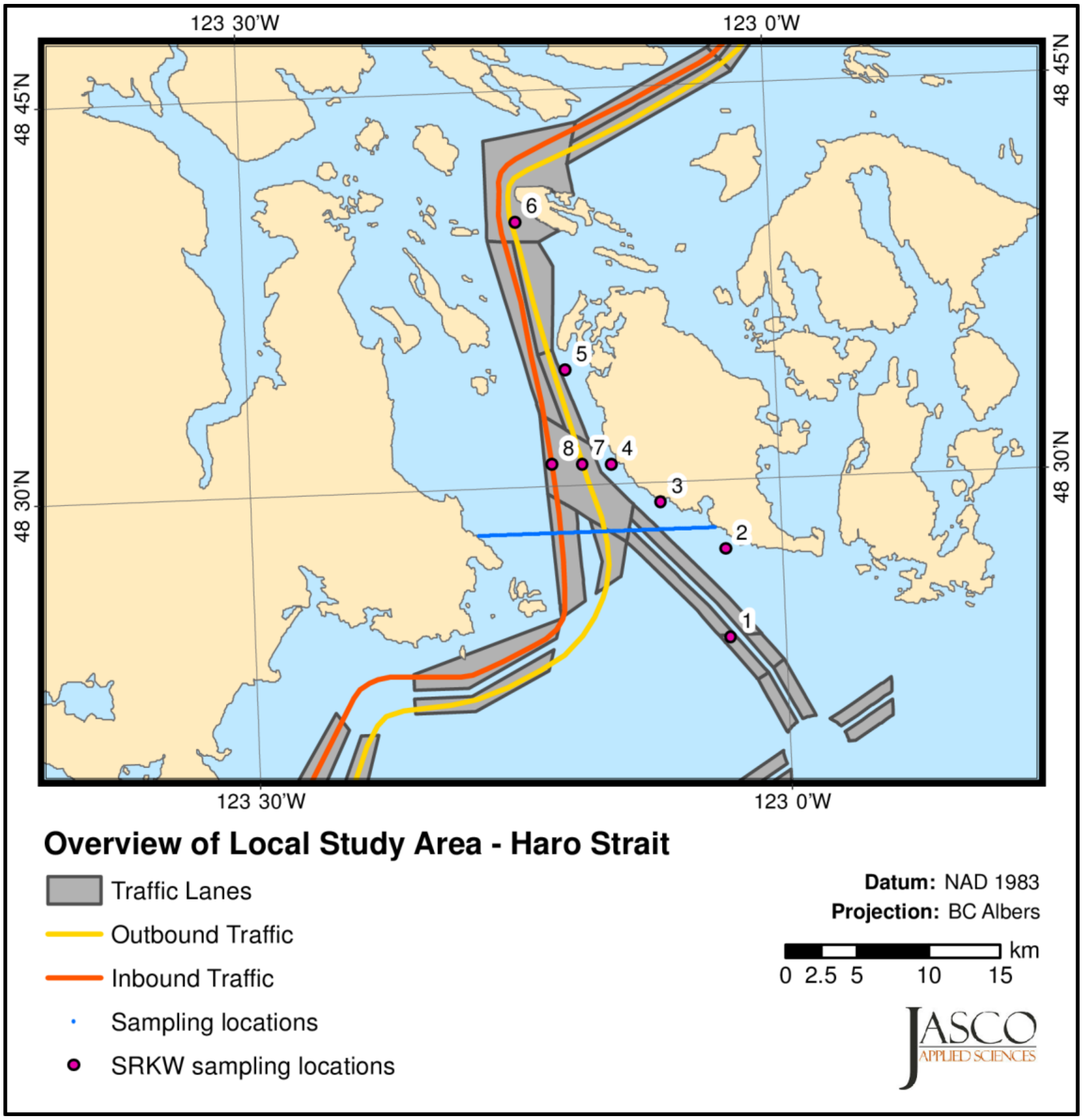


Figure 49. The sampling transect (blue line) is approximately perpendicular to the shipping lanes. Southern Resident Killer Whale (SRKW) sampling locations (red dots) are located in a known feeding area within SRKW critical habitat.

7.3. Noise Savings Results

This section presents equivalent noise levels (L_{eq}, unweighted and SRKW audiogram-weighted) for July 2015 in Haro Strait. Figure 50 present the L_{eq} of baseline unweighted and SRKW audiogram weighted noise levels. Figures 51, and 52 present maps of (left) L_{eq} and (right) change in L_{eq} relative to baseline levels. Table 11 present L_{eq} for the baseline and mitigated scenarios at the eight sample locations in the SRKW critical habitat.

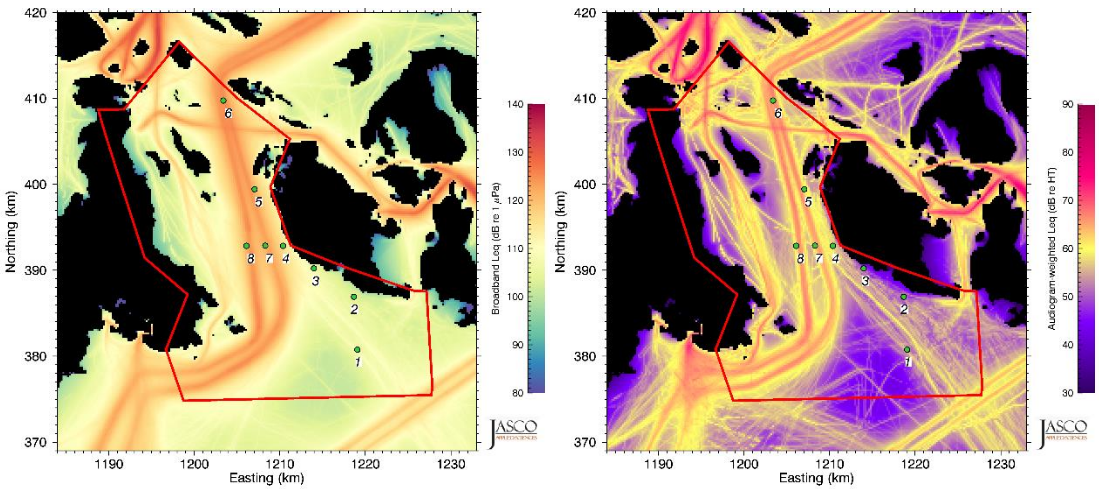


Figure 50. *Baseline*: Unweighted (left) and audiogram-weighted (right) equivalent continuous noise levels (L_{eq}) over Haro Strait. Grid resolution is 200 × 200 m. The green dots are located at the sample locations in the SRKW critical habitat. The red line outlines the boundary of area over which the noise statistics presented in Table 12 were derived.

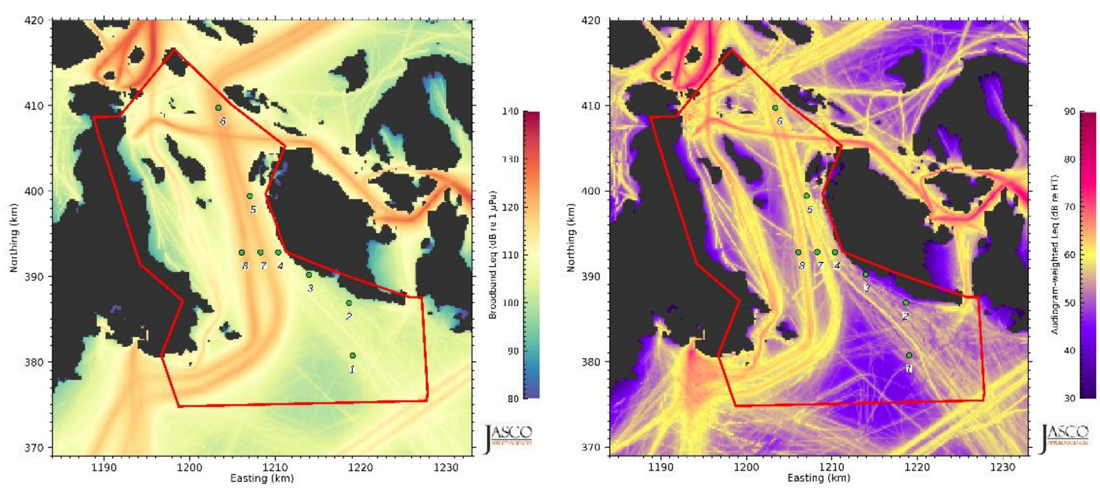


Figure 51. *Mitigated*: Unweighted (left) and audiogram-weighted (right) equivalent continuous noise levels (L_{eq}) over Haro Strait. Grid resolution is 200 × 200 m. The green dots are the sample locations in the SRKW critical habitat. The red line outlines the boundary of area over which the noise statistics presented in Table 12 were derived.

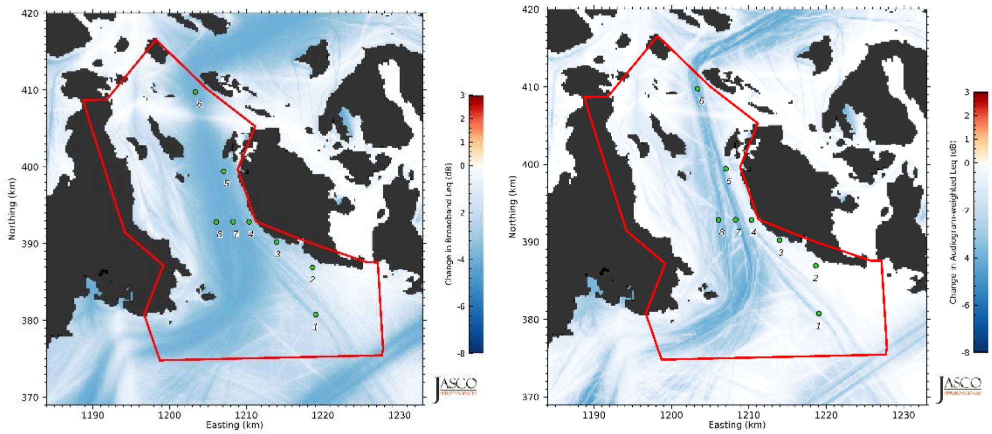


Figure 52. Changes in L_{eq} (dB) relative to July 2015 baseline levels, unweighted (left) and audiogram-weighted (right) in Haro Strait. Grid resolution is 200 × 200 m. The green dots are the sample locations in the SRKW critical habitat. The red line outlines the boundary of area over which the noise statistics presented in Table 12 were derived.

Table 11. Baseline versus mitigated received levels (dB re 1 µPa), changes in received levels (dB), and corresponding changes in acoustic intensity (%) at eight sample locations in the Southern Resident Killer Whale (SRKW) critical habitat.

Sample location	Unweighted				Audiogram-weighted			
	Baseline	Mitigated	Change in received level		Baseline	Mitigated	Change in received level	
			dB	%			dB	%
1	109.2	106.7	−2.5	−43.8	56.2	54.7	−1.5	−29.2
2	103.9	102.6	−1.3	−25.9	51.6	51.5	−0.1	−2.3
3	106.5	103.5	−3	−49.9	46.9	45.9	−1	−20.6
4	114.3	110.9	−3.4	−54.3	56.3	55.6	−0.7	−14.9
5	119.0	115.4	−3.6	−56.3	60.8	60.3	−0.5	−10.9
6	123.4	119.6	−3.8	−58.3	64.6	61.9	−2.7	−46.3
7	122.9	119.1	−3.8	−58.3	65.2	61.3	−3.9	−59.3
8	123.5	119.7	−3.8	−58.3	66.2	63.1	−3.1	−51.0

Table 12. Percentiles, extremes, and mean values for changes in noise levels (dB) and acoustic intensity (%) relative to baseline levels, across the specified region, for each time-averaged (monthly) scenario.

Scenario	Change in noise level statistics (dB)							
	Min	5th	25th	50th	75th	95th	Max	Mean
Unweighted	−4.01 (−60.2%)	−3.91 (−59.3%)	−3.48 (−55.2%)	−2.31 (−41.3%)	−1.36 (−26.9%)	−0.28 (−6.2%)	0.00 (0.0%)	−2.32 (−41.4%)
Weighted	−4.60 (−65.4%)	−3.49 (−55.2%)	−2.01 (−37.0%)	−0.78 (−16.5%)	−0.22 (−4.9%)	−0.02 (−0.5%)	0.00 (0.0%)	−1.20 (−24.1%)

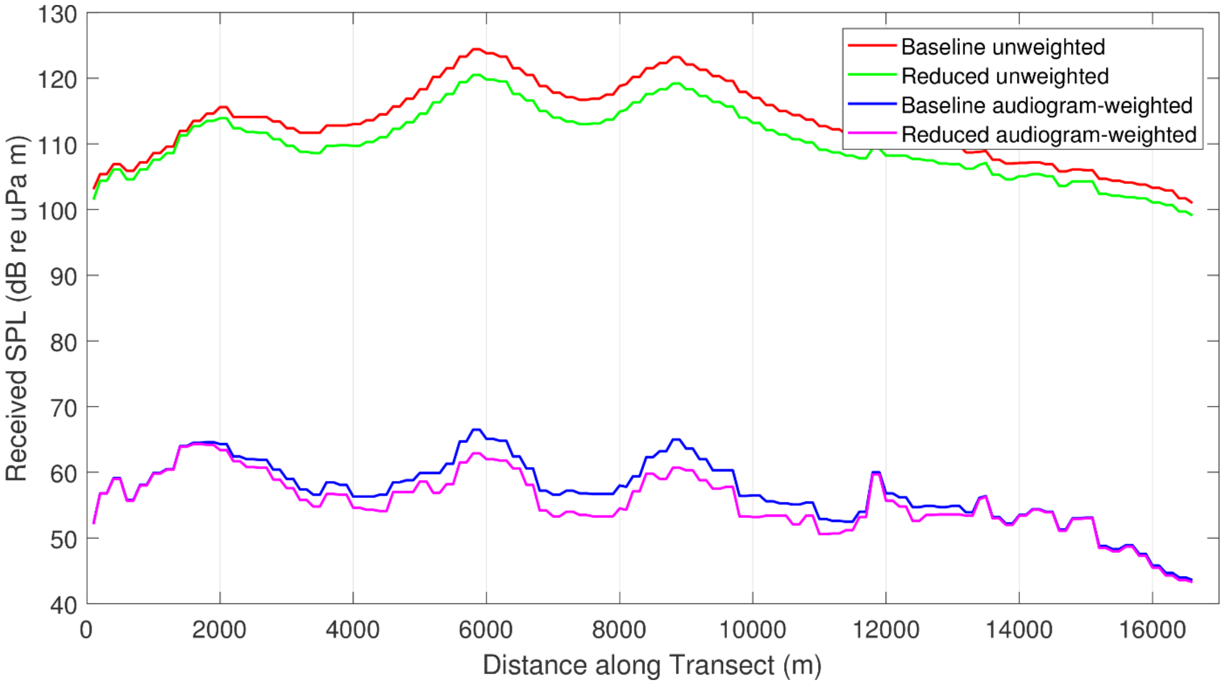


Figure 53. Received noise levels from west to east along the transect perpendicular to the vessel traffic lanes in Haro Strait. The outbound and inbound shipping lanes are centred approximately at 6000 m and 8800 m along the transect. These shipping lanes cause the peaks in sound levels at those locations.

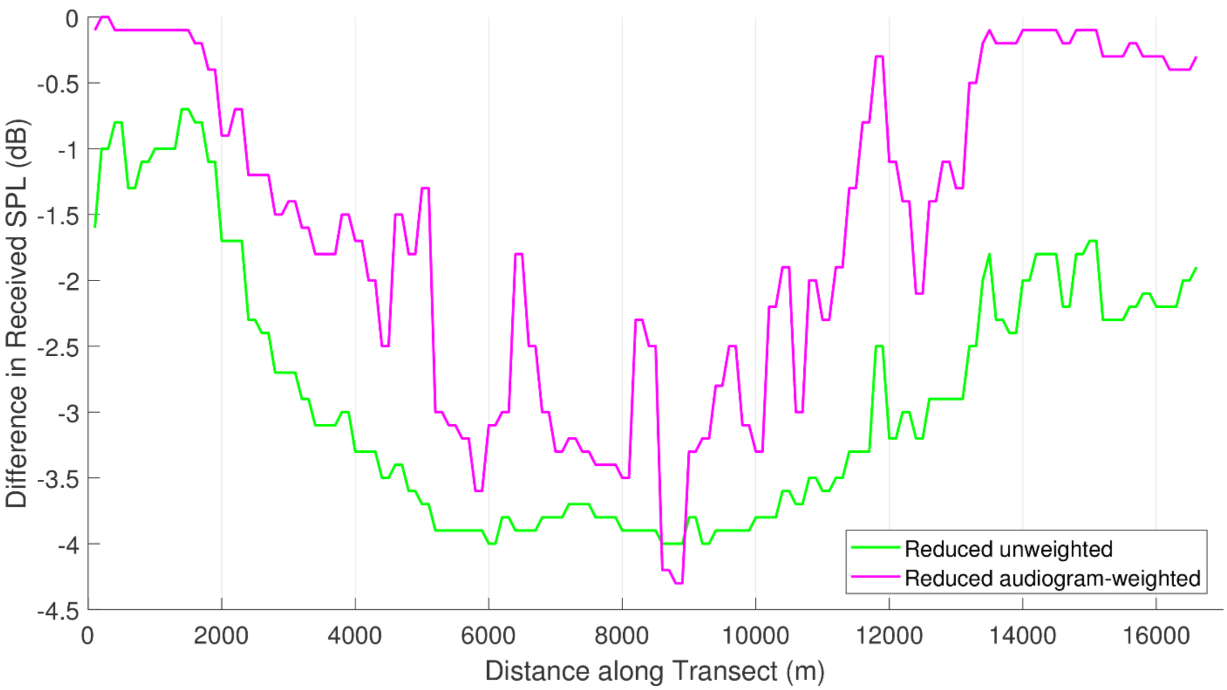


Figure 54. Change in L_{eq} with respect to baseline levels from west to east along the transect perpendicular to vessel traffic lanes in Haro Strait.

8. DISCUSSION

This report describes a sequence of related studies based on the large database of several thousand systematic commercial ship noise measurements acquired between September 2015 and April 2017 by the Vancouver Fraser Port Authority's ECHO program. The ECHO database is described in Section 2.

The initial study performed a multi-variate linear regression of the ECHO database's vessel noise measurements against several parameters that describe each measured ship and its and measurement conditions. The purpose of this analysis, described in Section 3 of this report, was to develop a method to scale the vessel noise measurements to account for differences between individual ships (e.g. of different sizes) and under different measurement conditions (e.g. a ship's speed during its measurement). The regression analysis produced a powerful vessel noise model that can predict 1/3-octave band monopole source levels (MSL) and radiated noise levels (RNL) from input parameters including: ship category, ship length, ship dead-weight-tonnage (DWT), ship static draught, effective wind speed magnitude and direction, ship speed, and surface angle. The resulting vessel noise model is likely the best available presently, worldwide. It is already very useful for understanding noise emissions variations with ship characteristics and operating conditions. The model was able to predict more than 70% of the variance observed in the MSL and RNL measurements for container ships. Its predictive power was less for other categories but still good. Nevertheless, considerable variance remains for some classes that cannot be explained by the present model. Evaluations by ECHO are underway to examine additional covariates to improve the explanatory power of the vessel noise model.

The second analysis of this project involved using the vessel noise model to scale the ECHO database measurements to account for differences in vessel characteristics within each category. This analysis is described in Section 4. The categories considered included container ships, bulkers, tankers, vehicle carriers, cruise ships and tugs. The model also accounted for differences in measurement conditions, including transit speed, static draught and wind conditions. The purpose of scaling the ECHO measurements was to create a modified dataset that could be compared in a systematic way against vessel noise certification society noise limit thresholds. All ECHO measurements for each vessel category were scaled to a set of reference characteristics, based on the average characteristics for the category, and to a set of reference operating conditions also based on average conditions across the measurements for the category. These scaled results are useful as nominal category-dependent noise emission levels. The model's scaling ability is also important as a key component of vessel noise ranking systems, such as implemented in the vessel measurement and ranking system used by the ECHO program.

The third analyses of this project compared the scaled ECHO measurements with the noise emission thresholds of five vessel certification societies. The societies considered here included:

- Det Norske Veritas: *Rules for Classification of Ships*. Part 6 Chapter 24. Newbuildings Special Equipment and Systems – Additional Class, Silent Class Notation (2010)
- Bureau Veritas: *Underwater Radiated Noise (URN)*. Rule Note NR 614 DT R00 E (2014)
- American Bureau of Shipping: *Guide for the Classification Notation: Underwater Noise* (2018)
- RINA: *Rules for the Classification of Ships: Amendments to Part F. Additional Class Notations. Introduction of the new additional class notations "dolphin quiet" and "dolphin transit"* (2016)
- Lloyd's Register: *ShipRight Design and Construction: Additional Design Procedures. Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise* (2018)

The scaled ECHO measurements were adjusted, as described in Section 5, to account for differences in measurement methods prescribed by each of these certification societies. The scaled and adjusted measurements were then compared in Section 6 with the certification society thresholds. It was found that the certification systems using MSL had better matches with these measurement data than the approaches using RNL. That is primarily because RNL measurements experience surface-reflection interference that reduces low-frequency sound levels, and none of the RNL-based thresholds properly accounts for that interference. MSL measurements on the other hand inherently account for reflection interference, so that metric has a more consistent trend through low frequencies.

The conservativeness of the certification society thresholds was found to vary with vessel category. Container ships produce the highest noise levels on average and their conformance was lowest for all societies. Only 13 percent of container ships fully conformed with the least conservative society thresholds. None of the container ships conformed with the most conservative society thresholds. Other vessel categories faired better but the lack of category-dependent thresholds led to substantial differences in conservativeness of the certifications across vessel categories.

While the classification society measurement methods were found to be well-designed, their lack of harmonization precludes direct comparisons of the measurements between the societies. Therefore, measurements obtained using the protocol of one society are generally not comparable with measurements of a different society or of ANSI S12.64. It is also not possible to apply the certification thresholds of one society with measurements obtained using the methods of another society.

None of the certification societies accounts for differences of vessels within a vessel category. Therefore, small ships are currently evaluated against the same thresholds as large ships. The scaling system developed using the ECHO dataset could be used to scale measurements (or thresholds) to account for different vessel sizes and operating conditions.

The final study of this project, described in Section 7, defined a set of “optimal” thresholds similar to those of the certification societies but with vessel category-dependent thresholds. The goal was to evaluate noise reductions that could be achieved in a real ocean environment by having a large fraction of vessels participate at meeting the optimal thresholds. The study used the medians of the scaled ECHO MSL measurements in each vessel category to define the 1/3-octave band optimal thresholds. We evaluated the noise savings that would occur near shipping lanes in Haro Strait, British Columbia, if 90% of commercial shipping traffic conformed with certification based on the optimal thresholds. While this participation rate is relatively high, the thresholds themselves are not aggressive and are easily attainable by new vessel construction using standard quiet engineering methods. In fact, almost half of existing vessels would already be conformant. A real-time ship noise model calculated noise levels at multiple receiver stations in Haro Strait, and along a track-line perpendicular to the commercial vessel lanes in the strait. The model used speed-scaled MSL in each class to calculate noise levels at all stations and along the track for all commercial vessel transit paths logged in Automatic Identification System (AIS) records for Haro Strait from the month of July 2015. The model was re-run using modified vessel MSL calculated with 90% of vessels in each class meeting the optimal thresholds. Noise savings were calculated simply by subtracting the mean mitigated noise levels from the baseline (unmitigated) noise levels. This study found that broadband monthly mean noise level savings at the key SRKW sites ranged from 1.3 to 3.8 dB, depending on location. We also calculated noise levels weighted according to the frequency-dependent hearing sensitivity (audiograms) of killer whales. The reductions of audiogram-weighted levels were 0.1 to 3.9 dB. More distant stations experienced less reductions in audiogram-weighted levels because the higher-frequency ship sounds, that are emphasized by killer whale audiogram weighting, propagate less well than lower-frequency sounds. The analysis of sound level along a track perpendicular to the shipping lanes found that mean unweighted noise levels were at least 3 dB lower over 10 km swath centred approximately between shipping lanes (themselves separated by 2.8 km). Mitigated killer whale audiogram-weighted levels were at least 3 dB lower than baseline levels over a swath about 5 km wide, also centred between the lanes. These results indicate that even a fairly non-aggressive noise certification approach for vessels could result in important noise savings near shipping lanes. That is largely attributed to the identification and exclusion of the noisiest existing vessels. More aggressive thresholds might be implemented later, resulting in further noise savings.

As a final note related to the last study of this project: Transport Canada has commissioned a vessel noise measurement system to be installed in Boundary Pass, just north of Haro Strait. This system is already capable of measuring the noise emissions of vessels and it can identify vessels with noise emissions much above the medians within their respective vessel categories. Many of these vessels visit Vancouver regularly. There might be opportunities to notify their owners to request they address significant noise issues before their next visit. If that were required, noise exposure savings similar to those modelled here could be achieved.

BIBLIOGRAPHY

[ABS] American Bureau of Shipping. 2018. *Guide for the Classification Notation: Underwater Noise*. Houston, TX, USA.

ANSI/ASA S12.64/Part 1. 2009. *American National Standard Quantities and Procedures for Description and Measurement of Underwater Sound from Ships Part 1: General Requirements*. American National Standards Institute and Acoustical Society of America, New York.

Branstetter, B.K., J. St. Leger, D. Acton, J. Stewart, D. Houser, J.J. Finneran, and K. Jenkins. 2017. Killer whale (*Orcinus orca*) behavioral audiograms. *Journal of the Acoustical Society of America* 141(4): 2387-2398. https://doi.org/10.1121/1.4979116.

Bureau Veritas. 2014. *Underwater Radiated Noise (URN)*. Rule Note NR 614 DT R00 E. Bureau Veritas, Marine & Offshore Division, Cedex, France.

Det Norske Veritas AS. 2010. *Rules for Classification of Ships*. Part 6 Chapter 24. Newbuildings Special Equipment and Systems – Additional Class, Silent Class Notation. Amended July 2011.

Lewis, E.V. 1988. *Principles of Naval Architecture*, Volume 1: Stability and Strength. The Society of Naval Architects and Marine Engineers, Jersey City.

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

R: A language and environment for statistical computing. 3.5.1. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

RINA. 2016. *Rules for the Classification of Ships: Amendments to Part F. Additional Class Notations. Introduction of the new additional class notations "dolphin quiet" and "dolphin transit"*. Genova, Italy.

Ross, D. 1976. *Mechanics of Underwater Noise*. Pergamon Press, New York.

APPENDIX A. ADDITIONAL COMPARISONS OF MEASUREMENT DATA AND CERTIFICATION SOCIETY LIMITS

A.1. Cumulative Percentage Histograms for Transit or Controlled Certification Thresholds

Figures A-1 to A-5 show the histograms of the cumulative percentage of vessel compliance except in the specified number of bands for each of the transit or controlled notations.

A.1.1. American Bureau of Shipping

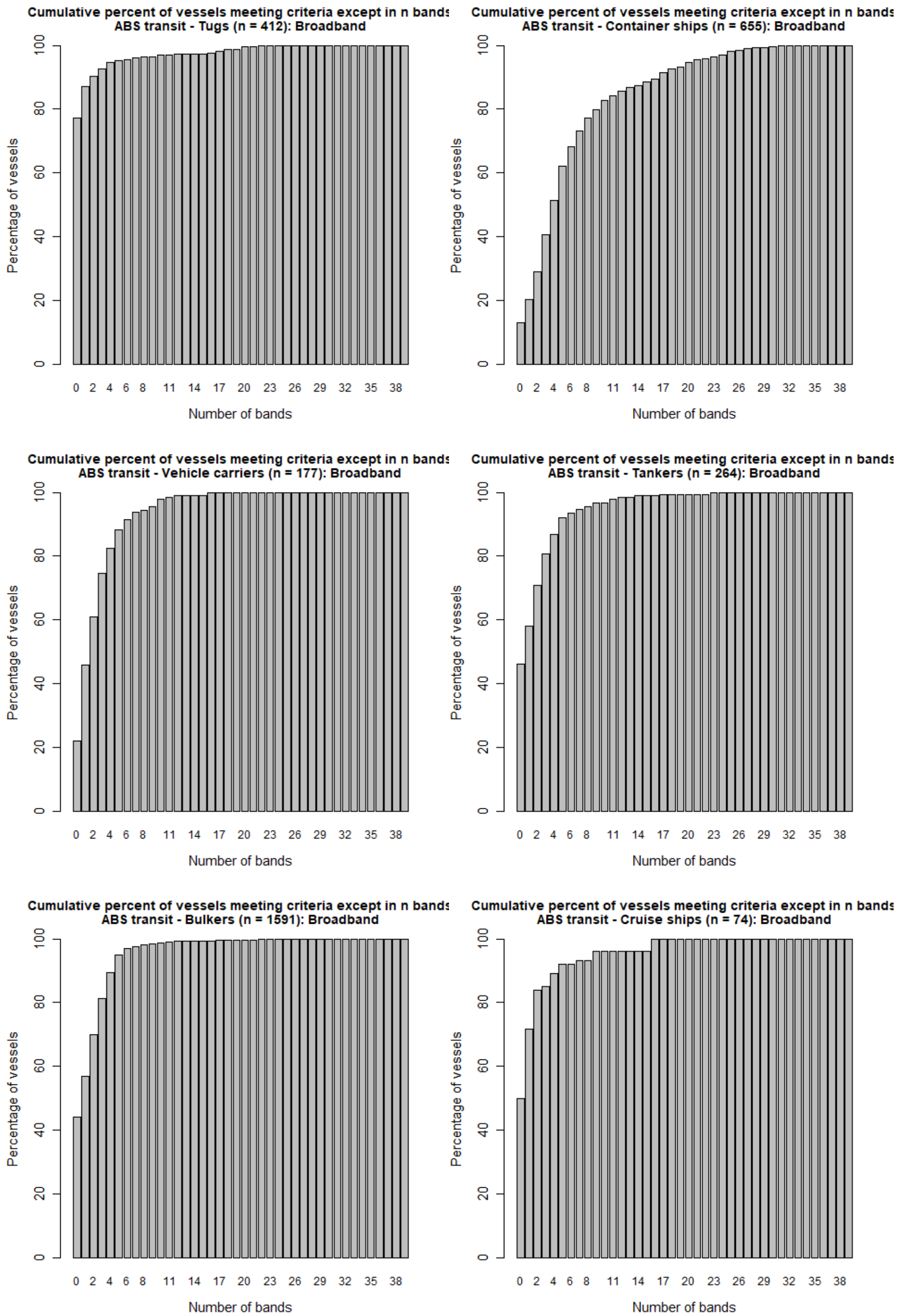


Figure A-1. *American Bureau of Shipping (ABS)*: Histograms of the cumulative percentage of vessel compliance in all but the specified number of bands for the transit notation for each vessel category.

A.1.2. Bureau Veritas

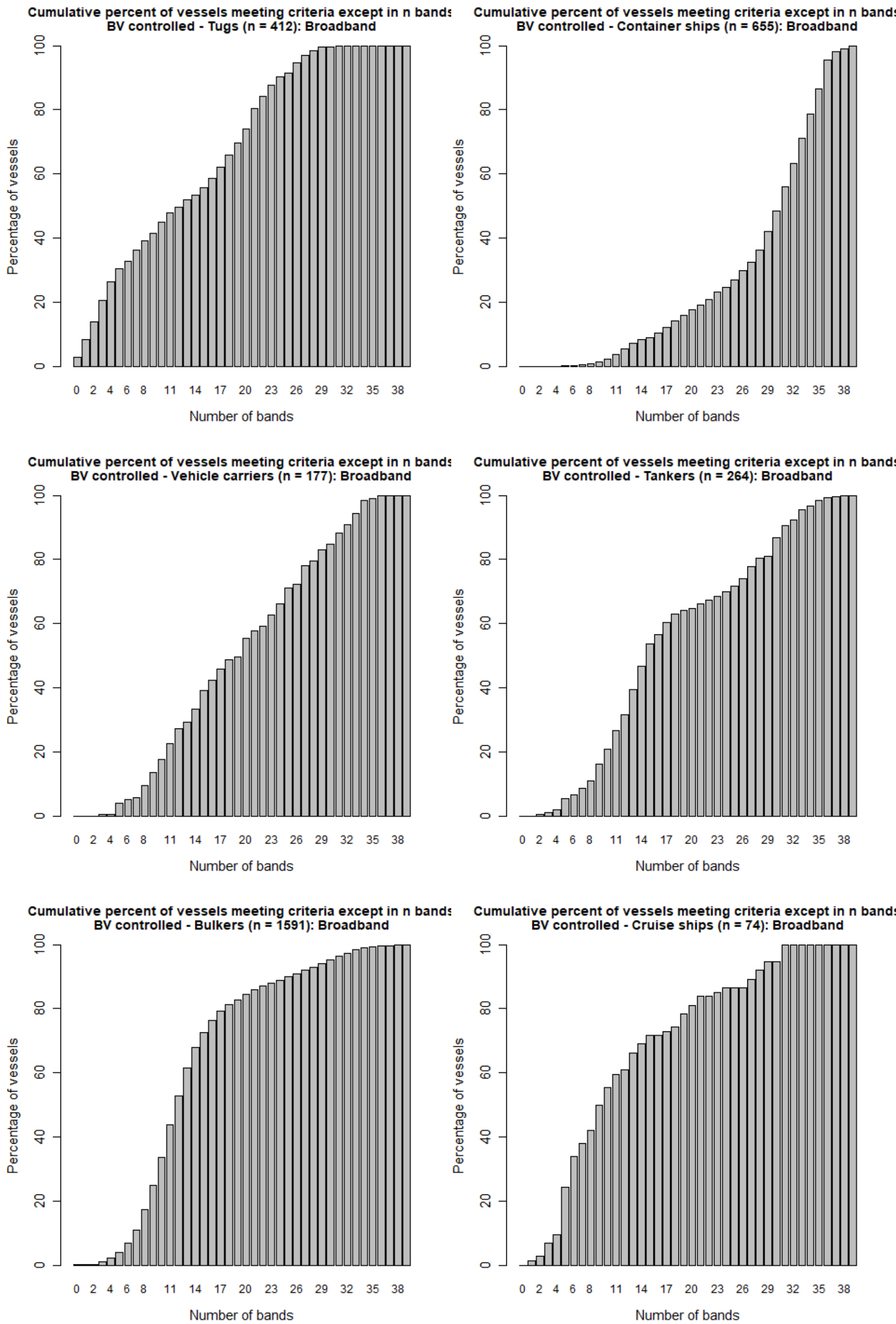


Figure A-2. *Bureau Veritas (BV)*: Histograms of the cumulative percentage of vessel compliance in all the specified number of bands for the controlled notation for each vessel category.

A.1.3. Det Norske Veritas

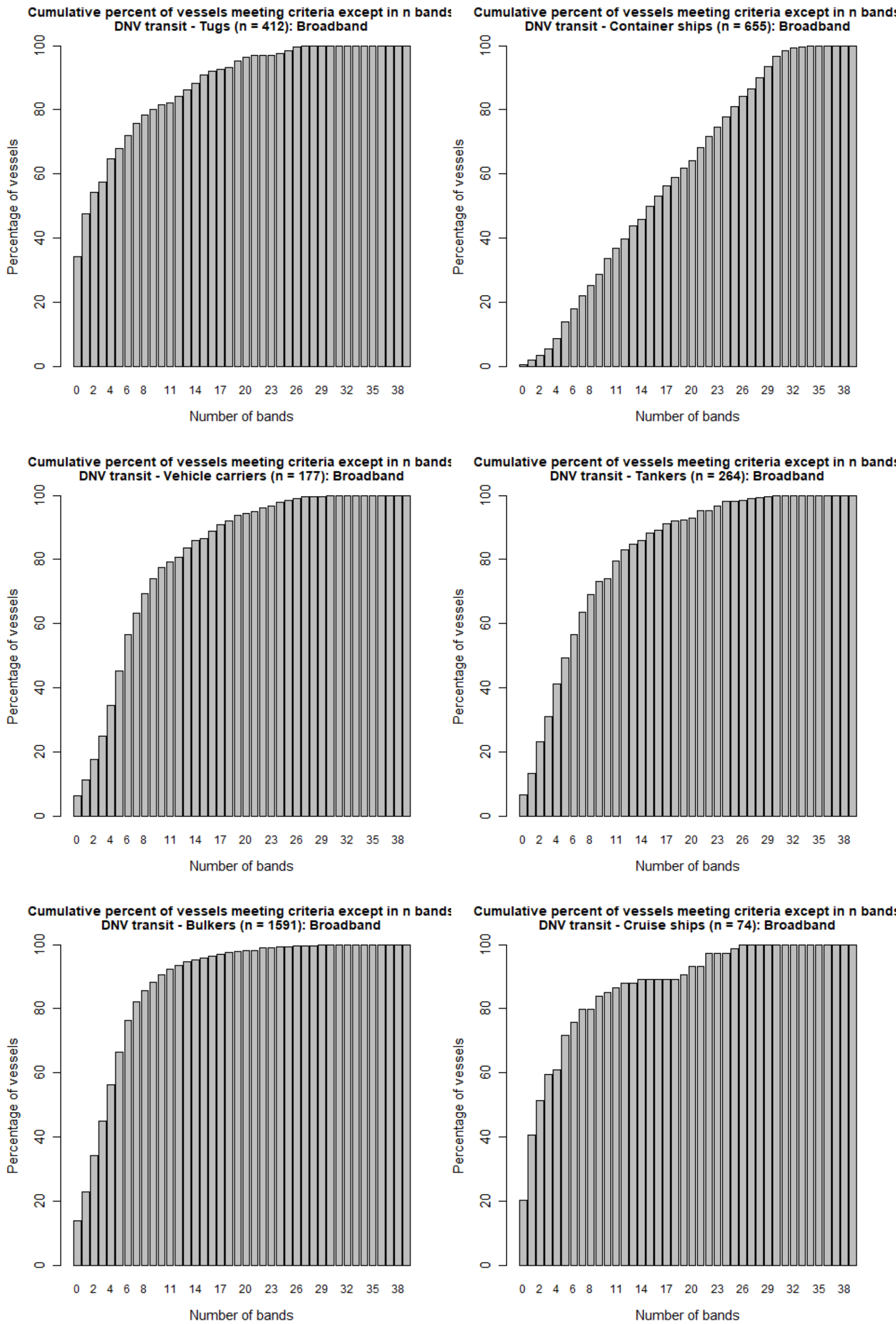


Figure A-3. *Det Norske Veritas (DNV)*: Histograms of the cumulative percentage of vessel compliance in all the specified number of bands for the transit notation for each vessel category.

A.1.4. Lloyd's Register

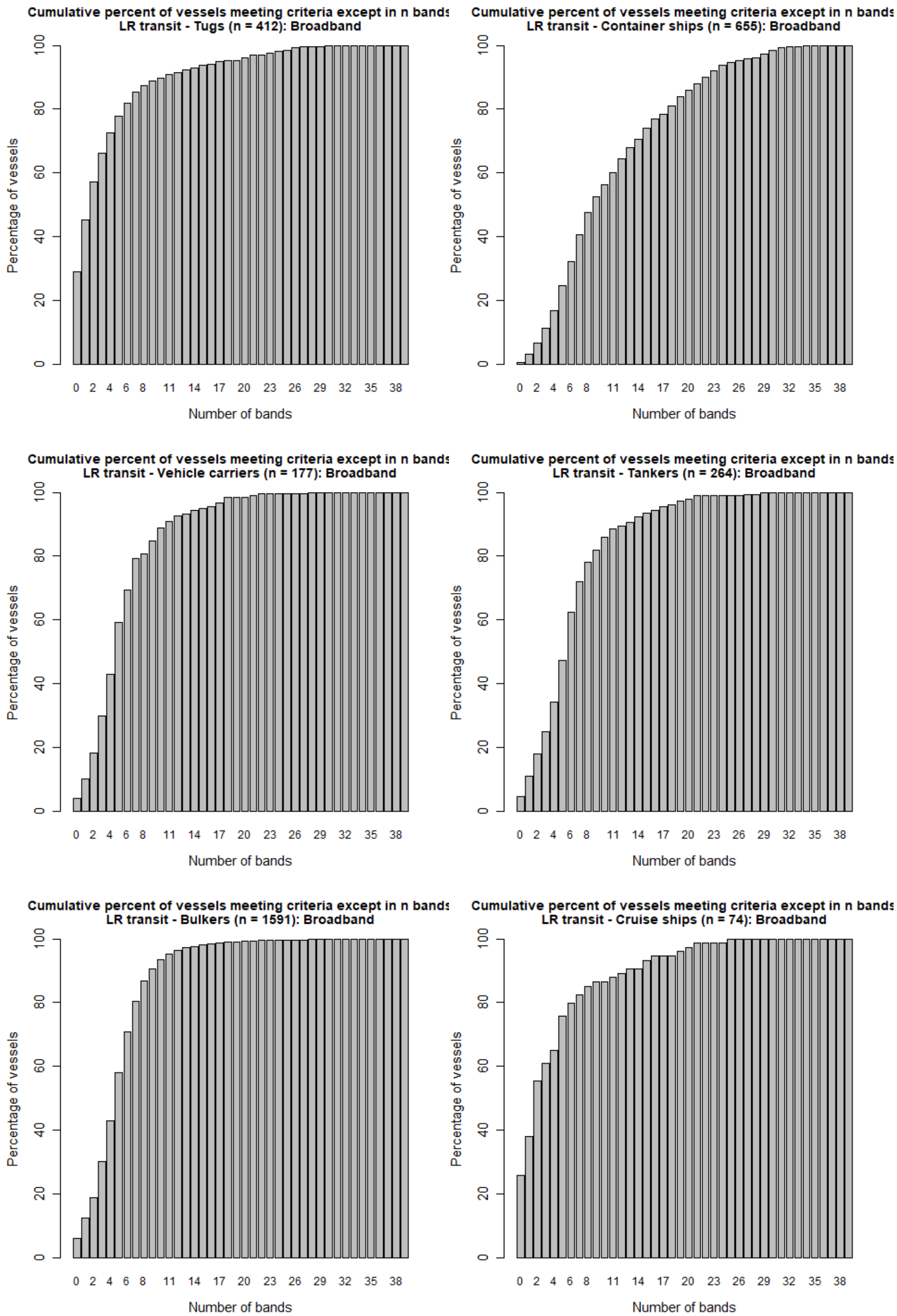


Figure A-4. *Lloyd's Register (LR)*: Histograms of the cumulative percentage of vessel compliance in all the specified number of bands for the transit notation for each vessel category.

A.1.5. RINA

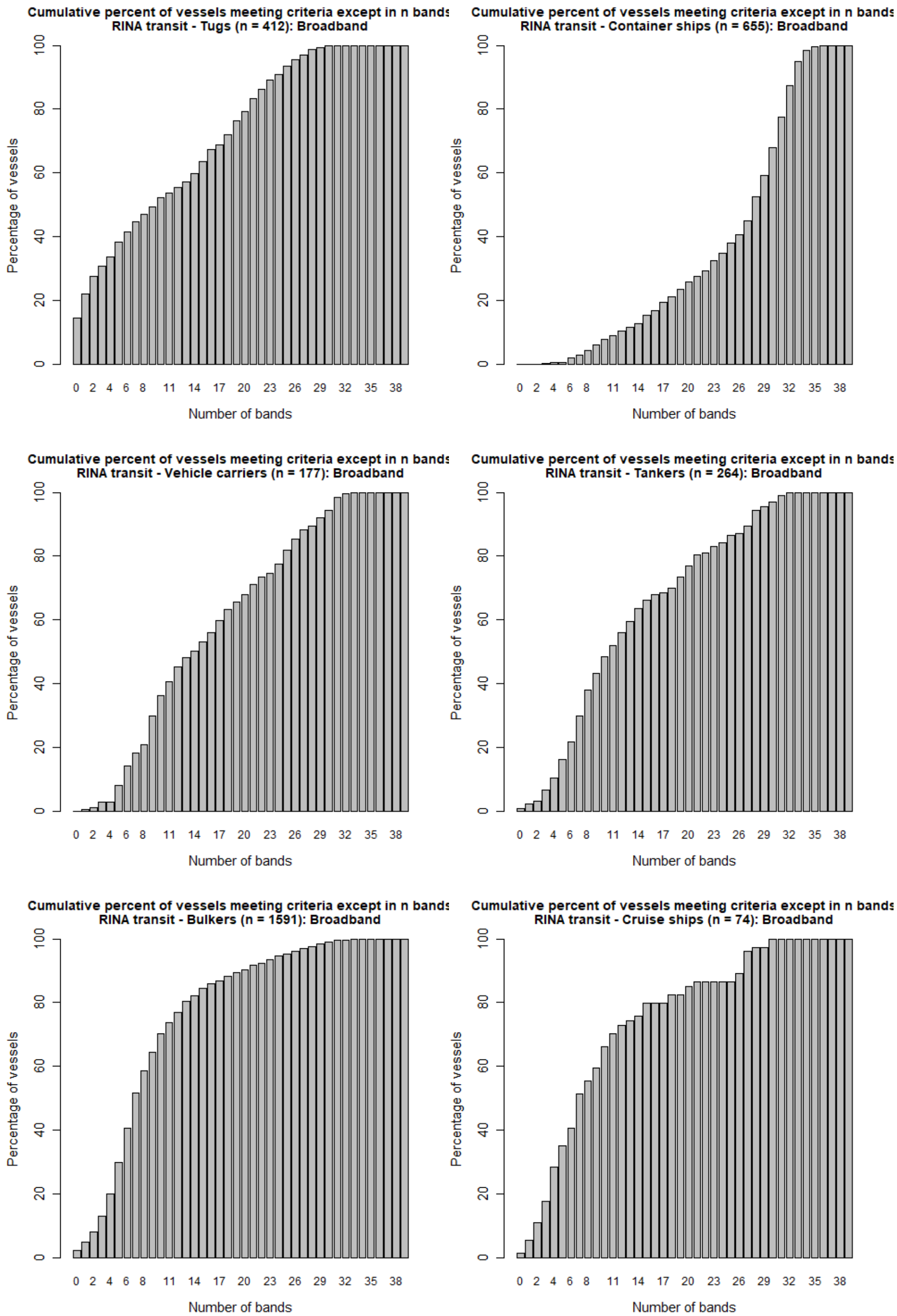


Figure A-5. *RINA*: Histograms of the cumulative percentage of vessel compliance in all the specified number of bands for the transit notation for each vessel category.

A.2. Quiet or Advanced Certification Threshold Results

A.2.1. American Bureau of Shipping

Table A-1 presents the percentage of vessels in each vessel category meeting the American Bureau of Shipping (ABS) notation standard except in the specified number of frequency bands (for the quiet notation). Figure A-6 shows the corresponding histograms of the cumulative percentage for all vessel categories.

Table A-1. *American Bureau of Shipping (ABS)*: Percentage of vessels in each category meeting the quiet notation except in the specified number of frequency bands.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	16	42	52	62	76	93
Container	0	1	8	14	23	35
Vehicle Carrier	1	10	33	52	67	81
Tanker	1	17	45	66	70	84
Bulker	2	30	72	84	89	94
Cruise	0	41	66	77	82	86

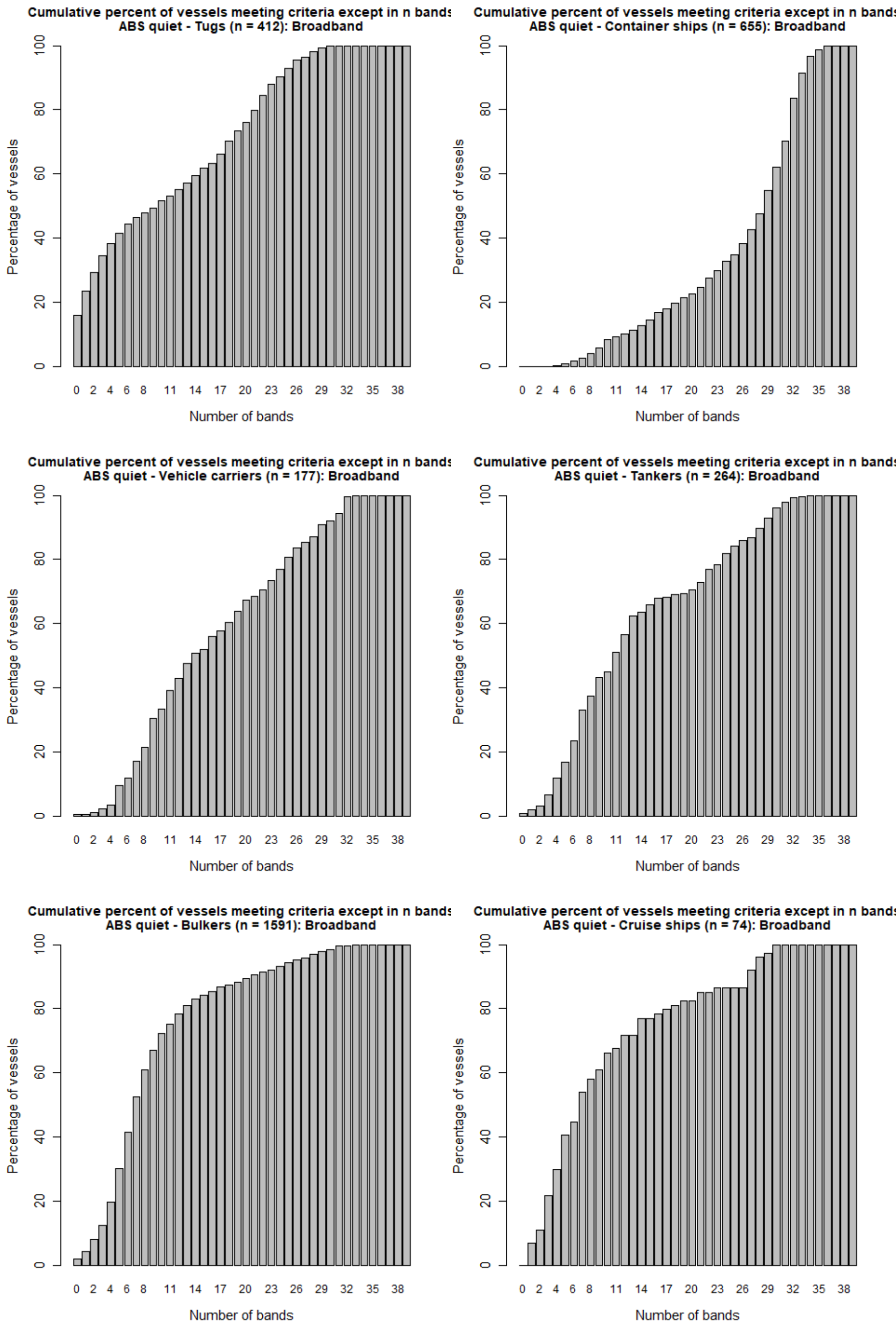


Figure A-6. *American Bureau of Shipping (ABS)*: Histograms of the cumulative percentage of vessel compliance in all but the specified number of bands for the quiet notation for each vessel category.

A.2.2. Bureau Veritas

Table A-2 presents the percentage of vessels in each vessel category meeting the Bureau Veritas (BV) notation standard except in the specified number of frequency bands (for the advanced notation). Figure A-7 shows the corresponding histograms of the cumulative percentage for all vessel categories.

Table A-2. *Bureau Veritas (BV)*: Percentage of vessels in each category meeting the advanced notation except in the specified number of frequency bands. Separate threshold per vessel category.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	0	2	5	9	14	24
Container	0	0	0	0	1	3
Vehicle Carrier	0	0	0	1	5	8
Tanker	0	0	0	2	7	14
Bulker	0	0	0	4	14	23
Cruise	0	0	0	1	5	22

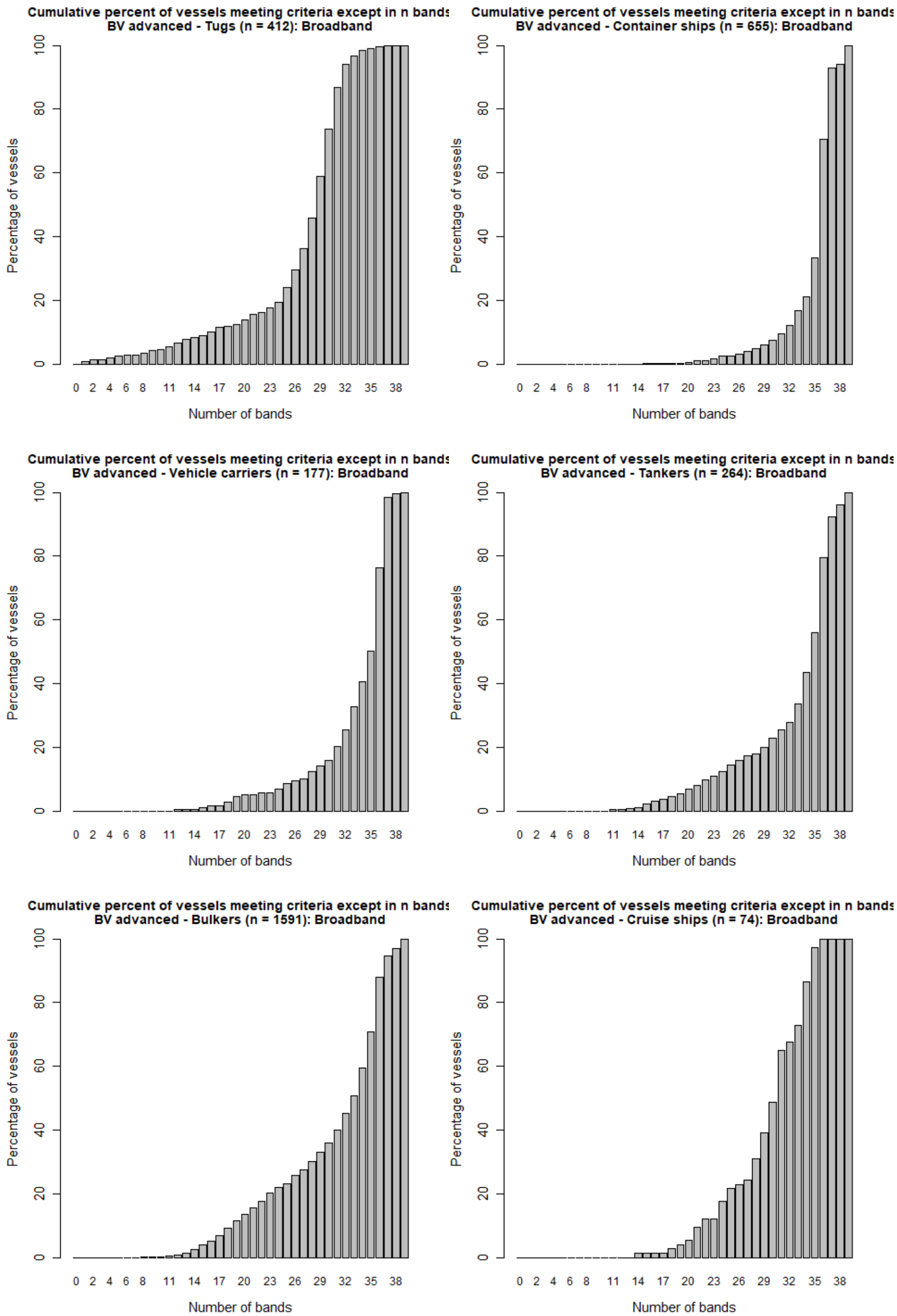


Figure A-7. *Bureau Veritas (BV)*: Histograms of the cumulative percentage of vessel compliance in all but the specified number of bands for the advanced notation for each vessel category.

A.2.3. Det Norske Veritas

Table A-3 presents the percentage of vessels in each vessel category meeting the Det Norske Veritas (DNV) notation standard except in the specified number of frequency bands (for the quiet notation). Figure A-8 shows the corresponding histograms of the cumulative percentage for all vessel categories.

Table A-3. *Det Norske Veritas (DNV)*: Percentage of vessels in each category meeting the quiet notation except in the specified number of frequency bands.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	5	18	27	34	45	67
Container	0	0	1	4	8	15
Vehicle Carrier	0	0	6	21	34	45
Tanker	0	2	20	36	50	63
Bulker	0	4	38	61	73	83
Cruise	0	7	24	54	64	81

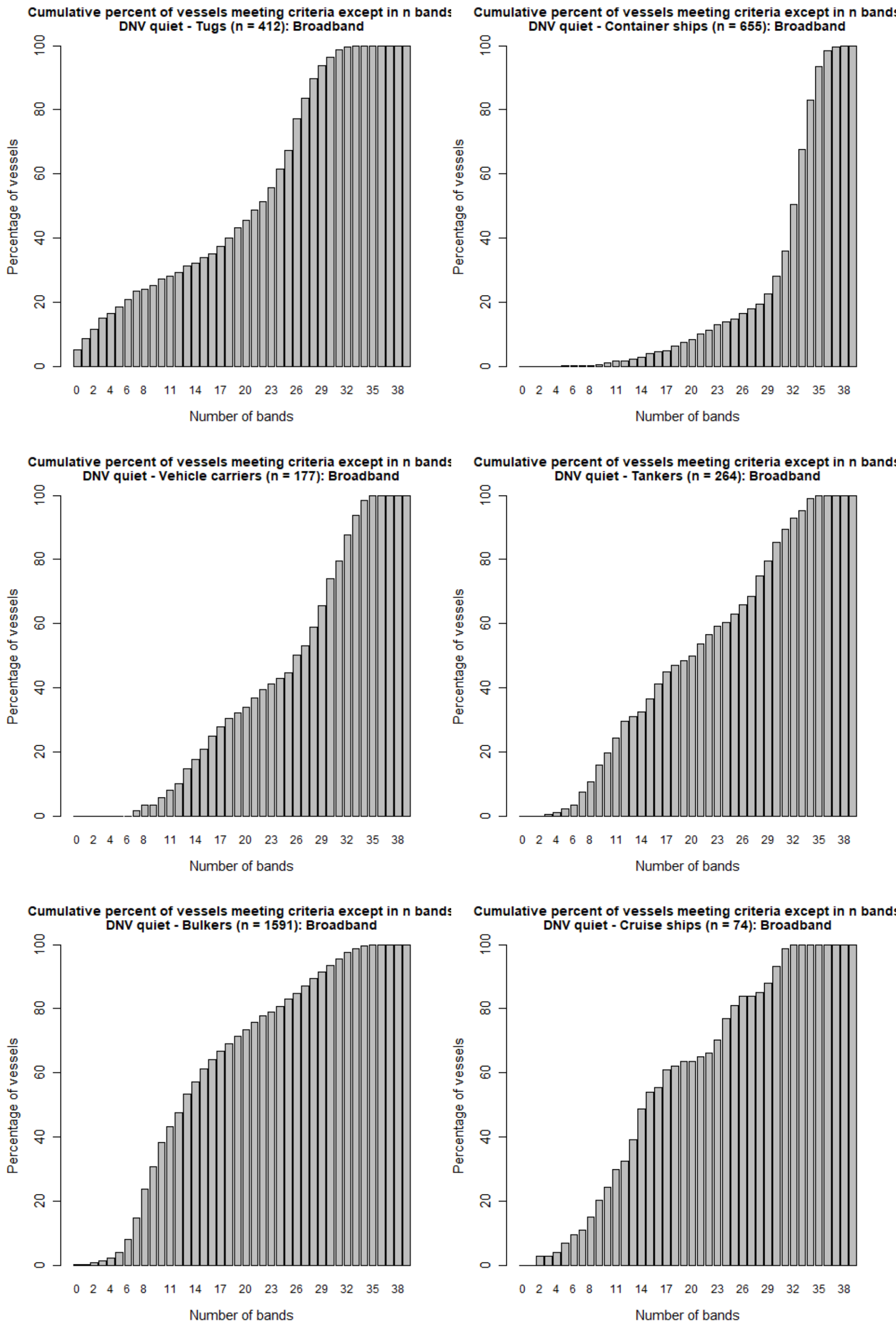


Figure A-8. *Det Norske Veritas (DNV)*: Histograms of the cumulative percentage of vessel compliance in all but the specified number of bands for the quiet notation for each vessel category.

A.2.4. Lloyd's Register

Table A-4 presents the percentage of vessels in each vessel category meeting the Lloyd's Register (LR) notation standard except in the specified number of frequency bands (for the quiet notation). Figure A-9 shows the corresponding histograms of the cumulative percentage for all vessel categories.

Table A-4. *Lloyd's Register (LR)*: Percentage of vessels in each category meeting the quiet notation except in the specified number of frequency bands.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	5	23	39	53	66	85
Container	0	1	4	13	22	36
Vehicle Carrier	0	3	20	47	64	79
Tanker	0	3	29	56	69	81
Bulker	0	5	48	77	87	94
Cruise	0	20	54	73	82	88

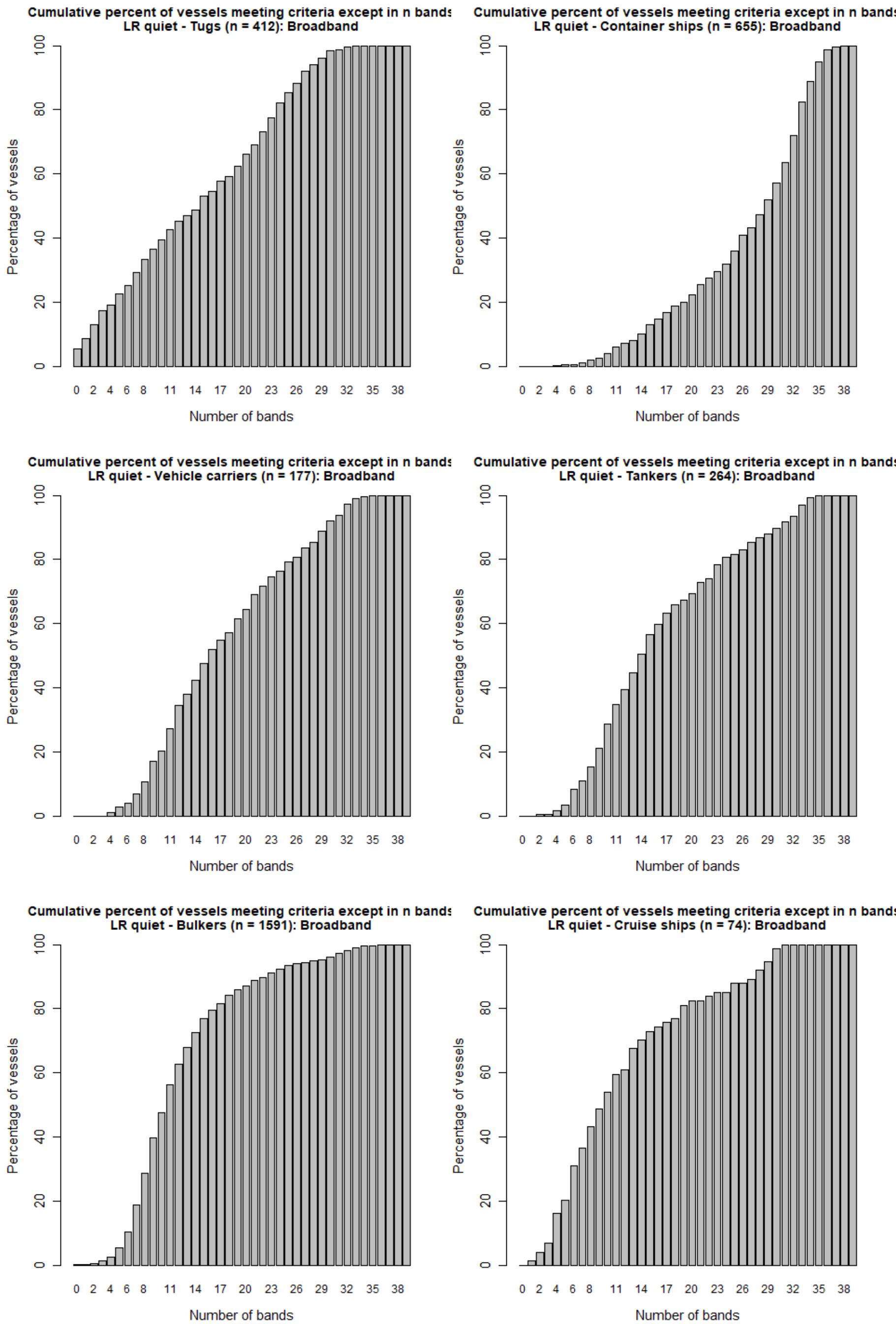


Figure A-9. *Lloyd's Registrar (LR)*: Histograms of the cumulative percentage of vessel compliance in all but the specified number of bands for the quiet notation for each vessel category.

A.2.5. RINA

Table A-5 presents the percentage of vessels in each vessel category meeting the RINA notation standard except in the specified number of frequency bands (for the quiet notation). Figure A-10 shows the corresponding histograms of the cumulative percentage for all vessel categories.

Table A-5. *RINA*: Percentage of vessels in each category meeting the quiet notation except in the specified number of frequency bands.

Category	All bands	All but 5 bands	All but 10 bands	All but 15 bands	All but 20 bands	All but 25 bands
Tug	1	6	13	18	22	36
Container	0	0	0	0	1	6
Vehicle Carrier	0	0	2	6	10	19
Tanker	0	0	5	15	23	34
Bulker	0	0	11	26	41	53
Cruise	0	0	5	19	26	49

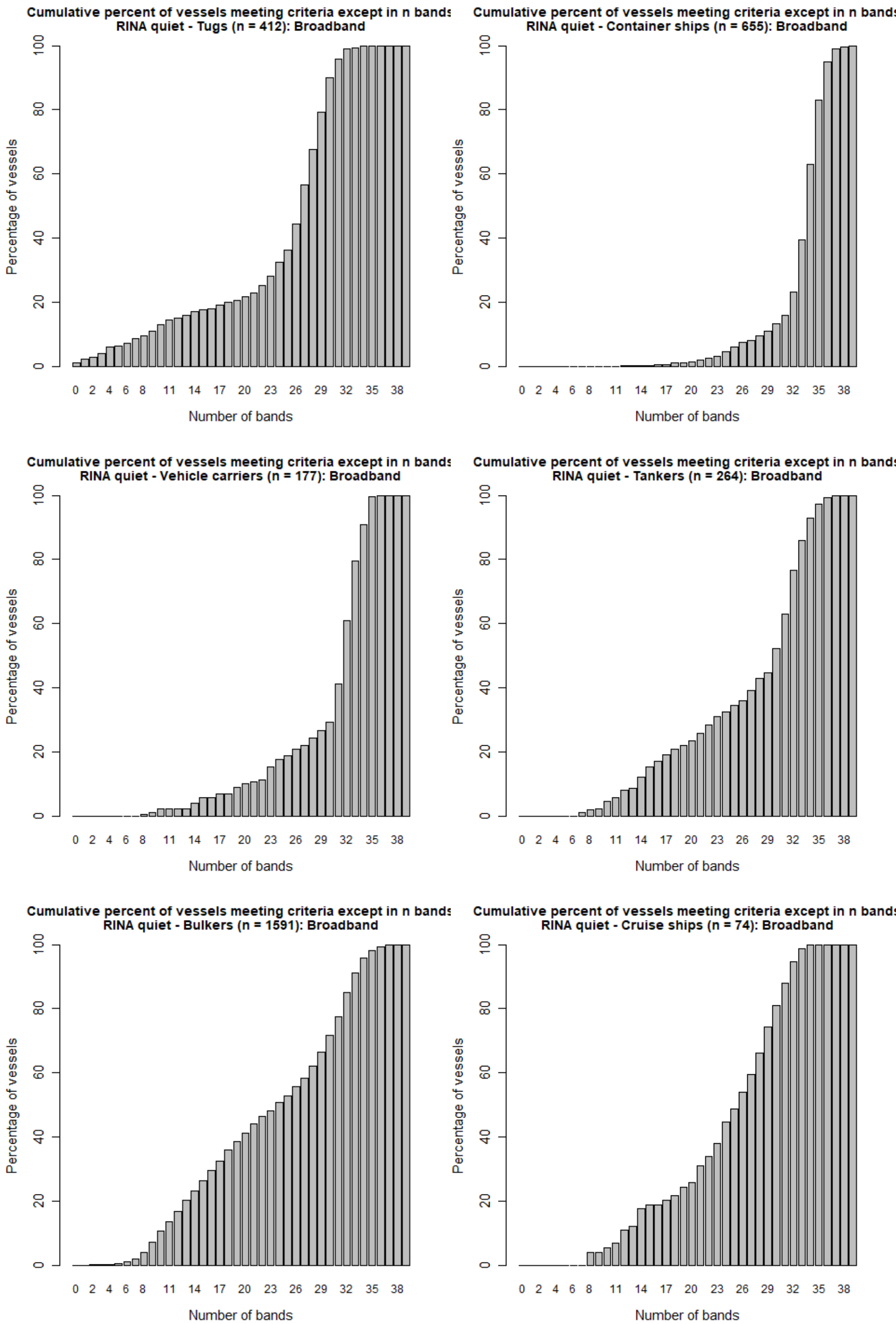


Figure A-10. *RINA*: Histograms of the cumulative percentage of vessel compliance in all but the specified number of bands for the quiet notation for each vessel category.