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A Meta-Analysis to Understand the Variability in Reported Source Levels of Noise Radiated by Ships From Opportunistic Studies

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Background: Commercial shipping is identified as a major source of anthropogenic underwater noise in several ecologically sensitive areas. Any development project likely to increase marine traffic can thus be required to assess environmental impacts of underwater noise. Therefore, project holders are increasingly engaging in underwater noise modeling relying on ships' underwater noise source levels published in the literature. However, a lack of apparent consensus emerges from the scientific literature as discrepancies up to 30 dB are reported for ships' broadband source levels belonging to the same vessel class and operating under similar conditions. We present a statistical meta-analysis of individual ships' broadband source levels available in the literature so far to identify which factors likely explain these discrepancies.

Methods: We collated ships' source levels from the published literature to construct our dataset. A Generalized Linear Mixed Model was applied to the dataset to statistically assess the contribution of *intrinsic* (i.e., related to ships' static and dynamic attributes) and *extrinsic* factors (i.e., related to both the protocol for hydroacoustic data acquisition and the noise data reduction procedure) to the reported broadband source levels.

Results: Amongst *intrinsic* factors, ships' speed-over-ground $\left(15.39\text{ dB} \times \log_{10}\left[\frac{v}{1\text{ knot}}\right],\ p\text{-value} < 0.001\right)$, ships' width $\left(12.03\text{ dB} \times \log_{10}\left[\frac{b}{1\text{ m}}\right];\ p\text{-value} < 0.001\right)$, and ships' class (–6.07 to 2.08 dB; p-value $\in$ [< 0.001 to 0.036]) have shown the strongest correlations with broadband source levels. The hydrophone-to-source closest point of approach $\left(\text{-4.83 dB} \times \left[\frac{\text{CPA}}{1\text{ nmi}}\right];\ p\text{-value} < 0.001\right)$ and the correction for surface-image reflections (21.73 dB; p-value $= 0.002$) contribute the most to explain the reported ships' broadband source levels' variability amongst *extrinsic* factors.

Conclusions: Our meta-analysis confirms a consensus that speed regulation can effectively reduce instantaneous ships' source levels. Neglecting Lloyd's mirror effects through the abuse of non-corrected spreading laws for propagation loss directly leads to a generalized under-estimation of the ships' source levels retrieved from the literature. This could eventually be addressed by a wider adoption of standardized methods of hydrophone-based sound recordings and of data processing to homogenize results and facilitate their interpretation to conduct environmental impact assessment.

Keywords: review of literature, ships' source levels, acoustic techniques, hydrophone-based observations, statistical methods

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1. INTRODUCTION

The exposure of marine life (e.g., fishes, invertebrates, mammals) to anthropogenic noise remains a worldwide environmental issue for marine ecosystems (Williams et al., 2015). The magnitude of the underwater radiated noise attributed to the merchant fleet has shown a monotonic increase over the past few decades (Nolet, 2017) forcing the international authorities to suggest recommendations and new laws of mitigation in order to maintain control of this trend (IMO, 2014). Recently, commercial shipping activities, regarded as the main contributor to the anthropogenic underwater noise budget, have shown constant year-to-year increases and are a global-wide phenomenon, hence adding to the concerns (Clark et al., 2009).

The impact of the shipping noise on marine mammals is of critical importance considering the vital role of acoustics for numerous species. Anthropogenic noise alters the social behavior of marine mammals (Gomez et al., 2016), masks their communications (Erbe et al., 2016), and impedes their ability to appropriately forage (Tyack et al., 2011). Instantaneous high-amplitude events or long-term exposition to continuous underwater noise can lead to temporary or permanent injuries to their auditory system (NOAA, 2015).

In Canada, for many species listed as endangered according to Canada's Species at Risk Act (2002), underwater noise of anthropogenic origin is already being regarded as a threat to their recovery and is identified as such in their recovery plans. In the St. Lawrence River (Québec, Canada), anthropogenic underwater noise is thus identified as a threat to the recovery of both the St. Lawrence Estuary beluga population and the Northwest Atlantic blue whale.

In this context and considering the expected increase of the maritime traffic (Kaplan and Solomon, 2016), especially in the St. Lawrence River (Gouvernement du Québec, 2015), multi-stakeholder processes are underway to identify options to mitigate merchant ships' underwater radiated noise (e.g., Audoly et al., 2014). However, a prerequisite to an underwater noise reduction campaign concerns the ability to properly measure sound pressure through hydrophone-based observations and to accurately estimate the ships' source levels, a challenge undertaken worldwide by several research groups (Audoly et al., 2014; MacGillivray et al., 2019).

In order to quantify the underwater radiated noise from merchant ships through opportunistic hydrophone-based observations, numerous steps must be carefully carried out including the choice of hydrophones, location, and an accurate hydrophone calibration (Robinson et al., 2014). This also involves a detailed understanding of the complex physical processes and their mathematical representation that describe the acoustic propagation in anisotropic underwater environments (Erbe et al., 2016).

Merchant ships' underwater noise have several origins, the principal being machinery, propellers, and cavitation (Audoly et al., 2017). It is well-known that variations in merchant ships' source levels exist inside a given vessel class and from one class to another (see e.g., Figure 2 of Veirs et al., 2016). Proper characteristics to each ship (e.g., architecture, type of engines, maintenance of the propellers and hull) and conditions of operation (e.g., speed, load) can have an impact on the source levels. For this work, these factors will be referred to as *intrinsic* in a sense that they originate from the ships' own static and dynamic characteristics.

Alternatively, large, and often intra-class, discrepancies on source levels are reported in the literature, hence suggesting a certain uncertainty on the measurements attributed to factors *extrinsic* to the ships themselves. These *extrinsic* factors refer to the data campaign protocol and the mathematical calculations required to convert received levels of sound at the hydrophones into source levels at the position of the ship's position. To list a few, we can think about the experimental design for data acquisition (e.g., hydrophones' locations) or how certain physical processes (e.g., surface-image reflections) are handled during the data processing phases. Although underwater radiated noise propagation is directly related to the medium's chemical and geophysical properties, measurements of source levels found in the literature are usually reported without corresponding error bars or uncertainties, hence making study-to-study comparison quite complicated.

In this context where regulators, natural resources and conservation managers are required to identify new ways to attenuate the underwater radiated noise attributed to the merchant fleet in a growing number of ecologically sensitive areas, the important variability in the results reported by acoustic experts in the literature needs further investigation. This motivated a meta-analysis to shed some light on the apparent discrepancies reported for source levels of merchant ships and to identify the contribution of quantifiable *intrinsic* and *extrinsic* factors responsible for those.

2. DEFINITIONS AND SCOPE

In this work, merchant ships include bulk carriers, unclassified cargo ships[1], container ships, passenger ships, tankers, and vehicles carriers. We followed the terminology regarding ships' source levels described in ISO 17208-1 (2016), ISO 18405 (2017), and ISO 17208-2 (2019).

1. Radiated Noise Level (RNL): Level of the product of the distance from a ship reference point of a sound source and the far field root-mean-square sound pressure at that distance for a specified reference value.
2. Monopole Source Level (MSL): Mean-square sound pressure level at a distance of 1 m from a hypothetical monopole source, placed in a (hypothetical) infinite uniform lossless medium.

[1]Simply referred as "cargo ships" by the different studies selected in section 4, these ships likely include a mixture of non-categorized bulk carriers, container ships, oil/chemical tankers, vehicles carriers and subcategories.

Source levels derived from underwater recordings that neglect surface-image reflections (i.e., Lloyd's mirror effects) are said to be RNL measurements. MSL values can be retrieved, in first approximation, using correction factors (listed in Appendix A of ISO 17208-2, 2019) applied to RNL measurements that were previously obtained using the standardized protocol described in ISO 17208-1 (2016). Higher precision can be obtained by using numerical algorithms (Collins, 1993; Porter and Liu, 1994) for the backpropagation of the received levels of noise instead of relying on the distance normalization of the standard spherical geometrical wave dilution. This latter method not only corrects for surface-image reflections but also compensates for the wave absorption of the seabottom sediments, bathymetric variations and channeling effects attributed to speed-of-sound gradients.

3. OBJECTIVES

The aims are to:

1. (a) Identify published studies that provide frequency-integrated (i.e., broadband) source levels for individual merchant ships;
   (b) Characterize inter-study variability in source level measurements;
   (c) Collate the data related to field campaigns and data processing.
2. Identify the contribution of quantifiable *intrinsic* and *extrinsic* factors that statistically explain the variability of the source level measurements. Emphasis will be accorded to *extrinsic* factors that can be objectively estimated from the information provided in each study. This excludes the precision of the hydrophone calibration as details of the pre-observations lab manipulations are rarely discussed in the selected studies.
3. Characterize the contribution of the ships' speed to the overall noise budget reported in the studies. Transiting speed is of particular interest as it appears to be a manageable factor to reduce the ships' radiated noise.

By achieving these objectives, we will provide key information and clarification about the interpretation of the ships' source levels reported in the literature. This will support ongoing management processes seeking to understand and mitigate the ships' radiated noise. This work will also be informative for the noise modeling endeavors carried out in the context of environmental impact assessment (e.g., Chion et al., 2017; Pennucci and Jiang, 2018).

4. METHOD

To identify studies that report opportunistic source level measurements of individual merchant ships and to quantitatively explore their variability, we first carried out a literature review using a keywords approach in databases of scholarly literature (Google Scholar, Scopus). The query used on these search engines is here listed as:

1. "Ship" AND
2. (a) "source levels" OR
   (b) "sound signature" OR
   (c) "acoustic signature" OR
   (d) "noise signature" OR
   (e) "radiated noise."

A close examination of the list of references of each returned hit was also carried out in order to identify articles and reports that have failed to be returned by the keywords combination mentioned above. Only studies displaying broadband source level measurements in units of dB re 1 μPa · m for individual merchant ships were selected. All source level measurements for single recordings were gathered in a unique datasheet in order to investigate agreements and discrepancies between studies and conduct subsequent analysis.

The fact that each selected study has its own protocol/methodology for data acquisition creates a non-independence of the datasheet's intra-study data i.e., a measurement taken from a specific study will likely be more similar to another measurement taken from the same study than a measurement taken arbitrarily from another study. This signifies that a standard generalized linear model (GLM) cannot be used in order to estimate how *intrinsic* and *extrinsic* factors contribute to explain the variability in reported ships' source levels. In our case, the data non-independence requires the use of a generalized linear mixed model (GLMM). The term "mixed" indicates that the model implies the use of at least one fixed effect (i.e., a variable for which we wish to quantify the effect on reported source levels) and at least one random effect (authors-specific in our case). Random effects are not calculated but they are used to indicate to the model that intra-study data are not independent which results in a proper estimation of the model's residual deviation and a non-biased quantification of the fixed variables' uncertainty.

GLMM analysis was conducted with the function *lmer* of the *lme4* package (Bates et al., 2015) using RStudio version 1.1.442 with R version 3.4.4. Confidence intervals and *p-values* (via Wald-statistics approximation) were calculated with the function *sjt.lmer* of the *sjPlot* package (Lüdecke, 2018). GLMMs were run using different combinations of fixed variables in order to minimize the Akaike information criterion (AIC) and explore the contribution of *intrinsic* and *extrinsic* factors to the variability in source level measurements. More specifically, *extrinsic* factors, in terms of methodological and technical parameters (see **Table 1**), will be regarded as possible sources for the inter-study variability.

Finally, we reviewed how the different studies characterized the relationship between ships' speed and source levels, either based on broadband measurements or from empirical models for ships' RNL/MSL predictions. This will deepen our understanding of the role played by speed on the ships' radiated noise.

5. RESULTS

5.1. Characterization of the Selected Studies

All in all, 2,275 single transits from 9 different studies are reported in this work. Technical details for each recording

TABLE 1 | Details of the Experimental Designs and Data Processing.

Selected articles	Date	Location	Protocol Water column (m)	Sample (Number of ships)	Standard	CPA (km)
Allen et al., 2012	2009–06 to 2009–09	Bar Harbor, ME USA	38.7–46.0	4	✗	$\mathcal{O}(1)$
Arveson and Vendittis, 2000	1980	Andros Island, Bahamas	1830	5	✗	$\mathcal{O}(<0.6)$
Bassett et al., 2012	2010–05 to 2011–05	Admiralty Inlet, WA USA	60	14[a]	✗	$\mathcal{O}(1)$
Kipple, 2002	2000–09 to 2001–06	Ketchikan, AK USA	360	12[b]	✗	$\mathcal{O}(0.1)$
Lesage et al., 2014	2004–2005	St. Lawrence Estuary, QC CANADA	20–250	11	✗	$\mathcal{O}(1)$
McKenna et al., 2012	2009–04	Canal de Santa Barbara, CA USA	580	29	✓	$\mathcal{O}(1)$
MCR International, 2011[c]	2011-06	English Channel, UK	87	28[d]	✓	$\mathcal{O}(0.1–1)$
…	2011–08	The Minch, Scotland	100	…	…	…
SMRU Canada, 2014	2013–06	Roberts Bank, Haro Strait, &	16–221	6	✗	$\mathcal{O}(1)$
…	…	Juan de Fuca Strait, BC CANADA	…	…	…	…
Veirs et al., 2016	2011–03 to 2013–10	Salish Sea, WA USA	10	2186	✗	$\mathcal{O}(1–<10)$

Selected articles	Manufacturer	Number of devices	Hydrophones Deployment depth (m)	Sensitivity (dB re 1 V μPa^{-1})	Bandwidth (kHz)	Type
Allen et al., 2012	C54XRS	3	5, 10, 25	−20	0.001–2.5	✗
Arveson and Vendittis, 2000	✗	5	60–460	✗	0.010–40	✗
Bassett et al., 2012	HTI 96 MIN	1	1 m above seabed	−166	0.020–30	Autonomous
Kipple, 2002	✗	3	60, 90, 120	✗	0.010–40	Autonomous
Lesage et al., 2014	ITC6050	1	15	−159	0.020–24	Monitored
McKenna et al., 2012	✗	1	570	✗	0.020–1	Autonomous
MCR International, 2011	Reson TC4032	1	∼29	✗	0.020–20	Autonomous
SMRU Canada, 2014	M8E Omni	5	3 m above seabed	−165 ± 3	0.010–64	Autonomous
Veirs et al., 2016	Reson TC4032	1	8	−164	0.012–40	Autonomous

Selected articles	Propagation loss[e]	Surface-image correction		Data processing Source approximation (m)	Source depth
Allen et al., 2012	CG, SG	✗	→	Dipole	✗
Arveson and Vendittis, 2000	SG	✗	→	Dipole	✗
Bassett et al., 2012	HG	✗	→	Dipole	10
Kipple, 2002	HG	✗	→	Dipole	✗
Lesage et al., 2014	HG	✗	→	Dipole	✗
McKenna et al., 2012	SG	✗	→	Dipole	7, 14
MCR International, 2011	SG	✗	→	Dipole	∝ Draft
SMRU Canada, 2014	RAM	N/A	→	Monopole	✗
Veirs et al., 2016	HG	✗	→	Dipole	✗

[a] *1364 transits were recorded by the authors although the individual results of only 14 merchant ships are provided.*
[b] *6 passenger ships constitute the dataset, each having been recorded twice in different operating modes.*
[c] *Two distinct observing missions were carried out in June and August of 2011.*
[d] *Includes both observing missions.*
[e] *CG: Cylindrical Geometry i.e., $10\log_{10}(r)$. SG: Spherical Geometry i.e., $20\log_{10}(r)$. HG: Hybrid Geometry i.e., $[10..20]\log_{10}(r)$. RAM: Range-dependent Acoustic Model (Collins, 1993).*
Upper panel: date and location where the recordings took place, height of the water column on deployment site, number of merchant ships' signature obtained, whether or not observations were carried using standard protocols, and the order of magnitude of the distances corresponding to the ships' closest points of approach (CPAs). Middle panel: hydrophones' technical details, number of devices used, and deployment depth. Bottom panel: backpropagation methods and corresponding source approximation.

TABLE 2 | Details of the Observational Results.

Selected articles	Data description	Vessel classes
Allen et al., 2012	• Individual broadband (0.001–2.5 kHz) source level measurements • Provides ships' individual physical properties • Provides ships' individual speed	• High-speed Crafts • *Passenger Ships* • Catamarans • Fishing Vessels
Arveson and Vendittis, 2000	• Individual broadband (0.010–40 kHz) source level measurements • Provides ship's physical properties • Provides ship's speed for each transit	• *Cargo Ships*
Bassett et al., 2012	• Mean broadband (0.020–30 kHz) source level measurements per vessel class • Provides means of the ships' physical properties per vessel class • Provides means of the ships' speed per vessel class • Individual broadband (0.020–30 kHz) source level measurements, physical properties, and speed for 24 ships of the authors' sample	• High-speed Crafts • Tugs • *Container Ships* • *Bulk Carriers* • *Vehicles Carriers* • *Cargo Ships*
Kipple, 2002	• Histograms of the individual broadband (0.010–40 kHz) source levels measurements as a function of the ships' speed • Provides ships' individual speed	• *Passenger Ships*
Lesage et al., 2014	• Individual broadband (0.010–24 kHz) source level measurements as a function of the ships' speed, length, gross tonnage, and year built • Provides ships' individual physical properties • Provides ships' individual speed	• *Oil/Chemical Tankers* • *Cargo Ships* • *Bulk Carriers* • *Container Ships*
McKenna et al., 2012	• Individual 1/3-octave frequency-dependent source level spectra • Individual broadband (0.020–1 kHz) source level measurements as a function of the ships' speed • Provides ships' individual physical properties • Provides ships' individual speed	• *Container Ships* • *Vehicles Carriers* • *Bulk Carriers* • *Cargo Ships* • *Chemical Products Tankers* • *Crude Oil Tankers* • *Product Tankers*
MCR International, 2011	• Individual broadband (0.020–2 kHz) source level measurements • Provides ships' individual physical properties • Provides ships' individual speed • Provides sea conditions and parameters for each recording	• *Tankers* • *Oil Tankers* • *Cargo Ships* • Fishing Vessels • *Bulk Carriers* • *Passenger Ships*
SMRU Canada, 2014	• Individual 1/3-octave frequency-dependent source level spectra as a function of the ships' speed • Individual broadband (0.010–70 kHz) source level measurements as a function of the ships' speed • Provides ships' individual physical properties • Provides ships' individual speed	• *Container Ships* • Tugs
Veirs et al., 2016	• Individual broadband (0.020–96 kHz) source level measurements • Provides ships' individual physical properties • Provides ships' individual speed	• Leisure Crafts • *Passenger Ships* • Tugs • Fishing Vessels • *Bulk Carriers* • *Tankers* • Military Vessels • *Container Ships* • *Cargo Ships* • Research Vessels • *Vehicles Carriers*

missions and a description of the data presented by each study are provided in **Tables 1**, **2**, respectively.

We emphasize, in **Table 1**, that all but one studies retained for this work backpropagated their received levels of noise to the sources' positions using variations of the geometrical spreading model while none of them reported having used corrections for surface-image reflections. From these specific studies, the retrieved RNLs (see section 2) are said to be surface-affected by the Lloyd's mirror effects (see e.g., Gassmann et al., 2017) and are hence referred to as dipole observations. SMRU Canada (2014) displays surface-corrected MSL measurements (see section 2) referred to as monopole observations in **Table 1**.

Vessel classes explored in this work are listed in italic in the right-hand column of **Table 2**. Whisker plots of each sample of merchant ships are plotted in **Figure 1**, hence illustrating the variability in broadband source level measurements between each study.

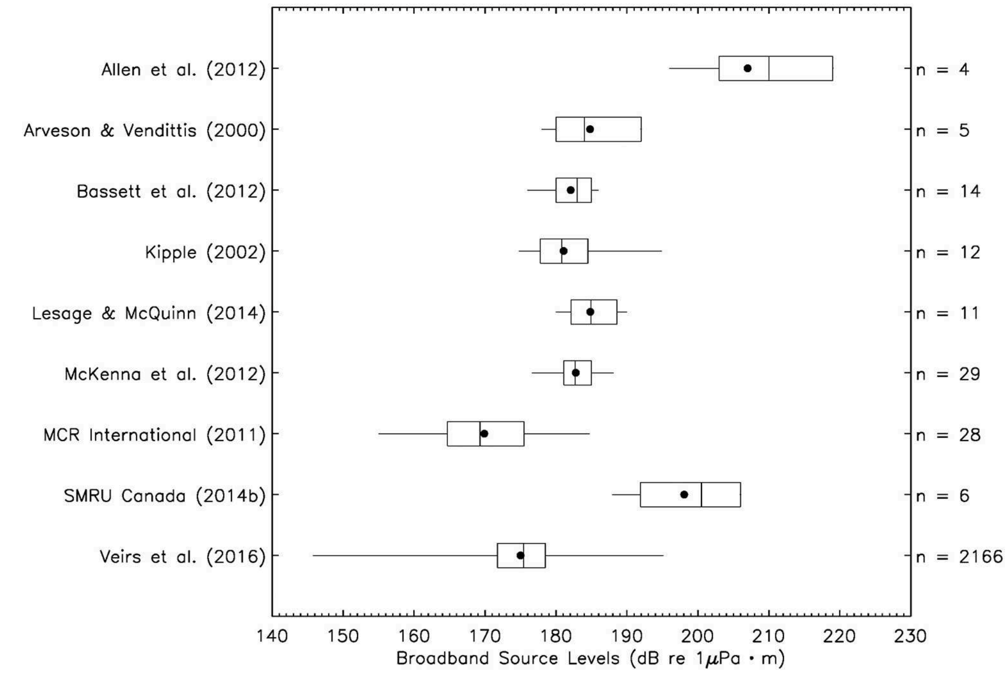

FIGURE 1 | Broadband source levels for merchant ships reported from studies listed in **Table 1**. The right-hand ordinate provides the number of vessels with available data published in each work. Whisker plots show the minimal value, the 25, 50, 75% quartiles, the maximal value, and the mean () of each sample.

5.2. Factors Explaining the Ships' Source Levels' Variability

Intrinsic factors available for the GLMM analysis are the ships' length (ℓ), width (b), speed (v), and classes (see section 2). Draft (d) and water displacement ($\propto \ell \times b \times d$) were not considered since the d parameter is missing from the Veirs et al.'s (2016) database (which accounts for the large majority of the 2,275 transits used in this work). The general consensus suggests that the logarithm of *intrinsic* factors, besides ships' classes, should be used to predict source level values (see **Table A1**).

Since we have no indications on how source level measurements behave with *extrinsic* factors that are linked to the methodological parameters and techniques of data processing, we chose to include them as linear predictors to the GLMM analysis. The *extrinsic* factors tested in the GLMM analysis are the lower and upper thresholds of the hydrophones' frequency bandwidth (f_0, f_1), the distance corresponding to the closest point of approach, the height of the water column at the hydrophones' position, the hydrophones' deployment depth, and the source approximation (i.e., whether RNL or MSL values were obtained). For the height of the water column and the deployment depth, we chose the largest value when an interval or more than one value are listed in **Table 1**. The source approximation was quantified as a standard Heaviside function that equals 1 when MSL values were gathered and 0 otherwise.

Different combinations of $\log_{10}$(*intrinsic* factors) + *extrinsic* factors were tested in an attempt to minimize the AIC using authors-specific random effects (see section 4). This was achieved using the v, b, class, CPA, and source approximation parameters while the 4 outliers provided by Allen et al. (2012) were ignored hereafter. The best-fitted model's coefficients are provided in **Table 3** and Equation (1) which indicate the correlation between *intrinsic*/*extrinsic* factors with the ships' source level values.

$$\begin{aligned}\text{Source Level} = {} & 147.94\,\text{dB} + 15.39\,\text{dB} \times \log_{10}\left[\frac{v}{v_0}\right] \\ & + 12.03\,\text{dB} \times \log_{10}\left[\frac{b}{b_0}\right] - 4.83\,\text{dB} \times \left[\frac{\text{CPA}}{r_0}\right] \\ & + 21.73\,\text{dB} \times H(\text{source}) + \phi(\text{class}),\end{aligned} \tag{1}$$

where $v_0 = 1$ knot, $b_0 = 1$ meter, $r_0 = 1$ nautical mile are reference values, and:

$$H(\text{source}) = \begin{cases} 1, & \text{if source approximation} = \text{MSL} \\ 0, & \text{if source approximation} = \text{RNL}, \end{cases} \tag{2}$$

$$\phi(\text{class}) = \begin{cases} (+)\,0.00\,\text{dB}, & \text{if class} = \text{Bulk Carrier} \\ (+)\,2.08\,\text{dB}, & \text{if class} = \text{Cargo Ship} \\ (+)\,1.66\,\text{dB}, & \text{if class} = \text{Container Ship} \\ (-)\,6.07\,\text{dB}, & \text{if class} = \text{Passenger Ship} \\ (+)\,1.31\,\text{dB}, & \text{if class} = \text{Tanker} \\ (+)\,0.81\,\text{dB}, & \text{if class} = \text{Vehicles Carrier}, \end{cases} \tag{3}$$

where the class reference was bulk carriers. Note that, in GLMM, qualitative parameters are always compared to the group's first element in alphabetical order.

TABLE 3 | Generalized Linear Mixed Model applied to our database.

	Source levels (dB)		
Predictor	**Estimate**	**Confidence interval**	***p*-value**
Intercept	147.94	141.20 to 154.67	<0.001
$\log_{10}(v/v_0)$	15.39	12.10 to 18.67	<0.001
$\log_{10}(b/b_0)$	12.03	9.78 to 14.28	<0.001
CPA/r_0	−4.83	−5.86 to −3.80	<0.001
H(source)	21.73	7.92 to 35.55	0.002
$\underbrace{\phi(\text{class})}$	...	...	...
Bulk carrier (reference)	0.00	–	–
Cargo ship	2.08	1.49 to 2.68	<0.001
Container ship	1.66	0.98 to 2.34	<0.001
Passenger ship	−6.07	−7.35 to −4.79	<0.001
Tanker	1.31	0.55 to 2.08	0.001
Vehicles carrier	0.81	0.05 to 1.58	0.036

Authors-specific were used as random effects to handle the non-independence of the intra-study data. Results shown here for fixed effects are those that minimize the Akaike information criterion (AIC). Parameters v_0, b_0, and r_0 are reference values for the ships' speed, width, and closest point of approach and are respectively equal to 1 knot, 1 meter, and 1 nautical mile.

Equation (3) suggests that cargo and container ships may have the noisiest acoustical footprint which agrees with the results presented by Jalkanen et al. (2018).

5.3. Ships' Speed vs. Source Levels Relation

This subsection explores the linearity between $\log_{10}(v)$ and source levels according to (1) the observational data collected in this work (see section 5.3.1) and (2) the empirical models for source level predictions available in the literature (see section 5.3.2).

5.3.1. Observations

Speed is an *intrinsic* factors that can be regulated in order to favor an instantaneous noise attenuation of the merchant fleet. Our GLMM analysis revealed a positive correlation between a ship's source levels and speed. Therefore, a deeper analysis of the ships' speed *vs.* source levels relation is here developed by individually investigating each selected study. Results are provided in the upper panel of **Table 4** and highly suggest a positive correlation between the magnitude of the RNL/MSL measurements and the ships' speed. Slopes, in the $\log_{10}(v)$-space, range from 11.71 to 49.94 with a median of roughly 21 that agrees relatively well with the estimate found in **Table 3**. Authors typically point out however that this relation is subject to variations from one ship to another, some ships are even likely to produce more noise at speeds below their optimal cruising speed.

A study properly engineered to investigate the impact of a speed reduction on the ambient noise and the noise emitted by merchant ships was recently conducted under the Echo Program in the water basin of the Port of Vancouver (MacGillivray et al., 2019). This voluntary vessel slowdown trial provided source level measurements for merchant ships both inside and outside a speed reduction area in which the proposed speed limit was 11 knots. The source levels' variations of transiting ships were therefore solely attributed to a speed decrease since all other ship-related factors were kept constant between measurements. This approach makes the Port of Vancouver's vessel slowdown trial a valuable source of information in order to understand the impact of speed regulation on the levels of noise emitted by merchant ships. Both RNL and MSL noise-to-speed slopes were provided by the authors and are listed in **Table 4**'s middle panel.

MacGillivray et al. (2019) reveals that a 40% speed reduction in this sector results in a MSL decrease of about 10 dB. Slopes are typically a factor 2–4 steeper than what we found for data in **Table 3** (if GLMMs are processed with a source levels $\propto v$ model). Depending on the ship class, the noise-to-speed slopes vary from 1.4 to 2.8 dB knot^{-1} and appear to be slightly steeper for MSL measurements when compared to RNLs. A similar behavior can also be retrieved from **Table 4**'s upper panel with the SMRU Canada (2014) study showing the second steepest relation between source levels and $\log_{10}(v)$.

Even though a variability exists from one study to another, a large consensus seems established in the scientific community that speed reduction does indeed favors a decrease of the noise budget attributed to the merchant fleet (e.g., Audoly et al., 2017). However, this reduction of the instantaneous underwater noise radiated comes at the expense of an increase of the time spent by ships in a speed-restricted zone, hence potentially exposing nearby marine mammals to noise pollution for longer periods of time (McKenna et al., 2013; Chion et al., 2017).

5.3.2. Models

Empirical source level models listed in **Table 5** can also be used to estimate how broadband ships' source levels vary with speed changes. As in **Table 2**, vessel classes explored in this work are listed in italic in **Table 5**. Results of the source levels $\propto \log_{10}(v)$ regressions are provided in the bottom panel of **Table 4**. All models that numerically depend on the speed parameter predict an increase of the noise radiated with increasing speed. Models were tested for standard dimensions in terms of length, width, draft, and water displacement (see the right-hand column in **Table 4**'s bottom panel). Speed limits correspond to the minimal and maximal speeds retrieved, for each specific vessel class, from our 2,275 ships database (see **Supplementary Material**). The noise-to-speed slopes, in the $\log_{10}(v)$-space, range between 3.7 and 60, with a mean value of 48, roughly three times steeper than what was obtained from the GLMM approach in **Table 3**.

The mathematical formalism of each source level models listed in **Table 5** is provided in **Table A1**.

6. DISCUSSION

6.1. Impact of the Experimental Methodology

This work identifies two *extrinsic* factors, proper to the experimental design and the data processing approach, that may impact the post-processed value of ships' broadband source levels (see **Table 3**). Our GLMM analysis reveals that the values computed for broadband source levels will (1) decrease with the ships' closest point of approach increasing, and (2) increase

TABLE 4 | Source levels vs. ships' Speed Relation. Upper panel: Observational studies listed in **Tables 1, 2**.

Observations	***a*** **($SL = a\log_{10}(v) + k$)**	***r***	**Vessel classes**	**Number of ships**
Arveson and Vendittis, 2000	49.94	0.95	Cargo ships	5
Bassett et al., 2012	21.32	0.52	Container ships Bulk carriers Vehicles carriers Cargos	14
Kipple, 2002	21.34	0.37	Passenger ships	12
Lesage et al., 2014	18.22	0.28	Tankers Cargos Bulk carriers Container ships	11
McKenna et al., 2012	11.71	0.13	Container ships Vehicles carriers Bulk carriers Cargos Tankers	29
MCR International, 2011	19.15	0.04	Tankers Cargos Bulk carriers Passenger ships	28
SMRU Canada, 2014	27.36	0.58	Container ships	6
Veirs et al., 2016	25.04	0.16	Bulk Carriers Cargos Container ships Passenger ships Tankers Vehicles carriers	2186
Study	RNL ($S = av + k$)	MSL ($SL = av + k$)	Vessel classes	Number of ships
MacGillivray et al., 2019	2.66	2.83	Bulk carriers & Cargos	485
	1.46	1.50	Container ships	260
	1.75	1.71	Passenger ships	30
	2.52	2.65	Tankers	74
	1.57	1.57	Vehicles carriers	86
Models	*a* ($SL = a\log_{10}(v) + k$)	*r*	Vessel classes	Details
Audoly and Rizzuto, 2015	45.46	0.99	Cargos	$0.001\ \text{kHz} \leq f \leq 50\ \text{kHz}$ $6.7\ \text{knots} \leq v \leq 22.1\ \text{knots}$ $\ell = 200$ m
	47.76	0.99	Container ships	$0.001\ \text{kHz} \leq f \leq 50\ \text{kHz}$ $9.0\ \text{knots} \leq v \leq 24.7\ \text{knots}$ $\ell = 300$ m
	42.01	0.98	Passenger ships	$0.001\ \text{kHz} \leq f \leq 50\ \text{kHz}$ $3.5\ \text{knots} \leq v \leq 25.3\ \text{knots}$ $\ell = 225$ m

(Continued)

TABLE 4 | Continued

Models	a ($SL = a\log_{10}(v) + k$)	r	Vessel classes	Details
	46.52	1.00	Tankers	0.001 kHz $\leq f \leq$ 50 kHz 8.5 knots $\leq v \leq$ 16.6 knots ℓ = 200 m
Breeding et al., 1996	60.00	1.00	Tankers	0.001 kHz $\leq f \leq$ 50 kHz 8.5 knots $\leq v \leq$ 16.6 knots ℓ = 200 m
Chion et al., 2017	5.78	0.95	Tankers Cargo ships Bulk carriers Container ships	0.001 kHz $\leq f \leq$ 50 kHz 6.7 knots $\leq v \leq$ 24.7 knots ℓ = 200 m
Luo and Yang, 2011	53.95	1.00	All 6 classes	0.001 kHz $\leq f \leq$ 50 kHz 3.5 knots $\leq v \leq$ 25.3 knots T = 20 kT
Ross and Alvarez, 1964	50.00	1.00	All 6 classes	0.001 kHz $\leq f \leq$ 50 kHz 5 knots $\leq v \leq$ 18 knots ℓ = 200 m
Simard et al., 2016	3.70	0.31	Cargo Ships Container ships Tankers	0.001 kHz $\leq f \leq$ 50 kHz 6.7 knots $\leq v \leq$ 24.7 knots ℓ = 200 m b = 32 m d = 8 m
Urick, 1983	60.00	1.00	Cargo Ships Tankers	0.001 kHz $\leq f \leq$ 50 kHz 6.7 knots $\leq v \leq$ 22.1 knots T = 20 kT m
Wales and Heitmeyer, 2002	0	–	–	Model speed-independent

Slopes a were computed using linear regressions on point-plot diagrams processed using the ($\log_{10}(v)$, Source Levels) data points provided in the authors' results. Pearson r correlation coefficient for each fit is provided. Middle panel: RNL and MSL speed-to-noise slopes provided by the ECHO Haro Strait slowdown project (MacGillivray et al., 2019). Bottom panel: Models from the literature providing source levels' mathematical formalisms. Slopes a were computed using linear regressions on point-plot diagrams processed using the ($\log_{10}(v)$, Source Levels) data points obtained by covering the parameter spaces given in the right-hand column.

when the methodological approach leads to MSL measurements (by opposition to range-independent RNLs). The following subsections detail these behaviors.

6.1.1. Closest Point of Approach

The closest point of approach between a ship and an array of hydrophones requires a compromise in order to increase the chances of good data quality. Distances below a few hundreds meters signify that the hydrophones could be located close to the ship's near field in which the approximation of a point source no longer holds. At such close range, noise is radiated from numbers of different points along the hull, each being characterized by its own source-to-receptor separation. Alternatively, very large CPAs require the use of numerical algorithms in order to properly estimate the transmission loss in complex environments that include variations of the geophysical properties of the underwater terrain and the physico-chemical characteristics of the body of water between the hydrophones and the source. In this work, 8 out of 9 studies retained present RNLs that were processed using geometrical spreading laws (see **Table 1**). Therefore, the impact attributed to complex underwater environments on the measurement of reliable source levels cannot be properly assessed. The data sample assembled in this work does show a decrease of the calculated source levels with greater CPAs to the source. This suggests that the error propagation caused by ignoring the underwater complexity in RNL measurements leads to an under-estimation of the true source level values.

6.1.2. RNL vs. MSL

Table 3 reveals that the use of spreading laws to backpropagate levels of sound received at the hydrophones to the sources' positions without adding corrective terms to compensate surface-image reflections may lead to an underestimation of the ships' source levels by as much as 35 dB (i.e., upper limit of the

TABLE 5 | Details of the theoretical models published in the literature that serve as RNL/MSL predictors.

Selected articles	Source	Parameters required	Vessel classes	Comments
Audoly and Rizzuto, 2015	Monopole	• Frequency (*independent variable*) • Length • Speed	• *Cargo Ships* • *Tankers* • Ferries • *Passenger Ships* • High-speed Crafts • Fishing Vessels • Research Vessels • Leisure Crafts • Tugs • Sailing Boats • *Container Ships*	• Provides individual models for each vessel class
Breeding et al., 1996	Dipole	• Frequency (*independent variable*) • Length • Speed	• *Merchant Ships* • *Tankers* • Fishing Vessels	• Known as the RANDI 3.1 model
Chion et al., 2017	Dipole	• Frequency (*independent variable*) • Length • Speed	• *Oil/Chemical Tankers* • *Cargo Ships* • *Bulk Carriers* • *Container Ships*	• Extension of the Breeding et al., 1996's model • Derived from the Lesage et al., 2014's sample
Luo and Yang, 2011	Dipole	• Frequency (*independent variable*) • Ship tonnage • Speed	• *Watercrafts*	• Extension of the original Ross model (see Ross, 2013) • Tonnage between 100 and 100 000 tons
Ross and Alvarez, 1964	Dipole	• Frequency (*independent variable*) • Length • Speed	• *Merchant Ships*	• Originally derived from the propellers' tip speed and the number of blades • Later, conveniently adapted to the ships' cruising speed
Simard et al., 2016	Monopole	• Frequency (*independent variable*) • Length • Breadth • Draft • Speed	• *Cargo Ships* • *Container Ships* • *Tankers*	• Referred as the LBDS model in the original paper • Notice the publication of a subsequent erratum
Urick, 1983	Dipole	• Frequency (*independent variable*) • Ship tonnage • Speed	• *Cargo Ships* • *Tankers* • Large Warships	• Originally derived from the propellers' tip speed • Later, conveniently adapted to the ships' cruising speed
Wales and Heitmeyer, 2002	Monopole	• Frequency (*independent variable*)	• *Merchant Ships*	• No statistically significant dependence between the source levels and the ships' physical dimensions and speed

Mathematical formalism is provided in ***Table A1***.

confidence interval) which is clearly assessed in Panels (a) and (b) of Farcas et al.'s (2016) Figure 1[2]. This contributes to explain, for example, median source level values in the vicinity of 200 dB re 1 μPa $\cdot$ m reported by Simard et al. (2016), results that are similar to those listed in SMRU Canada (2014). Given that 8 out 9 observational studies reported in this work (see **Table 1**) and 5 out 8 source level models (see **Table 5**) are based on RNL measurements, our GLMM analysis supports the need to more rigorously assess what is the best-suited [to the studys needs] numerical algorithm regarding the backpropagation processing (see Table 1 of Farcas et al., 2016).

7. STUDY'S LIMITATIONS

This study would definitely benefit from the addition of more MSL measurements in order to properly assess the impact of the monopole *vs.* dipole approach on source levels' variability.

Other *extrinsic* factors (i.e., related to the field campaign) that likely play a role on the determination of the source level values cannot be easily quantified *a posteriori* and are beyond the scope of this paper.

7.1. Directionality and Recommended Hydrophone Angles

Usually treated as a point source in its far field, noise emitted by a ship is in fact directional and anisotropic. Hence, the alignment between a ship and an hydrophone will play a role in the sound levels recorded (Arveson and Vendittis, 2000; Gassmann et al., 2017).

The hydrophone angle, sustained between the source-to-hydrophone line and the sea surface, appears to lead to smaller source level measurements when small angles ($< 1^\circ$) are involved (e.g., see results from Veirs et al., 2016). Standard protocols (e.g., ANSI, 2009; ISO 17208-1, 2016) recommend to average three (3) simultaneous recordings of a source at hydrophone angles of 15°, 30°, and 45° (see Figure 1 of ISO 17208-1, 2016). For the sake of comparison, an hydrophone angle of 0.2° results in source level values 5 to 10 dB lower than what is obtained for a 10° angle in the 0.020−1 kHz bandwidth using a spreading law for backpropagation calculation (Gassmann et al., 2017). This difference is somewhat reduced to 3–7 dB when correcting for surface-image reflections (cf. using Equation 3 in Gassmann et al., 2017).

7.2. Estimation of the Ship Source Depth

For MSL calculations, uncertainty on the determination of the ships' source depth will have an impact on the transmission loss profiles predicted and, therefore, on the value computed for the source levels. Numerical algorithms for backpropagation such as BELLHOP (Porter and Liu, 1994) and RAM (Collins, 1993) have proven to be highly sensitive to the value chosen for the source's depth as an input parameter. Estimations off by few meters have shown variations in MSL measurements up to 10 dB at low frequencies (Arveson and Vendittis, 2000; Gassmann et al., 2017).

Although the importance of the source's depth on MSL predictions have been demonstrated (see e.g., Figure 3 of Gassmann et al., 2017), this parameter is rarely discussed in observational studies, hence making it difficult to quantitatively estimate its impact on the data presented in this current study.

7.3. Other Factors

Methods of calibration of the hydrophones and the conditions in which these are stocked before deployment will impact the electrical response of the hydrophones to sound (Dakin and Heise, 2015). Calibration in laboratory will have a precision of $\pm$ (0.5–2) dB while *in situ* underwater calibration will have a precision of $\pm$ (3–6) dB (Dakin and Heise, 2015).

The reader will also note that the Veirs et al.'s (2016) sample represents the large majority of the data available for this study (see **Figure 1**). This may be at the origin of certain statistical bias in the quantification of fixed effects (e.g., the closest point of approach) on the values calculated for source levels.

Environmental conditions will also impact the magnitude of the received levels of sound at the hydrophones (e.g., sea roughness, rain lapping, strong winds, waves, currents). The subtraction of this background noise is not trivial and makes it difficult to properly isolate ships' acoustic signatures. Finally, gradients in speed of sound, attributed to a stratification in water temperature, acidity and/or salinity, will induce sound refraction and create tunneling effects that can contaminate sound samples recorded by hydrophones located at very large distances.

8. CONCLUSION

This work constitutes a literature review and a meta-analysis of the studies aiming at opportunistically assess the levels of noise emitted by merchant ships at the source. It is particularly aimed at supporting the interpretation of the variability in ships' broadband source levels reported in the literature. We specifically focused on the apparent lack of consensus throughout the literature and identify the common ground between different studies aiming at opportunistically estimate of ships' source levels and their contributing factors.

The main results of our study are:

1. Our analysis revealed a positive correlation between source level measurements and ships' speed-above-ground i.e., source levels $\sim$ 15.39 dB $\times$ $\log_{10}\left[\frac{v}{1\,\text{knot}}\right]$. Limitations in transiting should definitely be considered as measure of mitigation in order to maintain underwater noise attributed to merchant ships within reasonable levels.
2. We have demonstrated that differences in methodological protocols for opportunistic measurements of ships' underwater noise contribute to the inter-study variability reported for source level values of merchant ships. This is reflected by the presence of both CPA and Source

[2]One can estimate, in Panel (a), a transmission loss of approximately 35 dB between the source and the diagram's lower-left corner. Applying this loss to the received levels illustrated in Panel (b)'s lower-left corner and backpropagating to the position of the source yields a RNL roughly 25 dB re 1 μPa $\cdot$ m short of the MSL value.

extrinsic factors as statistically significant explanatory variables in the best-fitted GLMM describing source levels; see Equation (1). That said, our results support the necessity to use standardized approaches to conduct hydrophone-based recordings of underwater noise sources. The backpropagation methods used to estimate ships' source levels from hydrophone measurements also needs to be adapted to both the experimental setup and environmental characteristics to control as much as possible for the biasing factors. In particular, the commonly used geometrical spreading laws are clearly unadapted to some complex underwater environments, leading to an under-estimation of the backpropagated source levels.

3. Error estimation and propagation need to be refined as source level measurements provided in the literature never include envelopes of uncertainty.

This study recommends that:

1. Narrowband or 1/3-octave band measurements of ships' source levels instead of broadband values should be made available to the scientific community. Our study demonstrated that the interpretation of broadband source levels is subject to confusion, hence making the comparison between studies that focus on ships' underwater radiated noise particularly difficult. The publication of narrowband measurements would definitely benefit our field of study and contribute to facilitate the data interpretation of secondary users of ships' source level measurements.
2. In order to properly quantify the impact of individual *intrinsic* factors (e.g., speed, load, draft, working engines) on the underwater noise radiated by merchant ships and ultimately mitigate them, control experiments could be designed in order to favor the simultaneous control and monitoring of the factors contributing to ships' noise. This way, the impact of a single factor (e.g., ships' speed, ships' load, number of engines in operation) can be quantified while others are kept constant. This approach, although more costly, will help to gain a better understanding of onboard noise sources and could serve as a baseline to improve the interpretation of the growing number of ships' source level data coming from opportunistic measurements.

DATA AVAILABILITY STATEMENT

The datasets for this manuscript are not publicly available because Data were provided during the submission process. Requests to access the datasets should be directed to clement.chion@uqo.ca.

AUTHOR CONTRIBUTIONS

Review of literature, data processing, and statistical analysis were conducted by DL. CC was responsible for reaching out to authors in order to obtain methodological details that were not *a priori* available in the original studies. Responsibilities for the redaction, figures, and tables processing of this manuscript were equally shared between DL and CC. JD contributed to the revision of the early versions of this paper and also provided funding to support this work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2019.00714/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

APPENDIX

Mathematical Formalism of Empirical Source Level Models

Equations for the empirical source level models mentioned in sections 5.2 and 5.3.2. are provided in **Table A1**.

TABLE A1 | Models' mathematical formalism.

Selected articles	Equations
Audoly and Rizzuto, 2015	Individual model for each vessel class. See the authors' section 5. Detailed example for cargo ships: $SL(f,v) = SL_{mach}(f,v) + SL_{prop}(f,v) + SL_{cav}(f,v)$ $SL_{mach}(f,v) = 136 + 15\ \log_{10}(v)$ if $f \leq 200$ Hz $SL_{mach}(f,v) = 186 - 22\ \log_{10}(f) + 15\ \log_{10}(v)$ if $f > 200$ Hz $SL_{prop}(f,v) = 109 - 5\ \log_{10}(f) + 50\ \log_{10}(v)$ if $f \leq 80$ Hz $SL_{prop}(f,v) = 156 - 30\ \log_{10}(f) + 50\ \log_{10}(v)$ if $f > 80$ Hz $SL_{cav}(f,v) = 79 + 10\ \log_{10}(f) + 60\ \log_{10}(v)$ if $f \leq 50$ Hz and $v \geq v_{cav}$ $SL_{cav}(f,v) = 129 - 20\ \log_{10}(f) + 60\ \log_{10}(v)$ if $f > 50$ Hz and $v \geq v_{cav}$ $SL_{cav}(f,v) = 0$ if $v < v_{cav}$ where f and v are in units of Hertz and knots, and $v_{cav} = 10$ knots.
Breeding et al., 1996	$SL(f,v,\ell) = SL_0(f) + 60\log_{10}\left(\frac{v}{12}\right) + 20\log_{10}\left(\frac{\ell}{300}\right) + \mathrm{d}f \times \mathrm{d}\ell + 3.0$ $SL_0(f) = -10\ \log_{10}(10^{-1.06\ \log_{10}(f) - 14.34} + 10^{3.32\ \log_{10}(f) - 21.425})$ if $f \leq 500$ Hz $SL_0(f) = 173.2 - 18\ \log_{10}(f)$ if $f > 500$ Hz $\mathrm{d}f = 8.1$ if $f \leq 28.4$ Hz $\mathrm{d}f = 22.3 - 9.77\ \log_{10}(f)$ if $f > 28.4$ Hz $\mathrm{d}\ell = \left[\frac{\ell^{1.15}}{3643.0}\right]$ where f, v and ℓ are respectively in units of Hertz, knots, and feet.
Chion et al., 2017	$SL(f,v,\ell) = SL_0(f) - \left[\frac{144.7}{v-12}\right]\log_{10}\left(\frac{v}{12}\right) + 20\log_{10}\left(\frac{\ell}{300}\right) + \mathrm{d}f \times \mathrm{d}\ell$ $SL_0(f) = -10\ \log_{10}(10^{-1.06\ \log_{10}(f) - 14.34} + 10^{3.32\ \log_{10}(f) - 21.425})$ if $f \leq 500$ Hz $SL_0(f) = 173.2 - 18\ \log_{10}(f)$ if $f > 500$ Hz $\mathrm{d}f = 8.1$ if $f \leq 28.4$ Hz $\mathrm{d}f = 22.3 - 9.77\ \log_{10}(f)$ if $f > 28.4$ Hz $\mathrm{d}\ell = \left[\frac{\ell^{1.15}}{3643.0}\right]$ where f, v and ℓ are respectively in units of Hertz, knots, and feet.
Luo and Yang, 2011	$SL(f,v,T) = SL_0(v,T) + 20 - 20\ \log_{10}(f_0(v))$ if $f \leq f_0(v)$ $= SL_0(v,T) + 20 - 20\ \log_{10}(f)$ if $f > f_0(v)$ $SL_0(v,T) = 112 + 50\ \log_{10}\left(\frac{v}{10}\right) + 15\log_{10}(T)$ $f_0(v) = 1000 - 900\left[\frac{v}{40}\right]$ where f, v and T are respectively in units of Hertz, knots, and tons.
Ross and Alvarez, 1964	$SL(f,v,\ell) = 190.5 + 50\ \log_{10}\left(\frac{v}{10}\right) + 20\ \log_{10}\left(\frac{\ell}{150}\right) - 20\ \log_{10}(f)$ where f, v and ℓ are respectively in units of Hertz, knots, and meters.
Simard et al., 2016	$SL(f,\ell,b,d,v) = 285.40 + 0.0496\ f - 4.8 \times 10^{-7}\ (f - 2108.26)^2 - 69.33\ \log_{10}(f) -$ $49.29\ (\log_{10}(f) - 2.70016)^2 - 58.50\ (\log_{10}(f) - 2.70016)^3 -$ $41.54\ (\log_{10}(f) - 2.70016)^4 - 7.62\ (\log_{10}(f) - 2.70016)^5 +$ $13.47\ \log_{10}(\ell) - 0.55\ b + 0.0008\ (b - 26.8854)^3 + 0.706\ d +$ $20.164\ \log_{10}(v) - 505.1\ (\log_{10}(v) - 1.12024)^3 + 2891.9\ (\log_{10}(v) - 1.12024)^5$ where f, ℓ, b, d, and v are respectively in units of Hertz, meters, meters, meters, and knots.
Urick, 1983	$SL(f,v,T) = 95 + 60\ \log_{10}(v) + 9\ \log_{10}(T) - 20\ \ \log_{10}(f)$ where f, v and T are respectively in units of Hertz, knots, and tons.
Wales and Heitmeyer, 2002	$SL(f) = 230 - 45.94\ \log_{10}(f) + 9.17\ \log_{10}\left[1 + \left(\frac{f}{340}\right)^2\right]$ where f is in units of Hertz.

Intrinsic factors v, ℓ, b, d, and T are respectively the ship's speed, length, breadth, draft, and tonnage. Frequency is f in Hz units.