Slowing deep-sea commercial vessels reduces underwater radiated noise

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During 2017, the Vancouver Fraser Port Authority's Enhancing Cetacean Habitat and Observation program carried out a two-month voluntary vessel slowdown trial to determine whether slowing to 11 knots was an effective method for reducing underwater radiated vessel noise. The trial was carried out in Haro Strait, British Columbia, in critical habitat of endangered southern resident killer whales. During the trial, vessel noise measurements were collected next to shipping lanes on two hydrophones inside the Haro Strait slowdown zone, while a third hydrophone in Strait of Georgia measured vessels noise outside the slowdown zone. Vessel movements were tracked using the automated identification system (AIS), and vessel pilots logged slowdown participation information for each transit. An automated data processing system analyzed acoustical and AIS data from the three hydrophone stations to calculate radiated noise levels and monopole source levels (SLs) of passing vessels. Comparing measurements of vessels participating in the trial with measurements from control periods before and after the trial showed that slowing down was an effective method for reducing mean broadband SLs for five categories of piloted commercial vessels: containerships (11.5 dB), cruise vessels (10.5 dB), vehicle carriers (9.3 dB), tankers (6.1 dB), and bulkers (5.9 dB).

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I. INTRODUCTION

Marine shipping has long been recognized as a major source of underwater noise (Wenz, 1962) and is often the predominant source of man-made noise near major ports and shipping routes (NRC, 2003). Chronic noise from marine shipping has the potential to negatively affect marine animals that use sound for performing critical life functions (Richardson *et al.*, 1995). A number of at-risk cetacean species inhabit the protected waters of southern British Columbia and northern Washington State, referred to as the Salish Sea. In this region, marine shipping is the dominant source of underwater ambient noise (Bassett *et al.*, 2012). Key among these species is the endangered southern resident killer whale (SRKW), with a population of only 74 individuals as of 2018 (Center for Whale Research, 2018). This population was designated as endangered under Canada's Species at Risk Act in 2001, which initiated the development of a recovery strategy (DFO, 2011, 2016) and an action plan (DFO, 2017) to address the current threats to northern resident killer whales and SRKWs in Canadian Pacific waters. This recovery strategy designates much of the Salish Sea as SRKW critical habitat—the habitat necessary for the survival or recovery of the species. Under the U.S. Endangered Species Act, critical habitat has also been designated over much of the U.S. waters of the Salish Sea. These designations offer the species legal protection of vital habitat functions (e.g., ability to feed, socialize, and rest). As with other odontocetes, killer whales (*Orcinus orca*) use sound to navigate, communicate, and locate prey via echolocation. Thus, underwater noise generated by vessels can degrade their acoustical habitat and impede their life functions.

As part of its mandate to better understand and manage the impact of shipping activities on at-risk whales, the Vancouver Fraser Port Authority's (VFPA's) Enhancing Cetacean Habitat and Observation (ECHO) program organized and managed a voluntary vessel slowdown trial in Haro Strait. The trial investigated noise reductions in SRKW habitat that could be obtained by asking vessels to voluntarily reduce their speed through water to 11 knots. Vessels are usually quieter when traveling more slowly due to decreased propeller cavitation and machinery vibration. The trial focused primarily on piloted commercial vessels, but all types of motorized water craft were encouraged to participate. The trial ran from 7 August to 6 October 2017, during the time of year when SRKW density is historically highest in Haro Strait. Vessel source level (SL) measurements were carried out during the slowdown trial by JASCO Applied Sciences (JASCO), an international acoustical consulting and applied research company with Canadian branches located in Victoria, British Columbia, and Dartmouth, Nova Scotia.

This article describes the dedicated acoustic SL study that was carried out before, during, and after the slowdown trial to measure how vessel noise emissions were affected by

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the slowdown protocol. Calibrated sound recordings were collected on two hydrophone stations, situated directly adjacent to the northbound and southbound Haro Strait traffic lanes, to obtain high-quality SL measurements of individual vessels. A land-based automated identification system (AIS) receiver tracked vessels passing the Haro Strait hydrophone stations during the trial. Additional measurements from a third, cabled hydrophone station in the Strait of Georgia were used for measuring noise from vessels transiting at normal speed after leaving the slowdown zone.

Hydrophone data from these three stations were analyzed using an automated vessel noise measurement system (PortListen®) developed by JASCO. This system tracked passing vessels on AIS and automatically measured their underwater acoustic SLs using calibrated hydrophone data. To determine if slowdowns are an effective mitigation method for reducing vessel noise emissions, SLs were measured during the slowdown trial and the pre-trail and post-trial control periods.

II. METHODS

A. Slowdown trial overview

JASCO deployed two autonomous hydrophone stations inside the slowdown zone (Fig. 1) to measure SLs of transiting vessels. These Haro Strait hydrophones were installed one month before the trial started (on 6 July 2017) and removed three weeks after the trial ended (on 26 October 2017). The purpose of collecting data outside the trial period was to measure baseline vessel noise emissions and to provide experimental controls for the SL analysis. Additional vessel noise measurements outside the slowdown zone were captured on a cabled hydrophone array at the ECHO Strait of Georgia Underwater Listening Station (ULS; Hannay *et al.*, 2016).

From 7 August through 6 October 2017 (60 days), vessels were requested to voluntarily reduce their speeds to a target of 11 knots through water inside a designated slowdown zone in Haro Strait. At the completion of each piloted transit, British Columbia (BC) Coast Pilots reported to the Pacific Pilotage Authority (PPA) on the vessel's participation. A dataset that amalgamated the PPA logs of vessel participation with AIS information on vessel speeds (corrected for water currents) over the Haro Strait slowdown area was provided to JASCO for correlation with the noise measurements.

B. Hydrophone stations

The Haro Strait hydrophone stations consisted of two calibrated JASCO AMAR-G3 (Autonomous Multichannel Acoustic Recorders-Generation 3) units, deployed on subsea moorings next to the northbound and southbound traffic lanes. Mooring deployments and retrievals in Haro Strait were conducted using the *R/V Richardson Point*, a 20 m research vessel. After deploying the moorings, their precise on-bottom locations were surveyed to an accuracy of ±4 m using a surface-based transducer that measured the distance to their acoustic releases (Teledyne Benthos 875-T, Falmouth,

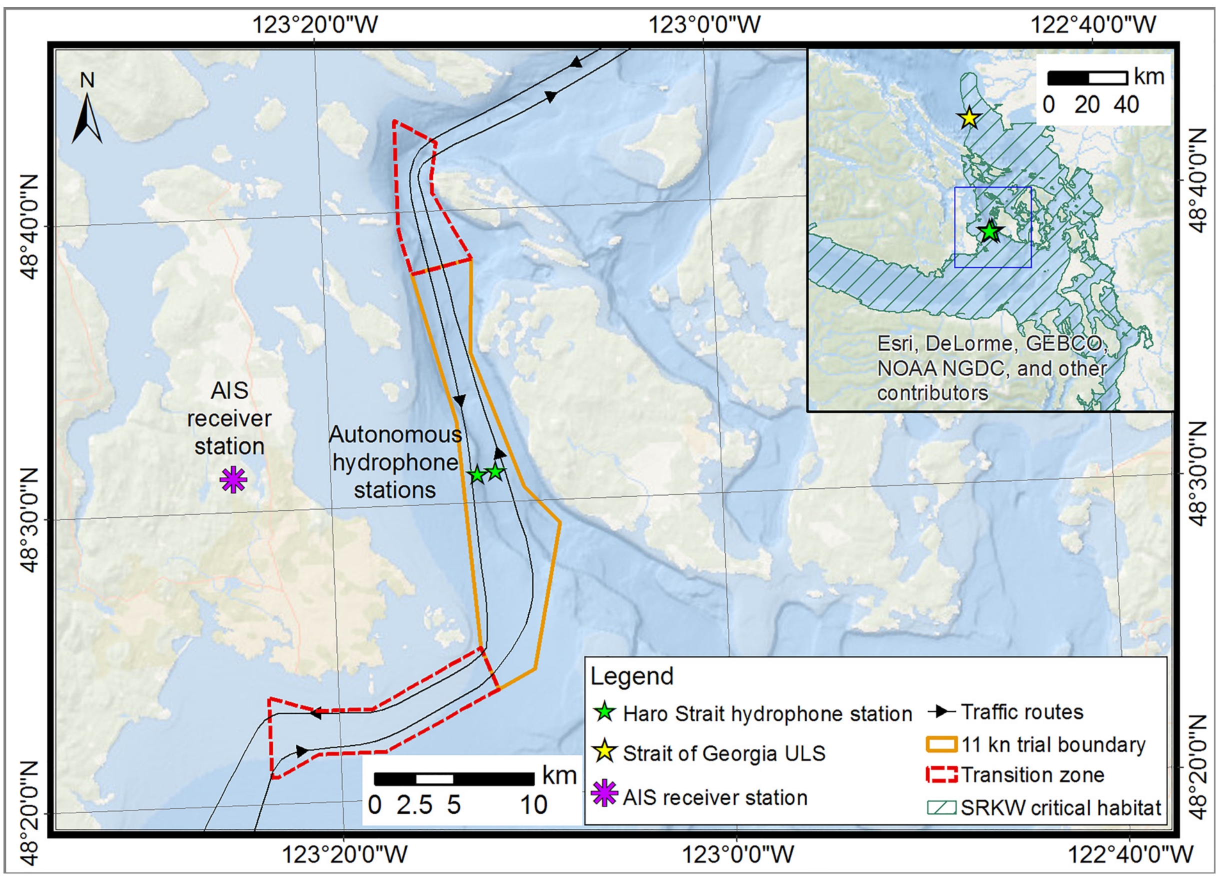

FIG. 1. (Color online) Map of slowdown trial boundary and hydrophone station locations in Haro Strait and Strait of Georgia. Locations of northbound and southbound vessel traffic routes were based on historical AIS ship tracking data.

MA). Water depths were 250 m at the northbound-lane AMAR and 210 m at the southbound-lane AMAR with hydrophones situated 3 m above the seabed.

Each AMAR used an M36 omnidirectional hydrophone (GeoSpectrum Technologies Inc., Dartmouth, Nova Scotia, Canada, -165 ± 3 dB re 1V/μPa nominal sensitivity) for measuring underwater sound pressure. The AMARs were programmed with a variable-bandwidth recording cycle to sample acoustic data at 96000 Hz for 21 h per day [09:00–06:00 PDT (Pacific Daylight Time)] and 128000 Hz for 3 h per day (06:00–09:00 PDT). The recording channel had 24-bit resolution with a spectral noise floor of 20 dB re 1 μPa^2/Hz and a nominal ceiling of 168 dB re 1 μPa. Each AMAR stored the hydrophone data on 1792 GB of internal solid-state flash memory. The frequency-dependent laboratory calibration of each AMAR and hydrophone was verified before and after deployment at 250 Hz using a Pistonphone Type 42AC precision sound source (G.R.A.S. Sound and Vibration A/S, Holte, Denmark) to ensure the sensitivity of the hydrophones did not change over the deployment period.

Additional vessel noise measurements at normal transit speeds were captured on the ECHO Strait of Georgia ULS, which was a real-time hydrophone node installed on the Victoria Experimental Network Under the Sea (VENUS) Observatory operated by Ocean Networks Canada. The Strait of Georgia ULS was situated on the seabed at 173 m water depth in the northbound traffic lane, approximately 30 km southwest of Vancouver. It recorded hydrophone data at a sampling rate of 64000 Hz with 24-bit resolution using a digital streaming version of the same AMAR G3 electronics used in the Haro Strait autonomous recorders.

C. AIS receiver

An AIS receiver was deployed atop Observatory Hill, approximately 17 km west of the Haro Strait hydrophone stations (Fig. 1). The receiver, which was located near the hilltop at the Herzberg Institute of Astrophysics, captured ship tracking data for the duration of the slowdown trial. The AIS receiver consisted of an SR161 scanning VHF (very high frequency) radio receiver and a 1.22 m whip antenna connected to a notebook personal computer (PC). Logging software (NMEA Router, Arundale) stored the raw AIS records on an internal hard disk on the PC, and chart plotting software (ShipPlotter, COAA, Portimão, Portugal) displayed the received ship tracks in real time. Data from the AIS receiver were periodically backed up to JASCO's servers in Victoria over the cellular network via a mobile Wi-Fi stick. Raw AIS data from the receiver were fed into the PortListen system to analyze the vessel SLs. Vessel tracks from the AIS receiver were matched to vessel transits recorded in the pilot logs according to international maritime organization (IMO) numbers and transit times.

D. SL calculation

The PortListen system analyzes underwater radiated noise measurements and AIS broadcasts from passing vessels to calculate vessel SLs in terms of radiated noise level (RNL) and monopole source level (MSL). While both RNL and MSL measurements are collectively referred to here as SLs, RNL is actually an affected SL (i.e., a SL measurement affected by surface and seabed reflections). Only MSL strictly corresponds to the ISO standard definition of a SL (ISO, 2017). Both quantities are reported here so that measurements from this study can be more easily compared with those from other studies.

For time periods when a passing vessel was detected on AIS, the system processed hydrophone data to obtain standard decidecade (i.e., 1/3-octave) band sound pressure level (SPL) inside a data window encompassing $\pm 30°$ of the vessel's closest point of approach (CPA) to the hydrophone, according to the methods specified in the ANSI S12.64 ship noise measurement standard (ANSI, 2009). PortListen automatically determined the measurement window and processed a single channel of hydrophone data in 1-s periods stepped in 0.5-s intervals (Fig. 2) using a Hanning-windowed fast Fourier transform (FFT). It used the AIS speed and vessel position together with a cepstral analysis of the Lloyd-mirror pattern to determine the timing and location of the CPA of the vessel to the hydrophone. The software calculated background noise in each frequency band when the vessel was more than 2 km away, and the measured vessel sound levels were corrected if they exceeded background by 3–10 dB or rejected if they were less than 3 dB above background, per the ANSI S12.64 standard (ANSI, 2009).

RNL was calculated assuming spherical spreading propagation loss [i.e., $\mathrm{PL} = 20 \times \log_{10}(r)$], per the ANSI standard, whereas MSL was calculated using a frequency-dependent PL model, based on the numerical solution of the acoustic wave equation, which accounts for the effect of the environment on sound transmission. Since no single acoustic model is applicable at all sampled ranges and frequencies, a hybrid PL model was used to calculate MSL as follows:

(1) At frequencies less than 4 kHz and ranges less than 120 m, PL was calculated using a wavenumber integration model (Hannay *et al.*, 2010; Jensen *et al.*, 2011), which computes reflection coefficients for layered elastic media (Brekhovskikh, 1980).

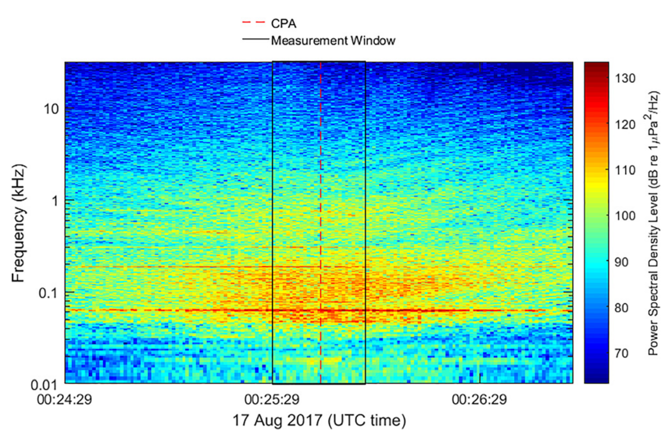

FIG. 2. (Color online) Spectrogram of a single vessel measurement, showing the CPA time (dashed line) and the measurement window (black box) used for calculating vessel SLs. Acoustic data were processed using 1-s fast Fourier transforms (FFTs; 50% overlap), shaded using a power-normalized Hanning window.

(2) At frequencies less than 4 kHz and ranges greater than 240 m, PL was calculated using a wide-angle parabolic equation model (Collins, 1993), modified to treat reflection losses for an elastic seabed using a complex-density equivalent fluid approximation (Zhang and Tindle, 1995).
(3) At frequencies less than 4 kHz and ranges between 120 m and 240 m, PL was calculated from the average of the parabolic equation and wavenumber integration models.
(4) At frequencies greater than 4 kHz, PL was calculated using an image-method model (Brekhovskikh and Lysanov, 2003), which accounts for surface and seabed reflection coefficients and frequency-dependent absorption (François and Garrison, 1982).

Average PL in each decidecade band was based on the mean propagation factor calculated at 50 frequencies, which were spaced logarithmically between the minimum and maximum band limits. Mean source depth for the MSL calculation was taken to be half the vessel static draft reported on AIS. The PL was smoothed by assuming the source depth had a Gaussian distribution in a manner similar to Wales and Heitmeyer (2002), in which the standard deviation was taken to be 30% of the source depth. Additional details regarding the automated SL measurement system are given in Hannay *et al.* (2016). Seabed geoacoustic profiles for the Haro Strait and Strait of Georgia sites were determined via inversion of transmission loss measurements obtained using a controlled sound source (Warner *et al.*, 2014).

To ensure high data quality, only SL measurements with CPA less than 1000 m from the hydrophones in Haro Strait were accepted for subsequent analysis. In addition, an experienced acoustic analyst performed a manual and systematic quality review of every SL measurement. For each measurement, the analyst inspected the vessel track, spectrogram, background noise levels, received levels, and SLs. Measurements were rejected under the following circumstances:

(1) When other AIS vessels were present within six times the measured CPA of the vessel of interest;
(2) When spectrograms visibly contained contaminating noise from sources other than the vessel of interest (including non-AIS vessels);
(3) When measurements had three or more decidecade bands with signal-to-noise-ratio less than 3 dB in the range 50–1000 Hz;
(4) When vessel tracks had an unsteady speed or heading in the measurement window.

E. Noise reduction analysis

SL measurements of piloted vessels in Haro Strait (i.e., inside the trial boundary) were assigned to one of the following trial groups based on the pilot participation logs:

(1) Control (measurements outside the trial period),
(2) Trial non-participants (vessels that did not slow down for the trial), and
(3) Trial participants (vessels that slowed down for the trial).

Five categories of vessels were captured in sufficient numbers in the pilot logs to be included in the trial groups:

(1) Containerships,
(2) Bulk carriers and general cargo (hereafter referred to as "bulkers"),
(3) Tankers,
(4) Vehicle carriers, and
(5) Cruise ships (hereafter referred to as "cruise").

Measurements were assigned to these categories based on vessel types identified in the pilot logs. Other categories of vessels were measured on the Haro Strait hydrophones but were not represented in the pilot logs and were therefore excluded from the trial groups. In rare instances, the vessel participation status from the pilot dispatch did not match the AIS speed. This resulted in participating vessels being identified as non-participants or vice versa. To account for these discrepancies, a small number of measurements with outlying speeds in the non-participant and participant groups were discarded from the trial groups.

SL measurements were analyzed in the following three frequency bands, which were recently identified by an expert working group convened by the Coastal Ocean Research Institute (CORI; Heise *et al.*, 2017) as being best suited for assessing the acoustical quality of SRKW habitat:

(1) Broadband (10–100 000 Hz) for evaluating behavioral or physiological impacts,
(2) Communication masking (500–15 000 Hz) for evaluating effects of noise on SRKW communication space, and
(3) Echolocation masking (15 000–100 000 Hz).

MSL measurements were evaluated for all three SRKW frequency bands (broadband, 0.5–15 kHz, and >15 kHz), whereas RNL measurements were evaluated only for broadband noise. MSL was the preferred metric for reporting SLs in the SRKW communication and echolocation bands because MSL better accounts for the effect of the environment on vessel SLs (e.g., from absorption, surface, and seabed reflections) than RNL.

Trends of SL versus speed were analyzed based on speed through water, as calculated from vessel speed over ground (from AIS) with speed and direction data for surface currents. Surface currents in the Strait of Georgia were obtained directly from acoustic Doppler current profiler (ADCP) measurements at the ECHO ULS. Time-dependent surface currents in Haro Strait were predicted using the Bedford Institute of Oceanography's WebTide model (Hannah *et al.*, 2008). Surface current measurements were not available for verifying the model in Haro Strait, but the WebTide predictions were found to be in good agreement with ADCP data at the ECHO ULS (mean and standard deviation model-data residuals were 0.03 ± 0.11 m/s).

Where SL measurements were obtained at different speeds, trend analysis was performed using Ross's classical power law model (Ross, 1976), which relates change in SL to relative changes in speed,

$$\mathrm{SL}(\mathrm{v}) - \mathrm{SL}_{\mathrm{ref}} = C_v \times 10 \log_{10}\left(\frac{v}{v_{\mathrm{ref}}}\right). \quad (1)$$

In this equation, SL(v) is the SL at speed through water v, $\mathrm{SL}_{\mathrm{ref}}$ is the SL at some reference speed v_{ref}, and C_v is a coefficient corresponding to the slope of the curve. Equation (1) was assumed to apply both to RNL and MSL.

The effects of voluntary slowdowns on vessel noise emissions were evaluated by comparing measurements in the participant group with measurements in the non-participant and control groups. The statistical significance of differences between the three trial groups were tested using a pairwise-t test[1] to test the experimental hypothesis (e.g., that mean SLs in the participant group were significantly lower than in the control group) against the null hypothesis (e.g., that mean SLs in the participant group were the same as in the control group).

III. RESULTS

A. Measurement summary

A total of 2765 vessel SL measurements were collected during the control and trial periods on the two hydrophone stations in Haro Strait and on the Strait of Georgia ULS. Of these measurements, which included non-piloted vessels, 1930 were accepted (i.e., passed the manual quality review). A total of 920 (out of 951) transits in the pilot logs were matched to vessel measurements during the slowdown trial period (many northbound transits matched two different measurements, as vessels were measured once in Haro Strait and once again in the Strait of Georgia). Summary statistics of vessel design characteristics and drafts were calculated from data broadcast over AIS during the study (Fig. 3).

Based on the logs, a total of 1340 SL measurements were assigned to the three experimental groups identified in Sec. II E. Twenty-three of these measurements were discarded because their measured speeds were inconsistent with the pilot participation logs, resulting in 1317 valid SL measurements for analysis. Analysis of the vessel tracks showed that 94% of vessels transiting through the slowdown zone passed within 1 km of the two hydrophones (mean and standard deviation horizontal CPA = 445 ± 313 m).

To investigate how speeds in different vessel categories were affected by slowdown participation, we calculated statistics of vessel speeds through water for the participant, non-participant, and control groups (Fig. 4). Of the 951 piloted transits through Haro Strait during the slowdown trial, 577 transits (or 61%) were reported as participating. While not all participating vessels achieved the target slowdown speed of 11 knots through water, 75% of participating vessels traveled 12 knots or slower and 95% of participating vessels traveled 13 knots or slower at the time of measurement on the Haro Strait hydrophones. Pairwise t-tests showed that mean speeds in the participant group were significantly less than those in the non-participant and control groups for all categories (Table I). Mean speed reductions were greatest for containerships (7.7 knots) and smallest for bulkers (2.1 knots).

The mean speeds of non-participant vessels were also found to be slightly lower than the control group for bulkers and vehicle carriers (cruise vessels had too few non-participant transits to compare with the trial period). This could indicate that non-participant vessels in these categories also slowed down slightly during the trial period, or it could be due to a small number of participating vessels being recorded as non-participants in the pilot logs. Regardless of the reason, the SL reduction for each category was therefore calculated based only on the differences between the participant group and the control group.

Vessel speed and SL statistics were calculated separately for measurements in seven additional vessel categories that were not captured in the pilot logs and therefore lacked information on slowdown participation (tug, fishing, government/research, naval, small passenger, recreational, and other vessels). In Haro Strait, 225 measurements in these

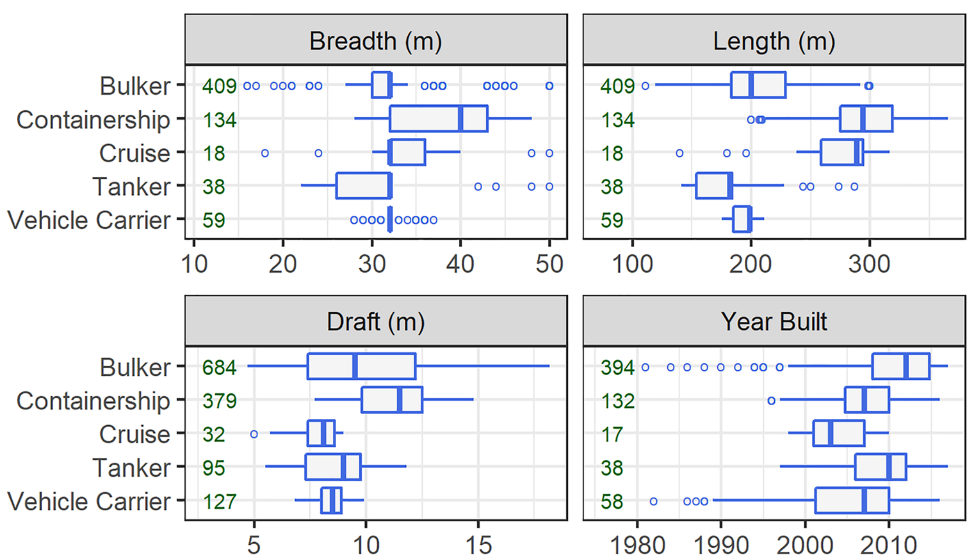

FIG. 3. (Color online) Box-and-whisker plots showing summary statistics for breadth, length, draft, and year built, versus vessel category, as broadcast over AIS. The total number of samples is indicated to the left of each box. Missing values are not counted, and some obviously incorrect values have been manually removed. Statistics of breadth, length, and year built are for unique vessels only (i.e., multiple measurements of the same vessel are counted only once). The ends of the box show the upper and lower quartiles and the line inside the box shows the median. The whiskers and dots extend outside the box to the highest and lowest observations, where the dots correspond to observations that fall more than 1.5 × IQR (interquartile range) beyond the upper and lower quartiles.

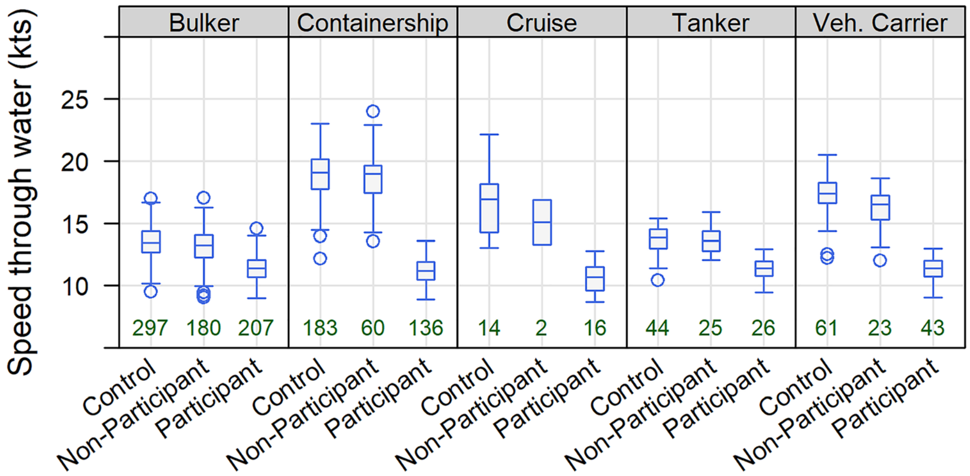

FIG. 4. (Color online) Box-and-whisker plots for five vessel categories, comparing speed through water in Haro Strait (at CPA) between the control, non-participant, and participant groups (accepted measurements only, excluding outlier speeds). The total number of measurements is indicated below each box. See Fig. 3 for an explanation of the box-and-whisker plots.

7 categories were assigned to 1 of 2 groups (control and trial), depending on when they were collected. Of these categories, only naval vessels were found to have a statistically significant reduction in mean speed (5.3 knots, $p = 0.001$) between the control and trial periods. While they were not captured in the pilot participation logs, vessels from the Royal Canadian Navy (RCN) were anecdotally confirmed as participating in the trial (all but three accepted measurements in the naval category were RCN vessels). Vessels in the remaining six categories did not appear to have reduced their speeds in significant numbers during the trial.

B. Effect of trial participation on SLs

To investigate the effects of the voluntary slowdown on vessel SLs, statistics of SLs across the participant, non-participant, and control groups were calculated (Fig. 5). In all five vessel categories, SLs (RNL and MSL) were lower in the participant group than in the control group at the 5th, 25th, 50th, 75th, and 95th quantiles. Pairwise t-tests showed strong evidence that mean SLs in the participant group were lower than those in the non-participant and control groups for all categories (Table II). Mean broadband SL (MSL) reductions ranged from 5.9 dB for bulkers to 11.5 dB for containerships. The CORI-band analysis showed that the reductions were frequency dependent with smallest mean reductions (3.1–10.8 dB) in the SRKW communication masking band (0.5–15 kHz) and greatest mean reductions (5.1–17.8 dB) in the SRKW echolocation band (>15 kHz). There was no evidence of significant differences in mean SLs between the non-participant and control groups for any vessel category, except for the broadband MSL of the bulker category, which was 1 dB lower during the trial for non-participants. This latter difference may be due to non-participating bulkers traveling 0.4 knot slower, on average, during the trial period than during the control period (see Table I). Note, however, that RNL source levels and MSLs above 500 Hz for bulkers did not show any significant differences between the non-participant and control groups.

TABLE I. Differences in mean vessel speeds (knots) between the participant, non-participant, and control groups (accepted measurements only). Asterisks indicate the statistical significance of the differences as determined from pairwise t-tests (* $=p < 0.05$, ** $=p < 0.01$, *** $= p < 0.001$). Boldface indicates a statistically significant difference ($p < 0.05$). Dashes indicate insufficient data.

Vessel category	Control versus Participant	Control versus Non-participant	Non-participant versus Participant
Bulker	**2.09*** **	**0.40** **	**1.69*** **
Containership	**7.67*** **	0.19	**7.48*** **
Cruise	**6.15*** **	—	—
Tanker	**2.30*** **	0.07	**2.23*** **
Vehicle Carrier	**5.89*** **	**1.03***	**4.87*** **

Noise reductions from the Haro Strait measurements were used to calculate equivalent speed scaling coefficients, according to Eq. (1), for the Ross power-law model (Table III). These speed coefficients (C_v) reflect the mean decibel reductions in SLs that were associated with the mean speed reduction measured in each category. It is important to note that the Ross model measures decibel changes in SL for relative changes in speed. Thus, for example, while the MSL scaling coefficient for bulkers ($C_v = 8.0$) was greater than that for containerships ($C_v = 5.0$), the overall broadband MSL reduction for bulkers (5.5 dB) was still smaller than that for containerships (11.0 dB) because participant containerships reduced their speed by a larger relative amount during the trial.

To investigate how slowdown participation affected frequency-dependent noise emissions, mean decidecade-band SLs (MSL) between the participant, non-participant, and control groups were compared (Fig. 6). SL reductions for participant vessels showed similar frequency dependence for all five categories: the largest reductions were generally below 100 Hz and above 1000 Hz, and the smallest reductions were in the intermediate-frequency range. This frequency-dependence was likely due to the different noise generating mechanisms that dominate different parts of the radiated vessel noise spectrum—e.g., cavitation often dominates at very low and very high frequencies, whereas

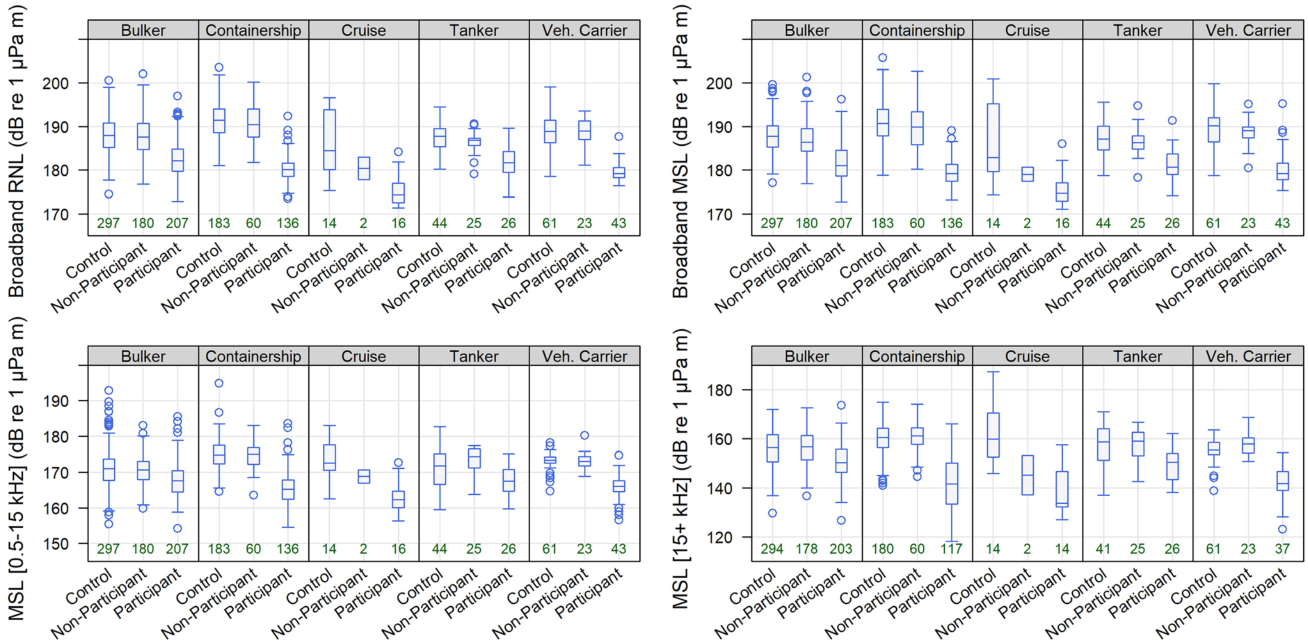

FIG. 5. (Color online) Box-and-whisker plots for the five vessel categories, comparing SLs in Haro Strait between the control, non-participant, and participant groups: broadband RNL, broadband MSL, MSL (0.5–15 kHz; SRKW communication masking), and MSL (15+ kHz; SRKW echolocation masking). The total number of measurements is indicated below each box. See Fig. 3 for an explanation of the box-and-whisker plots.

machinery noise dominates at middle frequencies (Kipple and Gabriele, 2007). A peak in the 25-kHz band for cruise vessels was observed during at least six cruise vessel measurements from the post-trial control period. Discussions with the cruise ship operators indicated that these narrow-band noise emissions originated from depth sounders used for navigational safety. We found no evidence of similar noise emissions during the slowdown trial period. As the sample size for cruise vessels was small (14 control period, 16 participating, and 2 non-participating), the peak at 25 kHz resulting from the use of depth sounders by some vessels limited the comparative analysis between control and trial periods in this decidecade band (and in the SRKW echolocation band >15 kHz).

For the seven categories of vessels not captured in the pilot logs, only naval vessels showed clear evidence of reduced noise emissions during the trial period. The mean broadband MSL of RCN vessels was 6.3 dB lower during the trial than during the control period, but this value should not be considered a high-confidence estimate because it was based on a small number of measurements ($n = 19$). Furthermore, SLs of naval vessels were already quite low, which resulted in relatively high numbers of rejections due to insufficient signal-to-noise ratios.

C. Effect of speed on SLs for individual vessels

Several factors other than speed, such as draft, size, and loading, may influence the underwater noise emissions of individual vessels. Furthermore, different vessels in the same category may normally transit at different service speeds and have different baseline noise emissions (due to differences in vessel design). To control for these effects, reduced-speed SLs measured on the Haro Strait hydrophones were directly compared with service-speed SLs of the same vessels measured on the Strait of Georgia ULS. To ensure consistency of vessel operating conditions (e.g., loading and draft), measurements were compared only if they were collected on the same northbound transit under direction of the same pilot. A total of 107 matched pairs of measurements met these criteria (Fig. 7). Data from these repeated measurements were then fit to the Ross model [Eq. (1)] to determine the trend of vessel SLs with changes in speed (Table IV). Measurements from all five categories of vessels were pooled to fit a common trend line to all the data. In addition, separate trend lines were fit to the three vessel categories (bulker, containership, and tanker) that contained enough measurements to permit a regression analysis.

The best-fit speed scaling coefficients for all the data were highly significant and strongly positive ($3.4 < C_v < 6.5$) for all four SL metrics (a higher C_v value corresponds to a greater reduction of SL with decreasing speed). This analysis showed that reductions in vessel SLs associated with slower speeds were greatest above 15 kHz in the SRKW echolocation band and lowest between 0.5–15 kHz in the SRKW communication band. The slope of the MSL trend was greater than that of the RNL trend, which indicates frequencies below ~50 Hz were more strongly affected by changes in speed (MSL is more heavily weighted toward low frequencies). These results are consistent with the findings of the decidecade-band analysis (Sec. IIIB), which showed SL reductions were greatest at low and high frequencies (see Fig. 6). The category-specific trends were largely consistent with the trends of the pooled measurements to within the estimated uncertainty bounds of the best-fit coefficients. Therefore, the speed scaling coefficients derived from measurements of individual vessels were broadly consistent with speed scaling coefficients derived from analysis of the slowdown trial groups (i.e., Table III).

TABLE II. Differences in mean SLs (dB) between the participant, non-participant, and control groups (accepted measurements only). The uncertainty (±) indicates the 90% confidence interval of the difference (control versus participant only). Asterisks indicate the statistical significance of the differences, as determined from pairwise *t*-tests (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). Boldface indicates a statistically significant difference ($p < 0.05$). Dashes indicate insufficient or missing data (the MSL [15+ kHz] band for cruise ships in the control group was removed due to noise from depth sounders—see the text).

Vessel category	Control versus participant	Control versus non-participant	Non-participant versus participant
Broadband RNL			
Bulker	**5.56 ± 0.75*** **	0.26	**5.30*** **
Containership	**11.17 ± 0.79*** **	0.71	**10.46*** **
Cruise	**10.74 ± 4.54*** **	—	—
Tanker	**5.78 ± 1.70*** **	1.08	**4.70*** **
Vehicle carrier	**9.24 ± 1.14*** **	0.08	**9.16*** **
Broadband MSL			
Bulker	**5.91 ± 0.74*** **	**1.02** **	**4.89*** **
Containership	**11.52 ± 0.88*** **	1.08	**10.44*** **
Cruise	**10.52 ± 5.20*** **	—	—
Tanker	**6.08 ± 1.82*** **	0.77	**5.31*** **
Vehicle carrier	**9.25 ± 1.60*** **	0.75	**8.50*** **
MSL (0.5–15 kHz; SRKW communication masking)			
Bulker	**3.05 ± 0.90*** **	0.55	**2.50*** **
Containership	**9.29 ± 0.98*** **	0.20	**9.09*** **
Cruise	**10.78 ± 4.15*** **	—	—
Tanker	**3.59 ± 2.21*** **	−1.94	**5.53*** **
Vehicle Carrier	**7.42 ± 1.24*** **	0.02	**7.40*** **
MSL (15+ kHz; SRKW echolocation masking)			
Bulker	**5.18 ± 1.32*** **	0.00	**5.18*** **
Containership	**17.77 ± 2.12*** **	−0.63	**18.40*** **
Cruise	—	—	—
Tanker	**7.89 ± 3.79*** **	0.07	**7.82*** **
Vehicle carrier	**13.87 ± 2.48*** **	−2.00	**15.86*** **

IV. DISCUSSION

A. Comparison with past studies

Previous studies of underwater radiated noise from marine shipping generally indicate that SLs are proportional to vessel speed (in accordance with intuition) but reported trends were not necessarily consistent between studies. Measurements of post-World-War-II shipping suggested a strong power-law relationship between SLs and vessel speed ($C_v = 5$–6), and that this trend carried across different vessel types (Ross, 1976). Measurements of individual cargo vessels (Arveson and Vendittis, 2000) and cruise vessels (Kipple and Gabriele, 2007) also showed a strong positive relationship between SL and speed that was broadly consistent with the Ross model. On the other hand, statistical analyses based on measurements of large numbers of vessels in a seaway reported insignificant or relatively weak speed trends: two studies found no significant relationship with speed (Wales and Heitmeyer, 2002; McKenna *et al.*, 2012) and three other studies found speed trends in the range 0.8–1.1 dB/knot (McKenna *et al.*, 2013; Simard *et al.*, 2016; Veirs *et al.*, 2016), which were weaker than the trends reported here (Table V). The ability of these latter studies to determine speed trends was likely limited because vessels in a seaway typically do not deviate substantially from their design speeds.

The present study overcame this limitation by implementing a voluntary slowdown protocol, which provided the necessary experimental controls for a high-confidence determination of source-level-versus-speed trends for different categories of vessels. Gray and Greeley (1980) showed that changes in a vessel's SL depend on its design speed, not necessarily on its absolute speed. Thus, grouping similar vessels was also important for determining speed trends (e.g., as recognized by McKenna *et al.*, 2013) because different types of vessels have different design speeds. The large number of measurements collected in the present study permitted grouping measurements of similar vessels into distinct categories, while maintaining sufficient numbers of measurements in each category for statistical confidence. The larger speed variations within each category gave the present study greater power than previous studies to accurately characterize speed trends of noise emissions. These two features are likely the reasons for higher source-level-versus-speed trends reported here than reported by past studies that analyzed measurements of large numbers of vessels in a seaway.

It is interesting that the broadband trends reported here for modern vessels (mean and standard deviation year built was 2009 ± 6.3) were broadly consistent with those originally reported by Ross for post-World-War-II vessels. The broadband speed trends reported by Ross (1976) were attributed, in large part, to noise originating from propeller cavitation. For fixed-pitch propellers (which comprise most of the present-day merchant fleet), the intensity of cavitation noise is related directly to propeller rotation rate and follows a power law (Ross, 1976). This suggests that the broadband noise reductions observed during the slowdown trial may

TABLE III. Equivalent power-law speed scaling coefficients (C_v) calculated from the mean SL reductions measured during the slowdown trial. Speeds correspond to mean speed through water recorded at the time of measurement for each category. SL reductions for each vessel category were taken to be the difference between the participant and control groups in Table II.

Category	Mean control speed (knots)	Mean slowdown speed (knots)	C_v (Broadband RNL)	C_v (Broadband MSL)	C_v [MSL (0.5–15 kHz)]	C_v [MSL (15+ kHz)]
Bulker	13.47	11.38	7.59	8.07	4.17	7.01
Containership	18.88	11.21	4.93	5.08	4.10	7.85
Cruise	16.76	10.62	5.41	5.30	5.44	—
Tanker	13.68	11.39	7.24	7.63	4.51	9.88
Vehicle carrier	17.26	11.37	5.09	5.10	4.09	7.66

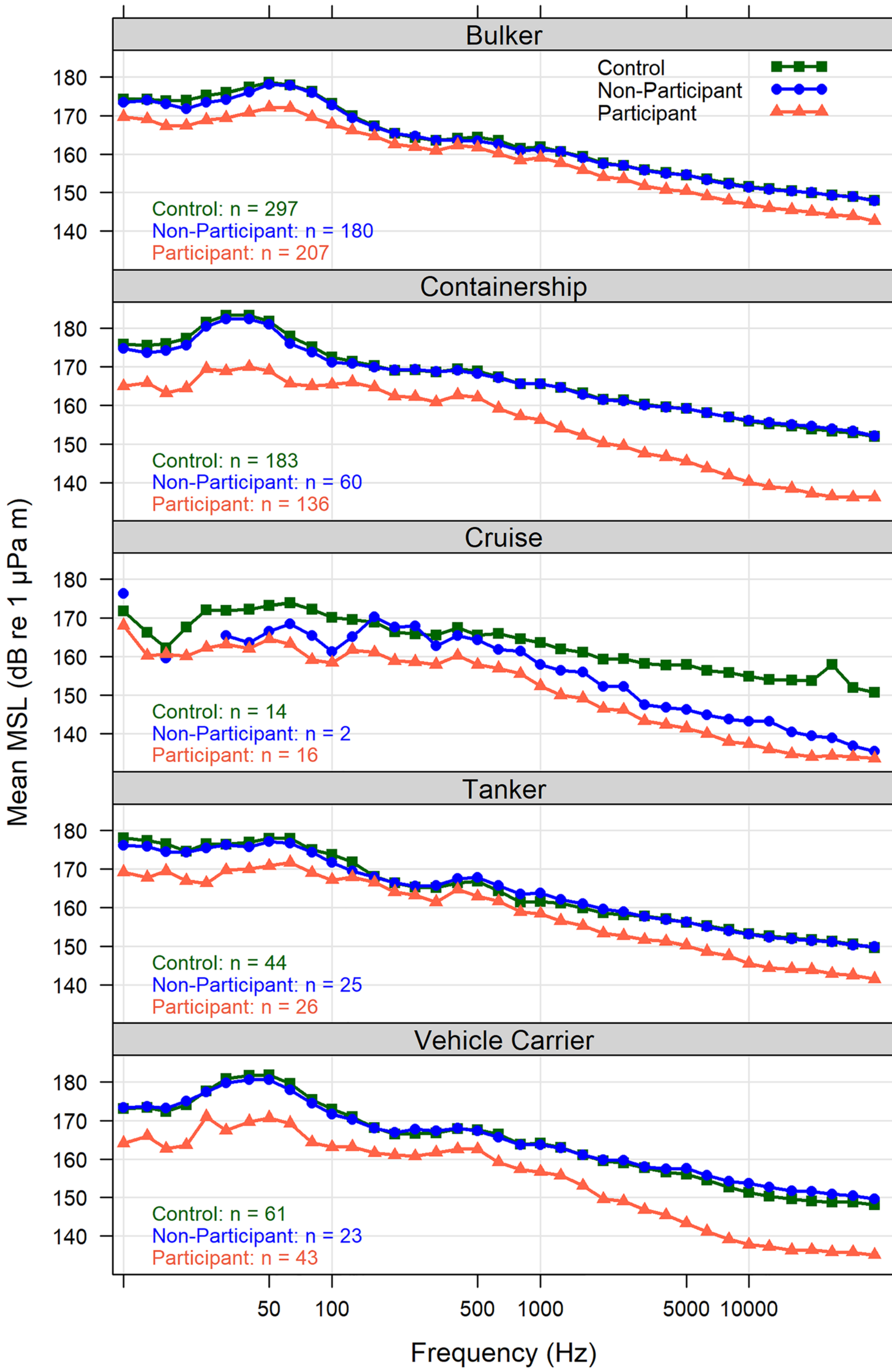

FIG. 6. (Color online) Mean MSL in decidecade frequency bands for the control, non-participant, and participant groups (Haro Strait measurements only). The total number of measurements in each group is indicated at the bottom of each panel. Missing data points below 30 Hz for non-participant cruise ships correspond to frequency bands with no valid measurements (i.e., where background noise exceeded signal level).

have been due, in large part, to reductions in cavitation noise, although additional research is needed to rigorously identify the importance of different noise generating mechanisms in this dataset. There is also evidence that variable-pitch propellers do not share the same noise-versus-rotation-rate characteristics as fixed-pitch propellers (Traverso *et al.*, 2015), and therefore slowdowns may not provide similar noise savings for vessels that use controllable-pitch propulsion (e.g., such as many of the ferries in the Salish Sea).

B. Benefit of slowdowns for SRKW

One possible drawback of slowdowns as a noise mitigation approach is that they prolong the overall time of noise exposure. This may result, e.g., in shorter durations of quiet periods between vessel transits and an increase in the minimum ambient noise level. Nonetheless, the overall noise sound exposure level (SEL) in any band, measured at a stationary receiver and assuming other noise sources do not

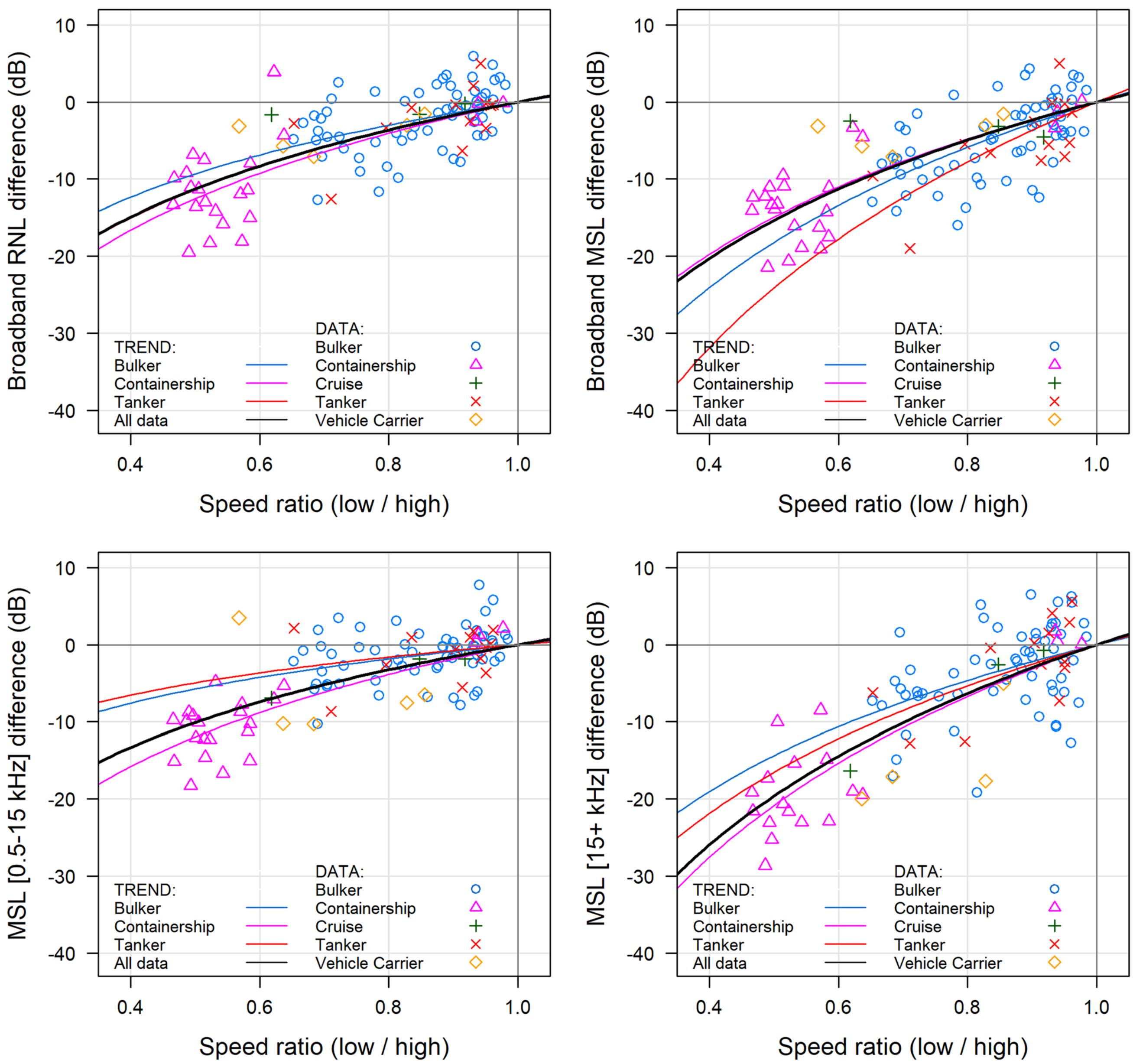

FIG. 7. (Color online) Change in SL versus speed ratio for vessels during the same northbound transit over the Haro Strait hydrophones and Strait of Georgia ULS (i.e., inside versus outside the slowdown zone). The lines are the best-fit trendlines, based on Eq. (1). Each point on the plots represents the difference in measured SLs for a pair of measurements (i.e., equal to the dB difference between the low-speed and high-speed measurement).

contribute, will be reduced for any single vessel transit provided that the speed scaling coefficient, C_v, exceeds 1 (Frankel and Gabriele, 2017). This criterion was amply met for all vessel categories and frequency bands analyzed in the present study. Thus, slowdowns are expected to provide a net reduction in noise exposure and average ambient noise level in SRKW critical habitat.

It is nonetheless important to consider the frequency dependence of specific mitigation measures when evaluating their benefits since broadband measures do not necessarily reflect the way that mammals use their acoustical environment. Analysis of the frequency dependence of the noise reductions, using the CORI bands, showed that the speed-related SL reductions were lower in the SRKW communication masking band (0.5–15 kHz) and greater in the SRKW echolocation masking band (MSL >15 kHz). Furthermore, sound propagation and baseline ambient noise is highly frequency-dependent, so changes in SLs do not necessarily reflect sound levels received by the animals themselves. Additional studies carried out through the ECHO program have used data presented here along with detailed modeling of vessel noise propagation and SRKW distribution to quantify the potential benefits of slowdowns on SRKW in their critical habitat (Joy *et al.*, 2019).

V. CONCLUSIONS

Analysis of 1317 SL measurements collected during the Haro Strait slowdown trial, and during the pre- and post-trial control periods, showed that slowing speed is an effective method for reducing underwater radiated noise from commercial vessels. We found statistically significant reductions

TABLE IV. Best-fit power-law speed scaling coefficients (C_v) calculated from SL measurements of the same vessels transiting northbound at different speeds over the Haro Strait hydrophones and Strait of Georgia ULS. The r^2 value indicates the fraction of data variance explained by the fitted model (i.e., the coefficient of determination). The uncertainty (±) indicates the 90% confidence interval of the fit. Asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

Fit parameter	Broadband RNL	Broadband MSL	MSL (0.5–15 kHz)	MSL (15+ kHz)
All data ($n = 107$)[a]				
C_v	3.75 ± 0.50***	5.10 ± 0.56***	3.35 ± 0.47***	6.52 ± 0.75***
r^2	0.677	0.755	0.653	0.752
Bulker ($n = 63$)[a]				
C_v	3.10 ± 1.00***	6.05 ± 1.15***	1.91 ± 0.89***	4.78 ± 1.52***
r^2	0.385	0.646	0.232	0.405
Containership ($n = 23$)[a]				
C_v	4.17 ± 0.78***	4.96 ± 0.71***	3.97 ± 0.55***	6.93 ± 0.94***
r^2	0.848	0.905	0.912	0.930
Tanker ($n = 13$)				
C_v	3.78 ± 2.74*	8.01 ± 3.25***	1.65 ± 2.45	5.50 ± 3.53**
r^2	0.429	0.706	0.151	0.490

[a]The n values were slightly lower in the MSL (15+ kHz) band for bulkers ($n = 59$) and containerships ($n = 19$) due to the lower signal-to-noise ratio in this frequency range.

in SLs for five categories of piloted vessels recorded on two hydrophone stations during the control and trial periods: containerships, bulkers, tankers, vehicle carriers, and cruise vessels. In all cases, reductions in noise emissions were proportional to changes in speed. Those categories with the fastest vessels (containerships, cruise vessels, and vehicle carriers) exhibited the greatest reductions, whereas categories with slower vessels (tankers and bulkers) exhibited more modest reductions. Mean reductions in broadband MSL were 11.5 dB for containerships, 10.5 dB for cruise vessels, 9.3 dB for vehicle carriers, 6.1 dB for tankers, and 5.9 dB for bulkers. Limited information on trial participation was available for seven other categories of non-piloted vessels. Except for naval vessels, there was no strong evidence that non-piloted vessels changed their speeds or reduced their noise emissions during the trial, relative to the control period.

Analysis of decidecade-band SLs for piloted vessels showed that noise reductions associated with slowdown participation were frequency dependent with the largest reductions measured at the low and high ends of the frequency range and a minimum reduction in the 100–1000 Hz range. This was also borne out in the CORI-band analysis, which showed that MSL reductions were largest in the high-frequency SRKW echolocation masking band (>15 kHz) and smallest in the mid-frequency SRKW communication masking band (0.5–15 kHz). The observed frequency dependence may have been related to differences in how slowing down affects the various noise generating mechanisms that contribute to the radiated noise spectrum of marine vessels. It is speculated that cavitation noise increases with speed at all frequencies, but that machinery noise dominates at mid-frequencies and has a weaker speed dependence. This would explain larger radiated noise variations at low and high frequencies than at mid-frequencies.

TABLE V. Equivalent decibel-per-knot SL reductions for each vessel category. Values were calculated by dividing the difference in mean SLs by the difference in mean speeds between the participant and control groups in Table III.

Category	dB/knot (broadband RNL)	dB/knot (broadband MSL)	dB/knot (MSL 0.5–15 kHz)	dB/knot (MSL 15+ kHz)
Bulker	2.66	2.83	1.46	2.46
Containership	1.46	1.50	1.21	2.32
Cruise	1.75	1.71	1.75	—
Tanker	2.52	2.65	1.57	3.43
Vehicle carrier	1.57	1.57	1.26	2.36

Results of the trial group analysis were cross-checked by directly analyzing repeat SL measurements of the same vessel transit at different speeds. A trend analysis of SLs versus change in speed based on 107 repeated measurements between Haro Strait and the Strait of Georgia resulted in overall frequency-dependent trends that were consistent with the analysis of the trial groups in Haro Strait. Thus, source-level-versus-speed trends for individual vessels were found to be consistent with the reductions in noise emissions achieved by slowing down the vessel population as a whole.

The speed trends identified in this study were broadly consistent with those reported by Ross (1976) but greater than those reported by several previous studies (Wales and Heitmeyer, 2002; McKenna *et al.*, 2013; Simard *et al.*, 2016; Veirs *et al.*, 2016). It is believed that this is due to the voluntary slowdown protocol, which was unique to the present study and provided an important experimental control with greater power for characterizing the effects of speed on vessel SLs.

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[1]Using the `pairwise.t.test` function in the *R* statistical analysis package (version 3.4.2).

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