SOUNDSCAPE ADDITIONS FROM VESSELS RELATED TO TRANSIT SPEED, DIRECTION AND MANOEUVRES

Brody Granger *[1], Rianna Burnham †[2] and Svein Vagle ‡[2]
[1]University of British Columbia, BC, Canada
[2]Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, BC, Canada

Résumé

Les changements de niveaux sonores sous-marins lors de la navigation des navires commerciaux sur les couloirs de navigation dans les eaux intérieures autour du Golfe de Géorgie et des îles San Juan ont été évalués. Ces mesures in-situ s'appuient sur des évaluations antérieures plus expérimentales. Les enregistrements de trois mouillages acoustiques à Boundary Pass, Turn Point et Haro Strait, dans le sud de l'île de Vancouver, en Colombie-Britannique, ont été utilisés pour comparer les mesures du champ acoustique au point d'approche le plus proche des navires avant, pendant et après un virage. Les types de navires évalués comprenaient des pétroliers, des vraquiers, des transporteurs de véhicules, des porte-conteneurs et des navires à passagers. Une régression linéaire multi-variable a confirmé la relation entre la vitesse du navire et les niveaux sonores, montrant que la trajectoire du navire avait également une influence. Les vitesses de transit les plus lentes, mais aussi les niveaux sonores à large bande (10 Hz à 100 kHz) et les niveaux sonores les plus élevés des navires ont été enregistrés lors de leurs manœuvres à Turn Point. Les émissions sonores dérivées des navires dans les moyennes et hautes fréquences étaient également considérables.

Mots clefs : bruit des navires, navigation commerciale, virages et manœuvres, bruit anthropique

Abstract

The changes in underwater sound levels as commercial vessels navigate through shipping lanes in the inland waters around the Gulf of Georgia and San Juan Islands were assessed. These in-situ measures build on previous, more experimental evaluations. Recordings from three acoustic moorings at Boundary Pass, Turn Point and Haro Strait, southern Vancouver Island, British Columbia, were used to compare sound field measures at vessels' closest point of approach before, during, and following a turn. Vessel types assessed included tankers, bulkers, vehicle carriers, containerships, and passenger vessels. A multi-variate linear regression confirmed the relationship between vessel speed and sound levels, showing that the course of the vessel was also influential. The slowest transit speeds, yet highest broadband (10 Hz to 100 kHz) and vessel noise levels were recorded as they manoeuvred at Turn Point. Vessel-derived sound emissions in the mid- to high-frequencies were also considerable.

Keywords: vessel noise, commercial shipping, turning and manoeuvres, anthropogenic noise

1 Introduction

Anthropogenic noise is quickly becoming an ubiquitous contribution to oceanic soundscapes. Increases in the ambient sound levels compared to those in pre-industrial conditions have been found to be significant [1,2]. This is particularly true for the low-frequency (< 1000 Hz) component of the vessel noise emissions, as these tonal components of the signal are able to propagate over long distances, with low absorption rates and transmission losses compared to higher frequencies [3,4]. These sound level increases have occurred simultaneously to an increase in the number, size and travel speed of merchant vessels in the global fleet. Additions from shipping can propagate to regions far removed from the source, however the additions from commercial vessels are particularly concentrated in areas near the coast, on shipping routes, and in ports [5-8].

Understanding the additions and impacts of commercial shipping on ocean soundscapes is complex. Additions from commercial and recreational vessels can dominate the soundfields at times and/or in places [1]. Commercial vessel passages can elevate the ambient sound levels substantially [9]. Acoustic signals of specific vessels and vessels during particular manoeuvres has so far been addressed by experimental recordings in controlled conditions [3, 10-12]. For example, Trevorrow et al. [10] showed the acoustic additions and its directionality from vessels manoeuvring. In addition, a linear relationship between vessel speed and noise emissions has been established from vessels transiting a monitored area [9]. During manoeuvres vessels slow, and so we might expect that the noise levels adding to the soundscape from these vessels may be reduced as per this established relationship [9]. However, mechanical adjustments and increased hydrodynamic drag during the turn, as well as potentially greater engine power being applied to maintain speed during the manoeuvre, may lessen any potential reductions.

Elevation of ambient underwater sound levels, particularly resulting from vessel noise additions, is increasingly

* grangerb@mail.ubc.ca
† rianna.burnham@dfo-mpo.gc.ca (corresponding author)
‡ svein.vagle@dfo-mpo.gc.ca

being recognised as a stressor for marine mammals who rely on acoustics to send and receive information about their surroundings. Also, critical habitat of at-risk species can overlap with areas of high human use.

The Salish Sea is the collective name for the inland waters around southern Vancouver Island, the San Juan Islands, and Puget Sound in Washington State. These waterways lead to ports in Vancouver, Seattle, Tacoma, Port Angeles, Nanaimo and Victoria (Figure 1). However, these waters are also designated as critical habitat for endangered southern resident killer whales (*Orcinus orca*, SRKW). The international shipping lanes in this area overlap with SRKW foraging habitat [13-14]. Acoustic disturbance in frequencies used for communication calls or echolocation could, for example, reduce SRKW ability to navigate, find and capture prey, or retain group contact. Additionally, this area is frequently used by humpback whales (*Megaptera novaeangliae*) and several dolphin and porpoise species [15-16].

To lessen the acoustic disturbance, in particular for SRKW, voluntary slowdown measures have been introduced for portions of the shipping lanes at Swiftsure Bank, at the western entrance to Juan de Fuca Strait, and around the southern Gulf Islands through Haro Strait and Boundary Pass (Figure 1) through the Enhanced Cetacean Habitat and Observation (ECHO) program [17]. These measures were first introduced in 2017, and have shown vessel participation rates to be high, demonstrating this to be an effective means to reduce underwater vessel noise [17]. The slowdown measure is initiated with a confirmed observation (visual or acoustic) of SRKW in the area following June 1, and continues until at least the middle of October or until SRKW have been absent from the Salish Sea for a number of weeks after this time.

Following on from the experimental work by Trevorrow et al. [10], we examined in-situ recordings from vessels transiting to and from ports in the Salish Sea. Comparisons of received vessel noise levels from recordings made before, during, and following a vessel turning and manoeuvring were made to ascertain how vessel acoustic signals change during these types of manoeuvres. As well as underwater broadband (10 Hz to 100 kHz) sound level changes, variations in sound levels in frequencies pertinent to species in the Salish Sea, in particular the SRKW, who are frequently sighted in this area [13-14] were given focus. The recordings were evaluated to establish how vessel signals may make acoustic additions during transit and turning which may impact on SRKW communication and echolocation frequencies. Our study area and period were part of a slowdown trial, and so the changes between pre- and during trial for vessel emissions from manoeuvres will also be examined.

2 Method

2.1 Acoustic data

Acoustic recordings

Calibrated Autonomous Multichannel Acoustic recorders (AMAR G4, JASCO Applied Sciences) with omnidirectional hydrophones (M36-100, GeoSpectrum Technologies) were deployed in Haro Strait, Turn Point and Boundary Pass in the

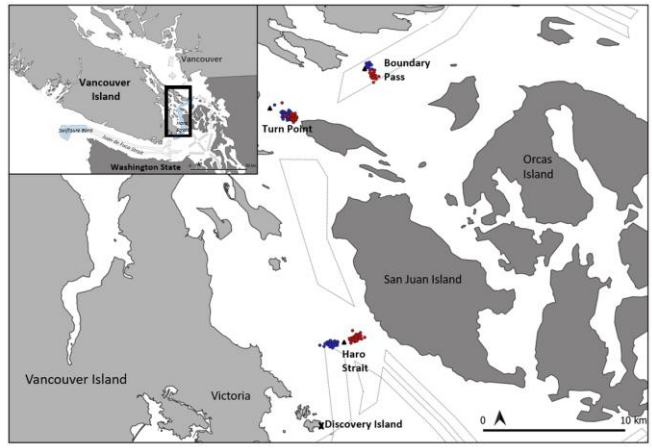

Figure 1: Study area map, with the inset showing vessel transit lanes and the recording locations at Boundary Pass, Turn Point and Haro Strait. Locations marked in red represent inbound vessels and outbound in blue. In the inset, the blue shaded areas are where the seasonal slowdown measures were in place.

Salish Sea (Figure 1).

Equipment was mounted onto specially designed quiet mooring systems manufactured by Oceanetic Measurement Ltd. The hydrophone was positioned 2 m from the sea floor with the deployment location in Haro Strait being 226 m, Turn Point 193 m and Boundary Pass 178 m deep. Each system was calibrated by the manufacturer and then again before the deployments using a 250 Hz piston phone. Recordings were made simultaneously at these locations from June 1 to August 18, 2019. The sampling rate was 256 kHz with 24-bit resolution. Data were stored on internal SD memory cards as wav files. On retrieval, these files were processed using custom Python scripts modified from Merchant et al. [18] to form 1-minute power spectra in 1-Hz bands of the full domain using 1 s Hanning window with 50% overlap and Welch's averaging.

Acoustic analysis

Changes in the underwater sound levels were considered through examining the sound pressure levels (SPL) in a broadband frequency range (10 Hz to 100 kHz). Vessel presence acoustic metrics (10-100 Hz, 53-71 Hz, 113-141 Hz [18-19]) were also examined to capture the low-frequency additions from commercial vessel traffic, while a 1-kHz frequency band centered at 50 kHz was used as an acoustic marker for smaller, recreational vessel presence [20-21]. These band metrics are consistent with previous studies and the EU Marine Strategy Framework [18-19].

To consider the potential impact on cetacean species the frequency range of 500-15000 Hz was considered for the potential acoustic masking of low- to mid-frequency calls of humpback (*Megaptera novaeangliae*) and killer whales (*Orcinus orca*), and 15-100 kHz for dolphin and porpoise echolocation. The 49.5-50.5 kHz band represents the centre frequency of the bimodal echolocation clicks used by SRKW [22], and so examination of this range might help estimate the potential for masking of these signals by vessels turning.

Comparisons were made between the received SPL at the recorders to evaluate the vessel noise additions before, during and after the manoeuvre at Turn Point. The L_{25}, L_{50} or median, and L_{75} SPL were examined. Non-parametric tests were used for comparisons of noise levels, and Student t-tests used for comparison of average vessel speed or distance from the mooring to a given vessel.

2.2 Vessel Data

Vessel transit data were obtained from terrestrial Automatic Identification System (AIS) receivers. The use of AIS transceivers is mandated for international vessels over 150 gross tons (GT) carrying more than 12 passengers, vessels over 300 GT engaged in an international voyage, or any vessel over 500 GT. This encompasses the commercial vessel traffic transiting to and from ports in the Salish Sea. A vessel's location, identity, type, and intended destination is transmitted every 5-30 seconds. For this analysis, commercial vessels were grouped into five classes: Passenger ships, vehicle carriers, tankers, containerships and bulkers.

The AIS data for the study period were cleaned and binned from the received time intervals into 1-minute periods for each vessel. Speed over ground (SOG) and acceleration over ground (AOG) were calculated using the distance between GPS locations and the time elapsed. Any data that appeared erroneous, for example expressing an excessive vessel SOG or AOG (>50 knots or >100 knots/s, respectively) or a GPS location on land, were removed. Any missing data were interpolated from adjacent data points. Locational data were converted to an orthogonal co-ordinate system, and then vessel travel direction and distance from each of the moorings as it transited, and its closest point of approach (CPA, Figure 1), were all obtained. This established a course over ground (COG) for each vessel. Vessel speed through water (STW) was derived from the SOG by correcting for tidal velocity and direction (WebTide model, [23]). Examining STW was used to determine whether a vessel was slowing down to turn. Maximum received levels (RL) of vessel noise additions in the vessel metrics were obtained from recordings when a vessel was at its CPA to the recorder. These RL and CPA distances were used to estimate the source levels (SL) of each vessel passing a hydrophone. Near spherical spreading losses were assumed, as:

$$SL\ (1\ \mu\text{Pa @ 1 m}) = RL + 18.6\log_{10}(r), \qquad (1)$$

where r is the CPA distance in meters. A previous study in the same region found that an empirically-based transmission loss coefficient of 18.6 +/- 0.4 dB/decade worked for $r < 3$ km [9]. Range dependent water absorption for all metrics was not included when calculating this for broadband (10 Hz to 100 kHz) and low-frequency vessel metrics due to the limited distances being considered, but for the 49.5 – 50.5 kHz metric a narrow-band absorption (αr) term was added to Equation 1 to form:

$$SL\ (1\ \mu\text{Pa @ 1 m}) = RL + 18.6\log_{10}(\alpha r), \qquad (2)$$

where α is the absorption coefficient at 50 kHz [24].

Some vessels made multiple transits through the study area during the study period. The five most recurring vessels in the AIS records, noted as passing through Haro Strait-Boundary Pass during the six weeks of this study from each of the five vessel classes, were selected for the acoustic analysis. The minute-wise acoustic and AIS data were matched manually. Also, periods of low wind (<15 km/h), as measured at a weather station at Discovery Island (Figure 1), and low tidal current speeds (<0.3 m/s), established using WebTide [22] measures, were used. Times when small vessels were absent in the AIS Class B data were also used; however, it is recognised that this represents the minimum presence of recreational vessels as this AIS transceiver if carried voluntarily by this vessel type. A comparison of the data recorded during the day (05:00-21:00) and night (from 21:00 to 05:00) was made to establish the potential contributions of smaller vessels that may not be seen in the AIS data, but could still be influential on the underwater sound levels, especially in the higher frequencies. It was presumed for this comparison that these smaller recreational vessels would be absent overnight when it is dark. This presumption of absence at night was made based on findings by Burnham et al. [20] from the Salish Sea.

A voluntary vessel slowdown was in place for commercial vessels from July 5 onwards, and continued throughout the latter part of the study period. These measures requested that bulker, tankers, ferries and government vessels limit their speed to 11.5 kts and vehicle carriers, cruise ships and containerships to 14.5 kts. Comparisons of underwater sound levels and received SPL from vessel transits from before and during the slowdown trial were considered as part of this analysis.

3 Results

The AIS data helped identify 245 1-minute acoustic recordings from the three moorings where a vessel was passing within 3 km of a mooring during the study period. These were then categorised by their direction of travel (inbound to ports or outbound away from ports) and then into the five vessel classes. These recording intervals were of the five most recurring vessels for each vessel class. They represented 46 full tracks of passage, and 47 partial tracks, due to the Boundary Pass recorder not recording between July 3- August 17, 2019.

3.1 Vessel passage and speed

During the study period the number of transits for container ships, bulkers and tankers averaged 11.21 +/- 5.90 vessels/day, with a maximum of 60 passages/day.

Tanker and bulker transit speeds tended to be slower, and vehicle carriers and containerships the fastest. Vessels transiting inbound were also typically slower compared to the outbound vessels. Of the three mooring locations, greater speeds were seen as the vessels were passing the Boundary Pass mooring, and most reduced as they were manoeuvring at Turn Point. For inbound transits to ports, vessel speeds were similar at both Boundary Pass and Haro Strait and reduced at Turn Point (Figure 2). Significant increases were seen for outbound passenger vessels compared to inbound passenger vessels at two of the three locations (Figure 2). Vehicle carriers leaving port transited significantly slower than when they were approaching as they manoeuvred at Turn Point. For outbound transits the greatest speeds were noted at Boundary

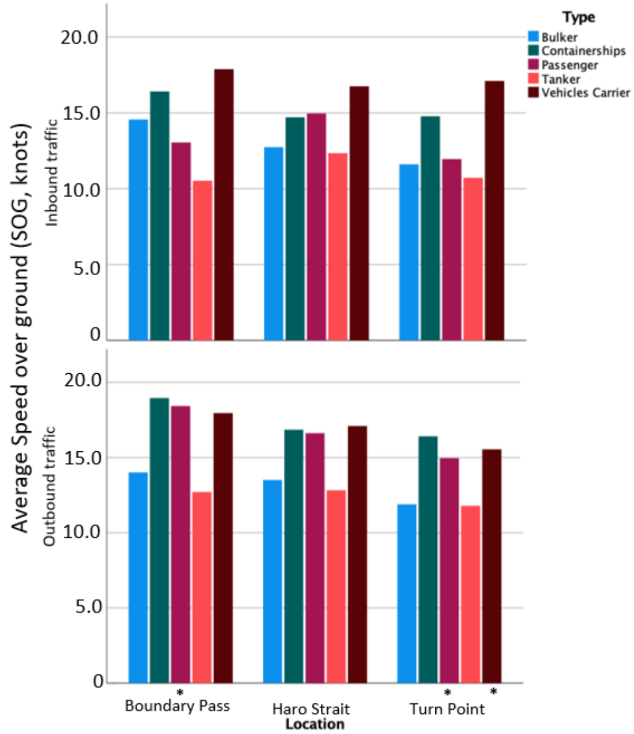

Figure 2: Comparison of SOG for each vessel type as they pass each of the moorings for inbound and outbound transits. Significantly different values between inbound and outbound are indicated by an asterisk on the lower x axis, established through Student t-test at the level p<0.05

Pass, and were increased at Haro Strait following the manoeuvre at Turn Point, but did not match speeds seen prior to the turn (Figure 2).

The voluntary slowdown initiation on July 5, 2019 was evident in the AIS data for vessel transit speed. Comparing vessel speeds by type, overall SOG was reduced for transits during the trial compared to pre-trial speeds in all cases except for tankers, and significantly for all vessel types except tankers and passenger vessels (Table 1). The average speed of all vessels through the area was reduced by 1.4 knots, with the greatest change from outbound transits (pre-trial $\bar{x}$ = 16.5 ± 2.9, trial $\bar{x}$ =13.9 ± 2.0), whereas the change in inbound transits on average was 0.7 knots, with less variation in speed during the trial (pre-trial $\bar{x}$ = 14.0 ± 4.0, trial $\bar{x}$ =13.3 ± 2.1). Comparing each vessel type at each location by direction of travel showed most reduction in both SOG and broadband (10 Hz to 100 kHz) underwater sound levels from vehicle carriers transiting inbound (Table 1).

The requested speeds are specified in SOG, however we also examined the change in STW. Significant changes in STW were only seen for inbound bulkers (t(8)=-3.894, p=0.005) and outbound containerships (t(12.485)=-4.965, p<0.001) between the pre-trial and trial passage average speeds. An average reduction in speed of more than 2 kts for bulkers and containerships were seen to meet the slowdown requirements [17, 21]. Vessel speeds may have been reduced through the Haro Strait-Boundary Pass slowdown area (Figure 1) for the turning/manoeuvring needed, and so the difference between the pre- and during trial speeds may be less than in other areas of the trial zone for other vessel types.

Table 1: Difference in SOG and broadband underwater sound levels from before to during the slow down trial. The average change of SOG (SOG diff.) and SPL (SPL diff.) is shown. Significant changes are indicated with an asterisk (*) established through a Student T-test at p<0.05. BP= Boundary Pass, TP= Turn Point and HS= Haro Strait.

Vessel	SOG diff. (kts)	SPL diff. . (dB)
Bulker	-2.04 *	-2.96
BP- In	-	-
BP-Out	-	-
TP- In	-	-
TP-Out	-0.72	-0.24
HS-In	-4.39	-4.39
HS-Out	-0.63	+1.64
Tanker	+0.46	-4.41 *
BP- In	-	-
BP-Out	-	-
TP- In	+1.19	-1.98
TP-Out	-0.32	+0.42
HS-In	+1.96	-2.99
HS-Out	+0.01	-6.55 *
Container	-2.19 *	-2.0
BP- In	-	-
BP-Out	-	-
TP- In	-2.68	-1.84
TP-Out	-1.86	-2.55
HS-In	-0.78	-1.51
HS-Out	-2.31	+1.65
Vehicle	-2.41 *	-7.92 *
BP- In	-	-
BP-Out	-	-
TP- In	-2.84 *	-9.99 *
TP-Out	-0.37	-5.37
HS-In	-4.08 *	-7.11 *
HS-Out	-1.83	-6.10 *
Passenger	-0.73	-2.39
BP- In	-	-
BP-Out	-	-
TP- In	+0.26	+1.50
TP-Out	-2.49 *	-4.57
HS-In	+0.64	+2.41
HS-Out	-3.29 *	-9.47 *

Vessels on average passed the moorings at a distance of 1.4 km. Typically, the distance at CPA was less for vessels transiting outbound from Boundary Pass to Juan de Fuca Strait than for inbound vessels (Figure 3). At this location the recorder was placed more towards the outbound lane (Figure 1). The difference between the centroid of the CPA locations for in- and outbound vessels locations was greatest here at 579 m.The difference between the inbound and outbound CPA distances were significantly reduced on average for each of the vessel classes when passing the Boundary Pass mooring, and for tankers, containerships, vehicle carriers and passenger vessels transiting Turn Point (Figure 3). The distance to the inbound centroids of vessel CPA locations was 445 m greater than the outbound at Turn Point. The mooring was located to the west of both the out and inbound transits (Figure 1). Differences in the CPA distances were not found to be significant at Haro Strait (Figure 3). The difference between the centroids of CPA vessel locations were the least here, with inbound traffic transiting 118 m closer to the mooring than outbound vessels. The mooring is located midway between both transit lanes (Figure 1). Vessel passages were generally closest to the Boundary Pass mooring (Figure 3), which was situated under the outbound shipping lane. However, a significant (t(82.112)=9.891, $p<0.001$) increase in CPA distance of, on average, 420 m was seen at Turn Point when comparing inbound to outbound transits during turning manoeuvres.

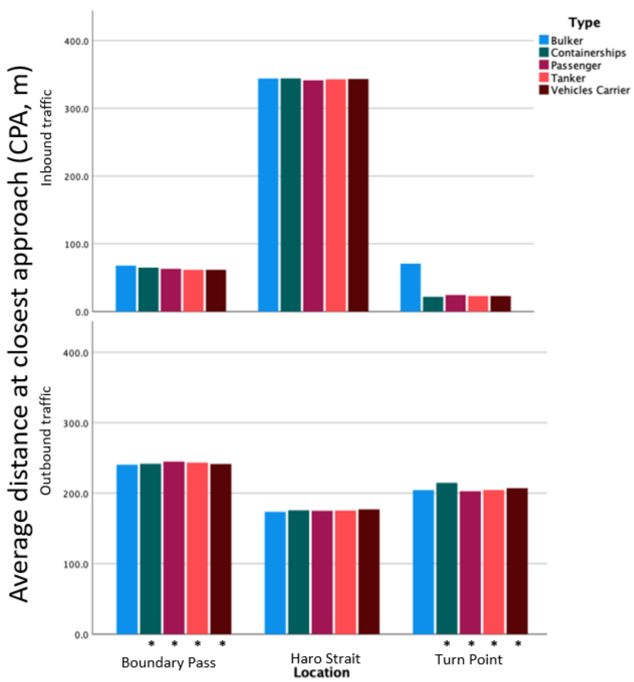

Figure 3: Comparison of distance from the mooring at closest point of approach (CPA) for each vessel type for inbound and outbound transits. Significantly different values are indicated by an asterisk on the lower x-axis, established by a Student T-test at $p<0.005$

3.2 Acoustic analysis

The estimated vessel SL were greatest during passages of containerships and bulk carriers at the Haro Strait and Boundary Pass mooring locations (Figure 4). This suggests they are the principal anthropogenic noise sources at these locations, in line with previous research which noted each passage can elevate the ambient sound levels up to 20 dB per transit [9, 12, 20].

The SL obtained from the measured SPLs were also in line with previous reporting [9, 24]. SL of outbound vessels showed elevated underwater noise levels in the broadband

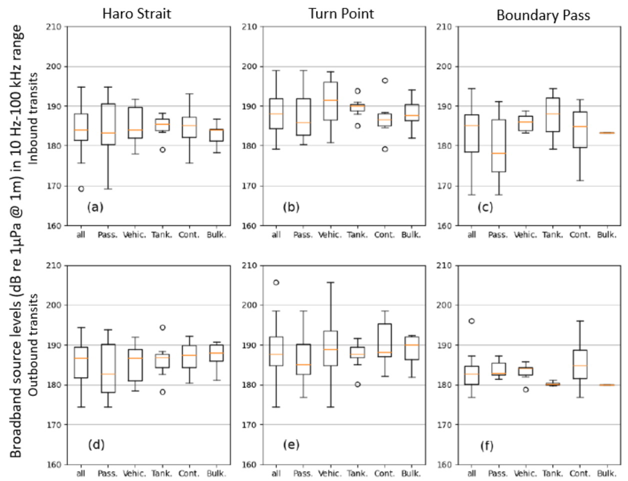

Figure 4: Estimated broadband SL (10-100,000 Hz) during the passage of each vessel type, mooring location and direction of travel.

frequency range (10-100,000 Hz) compared to inbound vessels (Figure 4). This is consistent with the differences in speed, where the higher outbound transit speeds would be expected to result in greater acoustic additions. The recordings at Boundary Pass and Turn Point showed this difference in SL to also be significant in the frequencies used to represent vessel noise (Table A-1 in Appendix).

Overall, the SL (10-100,000 Hz) were greater at Turn Point when the vessels were slowing and preparing to turn, or while manoeuvring. Comparing median SL by vessel type between the three locations showed an approximate 3 dB difference between Turn Point and Haro Strait, and 5 dB difference between Turn Point and Boundary Pass for all vessel passages (Figure 4). Aggregating all vessel data, median SL (10-100,000 Hz) at Haro Strait with vessels passing was 185 dB re 1 µPa @ 1 m, while at Boundary Pass it was 183 dB re 1 µPa @ 1m and at Turn Point it was 188 dB re 1 µPa @ 1 m. The differences between inbound vessels and outbound vessels were minimal in both median and inter-quartile SL despite there being a difference in average speed of 1.4 kts (Figure 2, Tables 1-2). The difference was more pronounced when considering the passage of vessels by type at each location in the vessel related metrics. In this case, the median low-frequency vessel metrics (10-100 Hz, 100-1000 Hz) were most elevated at Boundary Pass, and least at Turn Point.

A comparison between day and night measured SPL, to determine the potential influence of smaller non-commercial vessels on the soundscape showed no significant differences between periods, suggesting that these smaller vessels were not adding notably to sound levels for the 1-minute time periods used for this analysis in the broadband and lower-frequency vessel metrics.

The measured SPL and derived SL for the high-frequency component of the vessel noise centered at 50 kHz, were greatest at Turn Point compared to Boundary Pass and Haro Strait. This suggests that manoeuvring could elevate the vessel noise emissions throughout the frequency range (49.5-50.5 kHz) considered here. Higher outbound speeds increased the SL of the vessels per transit (Figure 5).

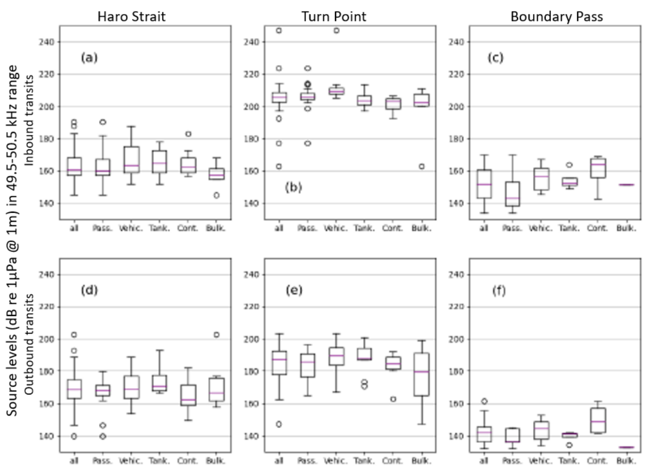

Figure 5: SL (49.5 – 50.5 kHz) by vessel class, mooring location and direction of travel. Median SL was determined to be 172 dB re 1 μPa @ 1m.

The linear regression ($F(3,491)=71.845$, $p<0.001$) of all vessels found that the directional change, speed, and distance between a vessel and a mooring, significantly influenced the received sound levels.

Travel speed through water influenced the SL most highly (coefficient 0.750, $p<0.001$). Significant negative coefficients between COG, and distance from the mooring (COG coefficient: -0.005, $p=0.020$; CPA coefficient: -0.003, $p<0.001$) were also found. The significance of the influence of speed on vessel noise emissions was consistently seen when vessel type and direction of travel were considered (Tables A2-6 in Appendix). Considered by vessel type, STW and CPA were seen to be the most influential variable to the broadband sound levels, with course direction also significant for bulkers (Table A-2 in Appendix). Distance from the mooring was not significant for container ships and tankers (Table A-3, A-6 in Appendix), which are the vessel types with the greatest passage rate in this area [9].

3.3 Marine Mammal Impacts

Elevated broadband underwater sound levels have potential to cause behavioural modification and increase physiological stress levels in cetaceans [e.g., 25], increases were seen in species-specific frequency ranges. Increases were seen in the mid- to high-frequency band of 500 Hz to 15 kHz during vessel transits. These increases could be impactful for SRKW and other whale species, such as humpback whales that are also frequently seen in the Salish Sea. Also, sound level increases were found to correlate with the number of vessel transits (500-15000 Hz, Boundary Pass: $r_s=0.451$, $p<0.001$, Haro Strait: $r_s=0.407$, $p<0.001$; 15-100 kHz Boundary Pass $r_s=403$, $p<0.001$, Haro Strait $r_s=0.301$, $p<0.001$). Inbound traffic showed the strongest correlation coefficient, albeit mild, to 1000-10000 Hz ($rs=0.463$, $p=0.001$), while outbound transits were most strongly correlated to 500-15000 Hz ($r_s=0.326$, $p=0.04$). Higher frequency additions were correlated with speed in Haro Strait, in frequency ranges above 15000 Hz for inbound transits (1500-10000 Hz, $r_s=0.694$, $p<0.001$), whereas outbound transits were most strongly correlated with 10-100 Hz ($r_s=0.398$, $p=0.010$). Short transmission distances were highlighted when high frequency SL were correlated with CPA distances. High-frequency signals are absorbed more rapidly than those in lower frequencies; this was demonstrated in the significant negative correlations found between the distance from the mooring (CPA) and SL in the 49.5-50.5 kHz band (Boundary Pass $r_s=-0.710$, $p<0.001$; Turn Point $r_s=-0.287$, $p=0.06$; Haro Strait $r_s=-0.337$, $p=0.001$). This, and the interpolation of the high frequency vessel SL, suggest that vessel turning and associated manoeuvres can have implication for marine mammal species in the area, elevating vessel additions to the soundscape. Also, the impact would be greater the closer the animals were to the shipping lanes.

4 Discussion

Vessel noise is the dominant anthropogenic addition to soundscapes. This analysis shows the impact that commercial vessels can have throughout a broad frequency range, including into the higher frequencies, not typically associated with these vessel types.

The Salish Sea is a high traffic area. The upper bound of our average value of passage rate is comparable to Veirs et al. ([9], 19.5 ships/day). However, Veirs et al. [9] derived this value from averaging all vessel passages noted by AIS divided by the study length in days, and not examining each day independently or limiting vessel classes, as we have done here. Veirs et al. [9] suggest that bulk carriers and containerships account for a little more than half these vessels, which does make our average rates comparable. However, averaging a total vessel count by the number of days of the study does not allow for examination of variability in passage rate, which we found to be up to 60 vessels a day at the maximum. Veirs et al. [9] also report that vessel passages in these waters can increase underwater sound levels by up to 20 dB, suggesting a substantial impact on sound fields especially on days when passage rate is high [26-29]. The impact of commercial traffic on ambient soundscape levels is a subject of ongoing work broadly [26-38], and in the Salish Sea [see e.g., 20, 26, 32].

We found the broadband underwater sound levels were at their greatest when vessels were slowed and completing manoeuvres at Turn Point. This was common to all vessel types. Indeed, the comparison of the median broadband SL at each site ranked the sites in reverse to what would be expected if one was to use speed of the vessel alone as a predictor. That is, vessels speeds were most reduced at Turn Point, but sound levels were most elevated. The highest vessel speeds were recorded at Boundary Pass, yet the recordings at this mooring showed the lowest median SL. Typically, the outbound traffic showed the most elevated underwater noise levels. This likely resulted from vessels typically running at higher speeds and having reduced distances at CPA. Noise additions in the higher frequency ranges considered mirrored the patterns seen in the broadband levels, with the greatest SL levels seen at Turn Point during vessel turns. In low frequencies (<1000 Hz) SL were greatest at Boundary Pass, perhaps reflecting vessels' increased speed. The underwater noise levels and

CPA distances from the mooring, for both in- and outbound traffic, were also the greatest at Turn Point.

This analysis represents an in-situ determination of vessel noise inputs to the soundscape, while also taking into account the behaviours of vessel operators as they transit through the Salish Sea. Distinct differences were seen between inbound and outbound traffic (Table 3, Figure 2). The increased broadband and high-frequency SL found in our measures are in agreement with the initial experimental work by Trevorrow et al. [10], where a rapid rise in noise emissions, up to 10 dB, was seen as a ship set its rudder and began to heel into the turn with the propeller speed increased to maintain consistent vessel speed through water. We confirmed a link between radiated vessel noise and ship speed, with underwater sound levels elevated in the broadband and vessel metrics frequency ranges. At Turn Point, it was also possible that acoustic signatures from propeller and machinery caused the observed increases in the higher frequency noise [10].

The addition of vessel noise to ocean soundscapes is a pressing issue for managers devising conservation actions aimed at reducing anthropogenic impact. Elevated underwater noise levels resulting from shipping reduces the effectiveness of calling for cetaceans, hindering, for example, their ability to navigate and forage. Elevated broadband noise levels can induce stress or behavioural modification [e.g., 25, 32]. Also, we found additions in more species-specific frequencies [20-22, 27, -32]. This has the potential to hinder the acoustics use of the species in social communications or echolocation signals [e.g., 30, 32]. Our data suggests that when vessels slow to turn, they add considerably more to these ranges, particularly in the frequencies used by SRKW and humpback whales for conspecific communication or social calling (500-15000 Hz), but also into echolocation frequencies of killer whales, dolphins and porpoises (15-100 kHz [27, 32]).

Operational measures implemented in this area, such as vessel slowdowns have been shown to be effective in reducing vessel noise emissions [17, 21, 33-34]. Participation rates of the slowdown trial during the study period were high, and the relationship between vessel speed and source level is well established (see [9]). The results of linear regression analysis substantiated this relationship, showing it to be formative to received sound levels. However, a reduction in speed to turn did not generate the same effect, showing that the disturbance from vessels does not decline in the same linear relationship as the one described by Veirs et al. [9] when vessels are manoeuvring. Furthermore, variables including hull shape, load, and draft, not accounted for in this analysis, also influence vessel signatures within each category. The influence of sea state or sea surface roughness [35], and multiple vessels transiting together, on manoeuvrability, and the resulting emissions, was also not considered in this study.

Detection and classification of vessels from sound signatures is one means to monitor maritime traffic. However, databases [3, 29, 35-38] are still in their infancy, and principally developed under controlled conditions. However, measured levels have shown up to a 20 dB difference in vessel noise emissions depending on the class of vessel [3, 28], predominantly from differing cavitation. Our recordings add to this work, suggestive of the impact that larger vessels can have over a broad frequency range [also see 26, 30, 36-37], including into the higher frequencies while maneuvering. More in-situ and realistic determinations of vessel noise will derive improved measures of the acoustic inputs to the sound field. This is the subject of ongoing work in the Salish Sea.

The global shipping fleet is expected to grow in both vessel number and capacity as a greater volume of material is shipped over greater distances [38-39]. In the absence of mitigation, this trend will potentially increase the maximum noise level of the fleet by a factor of 1.9, or an average of 102% in noise emissions, in the next 10 years [38]. Our results add a nuance that will help identify areas that will be most highly impacted. The consideration of change in vessel speed and direction highlighted the different components of vessel noise. Also, the proximity of vessel transits, and in particular regions of vessel turning or manoeuvring near to areas of importance to threatened species may also need to be considered, given the results seen in the difference in SPL when CPA to the mooring was reduced. Haro Strait, for example, is an area where SRKW have been frequently sighted foraging, and so increased noise in that areas could lessen their ability to find or capture prey through acoustic masking effects [32, 40]. Greater high frequency components of noise, perhaps from generators, engines and blade harmonics, add to propeller cavitation when manoeuvring to elevate SPL. Adding more detail to how vessel-derived noise changes throughout its transit will create for more spatially explicit estimates of sound field levels of ocean regions. Mitigation measures such as re-routing vessels, or the design and designation of protected areas should look to how vessel signatures vary throughout their transit to maximise their efficacy.

5 Conclusion

This work adds to observations of received vessel noise from commercial vessels quantified in controlled settings, which can be used to refine vessel noise models. The impacts of human-use on marine wildlife are increasingly realised, and mitigation measures are considered for noise in high vessel traffic areas, this will have implications for shipping lane design or redesignation, or marine protected area design. Difference in vessel types and travel direction was considered for the potential for acoustic disturbance. Our results suggest the focus of these measures should be on outbound container ships and bulk carriers if the application of measures were more limited. Additions to broadband ambient noise may instigate stress responses or modification to swimming/diving patterns, and ultimately area abandonment. The consideration of more species-specific frequencies allows us to estimate the potential interference the vessel noise additions could have in the use of communication calls or echolocation signals of the species present in the Salish Sea, through masking, and start to quantify the potential impact of vessel noise even in the absence of observable behavioural changes.

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Appendix

Table A-1: Results of a Student T-test to compare sound pressures levels (SPL) for the study period before (June 1-July 5, 2019) and during (July 5-August 18, 2019) a vessel slowdown trial through Haro Strait and Boundary Pass.

DF	T-value	Sign.
Boundary		
100-1000	-5.247	<0.001
113-141	-5.771	<0.001
57-71	-4.116	<0.001
Turn Pt		
100-1000	-3.727	<0.001
113-141	-4.028	<0.001
57-71	-0.695	0.488
Haro St		
100-1000	-2.389	0.018
113-141	-1.619	0.107
57-71	0.288	0.774

Table A-2: Multivariate linear regression for bulkers considering the SL (10-100,000 Hz) resulting from changes in vessel transit direction (course over ground, COG), speed (speed through water, STW) and distance (closest point of approach, CPA). Model summary for inbound: F(3,26) = 3.247, p=0.038 and outbound F(3,24) = 25.143, p<0.001. Significant results are indicated with bold text

Variable	Coeff.	Sign.
Inbound		
COG	**-0.015**	**0.010**
STW	0.123	0.732
CPA	**-0.004**	**0.010**
Outbound		
COG	0.047	0.250
STW	**2.391**	**<0.001**
CPA	-0.001	0.640

Table A-3: Multivariate linear regression for container ships considering the SL (10-100,000 Hz) resulting from changes in vessel transit direction (course over ground, COG), speed (speed through water, STW) and distance (closest point of approach, CPA). Model summary for inbound: F(3,33)=7.364, p=0.001 and outbound F(3,40) = 7.848, p<0.001. Significant results are indicated with bold text.

Variable	Coeff.	Sign.
Inbound		
COG	0.009	0.180
STW	**1.526**	**<0.001**
CPA	-0.001	0.640
Outbound		
COG	-0.005	0.165
STW	**1.678**	**<0.001**
CPA	**-0.003**	**0.041**

Table A-4: Multivariate linear regression for passenger vessels considering the SL (10-100,000 Hz) resulting from changes in vessel transit direction (course over ground, COG), speed (speed through water, STW) and distance (closest point of approach CPA). Model summary for inbound: F(3,142) = 26.937, p<0.001 and outbound F(3,41)=18.365, p<0.001. Significant results are indicated with bold text

Variable	Coeff.	Sign.
Inbound		
COG	-0.005	0.165
STW	**1.084**	**<0.001**
CPA	**-0.002**	**0.025**
Outbound		
COG	0.050	0.111
STW	**1.678**	**<0.001**
CPA	**-0.002**	**0.048**

Table A-5: Multivariate linear regression for vehicle carriers considering the SL (10-100,000 Hz) resulting from changes in vessel transit direction (course over ground, COG), speed (speed through water, STW) and distance (closest point of approach CPA). Model summary for inbound: F(3,48) = 5.282, p=0.003 and outbound F(3,34) = 5.480, p=0.004.

Variable	Coeff.	Sign.
Inbound		
COG	-0.001	0.813
STW	**1.136**	**0.003**
CPA	**-0.002**	**0.048**
Outbound		
COG	0.066	0.093
STW	-0.134	0.763
CPA	-0.003	0.075

Table A-6: Multivariate linear regression for tankers considering the SL (10-100,000 Hz) resulting from changes in vessel transit direction (course over ground, COG), speed (speed through water, STW) and distance (closest point of approach CPA). Model summary for inbound: F(3,45)=7.303, p<0.001 and outbound F(3,22) = 5.371, p=0.006.

Variable	Coeff.	Sign.
Inbound		
COG	-0.007	0.170
STW	-0.374	0.218
CPA	-0.004	<0.001
Outbound		
COG	0.034	0.349
STW	-0.227	0.576
CPA	-0.004	0.016

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