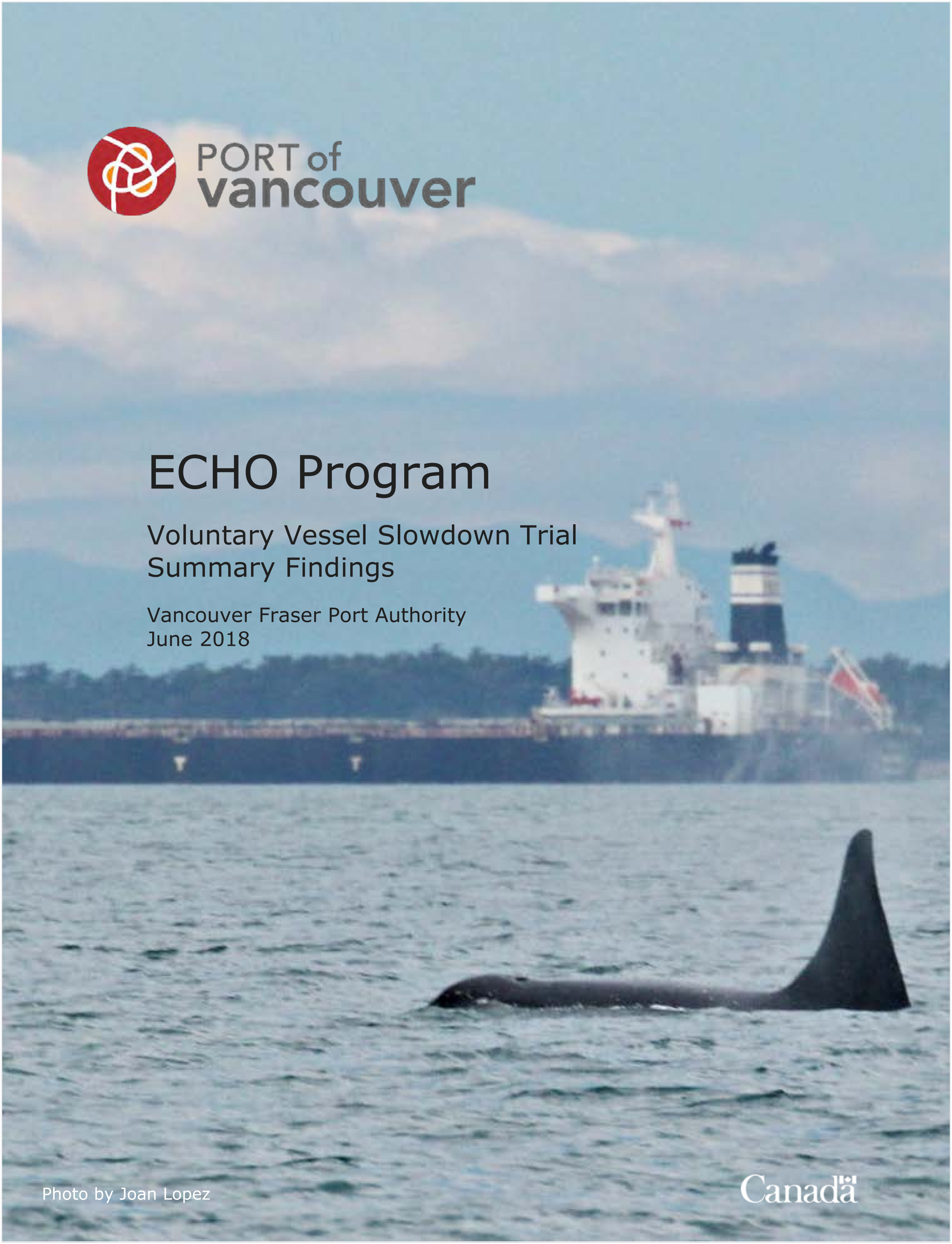

PORT of vancouver

ECHO Program

Voluntary Vessel Slowdown Trial Summary Findings

Vancouver Fraser Port Authority
June 2018

Photo by Joan Lopez

Canada

Executive summary

The Enhancing Cetacean Habitat and Observation (ECHO) Program is a research and management initiative led by the Vancouver Fraser Port Authority (the port authority). The program has benefited from early and ongoing collaborative input and advice from the marine transportation sector, conservation groups, First Nations individuals, government agencies and scientists. The program has a long-term goal of developing voluntary mitigation measures that will lead to a quantifiable reduction in threats posed by vessel traffic and port activities to at-risk whales in the region.

One such threat to the recovery of the endangered southern resident killer whale (SRKW), the critical habitat of which intersects with the international shipping routes to ports in the Pacific Northwest, is acoustic disturbance from vessels. In order to better understand this issue, the ECHO Program led a research trial in the summer of 2017 to evaluate how slowing vessels down might decrease underwater noise, and how this could potentially affect the behaviour and foraging of SRKW.

The voluntary vessel slowdown trial was designed and implemented through collaboration with a variety of stakeholders including members of the Chamber of Shipping, Shipping Federation of Canada, Cruise Lines International Association – North West and Canada, the Pacific Pilotage Authority and BC Coast Pilots, Washington State Ferries, Canadian federal government agencies, and scientists. In the trial design, consideration was given to navigational safety and potential biological, cultural and economic implications. The trial was conducted between August 7 and October 6, 2017, over an approximate 16 nautical mile distance through Haro Strait (a key foraging habitat for the SRKW) where large commercial and government vessels were asked to slow to 11 knots speed through water.

An economic analysis indicated that all vessel types could potentially incur both direct costs (including pilotage, ship time, fuel consumption) and indirect costs (including port disbursements such as longshore labour, tugs, ships' line handling and safety and security) as a result of participating in the trial. In an attempt to offset some of these costs, each participating transit was eligible for a $500 stipend. Because of the trial's short duration and because vessel operators could choose not to participate if their sailing schedule would be significantly impacted on a particular transit, the trial was not expected to have a material effect on potential indirect economic impacts such as customer service, international trade traffic movements or overall competitiveness of the Port of Vancouver.

During the two months of the trial, 951 piloted commercial vessel transits through Haro Strait were reported, with 577 transits (61 per cent) identified by the Pacific Pilotage Authority as having participated in the trial. This translated to 44 per cent of vessel transits achieving a speed of less than 12 knots, and 55 percent achieving a speed of less than 13 knots.

Vessel participation was monitored using Automated Identification System (AIS) receivers to identify vessel names, speed and location. During the trial and during representative "baseline" or "control" periods, data from underwater listening stations in Haro Strait and the Strait of Georgia, and a hydrophone located in the waters just off Lime Kiln State Park on San Juan Island, Washington were analyzed to understand how the slowdown trial affected underwater noise.

Analysis of vessel source levels indicated that slowing vessels down significantly reduced underwater noise emissions, when compared to normal speeds. Mean speed reductions varied by vessel type from 2.1 knots for bulk/general cargo ships, to as high as a 7.7 knot reduction in speed for container ships. These slower speeds resulted in reduced mean broadband (across all sound frequencies measured) vessel source levels of between 5.9 decibels (dB) for bulk/general cargo ships, and 11.5 dB for container ships. In general, slowing vessels reduced vessel noise emissions over the entire noise frequency range measured.

Assessment of total ambient noise received at the Lime Kiln hydrophone (located in an important SRKW foraging area) indicated that when compared to the baseline period, noise levels during the trial were reduced by a median value of 1.2 dB. This is approximately equivalent to a 24 per cent reduction in sound intensity. Small and recreational boat traffic was not targeted in this study, but was noted to significantly affect noise levels measured at Lime Kiln. To better assess the changes in noise resulting from slower large commercial vessels, ambient noise data were filtered to include only times when large vessels were within 6 kilometres of the hydrophone, to remove times of small boat presence, and remove times of high wind and current which can also affect received ambient noise levels. These filtered data showed a median reduction in broadband ambient noise levels of 2.5 dB, which is approximately equivalent to a 44 per cent reduction in sound intensity.

Information garnered from the trial was used to conduct computer modelling of vessel-generated underwater noise for the Haro Strait region. At a receiver location near Lime Kiln, the noise model indicated that the speeds and participation rates achieved during the trial likely resulted in noise reductions of between 0.6 dB on an average traffic day (14 piloted vessel transits) and 1.5 dB on a high traffic day (21 piloted vessel transits). This correlates well to the actual median noise reduction value of 1.2 dB measured at Lime Kiln during the trial period.

An SRKW behavioural response model used the data from the regional noise model to evaluate potential benefits to killer whale foraging from reduced noise. The SRKW behavioural response model indicated that the speeds and participation rates achieved during the trial could result in an 11.5 per cent reduction in affected foraging time for an average traffic day, and 10.3 per cent reduction for a high traffic day, when compared to baseline conditions.

Both visual observations and acoustic detections at Lime Kiln were used to evaluate SRKW presence, with only nine days of SRKW presence recorded during the two-month trial period. The summer of 2017 was a uniquely low year for SRKW presence in Haro Strait, noting a 70 per cent reduction in SRKW presence from 2016 to 2017.

The results of the vessel slowdown trial indicated that voluntary measures can be an effective way of managing threats to at-risk whales. Reducing vessel speeds is an effective way of reducing the underwater noise generated at the vessel source, as well as reducing total underwater noise in nearby habitats which may in turn benefit the behaviour and foraging success of SRKW.

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1 Background

This report summarizes the development, implementation and results of the voluntary vessel slowdown trial led by the Enhancing Cetacean Habitat and Observation Program in Haro Strait from August 7 to October 6, 2017.

1.1 The ECHO Program

The Enhancing Cetacean Habitat and Observation (ECHO) Program is a Vancouver Fraser Port Authority-led initiative aimed at better understanding and managing the impact of shipping activities on at-risk whales throughout the southern coast of British Columbia. Established in 2014, the ECHO Program has benefited from early and ongoing collaborative input and advice from the marine transportation sector, conservation groups, First Nations individuals, government agencies and scientists. The program has a long-term goal of developing voluntary measures that will lead to a quantifiable reduction in threats to at-risk whales in the region.

A number of at-risk species of cetaceans (whales, dolphins and porpoises) inhabit the Pacific waters of southern British Columbia and northern Washington State often referred to as the Salish Sea. Key among these species is the endangered southern resident killer whale (SRKW), with a population of only 76 individuals (Centre 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 (Fisheries and Oceans Canada (DFO) 2011, DFO 2016) and an Action Plan (DFO 2017) to address the current threats to the northern and southern resident killer whales in Canadian Pacific waters. Some of the identified key threats to killer whales, and other at-risk whales in this region include:

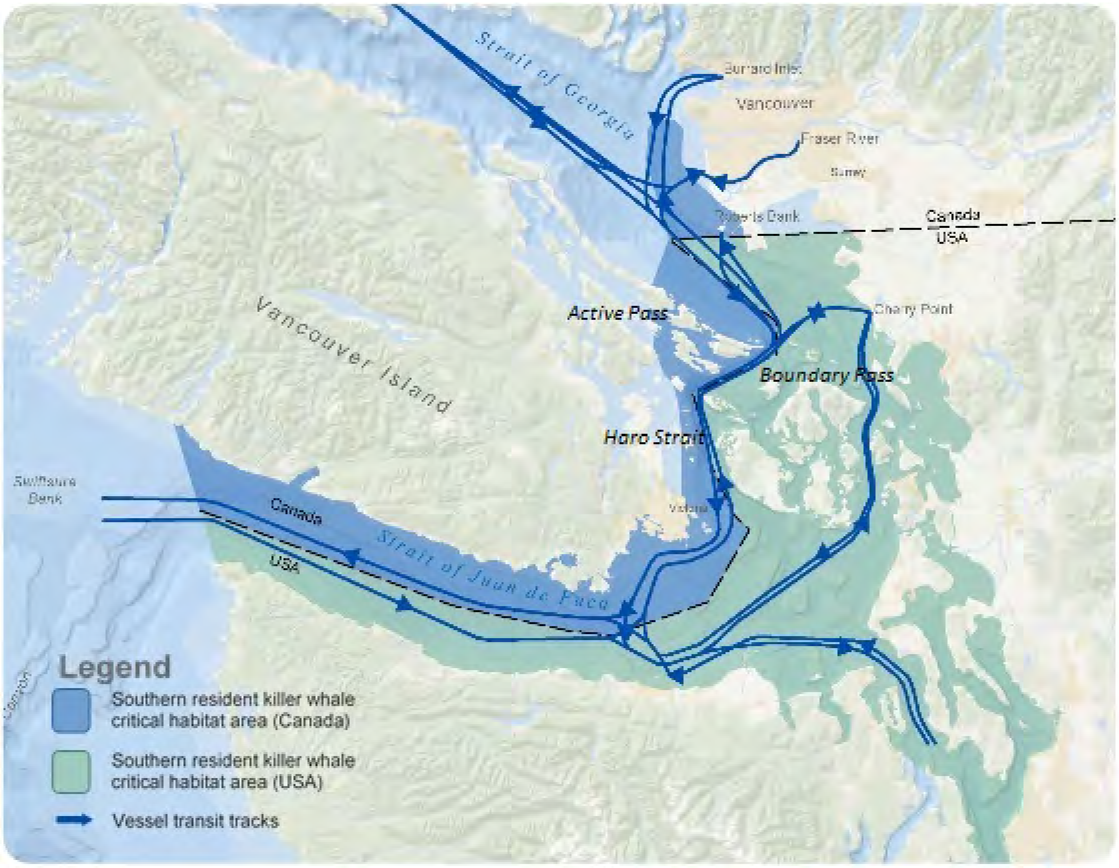
- environmental contaminants
- availability of prey
- physical disturbance (ship collisions)
- acoustic disturbance (underwater noise)

DFO's 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 *Endangered Species Act*, critical habitat has also been designated in 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, rest). Killer whales use sound to navigate, communicate and locate prey via echolocation, and underwater noise generated by vessels can impede these functions. As shown in Figure 1, the primary shipping lanes for vessels calling Canadian and U.S. ports in the Salish Sea transit through SRKW critical habitat.

Through consultation with the ECHO Program Advisory Working Group, comprising marine transportation, conservation, First Nations, government and scientific representation, acoustic disturbance to the endangered SRKW from vessel noise was identified as a top priority for program research and mitigation. In 2016, the ECHO Program's Advisory Working Group conducted a desktop assessment of a variety of potential mitigation measures to help reduce underwater noise in the Salish Sea. This screening level assessment considered the potential benefits of reducing vessel-generated underwater noise in SRKW critical habitat, and the potential implications to industry. The group evaluated a range of mitigation options including vessel slowdowns, route alterations and convoying.

Ultimately the working group identified that slowing vessels down in a geographic area of importance to SRKW should be the priority mitigation measure to trial.

FIGURE 1. SRKW critical habitat and primary shipping routes



1.2 Goals of the voluntary vessel slowdown trial

As identified in Section 1.1, the long-term goal of the ECHO Program is to develop voluntary mitigations to reduce threats to endangered whales. Based on the Advisory Working Group's evaluations of potential mitigation options, it was determined that a voluntary vessel slowdown trial should be advanced to better understand the relationship between commercial vessel speed and underwater noise levels, as well as the resultant potential benefit to SRKW in a key foraging area.

The trial was designed to answer the following key questions:

1. How does reduced vessel speed change the underwater noise generated by a specific vessel (vessel source level) and by type of vessel?
2. How does reduced vessel speed change the total underwater ambient noise received at a specific location of importance to the SRKW?
3. What are the predicted resultant effects on SRKW behaviour and foraging given the changes in noise as answered by questions #1 and #2?

1.3 Development of the trial parameters

The ECHO Program Advisory Working Group helped to establish the concept and parameters of the slowdown trial, which were further refined through the program's Vessel Operators Committee. The committee comprises representatives from the marine transportation industry and federal government, who assisted the ECHO Program team with the planning, logistics, communications and implementation of the trial. The composition and role of the committee is further described in Section 2 – Trial implementation.

The trial was designed to address the questions posed in Section 1.2 through the voluntary engagement of the shipping industry, at a location and in a timeframe that would yield the required data, provide benefit to SRKW with minimum disruption to stakeholders, and without compromising safety.

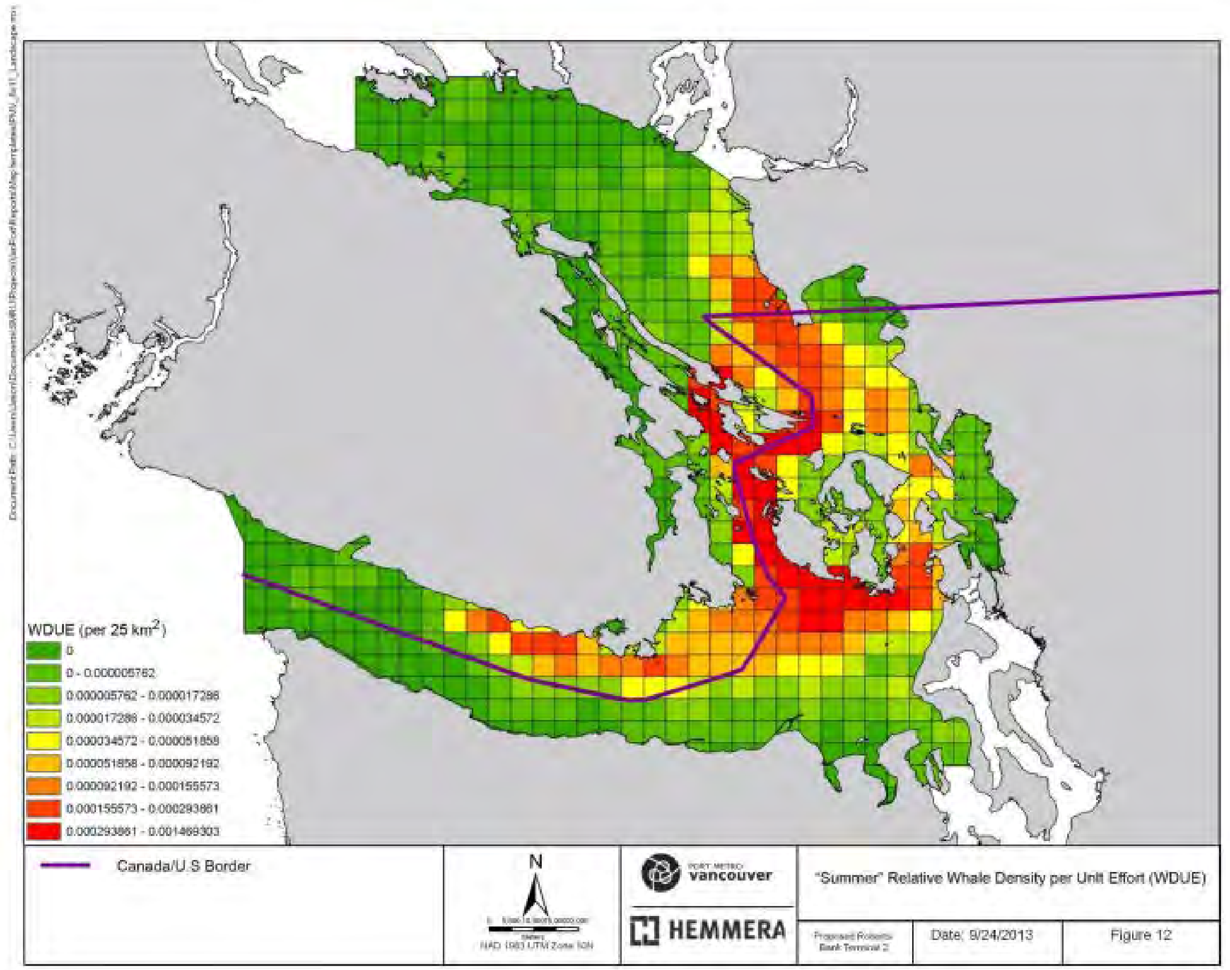
1.3.1 Determining trial location

In order to help determine the optimal location for conducting the vessel slowdown trial, an investigation of existing data on SRKW presence in the Salish Sea was conducted. One study (Hemmera and SMRU 2014) evaluated SRKW relative density and distribution in the inland waters of southern British Columbia and Washington State using consolidated sightings information from the BC Cetacean Sightings Network (BCCSN) in Canada and the OrcaMaster sightings network in the U.S. over an eleven-year period (2001-2011). This study used an effort-corrected relative density model and results indicated that over 90 per cent of the SRKW sightings in the study area were observed in the summer, between May and September. Figure 2 shows relative whale density per unit effort for the summer months (Figure 12 from Hemmera and SMRU 2014).

There is a clear indication of high SRKW presence in Haro Strait, Boundary Pass, and Active Pass (Figure 1), which intersect with the major international shipping lanes between the Pacific Ocean and the Port of Vancouver, and active ferry routes for both BC Ferries and Washington State Ferries. The majority of deep sea vessels inbound to or outbound from the Port of Vancouver transit the corridor, which includes Haro Strait, Boundary Pass, and the Strait of Georgia.

An additional modelling study (SMRU Consulting North America 2014) further evaluated potential SRKW behavioural response and echolocation masking resulting from vessel noise within these key areas of high SRKW presence and shipping traffic. The results of the study indicated that approximately 25 per cent of all potential SRKW lost foraging time resulting from commercial vessel noise was noted to be in Haro Strait, with Boundary Pass and Strait of Georgia being the next highest areas of impact, respectively.

FIGURE 2. Relative SRKW density in Salish Sea May-September



From Hemmera and SMRU 2014.

1.3.2 Determining trial speed

In evaluating what may be an appropriate speed for conducting the slowdown trial, several factors were considered including potential benefits of noise reduction to SRKW, potential impacts to industry from reduced speed, lessons learned from other jurisdictions, and most importantly, navigational safety. Vessel slowdowns have been implemented in other geographic areas in North America, notably to reduce the risk of lethal vessel strikes to endangered North Atlantic right whales on the approach to Boston Harbor, as well as to reduce potential impacts to endangered beluga whales in the Saguenay-St. Lawrence Marine Park. In both of these instances, vessel speed limits of 10 knots are used.

Review of information from the St. Lawrence study (Parrott et al. 2016) indicated that although a slowdown speed of 10 knots was proposed, data from 2014 (the second year of the program) showed that 21 per cent of transits achieved 10 knots or lower, whereas an additional 51 per cent achieved speeds between 10.1 and 11.8 knots. In discussions with those who conducted the initial assessment of the success of the slowdown, it was noted that significant currents and tidal influence in the St. Lawrence impacted the ability of vessels to safely achieve and maintain a speed of 10 knots (pers. comm. Parrott, L., March 2016).

An evaluation of what would be considered a safe speed for navigation of deep sea vessels in Haro Strait was conducted in consultation with the Advisory Working Group and Vessel Operators Committee. Given the constrained waters of Haro Strait, combined with the high currents frequently encountered in this area, a minimum speed of 11 knots (measured as speed through water) was proposed to achieve maximum potential benefit to underwater noise reduction, without compromising navigational safety.

Table 1 shows the average increase in transit time for vessels transiting Haro Strait during the trial relative to normal vessel speed.

TABLE 1. Average increases in transit time during trial

Vessel Type	Average increase in transit time (min)	
	Inbound 16.6nm	**Outbound 14.9nm**
Containers	41 mins	38 mins
Bulk/ general cargo	21 mins	20 mins
Oil tankers	23 mins	22 mins
Car Carriers	35 mins	32 mins

1.3.3 Determining trial timeframe

The timeframe for the trial was proposed as two lunar months in the summer period when SRKW presence in the Salish Sea is historically at its highest. Lunar months (as opposed to calendar months) were selected to evaluate total ambient noise in the region, as this helps account for the low frequency noise that may be associated with tidal cycles. The ECHO Program has been collecting and analyzing ambient noise on a lunar month cycle in Haro Strait since 2016, thus a comparative evaluation of the potential reduction in ambient noise resulting from the slowdown trial could be more effectively assessed using the same timeframe.

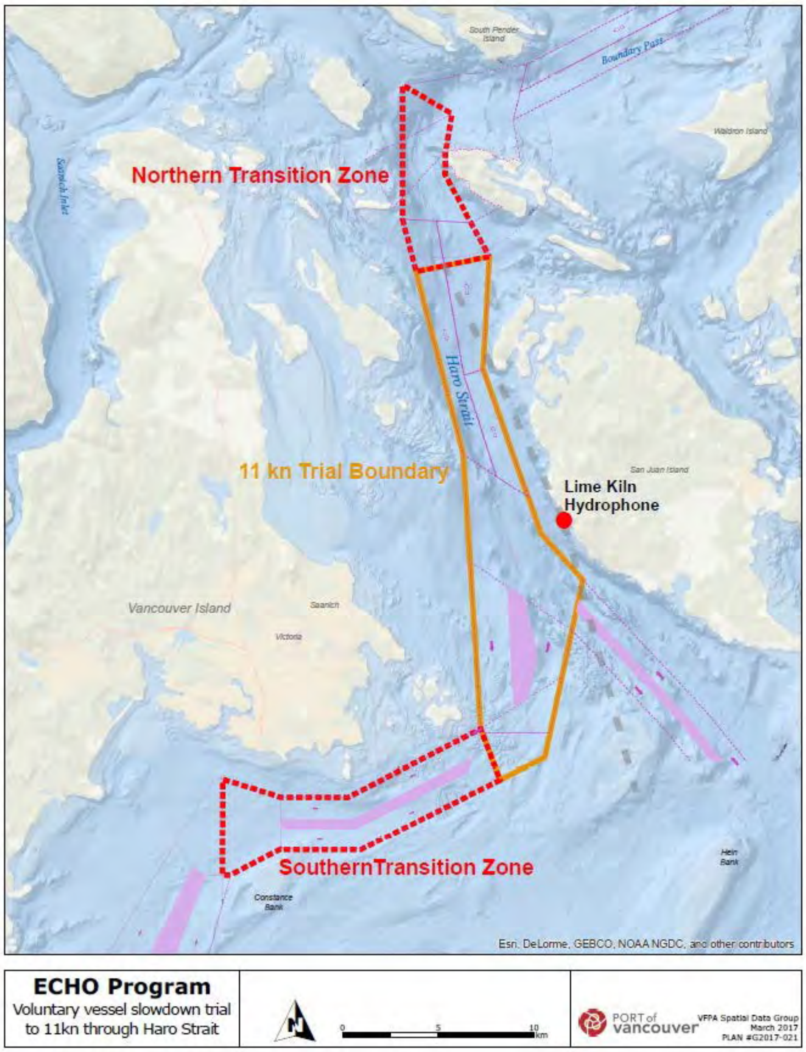
Every commercial vessel that is over 350 gross tonnes, and every pleasure craft over 500 gross tonnes, is subject to compulsory pilotage in British Columbia's coastal waters. The BC Coast Pilots embark and guide ships coming in or out of BC's ports to ensure safety, efficiency and environmental protection. In this report, we refer to these deep-sea commercial or pleasure craft as "piloted vessels". Based on historic vessel traffic data, at least 400 piloted vessels a month would be expected to transit Haro Strait. It was estimated that a two-month trial period would provide an adequate number of vessel transits to allow statistical analysis of the effects of the slowdown on vessel noise emissions and total ambient noise, while also balancing the potential impact to industry and benefit to SRKW at a time when they are historically present in the area.

1.3.4 Final trial design

Considering all of the factors discussed in Sections 1.3.1 to 1.3.3, and in consultation with the Vessel Operators Committee, the trial was designed to take place between August 7 and October 6, 2017 over an approximately 16 nautical mile distance in Haro Strait at a speed of 11 knots through the water. The selected boundaries of the trial are provided in Figure 3.

The August through October timeframe was selected to allow adequate time for engaging with and securing the participation of the shipping community, distributing various communication materials and official notices, and making the required changes to the Pacific Pilotage Authority Dispatch System. This dispatch system is used by agents and owners to book a coast pilot, and for the duration of the trial, also allowed vessel participation status to be recorded.

FIGURE 3. Defined trial area



2 Trial implementation

The implementation of the voluntary vessel slowdown trial required the preparation of materials, communication and engagement with stakeholders, as well as the technical aspects of measuring trial success through vessel participation and noise monitoring. The following report sections provide further details on the implementation of the trial.

2.1 Structure of the trial team

The ECHO Program Advisory Working Group helped to establish the concept and parameters of the slowdown trial, as outlined in Section 1. To refine the specifics of the trial and ensure adequate engagement of the shipping community, the ECHO Program Vessel Operators Committee was struck to assist with the planning, logistics, communications and implementation of the trial.

The Vessel Operators Committee included representatives from:

- BC Coast Pilots
- BC Ferries
- Canadian Coast Guard
- Chamber of Shipping
- Cruise Lines International Association – North West and Canada
- Hapag-Lloyd
- Holland America Group
- Pacific Northwest Ship & Cargo Services
- Pacific Pilotage Authority
- Shipping Federation of Canada
- Transport Canada
- Vancouver Fraser Port Authority
- Washington State Ferries

The ECHO Program team and port authority operations department worked with the Pacific Pilotage Authority, the BC Coast Pilots and Saab Technologies Ltd., to modify the pilot dispatch system so that agents and owners could indicate a vessel's intention to participate in the trial at the time a pilot order was placed, and so vessel participation data could be collected in real-time throughout the trial.

Significant engagement with the Vessel Operators Committee, in particular the Chamber of Shipping, Shipping Federation of Canada and Cruise Lines International Association – North West and Canada, was undertaken to determine how best to communicate the trial to the shipping community.

SMRU Consulting North America and JASCO Applied Sciences were contracted to collect, model and analyze acoustic and SRKW data before, during and after the trial period to assess the effects of reduced vessel speed on ambient noise, vessel noise emissions and the potential effect on SRKW behaviour and foraging.

Seaport Consultants and Colledge Transportation Consulting were engaged to conduct an economic, environmental and cultural analysis to assess the potential impact of the trial on the shipping industry and other regional interests.

2.2 Industry engagement and communications

In October 2016, the Chamber of Shipping and the ECHO Program co-hosted an industry lunch-and-learn event to inform shipping industry professionals about the ECHO Program, explain underwater noise threats to at-risk whales in the region, and to request proactive participation in research and mitigation projects, including the voluntary slowdown trial.

The Vessel Operators Committee was convened in December 2016, and with their input, a communications plan was developed with the objectives to:

- Inform industry about the ECHO Program objectives and the rationale for the trial
- Provide clear instructions on how to participate in the trial
- Encourage participation
- Share the results – during and after the trial
- Recognize trial participants for their participation

A number of communication tools including an infographic, presentations, and a web site were also developed and distributed to raise awareness.

To address industry's concern regarding the potential implications of participating in the slowdown trial, a financial analysis was conducted and results were communicated to stakeholders before the trial. Results of this analysis are provided in Section 3. In order to encourage participation and help offset additional costs to industry resulting from the trial, a $500 flat rate stipend was offered to vessel operators for both inbound and outbound participating transits. Further information on participation and the stipend is provided in Section 4.

Effective communication between agents, owners, vessel masters and pilots was crucial immediately before and during trial implementation. To ensure all stakeholders were aware of the timing and location of the trial, the following notifications were issued:

- Radio Navigational Warning issued July 24, 2017
- Temporary and preliminary notice and notice to industry issued July 24, 2017
- Notice to shipping issued August 6 and September 19, 2017

The Pacific Pilotage Authority dispatch system changed August 3, 2017 and thereafter the authority provided the ECHO Project team with weekly extracts of vessel transit and participation data from its dispatch system. This information was then communicated to industry through weekly newsletters and regular Vessel Operators Committee meetings.

Formal industry recognition activities were planned and communicated before and after the trial. These measures included local and national newspaper media release and advertisements featuring the organizations committed to trial participation, as well as a post-trial reception and special recognition for companies choosing to forgo their stipend.

2.3 Monitoring equipment

Once the final logistics for the slowdown trial were established, equipment and systems were put in place to monitor the success of the trial in achieving the original goal of answering the following questions:

1. How does reduced speed change the underwater noise generated by a specific vessel (vessel source level) and by type of vessel?
2. How does reduced speed change the total underwater ambient noise received at a specific location of importance to the killer whales?
3. What are the predicted resultant effects on killer whale behaviour and foraging given the changes in noise as answered by questions #1 and #2?

In addition to monitoring vessel participation through the Pacific Pilotage Authority dispatch system, the ECHO Program team contracted JASCO Applied Sciences and SMRU Consulting North America to monitor vessel speeds, vessel noise emissions, changes in ambient noise, and SRKW presence, and to use computer models to evaluate the predicted changes to SRKW behaviour and echolocation masking from slower vessels.

The equipment used to monitor vessel speed and acoustic information during the trial included:

- Automated Identification System (AIS) receivers to provide information such as vessel type, name, speed and draught on each AIS-enabled vessel transiting Haro Strait. AIS receivers were positioned atop Observatory Hill, approximately 17 kilometres to the west of the Haro Strait hydrophone deployments (see Figure 4),

and at the Lime Kiln light house on San Juan Island. These data were used to feed into JASCO's vessel noise emissions analysis, and to assess vessel speed compliance throughout the slowdown area.
- Autonomous multichannel acoustic recorders (hydrophones) or underwater listening stations to record vessel noise levels in the shipping lanes of Haro Strait
- The Strait of Georgia underwater listening station to record vessel noise levels at regular operating speeds on the approach to the Port of Vancouver
- A hydrophone cabled to shore at Lime Kiln State Park on San Juan Island, Washington State to record ambient noise levels in a key SRKW foraging area

2.3.1 Autonomous Multichannel Acoustic Recorders in Haro Strait

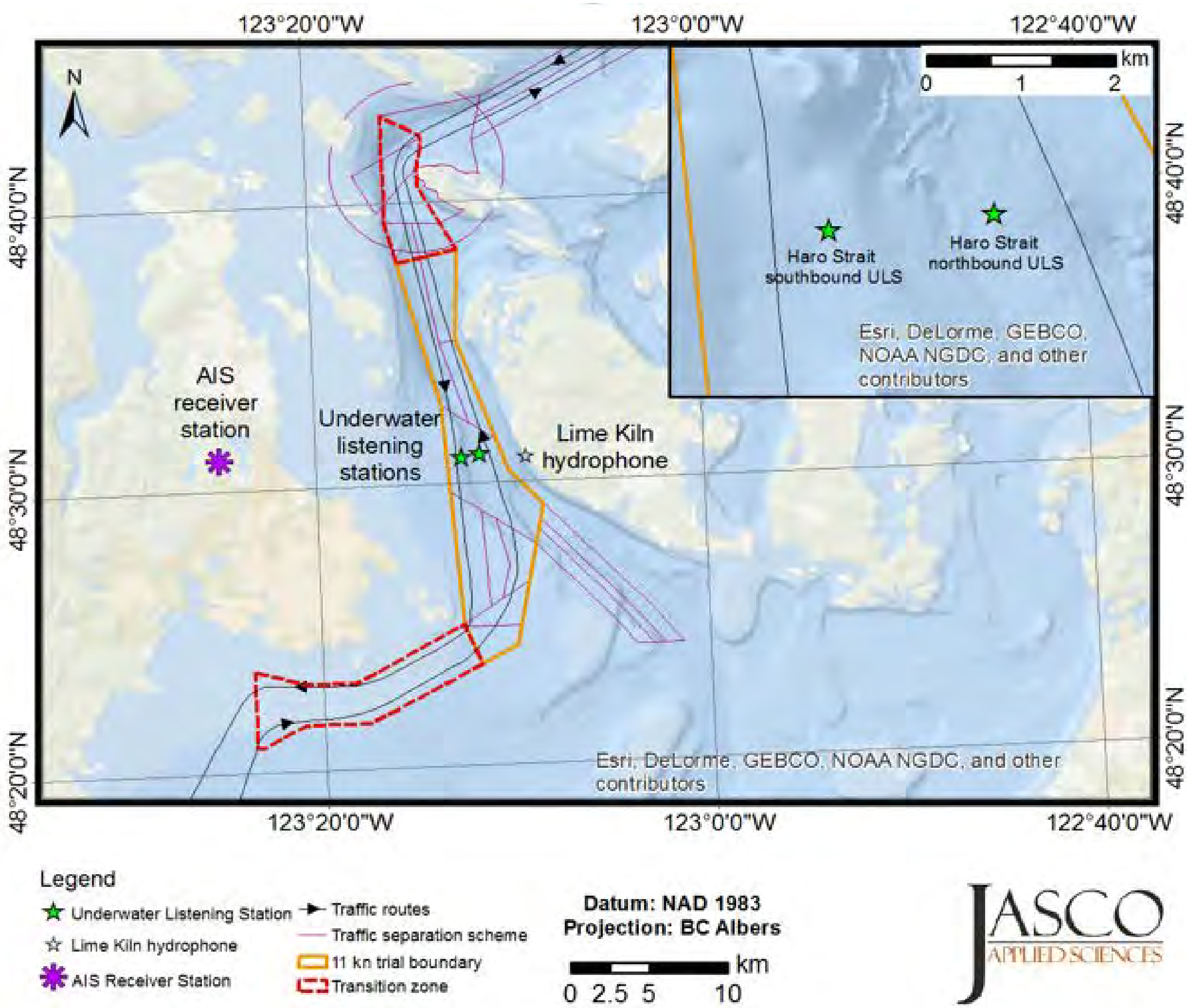
JASCO deployed two Autonomous Multichannel Acoustic Recorders or underwater listening stations to record received sound pressure levels produced by vessel traffic during the trial. These recorders were deployed directly adjacent to the southbound and northbound shipping lanes in Haro Strait, west of Lime Kiln lighthouse – see Figure 4. The recorders collected data to allow for determination of vessel source levels aligned with the Grade-C geometry of the American National Standards Institute vessel noise measurement standard (ANSI 12.64-2009 R2014). JASCO Applied Sciences has developed a software package called PortListen® that analyses noise data in combination with the information received via AIS to produce high-quality vessel source level analysis reports for each vessel accurately transiting the recorders.

It was necessary to schedule two deployments of the recorders to enable collection of data before, during and after the trial. Pre- and post-trial data were used as the "control" period against which changes in vessel source levels during the trial were evaluated. Figure 4 includes the locations, depth and timing for the deployments and retrievals of the recorders, as well as the location and depth of the Lime Kiln long-term hydrophone described in Section 2.3.3.

The data obtained from these temporary deployments allowed for the following analyses:
- Statistical comparison of vessel speeds and source levels in Haro Strait during the trial and control periods for different vessel types,
- Comparison of source levels for the same vessel at reduced speed in Haro Strait and at full operational speed at the existing underwater listening station in the Strait of Georgia, to further define the speed-sound relationship, and
- Analysis of the potential noise benefits achieved by slower speeds for different vessel types.

The results of the data analysis are provided in Section 5.1, with the complete technical report provided in Appendix A.

FIGURE 4. AMAR/ULS locations and deployment details



Station	Latitude	Longitude	Water depth (m)	Hydrophone depth (m)	Deployment (UTC)	Retrieval (UTC)
Recorders deployment 1						
Northbound	48.5181°N	123.1917°W	251	248	2017 Jul 6 21:00	2017 Sep 8 18:08
Southbound	48.5167°N	123.2076°W	210	207	2017 Jul 6 20:27	2017 Sep 8 17:45
Recorders deployment 2						
Northbound	48.5181°N	123.1917°W	249	246	2017 Sep 8 21:30	2017 Oct 26 18:47
Southbound	48.5161°N	123.2080°W	206	203	2017 Sep 8 20:08	2017 Oct 26 18:47
Lime Kiln	48.5155°N	123.1529°W	23	23	2016 Feb	ongoing

Modified from Appendix A: Vessel noise measurements report - JASCO Applied Sciences

2.3.2 Strait of Georgia underwater listening station

The Strait of Georgia underwater listening station is a collaborative project between the Vancouver Fraser Port Authority, Transport Canada, Fisheries and Oceans Canada, Ocean Networks Canada and JASCO Applied Sciences. This listening station has been in place since September 2015 and is now in its third year of operation. It is situated on the seabed at approximately 170 metres water depth, in the northbound traffic lane, approximately 30 kilometres southwest of Vancouver. Synchronized data from four hydrophones are streamed to shore in near real-time via the Victoria Experimental Network Under the Sea (VENUS) Observatory operated by Ocean Networks Canada.

The data obtained from the listening station allows for the capture and reporting of high quality vessel source levels aligned with the Grade-C geometry of the ANSI vessel noise measurement standard (ANSI 12.64-2009 R2014). The same methodology and software as the autonomous multichannel acoustic recorders deployed in Haro Strait (Section 2.3.1), are used to analyze vessel source levels at this station.

During the trial, source level measurements for vessels transiting at normal speeds were captured on the Strait of Georgia underwater listening station. These additional noise measurements were included in the JASCO Applied Sciences trial analysis to provide a group of service-speed source levels directly comparable to the same vessels measured at slower speeds in Haro Strait.

2.3.3 Lime Kiln hydrophone and observations

Since February 2016, SMRU Consulting North America has been conducting continuous monitoring of total ambient underwater noise using a Reson TC4032 hydrophone, installed at a water depth of 23 metres, approximately 70 metres in front of the Lime Kiln State Park light house on San Juan Island in Washington State. The hydrophone was calibrated prior to deployment in 2016 and again in June 2017.

As the western side of San Juan Island is an important foraging area for the SRKW, analysis of total received levels of noise at the Lime Kiln hydrophone site can serve as an indicator of potential received levels by whales feeding in the area.

The data obtained from the Lime Kiln hydrophone allowed for:

- Ambient noise analysis for the trial months (August and September 2017) providing monthly, weekly and daily plots of total received sound pressure levels at the Lime Kiln hydrophone
- A comparison of trial months to equivalent non-trial months (i.e. months with similar sound speed profiles, composition of vessel types and weather conditions) to assess differences in received noise levels
- A fine-scale analysis of the received sound pressure levels at the Lime Kiln hydrophone, taking into consideration vessel type and composition (including small boat presence near the hydrophone), vessel speed/participation in the trial, proximity of vessel passes to the receiving hydrophone, and weather and tidal conditions. This provides a more detailed statistical analysis of the ambient noise reduction, and identifies the important factors affecting total received noise at Lime Kiln.
- Identification of SRKW presence through acoustic detections.

In addition to the acoustic detections of SRKW on the Lime Kiln hydrophone, visual detections of killer whales were completed by scientists and observers stationed at the Lime Kiln lighthouse.

The results of the analyses are provided in Section 5.2 for ambient noise, and SRKW visual and acoustic observations are discussed in Section 5.3. The complete technical report is provided as Appendix B.

3 Trial evaluation and results – Economic, environmental and cultural analysis

Given the potential impacts (negative and positive) of the two-month vessel slowdown trial on the marine transportation industry and other users, ECHO Program Advisory Working Group members advised that some analysis of the economic, environmental and cultural implications should be undertaken prior to commencing the trial itself. To this end, a two-phased approach was employed. Phase 1, prepared by Seaport Consultants Canada, estimated the financial implications of the trial from a shipping industry perspective and Phase 2, completed by Colledge Transportation Consulting, used a multiple account evaluation framework to document the implications of the trial from several broad perspectives, or “accounts”.

The framework not only recognizes the direct costs borne by vessel operators due to the trial, but also any indirect costs to the industry, and potential impacts on local/regional economies and the implications for cultural and environmental values or accounts. The financial or economic impact analysis focused specifically on the projected cost impacts to industry of participating in the two-month, voluntary slowdown trial.

The results of both Phase 1 and 2 are presented in the Economic, Environmental and Cultural Analysis Report provided as Appendix C. Generalized results are provided in this section.

3.1 Financial account

The principal cost components evaluated in the financial or economic impact analysis were pilotage costs, vessel time (operating) costs and fuel costs (including potential fuel savings) for each vessel type.

The analysis used the Pacific Pilotage Authority dataset of 898 Haro Strait vessel transits over a similar timeframe (from August to October 2015) as the basis for the financial analysis. Anticipated increases in transit time resulting from the trial were derived from the difference between typical operating sea speed and the target slowdown speed of 11 knots in the trial zone, by vessel type. The slowdown was anticipated to add 30 to 60 minutes to the one-way sailing time of a vessel, depending on the vessel type.

Overall, the estimated direct financial impacts to vessels as a result of participating in the trial were as follows:

- All ship types could potentially incur increased pilotage costs.
- Bulk carriers, car carriers, general cargo ships and tankers would incur increased ship time costs.
- No additional ship time costs would be incurred by container and cruise ships because these vessels make up the time lost elsewhere in their schedules. However, containers and cruise vessels would instead incur makeup fuel cost impacts.

- All ship types would experience fuel cost savings because of lower fuel consumption rates when transiting at lower speeds through the slowdown zone.
- The trial was voluntary and not every vessel was required to participate, however the per-transit cost range for participation, considering pilotage, ship time, and fuel consumption by ship type (in Canadian dollars) were predicted as follows:
    - For bulk carriers, from a savings of $166 to a maximum cost of $2,683, with an average cost of $160
    - For car carriers, a minimum cost of $178 to a maximum cost of $453, with an average of $363
    - For containers, a minimum cost of $210 to a maximum cost of $4,371, with an average of $1,420
    - For general cargo, from a savings of $42 to a maximum cost of $2,095, with an average cost of $236
    - For passenger vessels, from a minimum of zero cost to a maximum of $3,526, for an average cost of $1,432
    - For tankers, from a savings of $46 to a maximum cost of $3,706, with an average cost of $327
- If all vessels transiting Haro Strait (898 vessels for same time period in 2015) participated in the two-month trial, the estimated aggregate industry cost of the trial by cost category would be (all figures in Canadian dollars):

- Pilotage	$180,882
- Ship time	$149,909
- Haro Strait fuel savings	-$438,315
- Makeup fuel required to maintain sailing schedules	$630,244
- Total cost	**$522,720**

Port disbursements that could be affected by a vessel slowdown include: longshore labour, tugs, ships' line handling and safety and security costs (cruise). The key determining factor to incurring additional costs is the ability of a ship to arrive within its designated berth window. The potential cost impacts and decisions by ship owners, operators, and/or agents to participate in the trial were evaluated on a case-by-case basis.

The case studies below illustrate some potential port cost implications:

- Container ships (in the case of a missed berth window):
    - Longshore labour: C$11,000 to $13,500 per hour of no work provided (which equates to an additional $90 to $110 per container onto the normal cost of $325 per container)
    - Ship time: U.S.$13,000 to $50,000 per day *
    - Demurrage: C$37.95 to $39.06 per container per day
    - On-time berthing: Risk of losing incentive discount offered by some terminals
- Bulk carrier and general cargo ships (in the case of delays in tendering notice of readiness or need to shift vessel due to delays):
    - Demurrage: Delays in tendering notice of readiness could result in additional US$8,000 to $15,000* time charter rates per day depending on type of ship and extent of the delay
    - Vessel shifting to/from anchorages: C$6,000 to $20,000 per occurrence for missed anchorage/berth window or tidal window at Second Narrows (Vancouver Harbour)

** Vessel costs are typically stated in U.S. dollars per day as either time-charter rates (what one pays under a contract for the use of a ship) or time-charter equivalent costs (estimates of daily costs built up by item).*

3.2 Customer service account

The customer service account assesses the anticipated impacts of the trial on commercial users of Haro Strait and their customers. The users of Haro Strait include a broad interest group made up of: vessel operators and their customers across many commodity sectors that pay the costs of transportation services; cruise lines and their passengers from around the world; and whale watching tour operators and their customers.

The key measures used to analyze the customer service account are sailing schedule reliability, navigation conditions (adverse tidal windows and currents) and customer satisfaction.

Sailing schedule reliability: As the trial was planned to take place over a reasonably short fixed period of time, and operators were given advance notice giving them the ability to make up time, the vessel slowdown was generally not anticipated to have a major impact on sailing schedules. It could be more difficult for operators to make up lost sailing time on shorter Pacific coast multi-port itineraries, as opposed to trans-Pacific voyages. However, because the trial was voluntary, operators could choose not participate if they were constrained by a sailing schedule on a specific transit.

Navigation conditions: For some vessels calling terminals located in the eastern parts of Burrard Inlet, east of the Second Narrows Bridge and the Fraser River, participating in the trial could result in a missed tidal window/tidal assist and could incur additional costs. Vessel operators could choose not to participate in these instances.

Customer satisfaction: In the cruise sector in particular, scheduling delays could have a significant impact on guest satisfaction, affecting their ability to make connecting flights, as well as influencing overall impressions of Vancouver as a tourism destination. In the cargo sector, the short duration of the trial was not anticipated to have a material impact on the customer satisfaction of cargo owners, who are the ultimate customers. The trial was not expected to negatively impact customer satisfaction in the whale watching sector, and may have a positive impact, by virtue of less disturbance (i.e. reduced vessel noise).

3.3 Economic account

The economic account evaluates the anticipated import/export trade related and associated economic impacts of the trial. The key measures used to analyze the economic account are trade volume and value at stake, port competitiveness (risk of traffic diversion), and the Port of Vancouver's international reputation (corporate social responsibility).

In terms of trade volume and value, the cost of the trial as a percentage of estimated trade value during the two-month trial for cargo vessels was 0.0021 per cent and for cruise vessels was 0.0477 per cent. The trial was not expected to have a material impact on international trade traffic moving through the Port of Vancouver because of its short duration, and because vessel operators could choose not to participate if they believed their sailing schedule or pilotage hours would be significantly impacted on a particular transit. A more permanent slowdown in which all vessels had to participate could, however, have a greater potential adverse impact on trade traffic transiting this area.

The Port of Vancouver trades approximately $550 million in goods each day, with approximately $375 million in foreign trade involving international traffic that may transit through Haro Strait. In terms of port competitiveness, the trial was not expected to impact the overall competitiveness of the port because of its voluntary nature and short duration.

However, a more permanent vessel slowdown in which all vessels had to participate, particularly if applied only to Canadian waters, could add cost and supply chain uncertainty and create a significant competitive disadvantage for the Port of Vancouver relative to competing West Coast ports. This in turn could potentially result in future diversions of international trade traffic and cruise passengers away from the Port of Vancouver.

The vessel slowdown trial presented an important opportunity for the port authority and users of the port to demonstrate proactive collaboration by developing and implementing voluntary measure to provide scientific evidence in support of any future decisions by Canadian and U.S. federal regulators to protect SRKW and their critical habitat. In terms of international reputation, the work of the collaborative ECHO Program can help enhance the international reputation and public trust of participating shipping owners and operators and the port itself, by showcasing their willingness to participate, adapt and manage change.

3.4 Cultural account

The cultural account captures coastal Aboriginal perspectives on the benefits and implications of the trial on cultural interests, values and objectives based on interviews undertaken with the two First Nations members of the ECHO Program Advisory Working Group. Although this section of the report focuses on cultural considerations associated with the trial, it is important to note that in Aboriginal societies, these considerations are inseparable from ecological, economic and social considerations. The key measures used to analyze the cultural account are: respect for and preservation of cultural values and practices; restoration and protection of SRKW and the marine ecosystem; and safety of Aboriginal canoe paddlers and fishers.

With regards to respect for and preservation of cultural values, the trial was viewed as an opportunity to raise industry and public awareness of the cultural significance of SRKW to Aboriginal peoples – an iconic species of importance to all British Columbians – and the purpose and importance of reducing threats such as underwater vessel noise. Although the trial was generally viewed as a positive undertaking, concern was expressed that through sharing cultural information, such information could be misconstrued or misrepresented by others. Concern was also voiced that Aboriginal support for the trial could be misrepresented as support for increased vessel traffic, however, commercial vessels operating at slower speeds in Haro Strait during the trial should generate less wake, potentially improving safety for Aboriginal fishers and traditional canoe paddlers if and when they were in the vicinity.

In terms of restoration and protection of SRKW and the marine ecosystem, the trial and its focus on underwater noise was viewed as a positive. The trial presented an opportunity to learn about what effects slowdowns could have, and potential for the whales to respond positively during the trial. The trial was further viewed as an opportunity to raise awareness within the marine industry, and of British Columbians in general, of an activity that is having an environmental effect. Concern was expressed that slowing to 11 knots may not be sufficient, and slowdowns to eight or nine knots would be required to make a difference, which could create more economic and safety issues for industry, potentially impeding further progress. Concern was also expressed that vessel noise reductions alone may not be sufficient to enable SRKW recovery and that prey availability was not being addressed through the trial.

3.5 Environment account

The environment account identifies the nature, magnitude and significance of the trial on the SRKW critical habitat associated with underwater noise reduction, as well as the implications of the vessel slowdown on air quality. The key measures used to analyze the environment account were protection of SRKW critical habitat, effects on underwater noise from vessels, and effects on air quality.

As detailed in Section 1.1, both Canadian and U.S. federal regulators have designated most of the southern Salish Sea as SRKW critical habitat. Recent studies indicate that SRKW are already impacted by existing levels of vessel traffic in the Salish Sea, and projected increases in urban population and future development projects with marine components will further increase marine traffic and underwater noise.

The trial was designed to have large commercial vessels slow down to 11 knots, which was estimated could result in significant at-source sound intensity reductions, the scale of which would reduce the number of behavioral and echolocation disruptions to SRKW. Given that the trial encompassed a period of typically high SRKW presence in Haro Strait, the trial was predicted to have overall positive effects on SRKW. The trial results, as they pertain to the environmental account are discussed in Section 6.

The relative change in air emissions (both air quality and climate change-related) as a result of the trial, was dependent upon vessel participation rates, whether any makeup fuel was consumed to compensate for lost time, and whether that makeup fuel was consumed within or outside the North American Emission Control Area. Predicted impacts ranged from a decrease in air emissions of -8 per cent if no vessels were required to make up their lost time, to +8 per cent if all vessels participated in the trial and had to make up lost time within the emission control area.

3.6 Do-nothing scenario

The implications of a "do nothing" scenario—not proceeding with an industry supported vessel slowdown trial— were also evaluated. Overall, it was determined that doing nothing would represent a missed opportunity to test and evaluate the feasibility of vessel slowdowns as a meaningful vessel noise reduction measure and a missed opportunity to reduce impacts to SRKW in an important foraging area and to demonstrate industry leadership. Finally, not proceeding with the trial would result in a missed opportunity to inform federal policy and related future conservation approaches with science-based evidence regarding the most effective measures that might contribute to the recovery of SRKW, while minimizing the adverse effects on the shipping industry and maritime commerce.

4 Trial evaluation and results – Industry participation

During the two month trial period between August 7 and October 6, the Pacific Pilotage Authority reported 951 piloted transits through Haro Strait. At the request of the ECHO Program, the authority modified the dispatch system so that agents could indicate a vessel operator's intention to participate in the trial at the time a pilot order was placed.

Orders could be flagged as 'Yes' (full commitment), 'Yes-Conditional' (based on prevailing conditions during the transit such as schedule and weather) or 'No' (would not participate).

4.1 Trial participation – Intent

At the outset of the trial, various organizations indicated their support of the trial and intent to participate, when economically and operationally feasible, including:

- AAL Shipping
- ACGI Shipping Inc.
- BC Coast Pilots
- BC Ferries
- Buchanan Cruises, LLC
- Carnival Cruise Line
- Celebrity Cruise Lines
- Chamber of Shipping
- CMA CGM
- Colley West Shipping Ltd.
- COSCO
- Cruise Lines International Association North West and Canada
- Crystal Cruises
- CSL International
- Disney Cruise Line
- Evergreen Line
- Fairmont Shipping (Canada) Ltd.
- Fisheries and Oceans Canada
- G2 Ocean
- Georgia Strait Alliance
- Hamburg Sud
- Hapag-Lloyd
- Holland America Line
- Hudson Shipping Lines
- Robert Reford
- Royal Canadian Navy
- Inchcape Shipping Services
- International Ship-Owners Alliance of Canada
- K Line
- Maersk
- Mason Agency Ltd.
- Mitsui O.S.K. Lines
- Montship Inc.
- MSC Mediterranean Shipping Company
- Navitrans Shipping Agencies West Inc.
- Neptune Bulk Terminal
- Norton Lilly Vancouver
- Norwegian Cruise Line
- NYK Line
- Oceaenia Cruises
- Oldendorff
- OOCL
- Pacific Pilotage Authority
- Ponant
- Princess Cruise Line
- Ravensdown Shipping Services Ltd.
- Oxbow Sulphur Canada
- Pacific Basin Shipping
- Pacific NorthWest Ship & Cargo Services Inc.
- Royal Caribbean International Cruise Line
- SAAM SMIT Vancouver Inc.
- Saga Welco AS
- Seabourn Cruise Line
- Seaspan ULC
- Shipping Federation of Canada
- Sinotrans
- Swire Shipping
- Trans-Oceanic Shipping Co. Ltd
- Transport Canada
- Valles Steamship (Canada) Ltd.
- Vancouver Fraser Port Authority
- Washington State Ferries
- Westward Shipping Ltd.
- Westwood Shipping Lines
- Wheelhouse Shipping Agency
- Wilhelmsen Ships Service
- ZIM

A ship's agent was responsible for relaying intent to participate at the time of ordering a pilot. The information obtained through the pilotage authority dispatch system indicated that for the duration of the trial 38 per cent of the orders were flagged as 'Yes,' a further 41 per cent were flagged as 'Yes-Conditional' and 21 per cent were flagged as 'No' at the time of pilot order.

This information regarding intent to participate was reviewed by the pilot and ship master at the time of embarkation in order to determine whether or not that particular transit could or should participate in the trial given the conditions at the time of boarding.

A breakdown of intent to participate, by vessel type, is presented in Table 2.

TABLE 2. Industry intent to participate as reported by Pacific Pilotage Authority

Vessel Type	Total Transits	'Yes'	Rate	'Yes-Conditional'	Rate	'No' Unable to Participate	Rate
Bulk Carrier	425	117	28%	210	49%	98	23%
Car Carrier	86	49	57%	20	23%	17	20%
Container	260	142	55%	69	27%	49	19%
General Cargo	66	20	30%	31	47%	15	23%
Passenger	30	11	37%	19	63%	0	0%
Tanker	74	26	35%	34	46%	14	19%
Tug	2	0	0%	2	100%	0	0%
Yacht	1	0	0%	0	0%	1	100%
Other	7	1	14%	1	14%	5	71%
Grand Total	951	366	38%	386	41%	199	21%

Agents gave three principal reasons for not being able to participate in the trial at the time of order: meeting schedule, meeting tidal windows and cost/excess hours considerations. For both inbound and outbound transits, the agents appear to have responded with above average 'No' designations for transits destined for or departing from mid-Vancouver Island and the eastern section of Vancouver's inner harbour (i.e. east of Second Narrows).

4.2 Trial participation – Pilotage authority reported results

Overall, 578 of 951 (61 per cent) of piloted vessels participated in the trial (having flagged participation intent as 'Yes' or 'Yes-Conditional'), as reported by the Pacific Pilotage Authority. Of the 951 transits, 199 (21 per cent) were flagged as 'No' at the time of pilot order and no further attempt to participate was made. There were 175 transits (18 per cent of the total) that were flagged by the agents as 'Yes' or 'Yes-Conditional', which were subsequently not reported as participating by the pilotage authority.

This information was taken from the pilot "Source Card" which is recorded immediately after the pilot debarks from the voyage. These participation values do not take into account whether or not the vessel conformed to the trial's target speed of 11 knots through the water, as the pilot would not have been aware of the exact speed of the vessel at the time of debarkation. Validation of vessel speed was conducted at the end of each two-week period, using AIS and tidal current data to evaluate the average speed through water of vessels over the designated trial area. Compliance with slowdown trial speed is discussed in Section 4.3.

The participation numbers as reported by the pilotage authority, broken down by vessel type, are provided in Table 3. These values reflect the industry's attempt to participate in the trial, where economically and operationally feasible.

TABLE 3. Vessel participation rates as reported by Pacific Pilotage Authority

Vessel Type	Total Transits	Pilot Reported Participation	Agent Flagged 'No'	Agent Flagged 'Yes-Conditional' or 'Yes' that did not participate	Pilot Reported Participation Rate
Bulk Carrier	425	232	98	95	55%
Car Carrier	86	57	17	12	66%
Container	260	178	49	33	68%
General Cargo	66	40	15	11	59%
Passenger	30	27	0	3	90%
Tanker	74	41	14	19	55%
Tug	2	1	0	1	50%
Yacht	1	0	1	0	0%
Other	7	2	5	0	29%
Grand Total	951	578	199	174	61%

The four principal reasons for vessels not being able to participate in the trial as noted by the BC Coast Pilots on their Source Cards at the end of a job were: ship master refused, schedule, cost/excess hours, and tidal/current. In some cases more than one condition was assigned to an order.

4.3 Trial participation – Actual speed compliance

The trial design stipulated a target of 11 knots, measured as speed through water. The international shipping industry's AIS, used by the Pacific Pilotage Authority and others, records speed over ground, and so transit data needed to be adjusted for tidal current to yield speed through water. Using the AIS receiver stationed at Lime Kiln State Park (Section 2.3.3), with supplemental data from JASCO Applied Sciences' AIS receiver on Observatory Hill and tidal current data at Kellet Bluff on Henry Island at the north east end of Haro Strait, SMRU Consulting North America calculated the average vessel speed over ground over the entire trial area and subsequently corrected for tidal current to obtain speed through water.

The values presented in Table 4 use both the pilots' annotation on the Source Card of the vessel having participated and the adjusted speed through water, therefore reflecting both the vessel's intent and success in meeting the trial's slowdown criteria.

These adjustments result in an overall vessel participation of 44 per cent (421 of 951 piloted transits during the trial) based on speed through water of less than 12 knots. When given leeway for adjusted speeds less than 13 knots, a result of 55 per cent (526/951 transits) was achieved.

TABLE 4. Participation based on adjusted speed through water

			Adjusted Speed < 12kn		Adjusted Speed < 13kn	
Vessel Type	**Total Transits**	**Pilot Reported as Participating**	**Count**	**Overall Rate**	**Count**	**Overall Rate**
Bulk Carrier	425	232	170	40%	214	50%
Car Carrier	86	57	36	42%	52	60%
Container	260	178	123	47%	155	60%
General Cargo	66	40	29	44%	36	55%
Passenger	30	27	26	87%	27	90%
Tanker	74	41	34	46%	39	53%
Tug	2	1	1	50%	1	50%
Yacht	1	0	0	0%	0	0%
Other	7	2	2	29%	2	29%
Grand Total	**951**	**578**	**421**	**44%**	**526**	**55%**

It must be noted that a specific targeted speed through water is difficult to achieve on an ocean-going vessel. Unlike land-based vehicles, vessels contend with environmental conditions such as currents and wind that vary significantly through their journey, affecting speed. An additional factor affecting the vessel speed and maneuvering characteristics is whether the vessel is fully loaded or in ballast. Vessels do not have a “speedometer”, rather a target engine load or rotations per minute is set, which can make achieving a specific speed through water challenging.

4.4 Trial participation – Stipend allocation

To alleviate some of the financial barriers to participation, a stipend of $500 CAD per transit was offered for vessels that were reported by the pilotage authority to have participated in the trial and were able to achieve the requested speed through water (Table 4). Vessel owners and agents were instructed to apply for each transit through an online application tool.

Of the 406 stipend applications submitted, 248 stipends were approved (61 per cent), however, some companies (listed below) subsequently returned the stipend. In total, of the 951 transits during the slowdown trial, 225 stipend applications were approved and paid.

The principal reasons for the port authority not accepting the stipend applications were vessel speed not meeting the slowdown criteria and/or the pilot flagging the transit as non-participant. Those applying for the stipend (largely agents) did not have real-time confirmation of valid participation for each transit, which may account for the relatively high application rejection rate.

Participating companies were also provided with an option to forgo their stipends, in order to support continued ECHO Program research. These companies were recognized both on the trial webpage and with a certificate of appreciation. The eleven companies who chose to forgo their stipends were:

- Evergreen Shipping Agency (America) Corporation
- Holland America Line
- K-Line

- OOCL
- Pacific Basin Shipping
- Princess Cruise Line
- Ravensdown Shipping Services Pty Ltd
- Saga Welco AS
- Seabourn Sojourn
- Sinotrans
- Washington State Ferries

5 Trial evaluation and results – Acoustic results

The ECHO Program team contracted JASCO Applied Sciences and SMRU Consulting North America to monitor vessel speeds, vessel noise emissions and changes in ambient noise during the trial and comparable control or baseline periods to answer the acoustic questions posed by the triall. The results of the acoustic analyses are described in this section.

5.1 Vessel source level measurements

The complete technical report on vessel source levels prepared by JASCO Applied Sciences Ltd. is provided as Appendix A to this summary report. Generalized results are provided in this section.

Data from the two Haro Strait listening stations, in conjunction with data from the Strait of Georgia listening station, were used in this vessel source level analysis to answer the trial question 1. How does reduced speed change the underwater noise generated by a specific vessel (vessel source level) and by type of vessel?

Results from this study are based on measurements collected before, during, and after the trial. A total of 2,765 source level measurements were collected over 3.5 months, from July 6 to October 27, 2017 at the three measurement stations. Of these measurements, 1,930 were accepted (i.e. passed a manual quality review). These measurements are comprised of all AIS-enabled vessel types, piloted or non-piloted, including the five major piloted commercial vessel categories: bulk/general cargo, container, large passenger/cruise, tankers and vehicle carriers. Other AIS-enabled vessel types measured included: fishing, naval, government/research, tugs, recreational and ships simply transmitting as “other”.

Determination of the effects of the trial were conducted by statistically comparing source levels during the control period (pre- and post-trial) to source levels during the trial. The trial “participant” vessels were determined by cross referencing a pilot-reported ‘Yes’ with a compatible vessel speed over the Haro Strait stations. During the trial, a total of 920 (out of 951) trips in the pilot logs were matched to the Haro Strait underwater listening station measurements.

5.1.1 Speed through water for source level measurements

Statistical analysis of vessel speed through water at the time of source level measurement (i.e. while transiting over the Haro Strait stations) was conducted for the control period, as well as the trial period. Speeds through water are shown in Table 5 for both the pre- and post-trial period (control) and for the participating vessels during the trial period (participant) for the five main commercial vessel categories: bulkers/general cargo, container ships, passenger/cruise vessels, tankers, and vehicle carriers.

The percentiles shown in Table 5 indicate the values for which a percentage of vessels were slower than the listed speed. For example, five per cent of vessels were slower than the fifth percentile values in Table 5, whereas 95 per cent of the vessels were slower than the 95th percentile values.

TABLE 5. Statistics of speed through water (knots)*

Vessel Type	Bulk	Container	Cruise	Tanker	Vehicle Carrier
Control					
5th %tile	11.4	15.8	13.3	11.5	14.5
Mean	***13.5***	***18.9***	***16.8***	***13.7***	***17.3***
95th %tile	15.4	21.9	21.2	15.2	19.7
Participant					
5th %tile	9.8	9.5	9.1	9.9	10.1
Mean	***11.4***	***11.2***	***10.6***	***11.4***	***11.4***
95th %tile	12.8	13.1	12.2	12.8	12.7

* Note that the speeds listed above are measured at the time of transit over the Haro Strait listening stations, and are therefore not the same values discussed in Section 4.3, which use the average speeds of vessels over the entire 16 nautical mile slowdown zone to assess compliance.

Based on the above, mean reductions of speed through water for vessels participating in the trial were on the order of:

- A 2.1 knot reduction in speed for bulk/general cargo ships
- A 7.7 knot reduction in speed for container ships
- A 6.2 knot reduction in speed for passenger/cruise ships
- A 2.3 knot reduction in speed for tankers
- A 5.9 knot reduction in speed for vehicle carriers

5.1.2 Differences in vessel source levels

Reducing speeds in Haro Strait was an effective method for reducing broadband (across all sound frequencies measured) source levels for all five commercial vessel categories. Statistical analysis of vessel source levels was conducted for the control period and the trial period. For the five main commercial categories, the broadband monopole source levels (MSL in dB re 1 μPa @ 1 m) are shown in Table 6 for the pre and post-trial period (control) and for the participating vessels during the trial period (participant).

The fifth percentile values in Table 6 are showing the vessel source level for which five per cent of vessels were quieter, whereas 95th percentile values indicate the source level for which 95 per cent of the vessels were quieter (i.e. five per cent of vessels were louder).

TABLE 6. Statistics of vessel source levels (MSL dB re 1µPa@1m)

Vessel Type	Bulk	Container	Cruise	Tanker	Vehicle Carrier
Control					
5th %tile	181.9	183.8	175.5	182.3	183.6
Mean	***187.8***	***191.0***	***186.3***	***187.2***	***189.4***
95th %tile	193.9	199.1	198.3	192.4	195.2
Participant					
5th %tile	176.1	174.8	171.4	175.9	175.8
Mean	***181.9***	***179.5***	***175.8***	***181.1***	***180.2***
95th %tile	190.5	185.1	183.2	186.5	188.4

The statistically significant differences in mean vessel source levels between control vessels and vessels participating in the trial were:

- A 5.9 dB reduction in source level for bulk/general cargo ships
- A 11.5 dB reduction in source level for container ships
- A 10.5 dB reduction in source level for passenger/cruise ships
- A 6.1 dB reduction in source level for tankers
- A 9.2 dB reduction in source level for vehicle carriers

Using the mean speed reductions and mean source level reductions between trial participant and control vessels, decibels (dB) per knot reduction (broadband MSL) relationships for the five main commercial vessel categories are provided below. Note that these are mean or average values, and that the relationship between vessel speed and source level noise emissions is not linear. Rather, the ratios provided below provide an estimate of the potential benefit of noise reduction on a dB per knot basis, and will not hold true for every ship within a vessel type, some will have greater reductions, while others will have smaller reductions.

- 2.8 dB/knot reduction for bulk/general cargo ships
- 1.5 dB/knot reduction for container ships
- 1.7 dB/knot reduction for passenger/cruise ships
- 2.6 dB/knot reduction for tankers
- 1.6 dB/knot reduction for vehicle carriers

Although not reported in commercial piloted vessel statistics, vessels from the Royal Canadian Navy also participated in the slowdown trial. The sample size for navy vessels is small, and the vessel source levels are generally lower/quieter than large commercial vessels, therefore the statistical confidence in the results is lower. However, the mean speed reduction for navy vessels between control and trial periods was 5.3 knots, resulting in a source level reduction of 6.3 dB.

Washington State Ferries pass east-west through the northern portion of the slowdown area, so they could not be measured by the Haro Strait listening stations. Washington State Ferries were, however, able to participate in slowing vessels in the trial area over a period of two weeks between August 7 and August 21, inclusive.

Several factors other than speed, such as vessel loading and draught, may influence underwater noise emissions from vessels. To evaluate the speed-sound relationship while such factors are controlled, a total of 107 matched pairs of vessel source level measurements were recorded, where each pair of measurements was for the same vessel, on the same day, with the same pilot and loading conditions, at both the northbound Haro

Strait listening station and the northbound Strait of Georgia listening station during the trial period. When the vessel source level and vessel speed data relationships for all 107 vessels are plotted together, the trend line predicts that slowing speed by 40 per cent can reduce broadband monopole noise emissions by approximately 11.3 dB.

An expert working group, convened by the Coastal Oceans Research Institute (Heise et al. 2017) recently proposed that the following three frequency ranges be used for assessing underwater noise impacts to SRKW:

- Broadband (10 Hz to 100,000 Hz)
- Communication range (500 Hz to 15,000 Hz)
- Echolocation range (15,000 Hz to 100,000 Hz)

In general, while slowing vessels reduced vessel noise emissions over the entire measured frequency range (broadband), the greatest relative reductions were observed below 100 Hz (lower than SRKW communication range) and above 15,000 Hz (in SRKW echolocation range). It should be noted that echolocation devices (depth-sounders and/or fish-finders) installed on vessels, typically operating in the 20,000-50,000 kHz range, can contribute significantly to the vessel noise measured (and subsequent calculation of vessel source levels), in the 15,000 Hz+ SKRW echolocation range. These contributions to noise are independent of speed.

5.2 Ambient noise

The complete technical report on ambient noise levels at the Lime Kiln hydrophone, prepared by SMRU Consulting North America is provided as Appendix B to this summary report. Generalized results are provided in this section.

5.2.1 Received levels at Lime Kiln

In order to answer the trial question #2 of "How does reduced speed change the total underwater ambient noise received at a specific location of importance to the killer whales?" received ambient noise data at the Lime Kiln hydrophone were analyzed for the trial time period (August 7 – October 6, 2017), as well as for two representative pre-trial (or baseline) months. The selected pre-trial baseline months include August 14 - September 14, 2016 and July 9 - August 7, 2017 and were chosen based on assumed similar sound speed through the water column (which vary between summer and winter months), and similar weather and vessel traffic conditions. The analytical methods applied take into account the combined effects of noise levels and exposure duration.

To evaluate potential changes in ambient noise resulting from the trial, a comparison of all (unfiltered) ambient noise data for pre-trial baseline versus trial months was conducted, as well as for a filtered data set. The filtered data set aimed to better evaluate changes in ambient noise that could be attributed to the vessel slowdown trial. Therefore the filtered dataset included only time periods when a large AIS-enabled vessel was within confident acoustic detection range (six kilometres) of the Lime Kiln hydrophone, and excluded time periods when there were other factors that could be significantly contributing to the received noise. The filtered data set excluded:

- Time periods of elevated wind (>5 metres per second)
- Time periods with high tidal current (>35 centimetres per second)
- Time periods with small boats present near the Lime Kiln hydrophone

Statistical analysis of the sound pressure levels received at the Lime Kiln hydrophone was conducted for the combined two baseline months and the combined two trial months. Note that the fifth percentile indicates the noise is below this level five per cent of the time, 95th percentile indicates the noise is below that level 95 per cent of the time, 50 percentile is the median. Table 7 presents the differences in sound levels between baseline and trial periods in unfiltered and filtered broadband, as well as in SRKW communication and echolocation frequency bands identified by Heise et al. (2017). Note that a negative value indicates a noise reduction, whereas a positive value indicates an increase in noise.

TABLE 7. Ambient noise differences in sound pressure levels (dB)

Frequency Range	**Data description**	**SPL (dB) difference between slowdown and baseline**		
		5th %tile (quiet)	**50th %tile Median**	**95th %tile (loud)**
Broadband 10 Hz -100,000 Hz	All (unfiltered) data	+0.2	***-1.2***	-1.3
Broadband 10 Hz – 100,000 Hz	Filtered data: large vessel w/in 6km, no small boat, high wind and current removed	-0.3	***-2.5***	-1.4
SRKW Communication 500 Hz – 15,000 Hz	Filtered data: large vessel w/in 6km, no small boat, high wind and current removed	-1.1	-2.1	-1.8
SRKW Echolocation 15,000 Hz – 100,000 Hz	Filtered data: large vessel w/in 6km, no small boat, high wind and current removed	+1.2	+0.4	-0.2

Results indicate a median reduction in broadband received sound pressure level (SPL) of 1.2 dB re 1 μPa at the Lime Kiln hydrophone for unfiltered data during the trial period as compared to the baseline period. For the filtered data, the median reduction in broadband received sound pressure level for the trial period, compared to the pre-trial control period was 2.5 dB re 1 μPa.

A noise reduction of 2.5 dB is roughly equivalent to a 44 per cent reduction in sound intensity and a reduction of 1.2 dB is roughly equivalent to a 24 per cent reduction in sound intensity.

The statistical analysis indicates that for greater than 90 per cent of the time, there was a clear, quantifiable noise reduction during the slowdown period as compared to baseline (based on the filtered data).

At very low ambient noise levels (such as the fifth percentile), there was little to no noise reduction measured, and during the slowdown trial months these lower ambient noise levels actually increased (i.e. got louder), likely due to the longer duration of vessels in the area. Increases are shown as positive values in Table 7.

For the filtered data, the greatest reduction in received sound pressure levels during the trial period was concentrated in the first two decade frequency bands (< 1000 Hz). This is due to the concentration of ship noise in those lower frequencies, as well as the more rapid attenuation of higher frequency noise from vessels which may not reach the Lime Kiln hydrophone located 2.3 km from the center line of the closest shipping lane.

Comparison to the recently developed noise metrics (Heise et al. 2017) of SRKW communication (500-15,000 Hz) and echolocation (15,000-100,000 Hz) frequency bands show a median reduction of 2.1 dB in the communication band but a slight increase in the higher frequency echolocation band during the trial period compared to the baseline period.

Factors that may be affecting these high frequency hydrophone measurements include potential interference of electrical/system noise from the hydrophone or energy source (seen above 20,000 Hz), and the limitations of the hydrophone to accurately measure these high frequency sounds at such low intensity (<85 dB mean value). Due to the large distance between passing ships and the hydrophone, much of the high frequency sound coming from vessels is attenuated below background and internal hydrophone system noise by the time it reaches the Lime Kiln hydrophone.

The ambient noise data set also allowed for a comparative analysis of received level at Lime Kiln when large vessels were proximate to the hydrophone. These analyses indicated that median ambient noise levels were 6.1 dB lower during the passage of a participating container vessel during the trial, and were 1.5 dB lower during the passage of a participating bulk/general cargo vessel, as compared to baseline. These values reflect the larger speed and source level reduction attributed to faster-moving vessels.

5.2.2 Evaluation of “quiet times” at Lime Kiln

Knowing that slowing a vessel down will result in the vessel being in an area longer and may impact “quiet times” between vessel transits, a comparison of “quiet times” at the Lime Kiln hydrophone was conducted. This analysis included all acoustic data (unfiltered), both natural and anthropogenic. Broadband thresholds of <110 dB re 1 µPa [noise level below which SRKW behavioural response is not anticipated, (SMRU Consulting North America 2014)] and <102.8 dB re 1 µPa (5 per cent quietest received noise level at Lime Kiln during the baseline period) were selected as representative quiet times thresholds for comparing the baseline and trial time periods.

The selection of thresholds for evaluating quiet times substantially affects the results of the analysis. Using the thresholds described above, quiet time analysis when comparing the baseline time period with the slowdown trial time period revealed:

- The mean duration of quiet times below each threshold was on the order of three to four minutes, due to considerable oscillation in received sound pressure levels, and was not statistically different between baseline and trial time periods.
- The maximum duration of quiet time was greater during the baseline period.
- The total percentage of time below each threshold was approximately three per cent greater during the trial period as compared to baseline. The received levels at Lime Kiln were below the 110 dB threshold 49% of the time during the baseline period and 54% of the time during the slowdown, and were below the 102.8 dB threshold 25% of the time during the baseline and 28% of the time during the slowdown trial.

5.3 SRKW presence

Both visual observations and acoustic detections at Lime Kiln were used for a general evaluation of killer whale presence before and during the trial period, however, the analysis of whether slower vessels have a positive effect on the behaviour and foraging of killer whales was undertaken using computer models as described in Section 6.2.

The summer of 2017 was an unusual year for SRKW presence. The SRKW would typically be present in the waters near Lime Kiln frequently over the summer months. For example, between June and early October 2016, SRKW were visually recorded 45 days at Lime Kiln, whereas over the same time period in 2017, the SRKW were only visually recorded on 13 days, a 70 per cent reduction in SRKW presence from 2016 to 2017.

Over the course of the slowdown trial, between August 7 and October 6, 2017, there were only six days of SRKW presence visually observed at Lime Kiln. An additional three days of SRKW presence were recorded acoustically during nighttime periods when no observers were present. Using the visual and acoustic detection information, SRKW were present on just nine days during the trial period, for a total of approximately 17 hours.

The poor return of Chinook salmon stocks observed during the 2017 season may have been a contributing factor in the reduced inshore presence of SRKW.

Further information regarding the presence of SRKW in Haro Strait during the trial period is provided in the SMRU Consulting North America report in Appendix B.

Killer whale sightings information for the broader Salish Sea is currently being compiled using information from the voluntary sightings databases of the British Columbia Cetacean Sightings Network (BCCSN) provided by Ocean Wise, as well as Washington State-based OrcaMaster database compiled by The Whale Museum. These data are not generally available until June of the following year, however, preliminary data from BCCSN indicates a 50 per cent decrease in the number of "whale days" that SRKW were sighted in the Salish Sea in July-October 2017, compared to the same time period in 2016.

6 Trial results and evaluation – Noise and SRKW behavioural modelling

The following modeling work was advanced in an attempt to answer the third trial question "What are the predicted resultant effects on SRKW behaviour and foraging given the changes in vessel source levels and ambient noise levels?"

The results of the vessel source level measurements (Section 5.1) and ambient noise analyses at Lime Kiln (Section 5.2) provided inputs to refine and validate an existing regional acoustic model developed by JASCO Applied Sciences. The information obtained from the trial developed new speed scaling relationships (i.e. the relationship between speed and noise) for different vessel types, which were used in the regional noise model to distribute vessel noise throughout the model area on a grid basis. This modeled vessel noise distribution was then used as an input to SMRU Consulting North America's SRKW behavioural response model. The complete technical reports from JASCO Applied Sciences and SMRU Consulting North America regarding noise and behavioural response modelling are provided in Appendix D and E, respectively.

Several scenarios were modelled before the trial (pre-trial modelling), to define an estimate of the baseline of noise and SRKW lost foraging time under different traffic conditions and to predict the potential noise benefits of the slowdown trial. The pre-trial scenarios were modelled using the best-available speed scaling relationships for vessel source levels, which were based on a relatively small number of historical measurements (Ross 1976). Similar scenarios were modelled after the trial (post-trial modelling), using the new speed scaling relationships developed through the slowdown trial, to estimate the differences in received underwater noise, as well as the differences in time SRKW foraging may be impacted from such noise. The following sections describe the noise modelling results and the SRKW behavioural response modelling results.

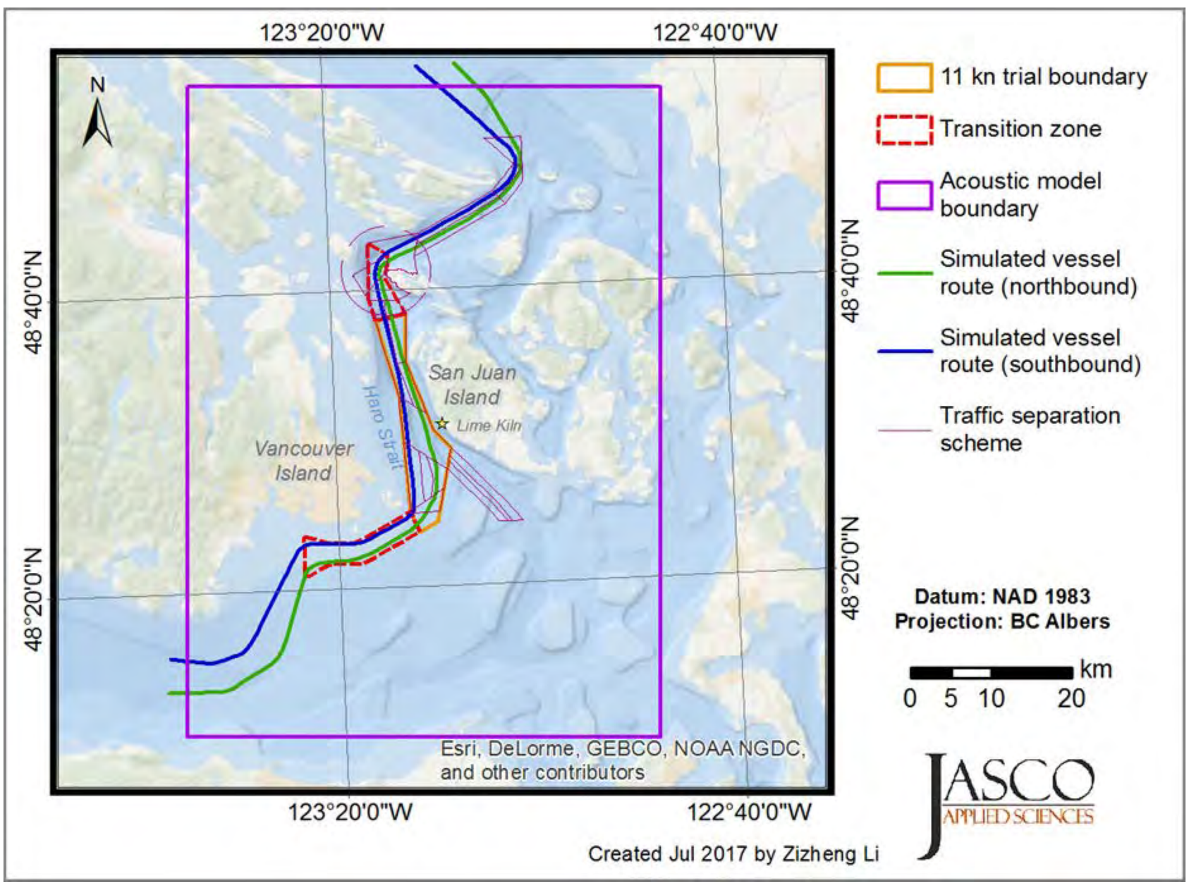
6.1 Underwater noise modelling

The area covered by the acoustic model is provided in Figure 5, and includes the trial slowdown area, as well as a buffer region to capture noise from vessel traffic outside the slowdown zone. Time-snapshots of underwater noise levels were simulated, based on historical ship movement data, using the JASCO Applied Sciences cumulative vessel noise model.

The cumulative vessel noise model combines vessel tracking data, noise emission data, ambient noise levels (without vessels present), and environmental data describing how sound attenuates through the water column for the study area, to predict the vessel noise on a computational grid. The noise model uses vessel source level values for AIS-enabled vessels, but does not account for non-AIS enabled small boat traffic, which cannot be accurately quantified.

When run in time-lapse mode, the model generates sequences of two-dimensional maps, or "snapshots", of the dynamic sound field, providing cumulative sound pressure level as a function of easting, northing, frequency, and time. The modelled frequency range covers 9 Hz to 78,000 Hz (details provided in Appendix D). For the purposes of this study, the noise model was run to provide sound pressure level data over a 24-hour period in the model area, to feed into the SMRU Consulting North America behavioural response model described in Section 6.2.

FIGURE 5. Underwater noise modelling area



From Appendix D: Vessel noise modelling report - JASCO Applied Sciences.

The vessel speed-sound relationships for different vessel categories that were developed through analysis of the trial data, as well as the extensive vessel source level database obtained from two years of measurements at the Strait of Georgia underwater listening station were used to update the regional acoustic model.

Pre-trial modelling was conducted to evaluate the potential benefits of the slowdown trial, and post-trial modeling was conducted using actual data from the slowdown trial to assess noise benefits. Fourteen model scenarios were developed as outlined below, to represent traffic conditions on an average day, as well as a high traffic day, under a variety of slowdown conditions. The modelled scenarios used for both noise modeling and behavioural response modelling are provided in Table 8.

TABLE 8. Modelling scenarios

Pre-trial Scenarios using Ross model for speed scaling coefficients			
Scenario number	***Traffic condition – volume***	***Ship speeds***	***Slowdown participation rate (%)***
S1	Baseline – average	Baseline	N/A
S2	Baseline – high	Baseline	N/A
S3	Baseline – average	11 knots	100%
S4	Baseline – high	11 knots	100%
S5	Baseline - average	Half @ 11 knots / half @ baseline	50%
S6	Baseline – high	Half @ 11 knots / half @ baseline	50%
Post-trial scenarios using new speed scaling coefficients from trial data			
S7	Baseline – average	11 knots	100%
S8	Baseline – high	11 knots	100%
S9	Baseline - average	Trial mean speeds and participation percentages / baseline speed remainder	Trial percentages (average to 57%): Bulker/general cargo 55% Container 68% Tanker 55% Vehicle Carrier 66% Cruise 90%
S10	Baseline – high	Trial mean speeds and participation percentages / baseline speed remainder	Trial percentages by type (as above)
S11	Future - average	Baseline	N/A
S12	Future - average	11 knots	100%
S13	Baseline – average	Baseline	N/A
S14	Baseline – high	Baseline	N/A

The numbers of daily piloted transits through Haro Strait used for acoustic modelling were based on a review of historic ship traffic data as well as data provided by the Pacific Pilotage Authority, and are provided in Table 9. As the noise and behavioural response models use a 24-hour (daily) time period, the participation rates used for modelling vary slightly from the actual participation rates reported for the two month trial. For example, an average traffic day has eight bulker transits (Table 9), and a reported trial participation rate of 55%. As a portion of a vessel transit cannot be modelled, a 50% participation rate (four of eight bulkers) were represented in the model. As such, scaling the participation rates for a 24-hour time period resulted in an overall vessel participation rate of 57%.

Future average vessel counts were based on a regional traffic forecast from the Vancouver Fraser Port Authority. In addition to the piloted vessel traffic shown below for the "Future" traffic scenario, two additional tanker escort tugs were also included in the model.

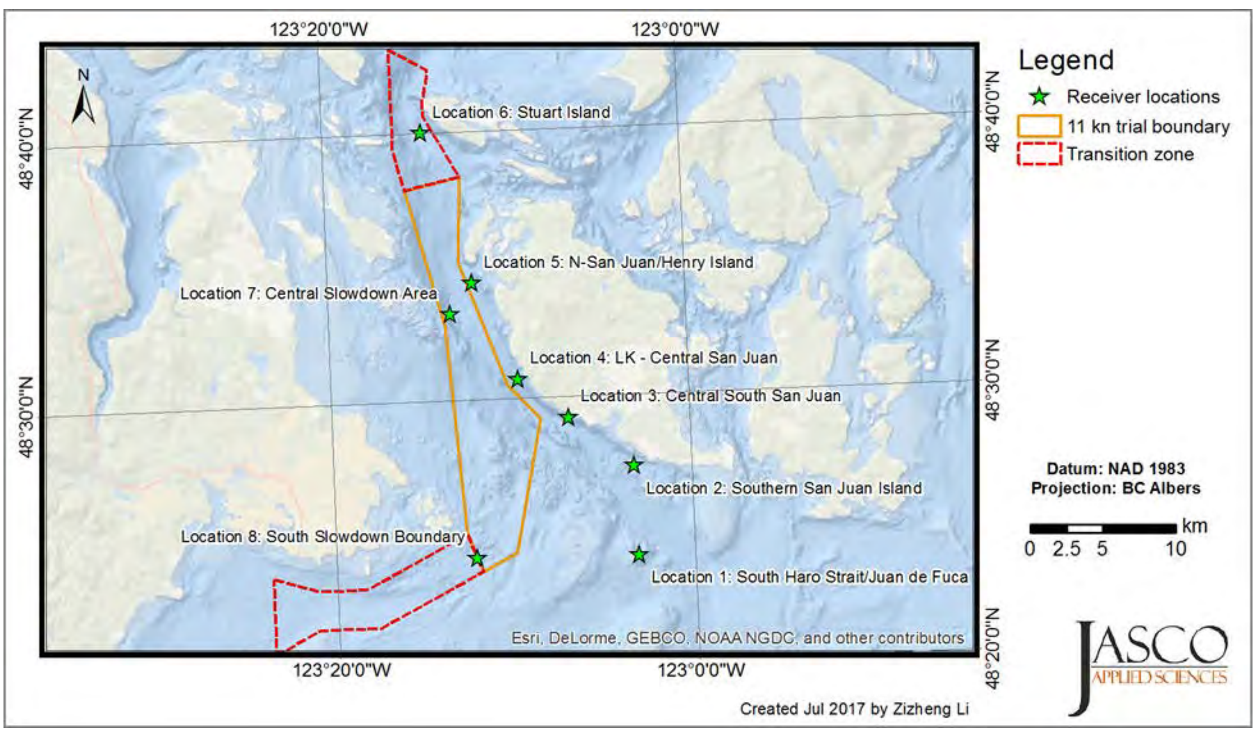
TABLE 9. 24-hour vessel traffic counts in Haro Strait

	Baseline average traffic	Baseline high traffic	Future average traffic
Bulker*	8	10	9
Containership	4	6	5
Tanker	1	2	2
Vehicle Carrier	1	2	1
Cruise	0	1	0
Total	**14**	**21**	**19**

* Includes both bulk carriers and general cargo vessels.

In order to assess the potential changes in underwater noise from the various scenarios, specific receiver locations were selected to provide examples of the model outputs. The receiver locations were selected to be in key SRKW feeding areas as well as locations in the slowdown and transition zones, and are shown on Figure 6. Locations 2 through 5 are positioned along the west bank of San Juan Island, Washington, representing SRKW feeding areas. Locations 1 and 6 are also in SRKW habitat, where the whales may be transiting to core foraging areas, while locations 7 and 8 are on the main vessel traffic route.

FIGURE 6. Example receiver locations in the noise model



From Appendix D: Vessel noise modelling report - JASCO Applied Sciences.

Sound level statistics were prepared for the various receiver locations for the defined traffic scenarios to indicate the percentage of time that a noise level falls below a certain value. The differences between the percentiles were used to calculate how slowdown participation may have affected the received noise at each location. While the intensity of vessel noise emissions is reduced by slowing vessels down, there is a resultant increase in noise exposure duration from longer transit times. The analysis therefore shows that during the trial, the greatest reductions in sound pressure levels were at the highest noise levels. At the lowest noise levels, reductions in sound pressure levels received were minimal, or in some cases the received levels increased.

Results of the pre-trial noise modelling (using a consistent speed scaling coefficient across all frequencies as per the Ross power law model) predicted median sound levels to decrease by between 1.6 dB for an average traffic day, and 3.3 dB for a high traffic day, at receiver Location 4, near Lime Kiln, if 100 per cent of vessels slowed to 11 knots as compared to the baseline scenario. For a 50 per cent participation scenario, these reductions were predicted to be 1.1 dB and 1.4 dB for average and high traffic days, respectively. The pre-trial modelling was conducted to provide trial participants with an indication of what potential changes in noise may be expected through the slowdown trial.

The post-trial modelling used the newly developed speed scaling coefficients by frequency range, developed as described in Appendix A. These modelling results are thought to more accurately reflect conditions in Haro Strait. Post-trial modelling results, giving the predicted change in received noise level at each receiver location, are provided in Table 10 and Table 11 for the trial participation rate by vessel type for an average and high traffic day, respectively. Receiver location #4, near Lime Kiln, is highlighted in each table, with the median, or fiftieth percentile value shown in bold text. The percentile values indicate the percentage of time a noise level is below a certain value.

For example, the fifth percentile values in Tables 10 and 11 are showing the difference in sound pressure level between baseline and trial conditions for the quietest five per cent of the time, whereas 95th percentile values indicate the difference in received levels for the loudest five per cent of the time. The 50 per cent value, therefore, indicates the difference between the baseline and trial noise levels where 50 per cent of the time it is louder, and 50 per cent of the time it is quieter. A negative value indicates a reduction in noise levels resulting from the slowdown trial, whereas a positive value indicates an increase in noise.

TABLE 10. Difference between baseline and trial sound pressure levels on an average traffic day (modelling trial participation rate by vessel type)

Receiver Location		**Difference in dB**				
#	Name	5th %tile	25th %tile	50th %tile	75th %tile	95th %tile
1	South Haro	-0.047	-0.352	-0.369	-0.171	-0.191
2	Southern San Juan	0.171	0.071	-0.403	-1.042	-0.922
3	Salmon Banks	0.304	0.053	0.054	-1.865	-1.185
4	Lime Kiln	0.159	-0.164	**-0.639**	-2.705	-2.722
5	Northern San Juan	0.06	-0.611	-0.891	-0.934	-2.085
6	Stuart Island	-0.295	0.133	-0.877	-0.821	-1.863
7	Central slowdown	0.022	-0.446	-0.734	-1.254	-2.439
8	Southern slowdown	0.455	-0.267	-0.116	-0.906	-2.358

TABLE 11. Difference between baseline and trial sound pressure levels on a high traffic day (modelling trial participation rate by vessel type)

Receiver Location		**Difference in dB**				
#	Name	5^{th} %tile	25^{th} %tile	50^{th} %tile	75^{th} %tile	95^{th} %tile
1	South Haro	0.000	-0.395	-0.117	-0.274	-0.187
2	Southern San Juan	0.155	-0.347	-0.456	-0.886	-0.865
3	Salmon Banks	0.097	-0.042	0.018	-1.33	-1.497
4	Lime Kiln	0.005	-0.076	**-1.536**	-2.024	-2.967
5	Northern San Juan	-0.499	0.474	-0.932	-0.989	-2.539
6	Stuart Island	0.046	0.358	-0.324	-0.627	-1.626
7	Central slowdown	-0.026	0.121	-1.014	-1.994	-2.708
8	Southern slowdown	0.006	0.032	-0.206	-1.323	-1.684

The tables above indicate how the differences in number of vessels transiting in a given day (average day 14 vessels as shown in Table 10, high traffic day 21 vessels as shown in Table 11) can affect the received noise levels. The values shown above for receiver location #4, proximate to Lime Kiln, of a 0.6 dB median reduction on an average traffic day and a 1.5 dB median reduction on a high traffic day correlate reasonably well with the values presented in Section 5.2 for ambient noise levels actually measured at Lime Kiln, which indicated a 1.2 dB difference between trial and baseline periods. Note that the model also does not account for the presence of small vessel traffic, which can have a significant impact on received noise at Lime Kiln. A discussion of the model validation is provided in Section 6.3.

Every model has inherent uncertainty, thus the focus of evaluation should be on the relative change in noise levels as a result of vessel slowdowns, rather than the absolute values.

6.2 SRKW behavioural response modelling

Studying whale behaviour in the presence of vessels is challenging, and reliant upon the two being present at the same time. As such, the main objective of the slowdown trial was to understand the differences in vessel source levels and total noise as a result of slowing vessels down, and the resultant noise differences were then used to model the behavioural response of SRKW.

To evaluate the potential effects of reduced noise on SRKW, the results of the 24-hour noise modelling conducted by JASCO Applied Sciences (Section 6.1) were used as input for a behavioural response model developed by SMRU Consulting North America (SMRU 2014). The behavioural response model uses 11 years of SRKW habitat use data coupled with the probability of a change in behaviour by the whale (e.g. stops foraging, moves away) for a given broadband received level of noise (in dB re 1uPa), and a high frequency (50 kHz) echolocation click masking (i.e. the whale may not be able to use echolocation to detect prey) model. Both a change in behaviour, and echolocation click masking could result in 'potential lost foraging time', a relative combined effect metric used for evaluation.

A 'moderate severity' behavioural response is defined as moderate to extensive changes in behaviour for a duration of approximately 25 minutes, whereas a 'low severity' response indicates a change in behaviour for approximately five minutes (SMRU 2014). The model first calculates the potential lost foraging time resulting from a behavioural response. If no behavioural response is triggered, the model evaluates potential echolocation click masking for the frequency band including 50 kHz.

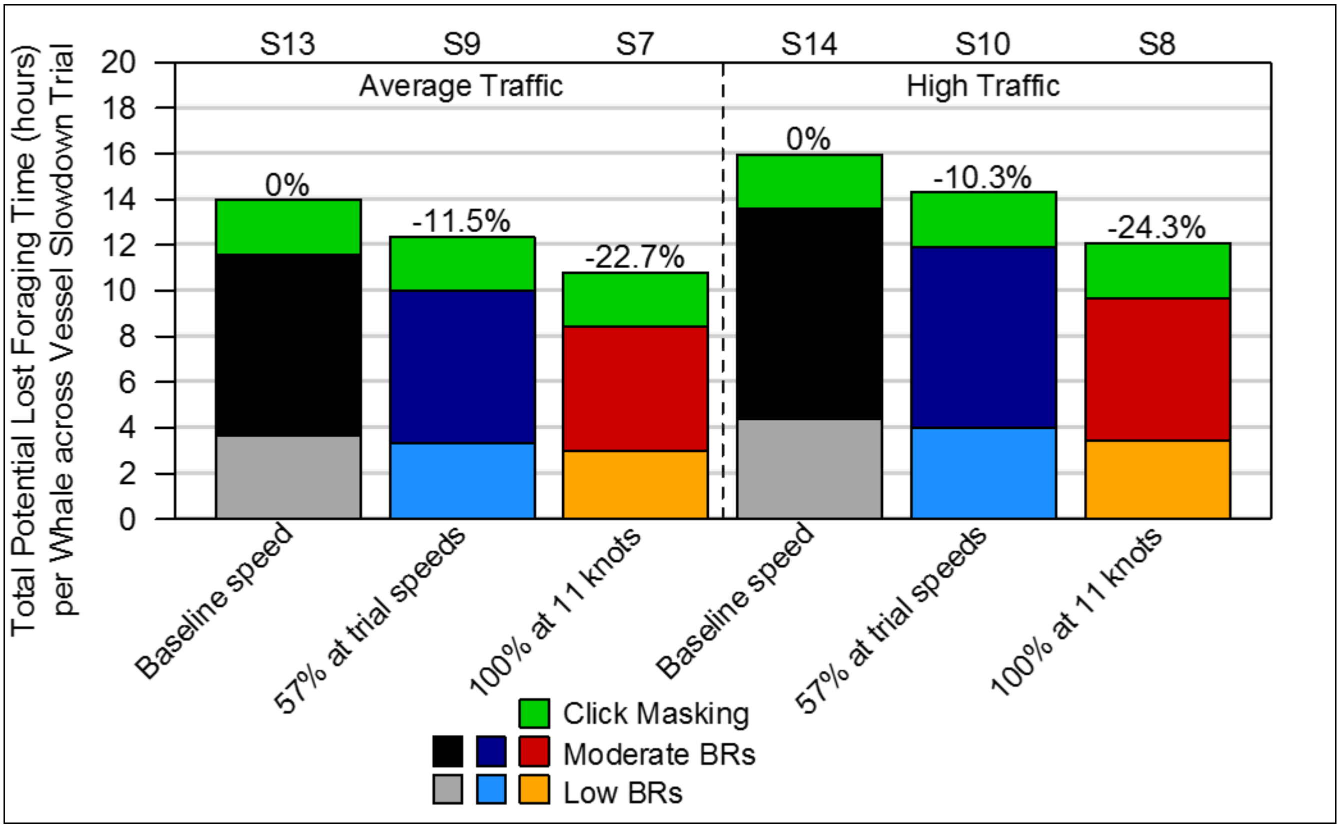
The model then accumulates the potentially lost foraging time over the 24-hour period for each individual whale, and can then be summed for various durations such as the six-month summer period when SRKW are anticipated to be present in the Salish Sea, or over the two-month period of the trial. The SRKW behavioural response model was run with the results of the 14 vessel traffic scenarios articulated in Table 8.

Pre-trial behavioural response modelling indicated that for the duration of the trial 'lost foraging time' would be decreased by approximately 20.6 per cent for an average traffic day, and 21.4 per cent for a high traffic day, if 100 per cent of vessels slowed to 11 knots as compared to the baseline scenario. For a 50 per cent participation scenario, these values were predicted to be eight per cent and 10.4 per cent for average and high traffic days, respectively. The pre-trial modelling was conducted to provide trial participants with an indication of what potential changes in effect to SRKW foraging may be expected through the slowdown trial.

Post-trial modelling indicated that for the duration of the trial, given the trial percentage participation rates (average 57 per cent) and speeds as described in Section 6.1, 'lost foraging time' would be decreased by 11.5 per cent for an average traffic day, and 10.3 per cent for a high traffic day from baseline conditions. Figure 7 visually displays the potential lost foraging time in hours, per whale, across the slowdown trial period. Moderate behavioural response, low behavioural response and click masking are presented as stacked plots for a sum total. Scenarios S13 and S14 show predicted 'lost foraging time' for baseline traffic conditions for average and high traffic days, respectively, using the new speed scaling relationships. The percentage values indicates the decrease or reduction from baseline in this lost time for scenarios S9 (trial speeds and participation rates on an average traffic day), S10 (trial speeds and participation rates on a high traffic day) and if 100% of vessels were to comply with an 11 knot speed limit. Note that the different colours in the stacked plots in Figure 7 are presented to align with the colour display for another figure within the modelling report in Appendix E.

Every model has inherent uncertainty, thus when evaluating the effect of reduced vessel noise on SRKW foraging time, the focus should be on the change in values (percentage reduction), rather than the absolute values of lost foraging time.

FIGURE 7. Modelled differences in potential lost foraging time



Note: BR indicates behavioural response
From Appendix E – SRKW behavioural response modelling report - SMRU Consulting North America

6.3 Noise model validation

SMRU Consulting North America conducted an analysis of the JASCO Applied Sciences noise model predictions against actual measurements at the Lime Kiln hydrophone. The technical memo is provided as Appendix F to this report.

To compare received levels at the Lime Kiln hydrophone against levels predicted by the JASCO Applied Sciences noise model, SMRU Consulting North America conducted a statistical analysis of the Lime Kiln ambient noise pooled data from August and September 2016, considered to be representative summer months. These were compared against the model outputs from the 24-hour baseline scenarios for average and high traffic (S1 and S2, respectively, as described in Section 6.1), indicative of summer conditions, for the model grid cell (Location 4) that included the Lime Kiln hydrophone. Key differences between the model and Lime Kiln hydrophone include:

- The noise model uses a receiver depth of 10 metres in Location 4, whereas the Lime Kiln hydrophone is actually located at 23 metres depth.
- Lime Kiln is a single point within the large regional area modelled (see Figure 5), and as such cannot validate data at other locations.
- Lime Kiln receives all ambient noise sources, including small vessel traffic, which is not captured through the noise model.

- Noise associated with the flow of water across the Lime Kiln hydrophone (generally below 35 Hz), cannot be accounted for within the noise model.
- The model predicts noise levels in the frequency range of 9 Hz to 78,000 Hz, whereas the Lime Kiln hydrophone measures from 10 Hz to 100,000 Hz.

The results of the model validation exercise completed by SMRU Consulting North America (Appendix F) indicate:
- The broadband, median sound pressure level recorded at the calibrated Lime Kiln hydrophone was 109.8 dB re 1µPa. In comparison, the noise model median sound pressure level predictions for average (S1) and high (S2) traffic volumes were 101 and 105.1 dB re 1µPa respectively, differences of 8.8 and 4.7 dB.
- To potentially account for the impact of small vessel noise, the Lime Kiln data were filtered to include only readings between 9:00 p.m. and 6:00 a.m. (i.e. night time), when small vessel traffic would be less, but large vessel traffic is the same. When only using night time data, model mismatches at the Lime Kiln hydrophone were smaller, at 6.9 and 2.7 dB for broadband median sound pressure levels.
- Evaluation of potential impact to SRKW high frequency click masking (centered at 50 kHz), indicated that the model predictions are slightly below the measured values at Lime Kiln by 1.5 dB re 1µPa^2/Hz for all data, and 0.7 dB re 1µPa^2/Hz for night time only data, respectively.
- Generally, the noise model appears to slightly underestimate the received level at the Lime Kiln hydrophone, however, given the differences noted above with regards to flow noise and small vessel presence, SMRU Consulting North America concludes there is good agreement between JASCO Applied Sciences noise modeling and empirical acoustic data at a single site (Lime Kiln).

Although not included in the model validation work described in the SMRU Consulting North America technical memo, the model predictions described in Section 6.1 show a predicted noise reduction in the model grid cell that includes Lime Kiln of 0.6 dB on an average traffic day and a 1.5 dB on a high traffic day, which correlates reasonably well with the mean ambient noise reduction of 1.2 dB measured at Lime Kiln during the trial.

7 Key findings and conclusions

The voluntary vessel slowdown trial was conducted between August 7 and October 6, 2017, over an approximately 16 nautical mile area through Haro Strait, a key foraging habitat for southern resident killer whales, where vessel operators were asked to slow to 11 knots speed through water. The trial goals were to better understand the relationship between vessel speed, underwater noise emissions, and the potential reduction in impact to killer whales from these slower transit speeds. The key findings of the trial are:

- The trial was designed through consultation with the ECHO Program Advisory Working Group and Vessel Operators Committee, and took into consideration navigational safety, potential biological benefits and potential industry implications.
- The trial was voluntary and not every vessel was required to participate, however the per-transit cost range for participation, considering pilotage, ship time, and fuel consumption by ship type (in Canadian dollars) were predicted as follows:
  - For bulk carriers, from a savings of $166 to a maximum cost of $2,683, with an average cost of $160
  - For car carriers, a minimum cost of $178 to a maximum cost of $453, with an average of $363
  - For containers, a minimum cost of $210 to a maximum cost of $4,371, with an average of $1,420

  - For general cargo, from a savings of $42 to a maximum cost of $2,095, with an average cost of $236
  - For passenger vessels, from a minimum of zero cost to a maximum of $3,526, for an average cost of $1,432
  - For tanker, from a savings of $46 to a maximum cost of $3,706, with an average cost of $327
- If all vessels participated in the trial, the estimated aggregate industry cost of the trial (accounting for pilotage costs, ship time, fuel consumption) was estimated (in Canadian dollars) to be $522,720.
- Other potentially significant cost impacts that could be incurred on a case-by-case basis depending on a vessel's participation in the trial include port disbursements such as longshore labour, tugs, ships' line handling and safety and security costs.
- In an attempt to offset some of the costs identified above, each participating transit was eligible for a $500 stipend. Of the 951 piloted vessel transits that took place during the trial period, 225 stipend applications were approved and paid. Eleven organizations intentionally chose to forgo their stipend allocations.
- Due to the trial's short duration, and the option to not participate if the sailing schedule would be significantly impacted, the trial was not expected to have a material effect on potential indirect economic impacts such as customer service, international trade traffic, or overall competitiveness of the Port of Vancouver. However, a more permanent and mandatory vessel slowdown, particularly if applied only to Canadian-bound vessels, could potentially have an adverse impact on these elements, creating competitive disadvantage for the Port of Vancouver.
- From a cultural and environmental perspective, although the trial was anticipated to have overall positive effects, the need to address increases in vessel traffic, as well as the other anthropogenic threats to the recovery of SRKW was highlighted.
- Of the 951 piloted transits occurring over the trial period, 577 transits (61 per cent) were reported by the Pacific Pilotage Authority as having participated. This translated to 44 per cent of vessel transits achieving a speed of less than 12 knots, and 55 per cent achieving a speed of less than 13 knots, when aiming for 11 knots speed through water.
- Analysis of vessel source levels in Haro Strait indicated that slowing vessels significantly reduced underwater noise emissions, when compared to a control period when vessels transited at normal speeds. Mean speed reductions varied by vessel type from a 2.1 knot reduction in speed for bulk/general cargo ships as high as a 7.7 knot reduction in speed for container ships. These reductions resulted in reduced vessel source levels of:
  - A 11.5 dB reduction in source level for container ships
  - A 10.5 dB reduction in source level for passenger/cruise ships
  - A 9.3 dB reduction in source level for vehicle carriers
  - A 6.1 dB reduction in source level for tankers
  - A 5.9 dB reduction in source level for bulk/general cargo ships
- In general, while slowing vessels reduced vessel noise emissions over the entire frequency range (broadband), the greatest relative reductions were observed below 100 Hz (lower than SRKW communication range) and above 15,000 Hz (in SRKW echolocation range).
- Comparison of all (unfiltered) ambient noise data for pre-trial baseline vs. trial months indicated a median, or fiftieth percentile, reduction in broadband received sound pressure level (SPL) of 1.2 dB re 1 μPa at the Lime Kiln hydrophone during the trial period. This is roughly equivalent to a 24 per cent reduction in sound intensity.
- When filtered to include only times when a large vessel was within confident acoustic detection range of the hydrophone, and to remove times of elevated wind and tidal

current effects and small boats presence, the median reduction in broadband received sound pressure level for the trial period, was 2.5 dB re 1 µPa. A noise reduction of 2.5 dB is roughly equivalent to a 44 per cent reduction in sound intensity.
- Regional noise modelling, using new speed scaling relationships developed through vessel source level measurements during the trial, indicated that the speeds and participation rates achieved during the trial likely resulted in noise reductions at a receiver location near Lime Kiln of between 0.6 dB on an average traffic day (14 vessel transits) and a 1.5 dB reduction on a high traffic day (21 vessel transits)
- The sound pressure level outputs of the regional noise model were used in a behavioural response model to evaluate potential benefits to killer whale foraging from reduced noise. The SRKW behavioural response model indicated that the speeds and participation rates achieved during the trial could result in an 11.5 per cent reduction in affected foraging time for an average traffic day, and 10.3 per cent reduction for a high traffic day, when compared to baseline conditions.
- The noise modelling, when validated against in-situ data recorded at the Lime Kiln hydrophone, shows good agreement between predicted and measured values.

The following conclusions are drawn from the key findings of the trial:
- The five main commercial vessel types included in this study (bulk/general cargo, container, cruise, tanker, vehicle carrier) potentially incurred some direct and indirect costs as a result of participating in this voluntary trial.
- The underwater noise generated by all of these vessel types was significantly reduced at slower vessel speeds.
- Slower vessel speeds and associated reduced vessel noise resulted in quieter ambient noise conditions in a key SRKW foraging habitat.
- Noise reductions achieved as a result of slower ship speeds can lessen the amount of time SRKW behaviour and foraging is affected by vessel noise.
- Overall, voluntary measures can be an effective means of managing threats to endangered whales.

8 References

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Appendix A

Vessel noise measurements report - JASCO Applied Sciences

Vessel Noise Measurements from the ECHO Slowdown Trial

Final Report

Submitted to:

Krista Trounce
Vancouver Fraser Port Authority ECHO Program
Contract: 17-0070

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Disclaimer:

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

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Executive Summary

The Vancouver Fraser Port Authority's Enhancing Cetacean Habitat and Observation (ECHO) program carried out a voluntary vessel slowdown trial in Haro Strait to investigate whether limiting vessel speeds to 11 knots would decrease noise in Southern Resident Killer Whale (SRKW) habitat. The trial ran from 7 Aug to 6 Oct 2017, to measure speed-associated reductions in vessel noise during the time of year when SRKW density is highest. JASCO collected acoustic measurements on two underwater listening stations adjacent the Haro Strait traffic lanes, to measure vessel noise emissions in the slowdown zone. A third listening station in Georgia Strait measured noise from vessels transiting at normal speed after leaving the slowdown zone. Hydrophone data from these three listening stations were analyzed using JASCO's PortListen® noise measurement system, which automatically measures the acoustic source levels of passing vessels.

Results from this study are based on measurements collected before, during, and after the slowdown trial. A total of 2765 source level measurements were collected over 3.5 months, from 6 Jul to 27 Oct 2017. The effects of voluntary slowdowns on vessel noise emissions were evaluated by comparing a) measurements of vessels participating in the trial with those of non-participating vessels and b) measurements from the control periods before and after the trial. Approximately 60% of piloted vessels participated in the trial by voluntarily slowing down in Haro Strait.

Mean reductions in speed for participating vessels ranged from 7.7 knots for containerships to 2.1 knots for bulkers. Analysis of the underwater listening station data showed that reducing speeds in Haro Strait was an effective method for reducing mean broadband source levels (MSL) 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). Royal Canadian Navy (RCN) vessels also participated in the trial, but the already-low noise emissions of this category made it difficult to accurately measure source level reductions due to interference from background noise. No information on slowdown participation was available for other categories of vessels, and there was no evidence that their speeds or noise emissions were reduced during the trial. A trend analysis of source level versus speed for 107 repeated vessel measurements showed that slowing speed by 40% reduced broadband noise emissions (MSL) of individual vessels by approximately 11.3 dB. The trend was even stronger at southern resident killer whale echolocation frequencies (>15 kHz), where slowing speed by 40% reduced noise emissions by approximately 14.5 dB.

1. Introduction

The Vancouver Fraser Port Authority's (VFPA) Enhancing Cetacean Habitat and Observation (ECHO) program carried out a voluntary vessel slowdown trial in Haro Strait to investigate whether lowering vessel speeds to 11 knots would decrease noise in Southern Resident Killer Whale (SRKW) habitat. Vessels are usually quieter when travelling more slowly, due to decreased propeller cavitation and machinery vibration. The aim of the trial, which was focused primarily at commercial vessels but encouraged for all types of motorized water craft, was to measure the noise reductions that could be achieved by limiting vessel speeds. The slowdown trial ran from 7 Aug to 6 Oct 2017, during the time of year when SRKW density is historically highest in Haro Strait.

JASCO carried out acoustic measurements before, during, and after the trial to quantify how vessel noise emissions (i.e., source levels) were affected by the slowdown protocol. Calibrated sound recordings were collected on two underwater listening stations (ULSs), situated directly adjacent to the northbound and southbound Haro Strait traffic lanes, to obtain high-quality source level measurements of individual vessels. A land-based Automated Identification System (AIS) receiver tracked vessels passing the Haro Strait listening stations during the trial. Additional measurements from a third listening station in Georgia Strait were used for measuring noise from vessels transiting at normal speed after leaving the slowdown zone.

Hydrophone data from these three listening stations were analyzed using ShipSound, a component of JASCO's PortListen® noise measurement system. PortListen tracks passing vessels on AIS and automatically measures their underwater acoustic source levels using calibrated hydrophone data. This report provides the final results based on source level data collected during the slowdown trial and during the pre-trail and post-trial control periods (from 6 Jul to 27 Oct 2017). The ECHO team will use these data to assess whether slowdown zones are an effective mitigation method for improving acoustic conditions in key SRKW habitat.

2. Methods

2.1. Slowdown Trial Overview

JASCO deployed two autonomous underwater listening stations inside the slowdown zone (Figure 1) to measure source levels of transiting vessels. These Haro Strait listening stations were installed 1 month before the trial started and removed 3 weeks after the trial ended (Figure 2). The purpose of collecting data outside the trial period was to measure baseline vessel noise emissions and to provide experimental controls. JASCO carried out a service trip of the Haro Strait listening stations on 7 Sep 2017, to download acoustic data collected during the first half of the trial. Additional vessel noise measurements, outside the slowdown zone, were capture on a cabled listening station in Georgia Strait.

From 7 Aug through 6 Oct 2017 (60 days), vessels voluntarily limited their speeds to 11 knots inside a designated slowdown zone in Haro Strait. The ECHO team, assisted by the Pacific Pilotage Authority (PPA), collected commercial vessel participation logs, which were prepared by pilots aboard vessels transiting through the slowdown zones. These logs tracked speed and participation, as well as other variables that could be correlated with noise emissions, including draft and shaft RPM. The ECHO team summarized these logs and provided them to JASCO for correlation with noise measurements collected during the trial.

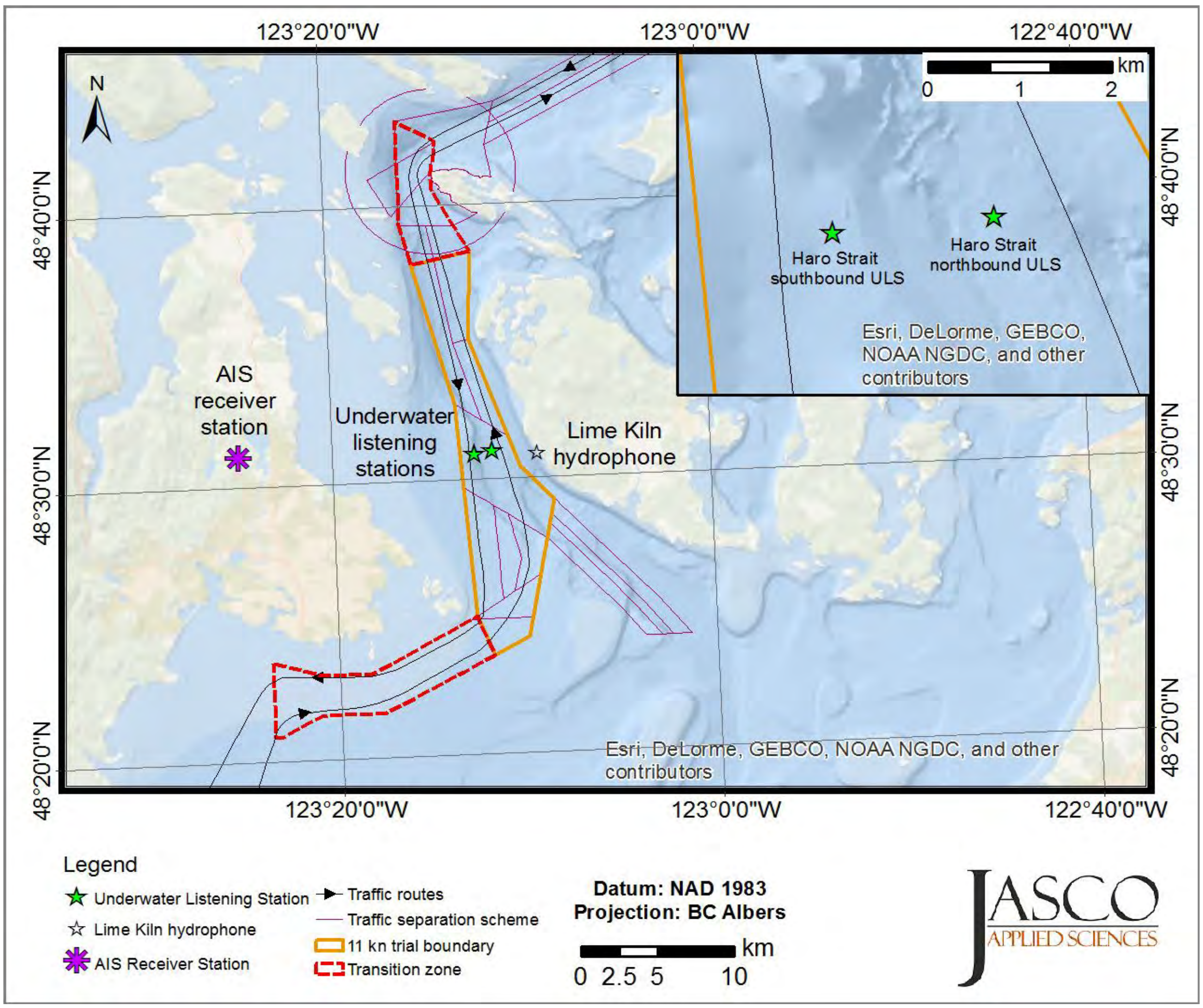


Figure 1. Slowdown trial boundary and underwater listening station locations in Haro Strait. Locations of northbound and southbound vessel traffic routes are based on 2015 ship tracking data.

<table>
<tr><th>July</th><th>August</th><th>September</th><th>October</th></tr>
<tr><td>Pre-trial Control Period
6 Jul–6 Aug</td><td colspan="2">Trial Period
7 Aug–6 Oct</td><td>Post-trial Control Period
7 Oct–26 Oct</td></tr>
<tr><td colspan="2">Haro Strait ULS Deployment 1
6 Jul–7 Sep</td><td colspan="2">Haro Strait ULS Deployment 2
8 Sep–26 Oct</td></tr>
</table>

Figure 2. Slowdown trial timeline and ULS deployment schedule (2017).

2.2. Underwater Listening Stations

The Haro Strait listening stations consisted of two calibrated JASCO AMAR-G3 (Autonomous Multichannel Acoustic Recorders-Generation 3) units, deployed on sub-sea moorings next to northbound and southbound traffic lanes. The sub-sea moorings incorporated backup measures, including tandem acoustic releases and satellite beacons, to reduce the likelihood of failure (Figure 3). Each AMAR used an M36 omnidirectional hydrophone (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/µPa nominal sensitivity) for measuring underwater sound pressure. The AMAR were programmed with a variable-bandwidth recording cycle, to capture acoustic data at 96,000 Hz for 21 hours a day and 128,000 Hz for three hours a day (Table 1). The 128,000 Hz recording was scheduled from 06:00–09:00 PDT to capture high-frequency noise from dedicated measurements of whale-watching boats (not reported here). 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. The AMARs stored the hydrophone data on 1792 GB of internal solid-state flash memory.

Deployment and retrievals of the ULS moorings in Haro Strait were conducted using the R/V *Richardson Point*, a 20 m research vessel operated by Seaward Engineering (Figure 4). After the moorings were deployed, their precise on-bottom locations were surveyed using a surface-based transducer that measured the distance to the acoustic releases (Table 2). Ranging was performed at four GPS waypoints in a square pattern surrounding the moorings. The on-bottom coordinates of the moorings were then calculated by minimizing the rms error of the surface measurements. The estimated accuracy of the surveyed coordinates was ±4 m.

The laboratory calibrations of the AMARs were verified before and after deployment using a Pistonphone Type 42AC precision sound source (G.R.A.S. Sound & Vibration A/S). The pistonphone calibrator produces a constant tone at 250 Hz at the hydrophone sensor. The level at which the AMAR records the reference tone yields the total pressure sensitivity for the instrument, i.e., the conversion factor between digital units and pressure. Verifying calibrations before and after deployment ensured that the sensitivity of the hydrophone did not change over the deployment period.

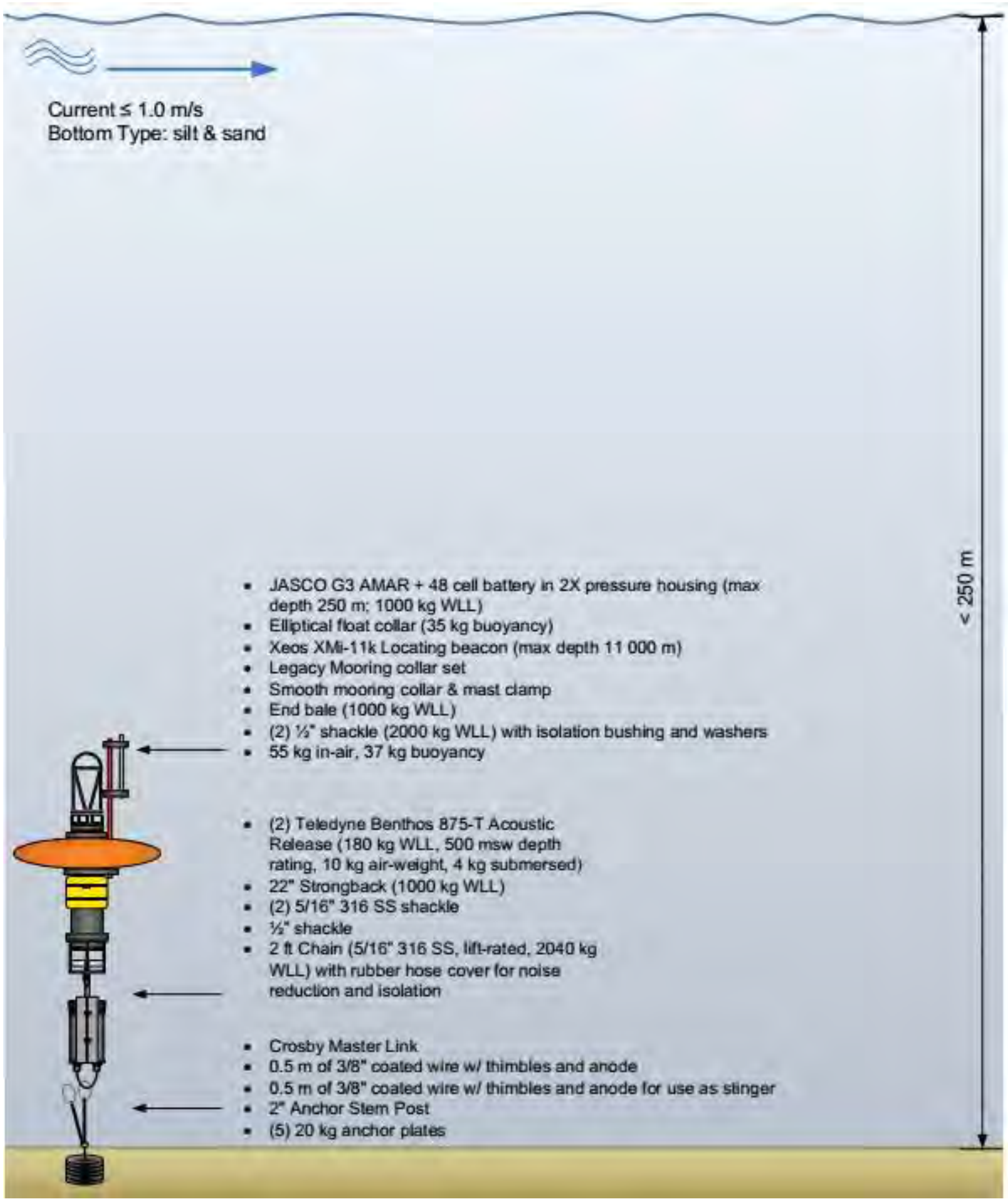


Figure 3. Haro Strait ULS mooring. The hydrophone is located 3 m above the seabed, inside the cage at the top of the AMAR.

Table 1. Daily (repeated every 24 hours) recording schedule on the Haro Strait ULS AMARs.

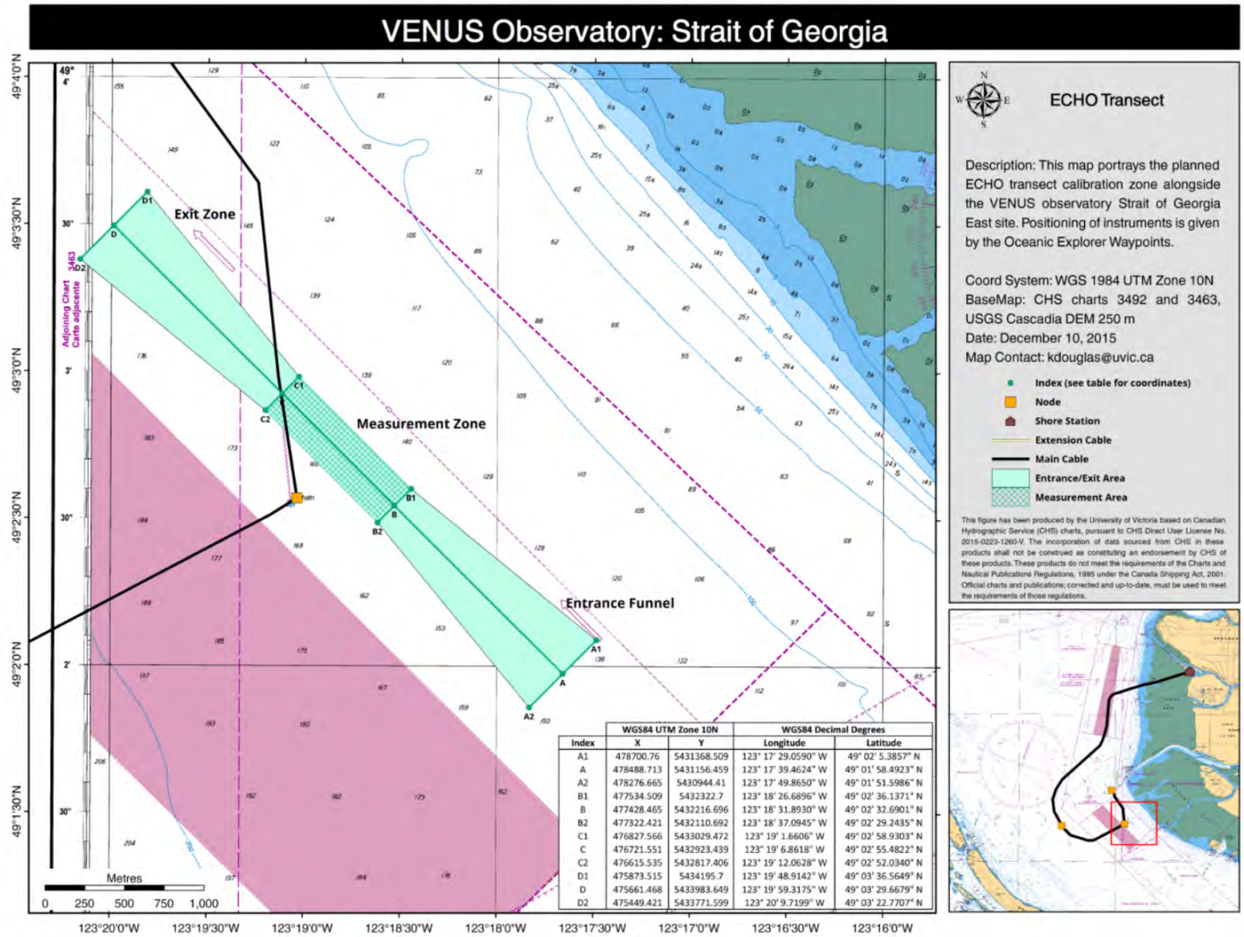
Time (PDT)	Duration (hr)	Sampling rate (Hz)	Recording bandwidth (Hz)
06:00–09:00	3	128,000	5–64,000
09:00–06:00	21	96,000	5–48,000

Figure 4. Left: R/V *Richardson Point*. Right: Deploying the Haro Strait ULS moorings. Photo credits: Krista Trounce, Vancouver Fraser Port Authority.

Table 2. Haro Strait ULS mooring deployment and retrieval details.

Station	Latitude	Longitude	Water depth (m)	Hydrophone depth (m)	Deployment (UTC)	Retrieval (UTC)
Deployment 1						
Northbound	48.5181°N	123.1917°W	251	248	2017 Jul 6 21:00	2017 Sep 8 18:08
Southbound	48.5167°N	123.2076°W	210	207	2017 Jul 6 20:27	2017 Sep 8 17:45
Deployment 2						
Northbound	48.5181°N	123.1917°W	249	246	2017 Sep 8 21:30	2017 Oct 26 18:47
Southbound	48.5161°N	123.2080°W	206	203	2017 Sep 8 20:08	2017 Oct 26 18:47

Additional vessels noise measurements, at normal transit speeds, were captured on the ECHO Georgia Strait ULS, which is installed on the Victoria Experimental Network Under the Sea (VENUS) Observatory operated by Ocean Networks Canada. This listening station has been in place since September 2015. The Georgia Strait ULS is situated on the seabed at 173 m water depth, in the northbound traffic lane, approximately 30 km southwest of Vancouver (Figure 5). It records hydrophone data at a sampling rate of 64,000 Hz with 24-bit resolution using AMAR G3 units. Synchronized data from four hydrophones are streamed to shore in near real-time via the VENUS Observatory. The ECHO program has requested vessel pilots sail over a measurement funnel, which consists of an entrance funnel, a measurement zone, and an exit area. The transit area is designed to position vessels approximately in conformance with the Grade-C geometry of the ANSI vessel noise measurement standard (ANSI 12.64-2009 R2014), and to minimize acceleration and turning during the measurement.



	WGS84 UTM Zone 10N		WGS84 Decimal Degrees	
Index	X	Y	Longitude	Latitude
A1	478700.76	5431368.509	123° 17' 29.0590" W	49° 02' 5.3857" N
A	478488.713	5431156.459	123° 17' 39.4624" W	49° 01' 58.4923" N
A2	478276.665	5430944.41	123° 17' 49.8650" W	49° 01' 51.5986" N
B1	477534.509	5432322.7	123° 18' 26.6896" W	49° 02' 36.1371" N
B	477428.465	5432216.696	123° 18' 31.8930" W	49° 02' 32.6901" N
B2	477322.421	5432110.692	123° 18' 37.0945" W	49° 02' 29.2435" N
C1	476827.566	5433029.472	123° 19' 1.6606" W	49° 02' 58.9303" N
C	476721.551	5432923.439	123° 19' 6.8618" W	49° 02' 55.4822" N
C2	476615.535	5432817.406	123° 19' 12.0628" W	49° 02' 52.0340" N
D1	475873.515	5434195.7	123° 19' 48.9142" W	49° 03' 36.5649" N
D	475661.468	5433983.649	123° 19' 59.3175" W	49° 03' 29.6679" N
D2	475449.421	5433771.599	123° 20' 9.7199" W	49° 03' 22.7707" N

Figure 5. Measurement funnel and ULS in Georgia Strait, on the VENUS East node. The hydrophones are located at 49°02'33.522"N, 123°19'02.798"W in 173 m water depth.

2.3. ShipSound Analysis

JASCO's ShipSound software monitors sound level measurements and AIS broadcasts from passing vessels. It identifies vessels that traverse a predefined transit area and then automatically extracts the corresponding acoustic data for analysis. It uses a vessel's broadcast speed together with a cepstral analysis of the Lloyd mirror pattern to determine the timing and location of closest point of approach (CPA) of the vessel's acoustic centre. ShipSound can analyze streaming data from a hydrophone in real time or, as in the case of the Haro Strait listening stations, can analyze archival hydrophone data downloaded from autonomous recorders.

The ANSI/ASA S12.64 data window is defined by the period over which the acoustic centre is within ±30° of the CPA. ShipSound automatically determines the data window and processes a single acoustic channel in 1-second periods stepped in 0.5-second intervals (Figure 6). Spectrum measurements are calculated using 1-second fast Fourier transforms, shaded using a Hanning window.

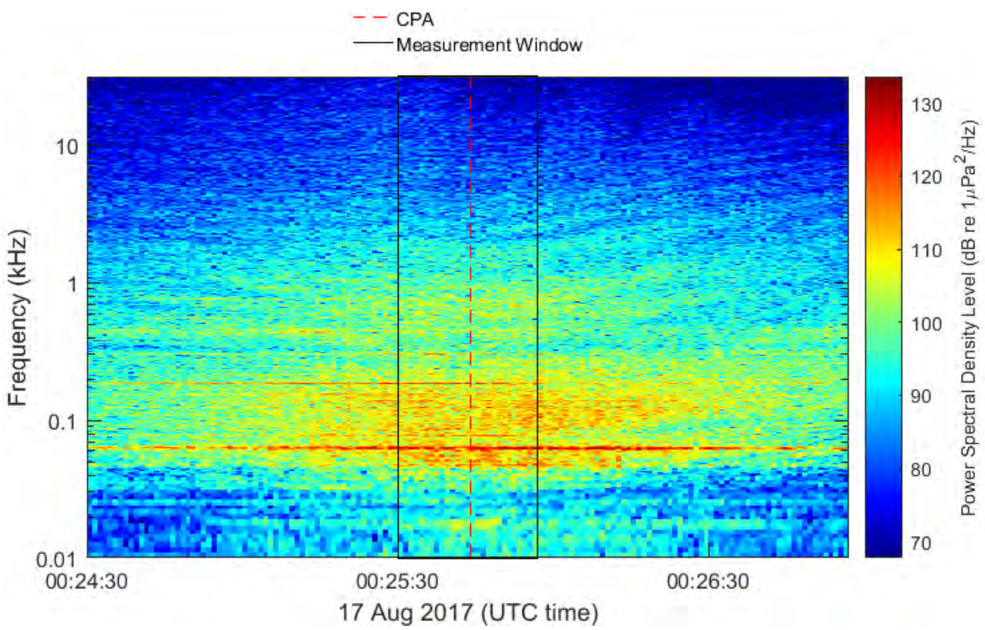


Figure 6. Spectrogram of a single vessel measurement from ShipSound, showing the CPA time (dashed red line) and the measurement window (black box) used for calculating vessel source levels. The spectrogram shows the spectrum of the underwater sound pressure recorded on the ULS hydrophone versus time and frequency.

ShipSound calculates two different kinds of vessel source levels from the data window: Radiated Noise Level (RNL) and Monopole Source Level (MSL). RNL is equal to the measured sound pressure level, back-propagated according to the distance between a source and the hydrophone. The software applies the ANSI/ASA S12.64 Grade-A method for back-propagation distance: it determines instantaneous vessel range (R) in metres from the measurement hydrophone for each 1-second step within the data window. The RNL back propagation method of 20 x Log_{10}(R) is applied to the spectra of each step separately. MSL is equal to the measured sound pressure level scaled according to a numerical acoustic transmission loss (TL) model that accounts for the effect of the local environment on sound propagation (i.e., sea-surface reflection, water column refraction and absorption, and bottom loss). MSL back-propagation is performed using predictions of the Parabolic Equation model RAM, modified to treat shear wave reflection losses, in 1/3-octave-bands to 5 kHz, and an image reflectivity model at higher frequencies. MSL back-propagation requires a source depth, which is defined in ShipSound as a Gaussian distribution centred at the shaft depth minus 0.7 of the propeller radius, when that information is available, or half the vessel draft otherwise. RNL is the source level calculation method specified by the ANSI standard whereas most acoustic models used for assessing shipping noise effects on marine fauna use MSL.

ShipSound also calculates background noise in each frequency band when a vessel is more than 2 km away from the ULS hydrophones. ShipSound only accepts measured source band levels if they exceed the background levels by 3 dB or more. ShipSound corrects the band levels if they exceed background levels by 3–10 dB, but rejects them if they are less than 3 dB above background. Adjusted and rejected levels are flagged in the database. Figure 7 summarizes this approach.

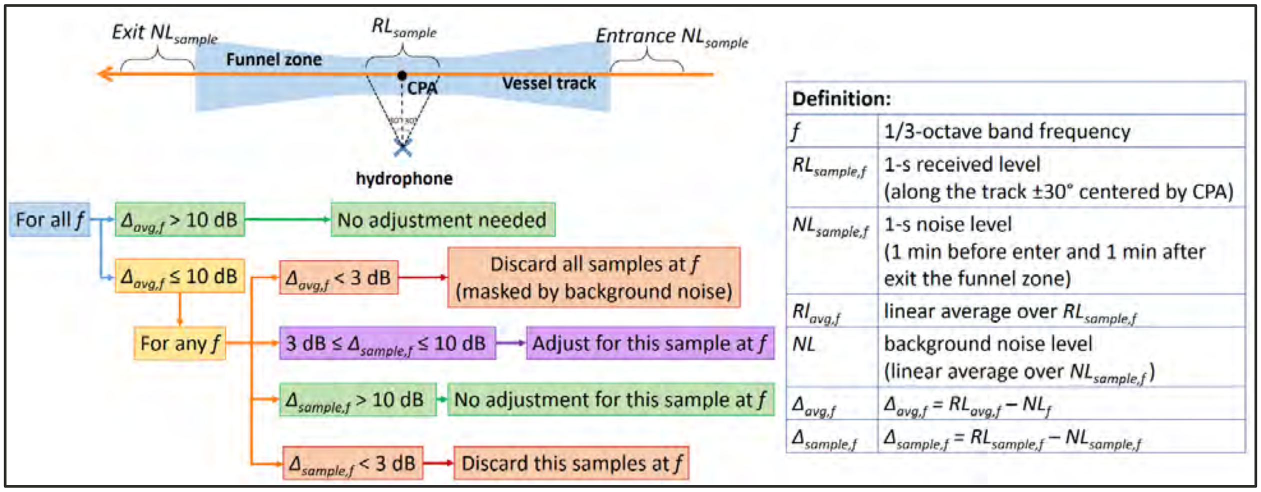


Figure 7. Background noise comparison and adjustment process.

Environmental conditions (wind speed, current speed) were also recorded for each measurement. Meteorological data for Haro Strait and Georgia Strait were obtained from the Environment Canada weather stations at Kelp Reefs and Sands Head Light Station, respectively (Environment Canada). Ocean current data for the Georgia Strait ULS were obtained from an Acoustic Current Doppler Profiler (ADCP) on the VENUS East node. Direct ocean current measurements were unavailable for Haro Strait, so ocean current data at the Haro Strait ULS were obtained from the WebTide Tidal Prediction Model (v 0.7.1), provided by Fisheries and Oceans Canada (Bedford Institute of Oceanography). Ocean current data were used to calculate speed through water from speed over ground (SOG) information received via AIS for each vessel measurement.

PortListen includes a web-based user interface to access vessel and measurement information. A table view screen lets the user select and view multiple measurements by vessel criteria. This information, including broadband MSL and RNL source levels, can be exported as a spreadsheet. Vessel measurements are summarized in PDFs, presenting vessel and environment information, and the 1/3-octave-band MSL and RNL source levels. A manual quality review of every measurement was performed by an experienced analyst using the web-based interface. An analyst may reject a measurement because it contains interference from other vessels, has high levels of background noise, or if a vessel does not have constant speed and a straight track inside the data window.

2.4. Automated Identification System (AIS) Receiver Station

An AIS receiver station was deployed atop Observatory Hill, approximately 17 km to the west of the Haro Strait ULS (Figure 1). The station, which was located 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 receiver and a 1.22 m whip antenna connected to a notebook PC. Logging software (NMEA Logger, Arundale) stored the raw AIS records on an internal hard disk on the PC and chart plotting software (ShipPlotter, COAA) displayed the received ship tracks in real time (Figure 8). Data from the AIS receiver were periodically backed up over the cellular network via a mobile USB Wi-Fi stick to JASCO's servers in Victoria. Raw AIS data from the receiver station were fed into the ShipSound system for vessel source level analysis.

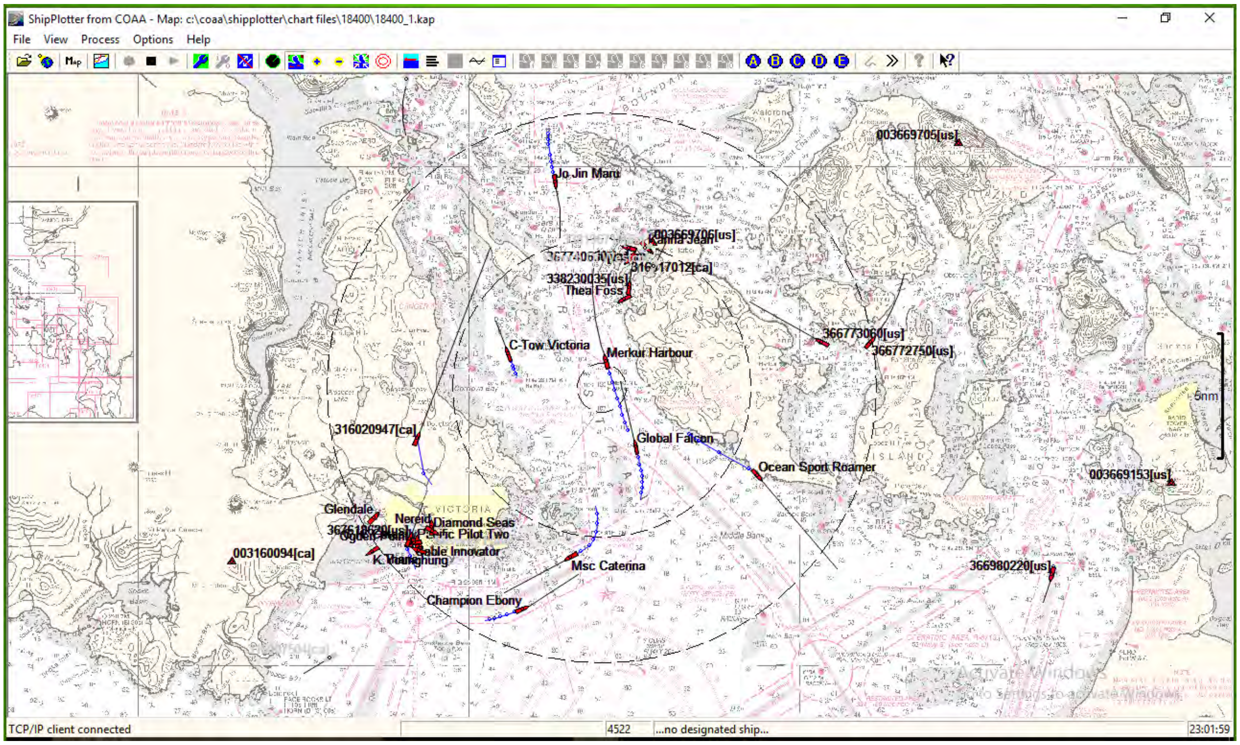


Figure 8. Screen capture of PC-based AIS logging system.

2.5. Data Analysis

Automated source level measurements from the ShipSound system were further analyzed to determine the effect of the slowdown trial on vessel noise emissions. To ensure adequate data quality, only source level measurements with closest point of approach (CPA) less than 1000 m from the hydrophones were accepted for subsequent analysis. Vessels were assigned to one of 12 different categories, based on their classification as transmitted by the AIS system (shorthand names in parentheses):

1. Bulk Carrier/General Cargo (Bulker)
2. Containership
3. Fishing
4. Government/Research
5. Naval
6. Other
7. Passenger under 100 m (Passenger100m-)
8. Passenger over 100 m (Cruise)
9. Recreational
10. Tanker
11. Tug
12. Vehicle Carrier

Note that roll-on-roll-off ferries were excluded from the analysis, since they do not typically transit the shipping lane in Haro Strait and were therefore not considered part of the slowdown study. The classifications of all vessels were checked against online databases and pilot logs, and corrected if necessary (approximately 20% of vessels identified as bulk carriers or general cargo on AIS were found to be containerships or vehicle carriers).

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

- Trial participants
- Trial non-participants
- Trial unknown (for measurements not captured in the participation logs)
- Control (for measurements outside the trial period)

Five vessel categories were captured in sufficient numbers in the participation logs to be included in the trial groups: Containership, Bulker, Tanker, Vehicle Carrier, and Cruise. The remaining categories were either sparsely represented in the participation logs or were not represented at all. Measurements in these categories were instead divided into two groups (corresponding to the control and trial periods) and analyzed separately. In rare instances, the pilot dispatch incorrectly recorded vessel participation status, which resulted in participating vessels being identified as non-participants, and vice-versa. To account for these discrepancies, measurements with significantly outlying speeds in the non-participant and participant groups were discarded from the trial groups (these measurements were retained, however, for speed trend analysis).

Vessel noise measurements (i.e., source levels) were analyzed in terms of the following three frequency bands, that were recently identified by an expert work group convened by the Coastal Ocean Research Initiative (Heise et al. 2017) as being particularly relevant to the acoustic quality of SRKW habitat:

- Broadband (10–100,000 Hz), for evaluating behavioural or physiological impacts.
- Communication masking (500–15,000 Hz), for evaluating effects of noise on communication space.
- 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 source levels in the SRKW bands, because MSL back-propagation better accounts for the effect of the environment on vessel source levels (e.g., from absorption, surface, and seabed reflections) than RNL back-propagation.

Quantiles of source level measurements were calculated and are presented using box-and-whisker plots. These plots illustrate the centre, spread, and overall range of data from a visual five-number summary (Figure 9). The ends of the box are the upper and lower quartiles (25th and 75th percentiles). The horizontal line inside the box is the median (50th percentile). The whiskers and points extend outside the box to the highest and lowest observations, where the points correspond to outlier observations (i.e., observations that fall more than 1.5×IQR beyond the upper and lower quartiles, where IQR is the interquartile range).

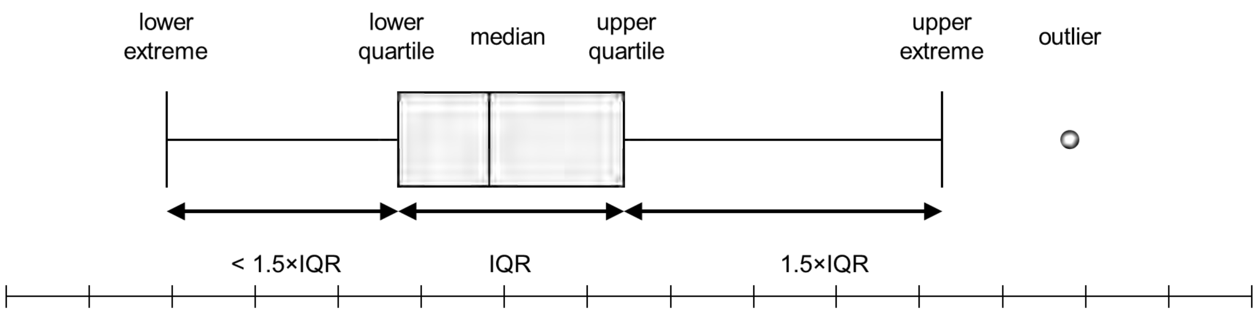


Figure 9. Diagram showing how quantiles are displayed on a box-and-whisker plot. IQR = interquartile range (i.e., the range between the 25th and 75th percentile).

Trends of source level versus speed were analyzed for speed through water, since this accounts for the effect of ocean currents on vessel movements. Where measurements were obtained at different speeds, trend analysis was performed using Ross's classical power law model (Ross 1976), which relates change in source level (SL) to relative changes in speed:

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

In this equation, SL is the source level at speed through water v, $\mathrm{SL}_{\mathrm{ref}}$ is the source level at some reference speed v_{ref}, and C_v is a coefficient corresponding to the slope of the curve. A higher coefficient indicates a larger difference in noise emissions per percentage change in speed. For example, according to Eqn 1, a 50% reduction in speed corresponds to a decibel SL reduction of 3xC_v. Where source level measurements were available at two different speeds (e.g., for the trial and control groups), an equivalent speed coefficient was calculated from Eqn 1 as follows:

$$C_v = \frac{\mathrm{SL}_2 - \mathrm{SL}_1}{10\log_{10}(v_2/v_1)}, \tag{2}$$

where v_1 and v_2 are the two speeds and SL_1 and SL_2 are the respective source levels at those speeds. Speed coefficients from this study were calculated to update an acoustic modelling assessment of cumulative vessel noise in Haro Strait (MacGillivray et al. 2017).

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], which is a statistical technique that tests an experimental hypothesis (e.g., source levels in the participant group were lower than source levels in the non-participant group) against a null hypothesis (e.g., source levels in the participant group were the same as source levels in the non-participant group). The strength of evidence against the null hypothesis is expressed in terms of a p value, which is the probability that the null hypothesis is true, given the experimental evidence. A small p value (by convention, less than 0.05) corresponds to strong evidence against the null hypothesis.

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

3. Results

3.1. Measurement Summary

We used ShipSound to process a total of 2765 vessel noise measurements collected during the control and trial periods. Of these measurements, 1930 were accepted (i.e., passed a manual quality review). Counts of accepted and rejected measurements were tabulated for all three underwater listening stations (Table 3). Some measurements in Haro Strait were rejected by the automated system, due to occasional time differences between the AIS data and hydrophone data (<1 minute). In these cases, the CPA time of the vessel was manually corrected by an analyst during quality review.

Table 3. Accepted, rejected, and total number of measurements collected on the underwater listening stations during the control and trial periods. Only measurements with CPA distance <1000 m are included in the totals. Note that roll-on-roll-off ferries were excluded from the Georgia Strait ULS totals, since they do not typically transit in Haro Strait and were therefore not considered part of the slowdown study.

Period	Haro Strait ULS southbound	Haro Strait ULS northbound	Georgia Strait ULS northbound
Control periods (6 Jul to 5 Aug and 7 to 26 Oct)			
Accepted	361	336	143
Rejected	93	117	116
Total	**454**	**453**	**259**
Trial period (6 Aug to 6 Oct)			
Accepted	487	389	214
Rejected	139	204	166
Total	**626**	**593**	**380**

Analysis of the vessel tracks showed that most vessels transiting through the slowdown zone passed within 1 km of the underwater listening stations (Figure 10). Vessel speed through water was recorded for all vessels passing within 2 km of the listening stations in Haro Strait (Figure 11). Changes in vessel speeds during the trial were greatest for those categories that employed pilots and had pre-trial speeds much greater than 11 knots (e.g., containerships, vehicle carriers, and cruise vessels).

Source level measurements from the trial were matched with pilot logs from the ECHO team, and each matching measurement was then assigned to either the participant or non-participant group (Table 4). Nine different vessel categories were represented in the participation logs, but only five of these categories contained a sufficient number of accepted measurements for statistical analyses. Vessels in the remaining categories rarely employ pilots and were thus sparsely represented in the participation logs. A total of 920 (out of 951) trips in the pilot logs were matched to the Haro Strait ULS measurements during the trial period.

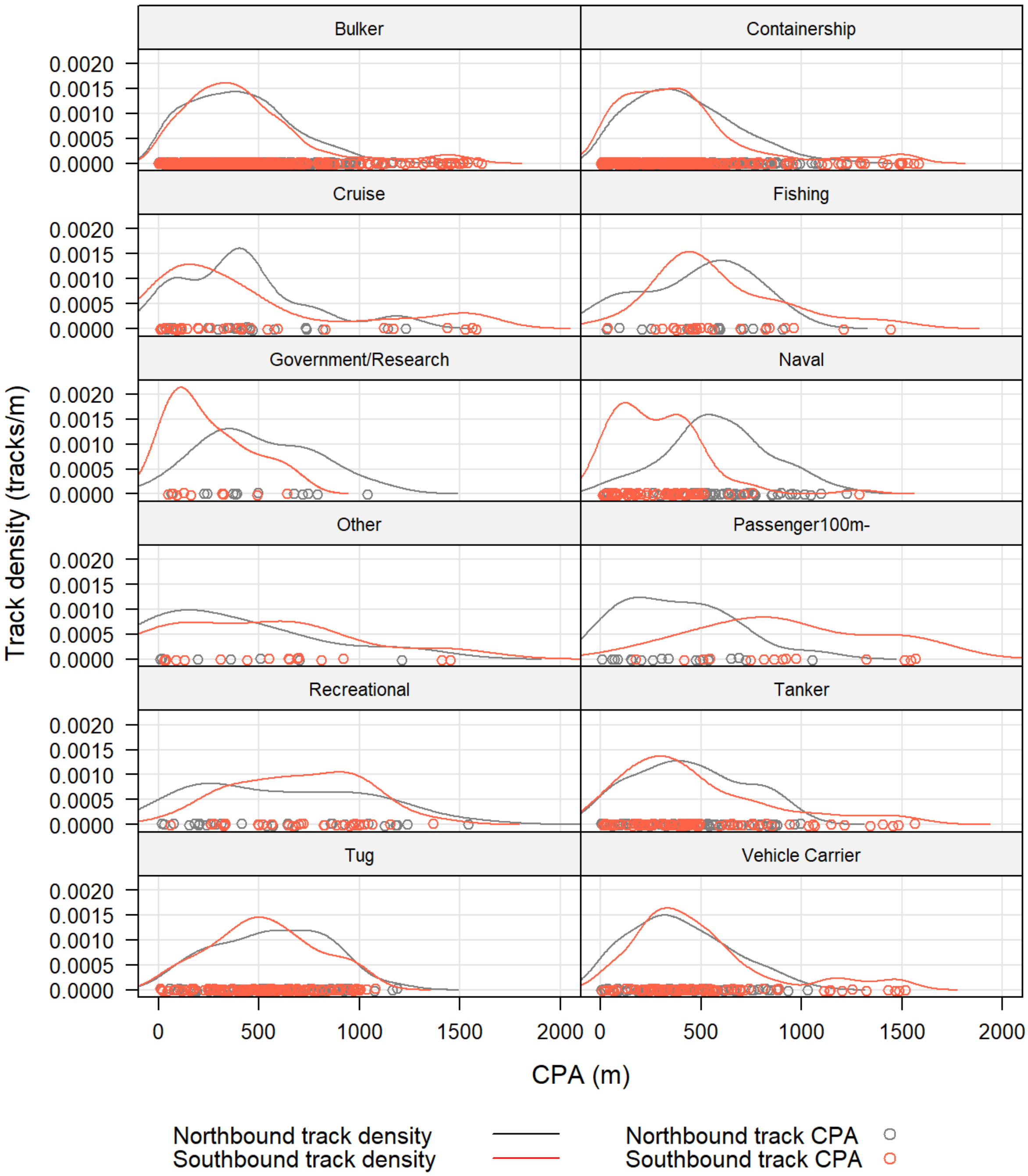


Figure 10. Density plots of vessel CPA distance to the two underwater listening stations in Haro Strait (all measurements).

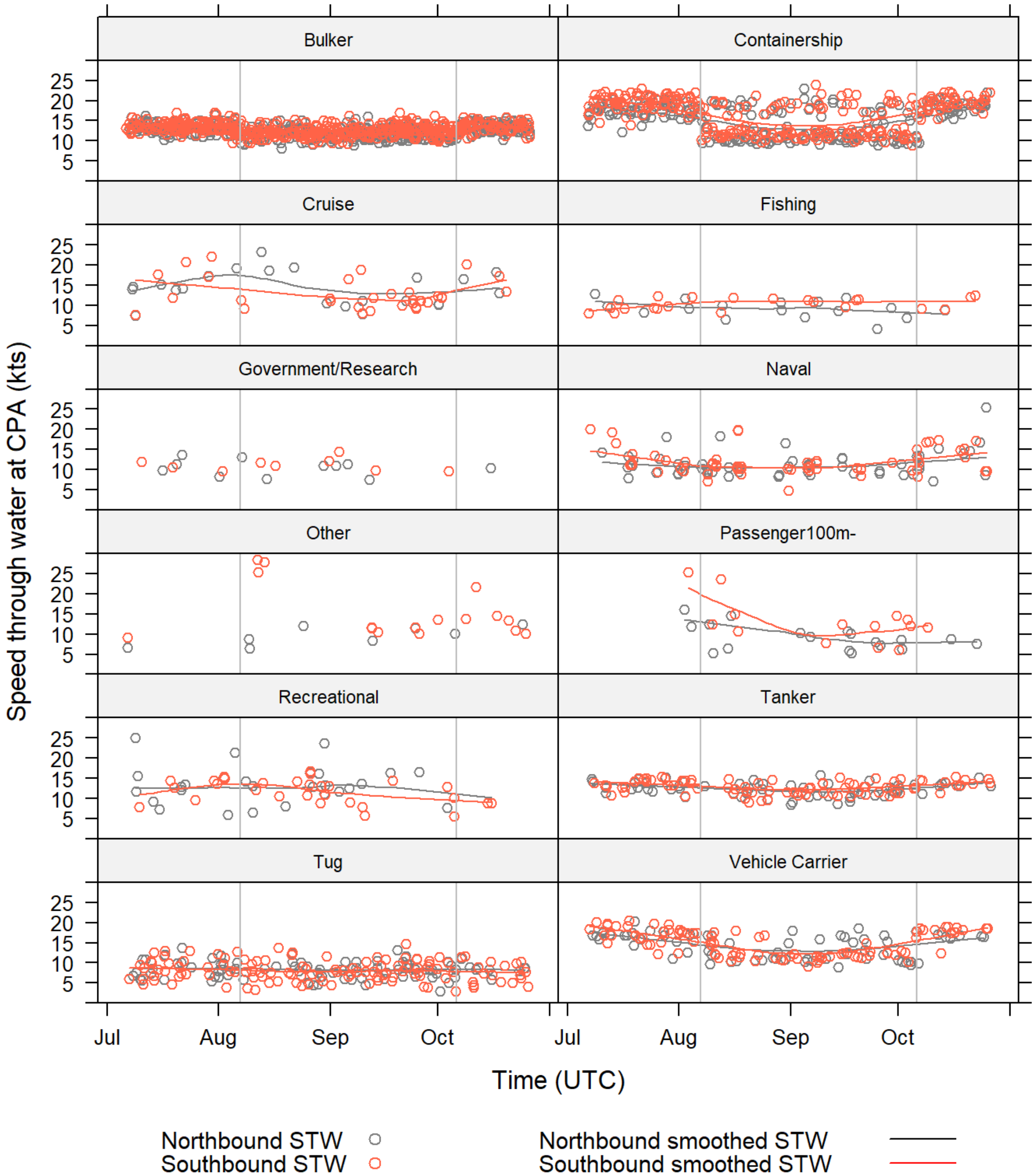


Figure 11. Vessel speed by category in Haro Strait (all measurements). Smoothed data shown for $n > 30$ only. The gray vertical lines indicate the start and end of the trial period.

Table 4. Total number of accepted and rejected measurements during control and trial periods for each vessel category (Haro Strait measurements only). Participant and non-participant groups were determined by matching measurements to participation status recorded in the pilot logs. The trial unknown group consisted of measurements collected during the trial period that could not be matched to the pilot logs. Only measurements with CPA distance less than 1000 m are included in the totals. The acceptance rate is the percentage of total measurements that passed a manual quality review.

Category	Control		Trial non-participant		Trial participant		Trial unknown	
	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected	Accepted	Rejected
Bulker	297	78	180	33	207	50	2	0
Containership	183	22	67	11	144	34	2	0
Fishing	9	9					11	8
Government/Research	5	4			0	1	3	8
Naval	12	31	1	3			9	57
Other	4	5	0	1	1	2	3	6
Passenger100m-	2	3					3	20
Cruise	14	4	3	0	16	7	3	3
Recreational	7	9					9	24
Tanker	44	12	28	6	27	13	3	2
Tug	59	24	0	1			85	38
Vehicle Carrier	61	9	24	3	45	12		
Total	**697**	**210**	**303**	**58**	**440**	**119**	**133**	**166**
Acceptance rate	**77%**		**84%**		**79%**		**44%**	

3.2. Effect of Trial Participation on Speed for Piloted Vessels

To investigate how speeds in different vessel categories were affected by slowdown participation, we calculated statistics of vessel speeds through water across the participant, non-participant, and control groups (Figure 12 and Appendix B.1). Measurements with outlier speeds, corresponding to cases where participation information was recorded incorrectly in the pilot logs, were removed from the analysis (Table 5). 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 6). Mean speed reductions were greatest for containerships (7.7 knots) and smallest for bulkers (2.1 knots). The speeds of non-participant vessels were identical to the control period for containerships and tankers, but slightly lower than the control period for bulkers and vehicle carriers (cruise vessels had too few non-participant trips to compare with the trial period). This could indicate that even non-participant vessels slowed down slightly during the trial period, or it could be due to participating vessels being incorrectly recorded as non-participants in the pilot logs. We calculated the overall speed reduction for each category by subtracting mean speeds of the participant group from that of the control group.

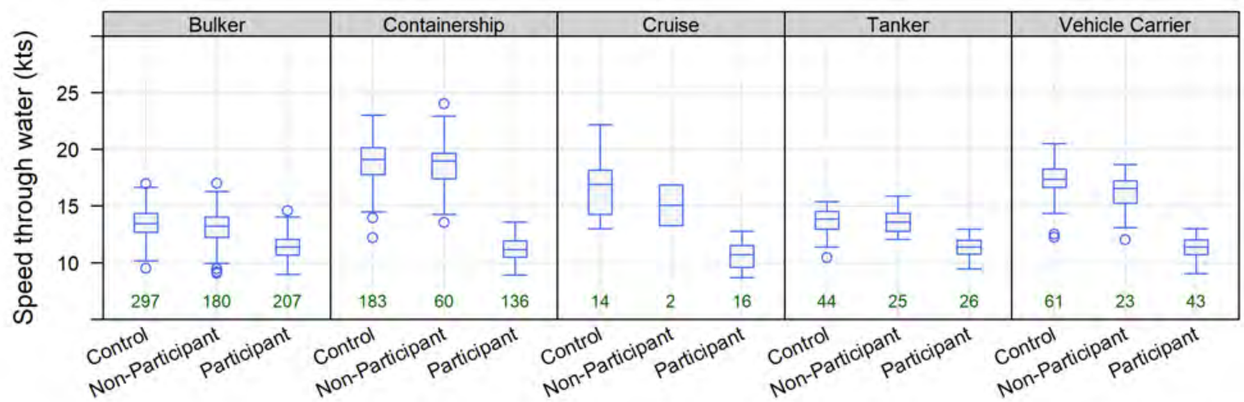


Figure 12. Box-and-whisker plots for five vessel categories, comparing speed through water in Haro Strait (at CPA) between the control, non-participant, and participant groups(accepted measurements only, excluding outlier speeds). The total number of measurements is indicated below each box.

Table 5. Number of measurements with outlier speeds removed from the trial participant and trial non-participant groups in each vessel category.

Group	Bulker	Containership	Cruise	Tanker	Vehicle Carrier
Non-participant	0	7	1	3	1
Participant	0	8	0	1	2

Table 6. 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 (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). Differences with no asterisk are not statistically significant ($p > 0.05$). Blank cells indicate missing data. Shading indicates whether the difference was significant (orange) or not (blue).

Vessel category	Non-participant vs. Control	Participant vs. Control	Participant vs. Non-participant
Bulker	0.397**	2.091***	1.694***
Containership	0.194	7.671***	7.477***
Cruise		6.146***	
Tanker	0.071	2.296***	2.225***
Vehicle Carrier	1.027*	5.894***	4.867***

3.3. Effects of Trial Participation on Source Levels for Piloted Vessels

To investigate the effects of the voluntary slowdown on vessel noise emissions (i.e., source levels), we calculated statistics of source levels across the participant, non-participant, and control groups (Figure 13 and Appendix B.2). Pairwise *t*-tests showed strong evidence that mean source levels in the participant group were lower than those in the non-participant and control groups for all categories (Table 7). Mean broadband source level (MSL) reductions ranged from 5.9 dB for bulkers to 11.5 dB for containerships. Analysis in the CORI bands showed that the reductions were frequency dependent, with smallest mean reductions (3.1–10.8 dB) in the 0.5–15 kHz range, and greatest mean reductions (5.1–24.0 dB) above 15 kHz. There was no evidence of significant differences in mean source levels 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 travelling 0.4 kn slower, on average, during the trial period than during the control period (see Table 6). Note, however, that RNL and MSL source levels above 500 Hz for bulkers did not show any significant differences between the non-participant and control groups.

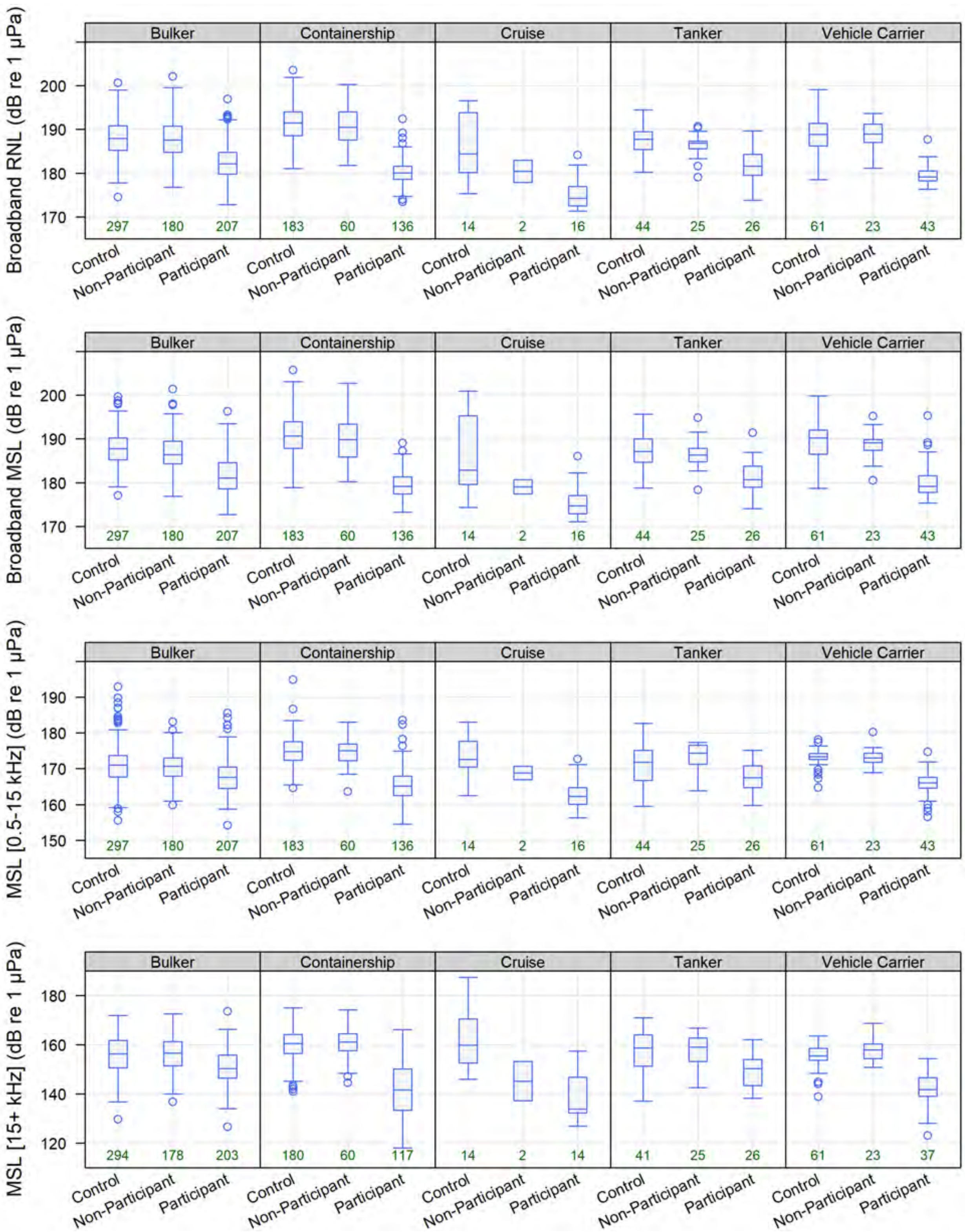


Figure 13. Box-and-whisker plots for the five vessel categories, comparing source levels in Haro Strait between the control, non-participant, and participant groups (accepted measurements only). From top to bottom: Broadband RNL, Broadband MSL, MSL [0.5–15 kHz] (SRKW communication masking), and MSL [15+ kHz] (SRKW echolocation masking). The total number of measurements is indicated below each box.

Table 7. Differences in mean source levels (dB) 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 (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$). Differences with no asterisk are not statistically significant ($p > 0.05$). Blank cells indicate missing or insufficient data. Shading indicates whether the difference was significant (orange) or not (blue).

Vessel category	Non-participant vs. Control	Participant vs. Control	Participant vs. Non-participant
Broadband RNL			
Bulker	0.261	5.562***	5.301***
Containership	0.709	11.168***	10.458***
Cruise		10.737***	
Tanker	1.081	5.777***	4.696***
Vehicle Carrier	0.078	9.236***	9.158***
Broadband MSL			
Bulker	1.017**	5.912***	4.895***
Containership	1.080	11.515***	10.435***
Cruise		10.515**	
Tanker	0.768	6.082***	5.314***
Vehicle Carrier	0.750	9.252***	8.503***
MSL [0.5–15 kHz] (SRKW communication masking)			
Bulker	0.551	3.051***	2.500***
Containership	0.198	9.290***	9.093***
Cruise		10.781***	
Tanker	−1.941	3.594**	5.535***
Vehicle Carrier	0.023	7.423***	7.400***
MSL [15+ kHz] (SRKW echolocation masking)			
Bulker	−0.002	5.134***	5.136***
Containership	−0.689	17.786***	18.475***
Cruise		23.981***	
Tanker	0.071	7.878***	7.807***
Vehicle Carrier	−2.026	13.897***	15.922***

We calculated the noise reductions associated with the slowdown by subtracting source levels of slowed vessels from those of vessels transiting at normal speeds, on a per-category basis (Figure 14, Appendix B.3). Reference source levels for vessels transiting at normal speeds were based on measurements from the pre-and-post-trial control periods. Reductions were calculated by subtracting mean and quantile source level statistics of the participant group from those of the control group (i.e., the top 5th percentile of participants was compared with the top 5th percentile of the control group, and so forth). This analysis also showed, for example, that tankers had consistent broadband MSL reductions as a group (~ 6 dB), whereas containerships had greater MSL reductions for louder vessels (14.0 dB at the 95th percentile) than for quieter vessels (9.0 dB at the 5th percentile). As expected, the reductions in source levels associated with the voluntary slowdown were greatest for those categories with the highest pre-trial speeds (i.e., containerships, vehicle carriers, and cruise vessels).

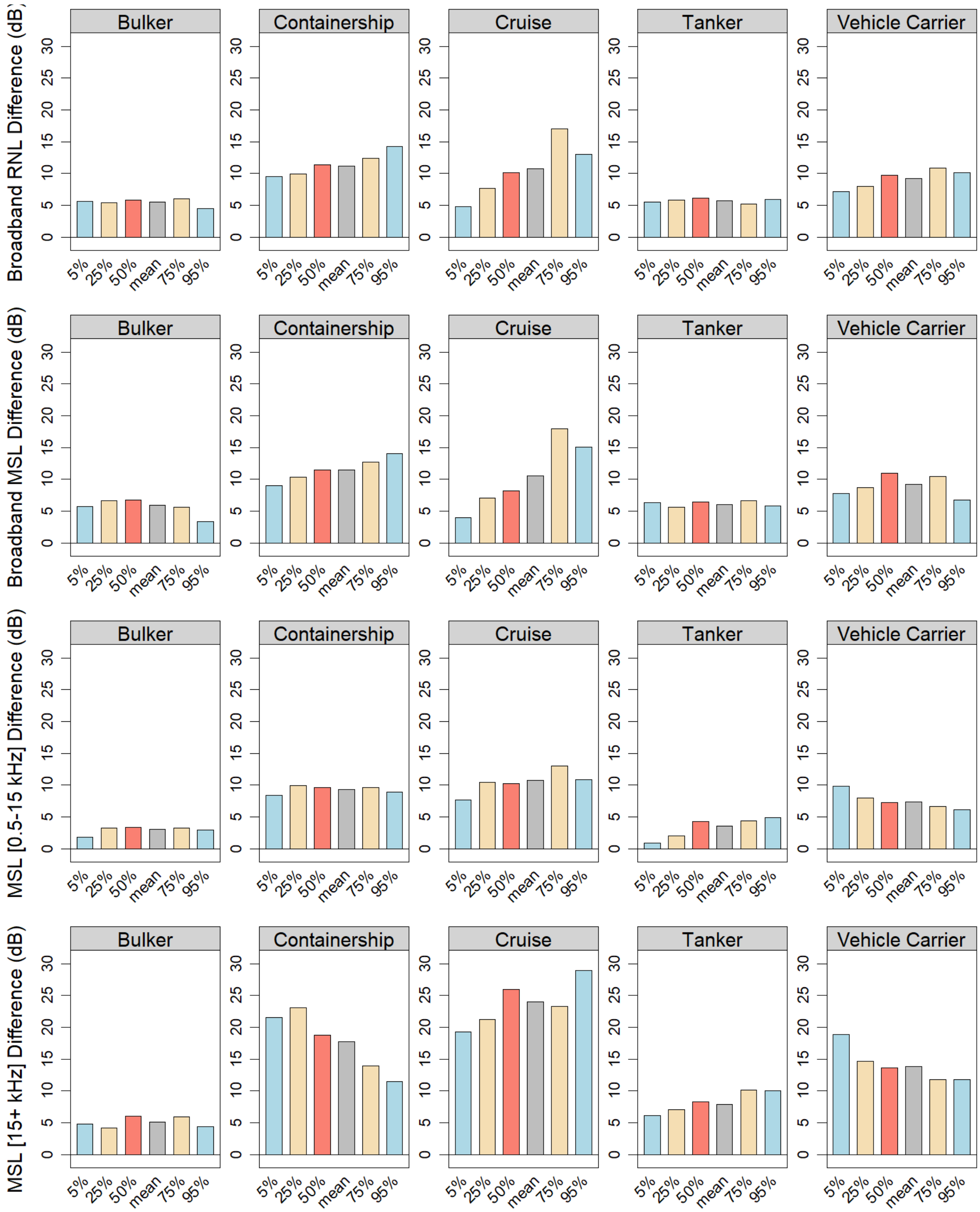


Figure 14. Reductions in vessel source levels that resulted from slowdown participation (mean and quantiles). Differences were computed by subtracting source levels statistics in the participant group from those in the control group. From top to bottom: Broadband RNL, Broadband MSL, MSL [0.5–15 kHz] (SRKW communication masking), and MSL [15+ kHz] (SRKW echolocation masking).

Noise reductions from the Haro Strait measurements were used to calculate equivalent speed scaling coefficients, according to Eqn 2, for the Ross power-law model (Table 8). These speed coefficients (C_v) reflect the mean decibel reductions in source levels 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 source level for relative (i.e., percentage) 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 percentage during the trial. Mean decibel-per-knot source level reductions were also calculated from the Haro Strait measurements, for comparison with other studies (Table 9).

To investigate how slowdown participation affected frequency-dependent noise emissions, we compared mean 1/3-octave-band source levels (MSL) between the participant, non-participant, and control groups (Figure 15). Source levels reductions for participant vessels showed a similar frequency dependence for all five categories: the largest reductions were generally below 100 Hz and above 1000 kHz, and the smallest reductions were in the intermediate-frequency range. This frequency-dependence may be due to the different noise generating mechanisms that dominated different parts of the radiated vessel noise spectrum (e.g., cavitation often dominates at very low and very high frequencies, whereas machinery noise dominates at middle frequencies). We also observed an unusual peak in the 25-kHz band for cruise vessels in the control group. Inspection of the raw data showed evidence of sonar-like acoustic pulses during at least six cruise vessel measurements from the post-trial control period (Figure 16). We found no evidence of similar noise emissions during the slowdown trial period. The source of these narrow-band noise emissions is unknown, but they likely exaggerated the measured reductions for participating cruise vessels in the SRKW echolocation masking band (15+ kHz).

Table 8. Equivalent speed scaling coefficients for the Ross power law model (Eqn 2) calculated from the source level reductions measured during the slowdown trial. Speeds correspond to speed through water recorded at the time of measurement. Source level reductions for each vessel category were taken to be the difference between the participant and control groups in Table 7.

Category	Mean reference speed (knots)	Mean slowdown speed (knots)	C_v (Broad-band RNL)	C_v (Broad-band MSL)	C_v (MSL [0.5-15kHz])	C_v (MSL [15+kHz])
Bulker	13.473	11.382	7.594	8.071	4.165	7.009
Containership	18.876	11.205	4.931	5.084	4.102	7.853
Cruise	16.762	10.617	5.413	5.301	5.435	12.090
Tanker	13.683	11.387	7.243	7.625	4.505	9.876
Vehicle Carrier	17.263	11.369	5.092	5.101	4.092	7.661

Table 9. Equivalent decibel-per-knot source level reductions for each vessel category. Values were calculated by dividing the difference in mean source levels by the difference in mean speeds, between the participant and control groups in Table 7.

Category	dB/knot (Broadband RNL)	dB/knot (Broadband MSL)	dB/knot (MSL 0.5-15kHz)	dB/knot (MSL 15+kHz)
Bulker	2.660	2.827	1.459	2.455
Containership	1.456	1.501	1.211	2.319
Cruise	1.747	1.711	1.754	3.902
Tanker	2.516	2.649	1.565	3.431
Vehicle Carrier	1.567	1.570	1.259	2.358

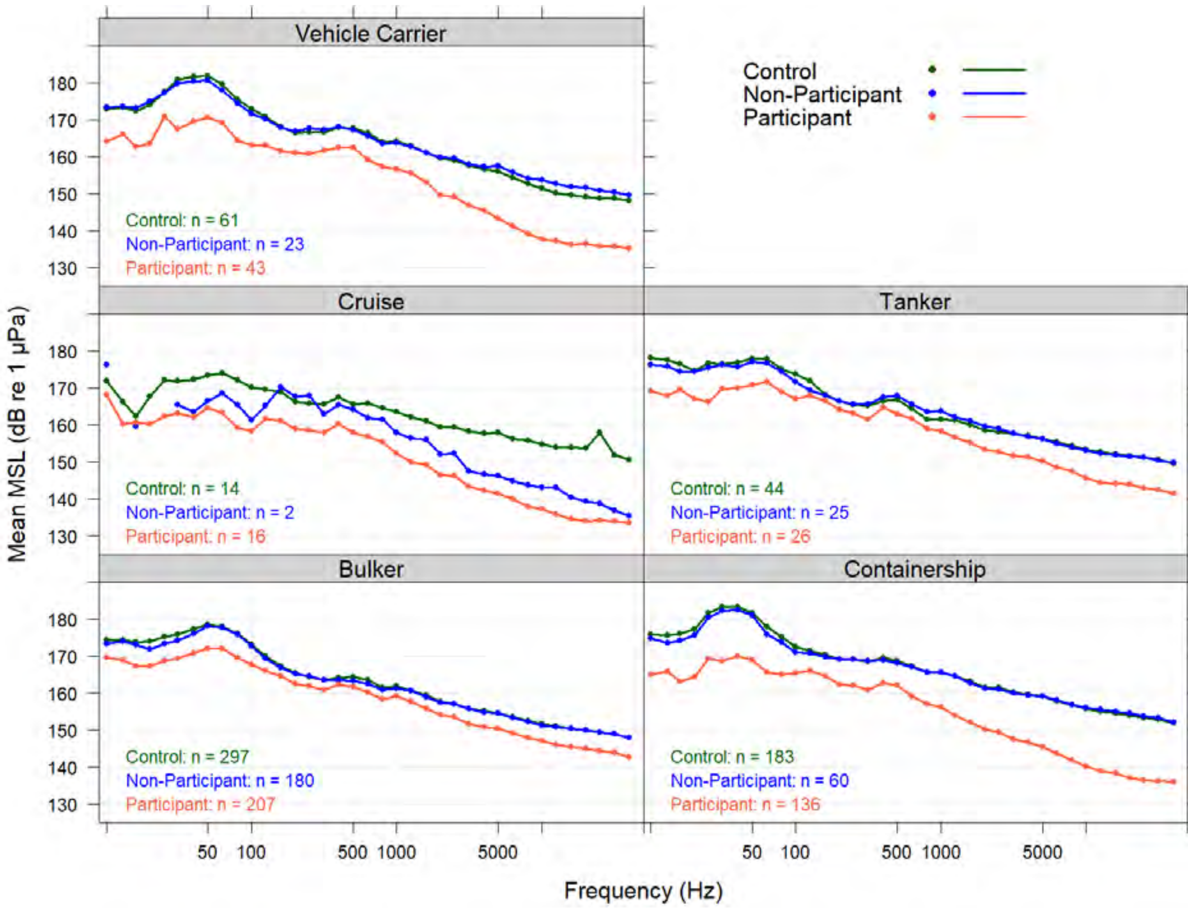


Figure 15. Mean MSL in 1/3-octave frequency bands for the control, non-participant, and participant groups (Haro Strait accepted measurements only). The total number of measurements in each group is indicated at the bottom of each panel. Missing data points below 30 Hz for non-participant cruise ships correspond to frequency bands with no valid measurements (i.e., where background noise exceeded signal level).

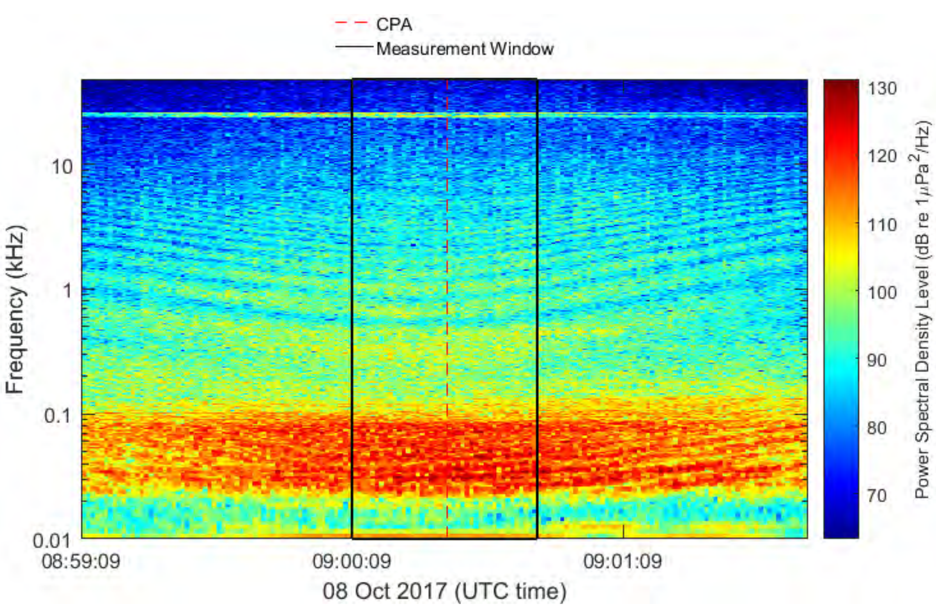


Figure 16. Spectrogram showing evidence of narrow-band, high-frequency sound emissions (~25 kHz) from a cruise vessel measured on the northbound ULS in Haro Strait during the post-trial control period.

3.4. Effects of Trial Participation on Source Levels for Other Vessel Categories

Vessel speed and source level statistics were calculated separately for those vessel categories that were not typically piloted and therefore lacked information on slowdown participation (Table 10, Figures 17 and 18). Measurements in these seven categories were assigned to one of two groups (control and trial), depending on when they were collected. Of these categories, only the naval category was found to have a statistically significant reduction (p = 0.001) in speeds 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). The mean MSL of RCN vessels was 6.3 dB lower during the trial than during the control period (Table 11), but this value should not be considered a high-confidence estimate because it is based on a small number of measurements. Furthermore, source levels of naval vessels were already quite low, which resulted in large numbers of rejections due to interference from background noise. No information on participation was available for other categories of vessels, and their measurements showed no clear evidence of reduced noise emissions during the trial period.

Table 10. Number of accepted source level measurements in Haro Strait, during the control and trial periods, for vessels not represented in the pilot participation logs.

Category	Control	Trial
Fishing	9	11
Government/Research	5	3
Naval	12	10
Other	4	4
Passenger100m-	2	3
Recreational	8	9
Tug	59	86
Total	**99**	**126**

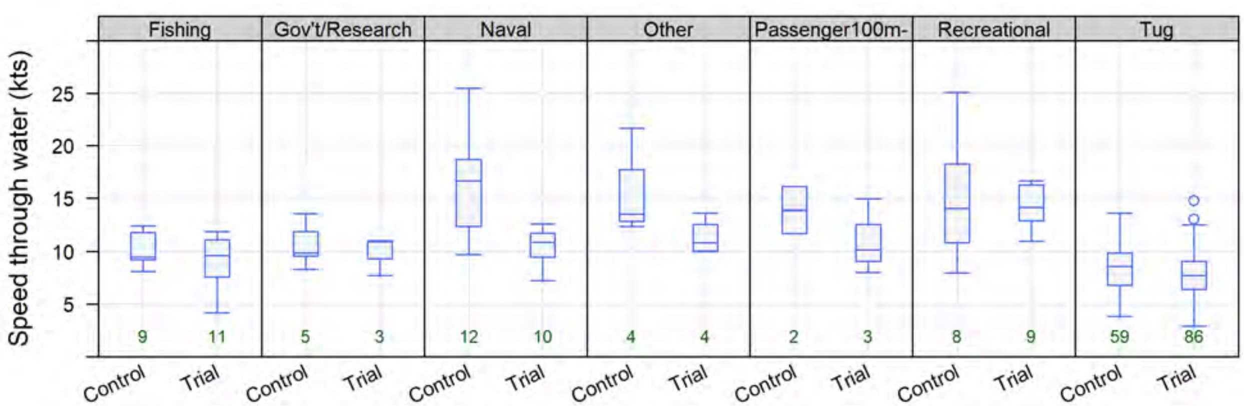


Figure 17. Box-and-whisker plots comparing vessels speeds in Haro Strait, during control and trial periods, for categories not represented in the pilot participation logs (accepted measurements only). The total number of measurements is indicated below each box.

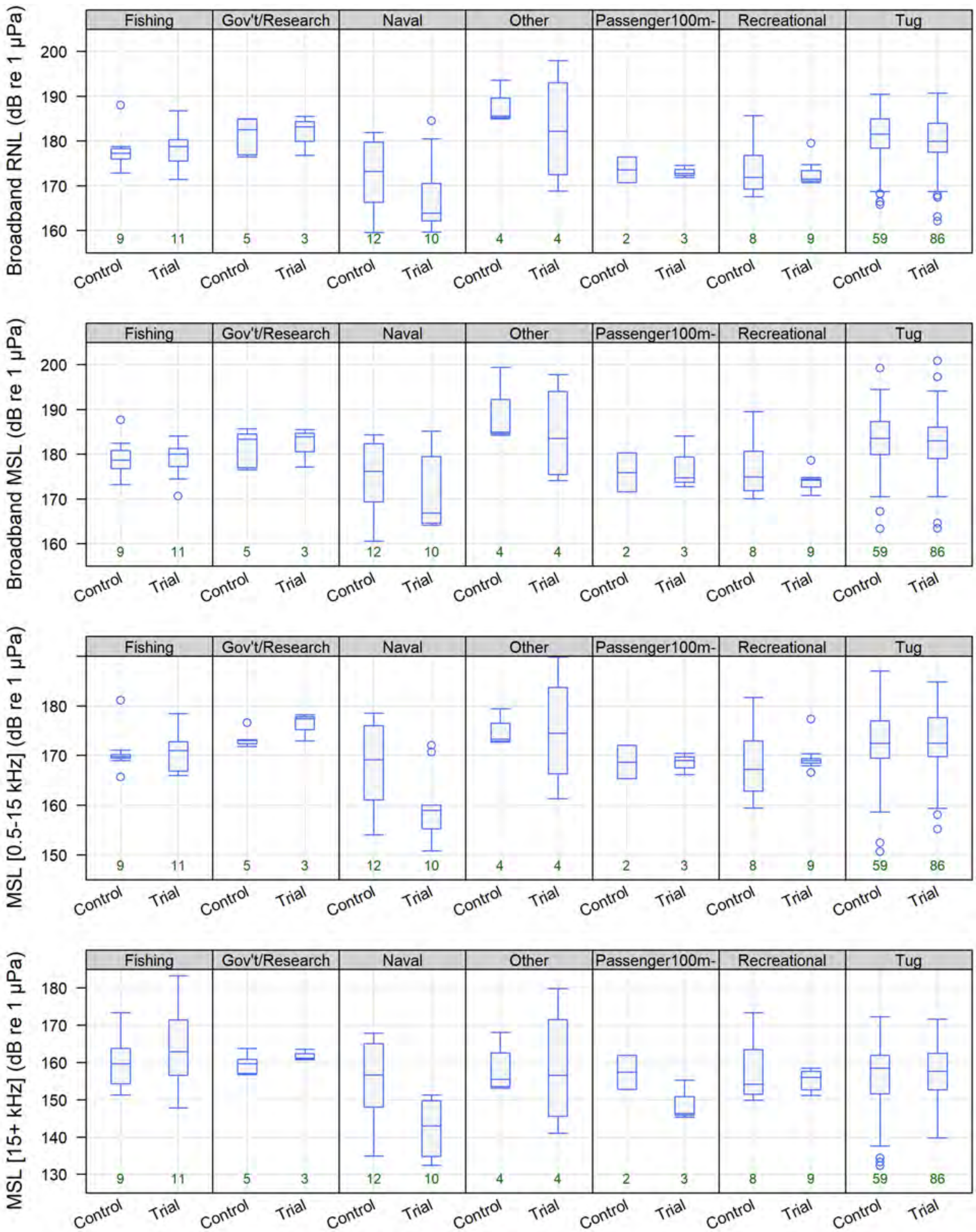


Figure 18. Box-and-whisker plots of measured source levels in Haro Strait, during control and trial periods, for vessel categories not represented in the pilot participation logs (accepted measurements only). From top to bottom: Broadband RNL, Broadband MSL, MSL [0.5–15 kHz] (SRKW communication masking), and MSL [15+ kHz] (SRKW echolocation masking). The total number of measurements is indicated below each box.

Table 11. Mean (± standard deviation) source levels for Royal Canadian Navy (RCN) vessels measured on the Haro Strait listening stations during the control and trial periods.

Period	*n*	STW (knots)	Broadband RNL (dB re 1 µPa @ 1 m)	Broadband MSL (dB re 1 µPa @ 1 m)	MSL [0.5-15kHz] (dB re 1 µPa @ 1 m)	MSL [15+kHz] (dB re 1 µPa @ 1 m)
Control	11	15.9 ± 4.6	172.0 ± 8.0	174.6 ± 8.4	167.6 ± 8.8	154.4 ± 11.3
Trial	8	10.6 ± 1.8	164.8 ± 6.7	168.3 ± 7.0	158.5 ± 5.8	142.6 ± 6.5

3.5. Effect of Speed on Source Levels for Repeated Measurements of Individual Vessels

Several factors other than speed, such as draft, size, or 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 (e.g., due to differences in vessel design, etc.). To control for these effects, we directly compared reduced-speed source levels measured on the Haro Strait ULS with service-speed source levels of the same vessels measured on the Georgia Strait ULS. Note, however, that Vehicle Carriers typically transited faster in Haro Strat than in Georgia Strait. To ensure consistency of vessel operating conditions (e.g., loading, draft, etc.), measurements were compared only if they were collected on the same northbound trip, under direction of the same pilot. A total of 107 matched pairs of measurements met these criteria (Figure 19). Data from these repeated measurements were then fit to the Ross model (Eqn 1) to determine the trend of vessel source levels with changes in speed (Table 12). Measurements from all five categories of vessels were pooled together 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 a sufficient number of 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 source level metrics (a higher C_v value corresponds to a greater reduction of source level with decreasing speed). This analysis showed that reductions in vessel source levels associated with slower speeds were greatest above 15 kHz, in the SRKW echolocation band, and lowest between 500–15000 Hz, in the SRKW communication band. The slope of the MSL trend was greater than that of the RNL trend, which indicates that 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 1/3-octave-band analysis, which showed that the source level reductions were greatest at low and high frequencies (see Figure 15). 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 (Figure 20). Thus, based on the repeated measurements, it was not possible to calculate distinct speed scaling coefficients for each vessel category, to within the limits of the experimental uncertainty.

The scaling coefficients from Table 12 estimate the source level reduction associated with a percentage speed reduction. For example, the best-fit MSL speed scaling coefficient for all data was $C_v = 5.10$, so the estimated change in source level corresponding to a 40% speed reduction (i.e., $v = 0.6 \times v_{ref}$) would be calculated from Eqn 1 as follows:

$$\Delta\text{MSL} = 5.1 \times 10\log_{10}(0.6) = -11.3\text{ dB}$$

where the negative change corresponds to a positive reduction. Taking into account the associated uncertainty of the trend (± 0.56), the estimated reduction in source level is 11.3 ± 1.2 dB. Likewise, the best-fit MSL speed scaling coefficient at SRKW echolocation frequencies (> 15 kHz) was $C_v = 6.52 \pm 0.75$, so a 40% speed reduction would result in a source level reduction of 14.5 ± 1.7 dB in this band.

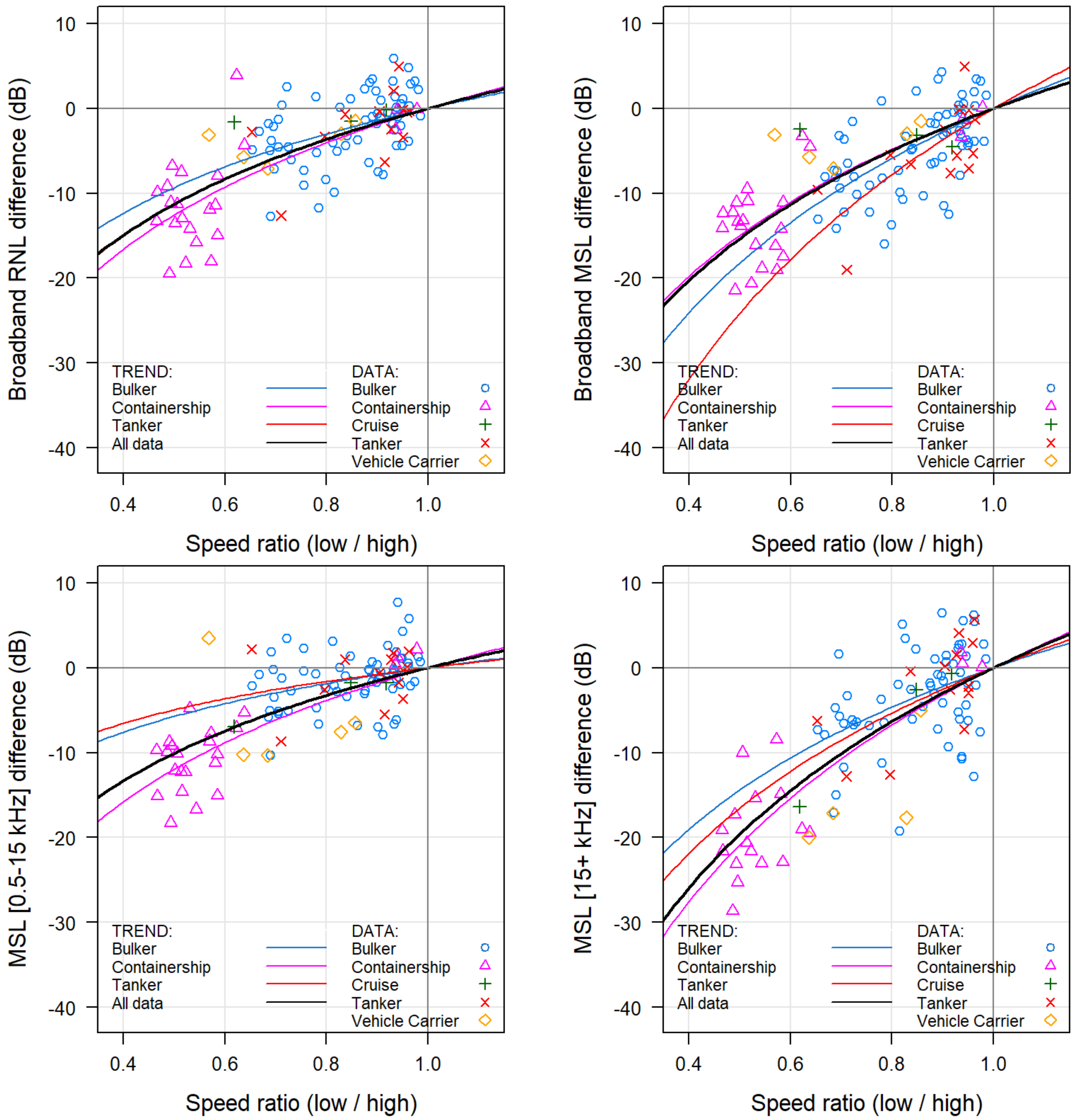


Figure 19. Change in source level versus speed ratio for vessels during the same northbound trip over the Haro Strait ULS and Georgia Strait ULS (i.e., inside versus outside the slowdown zone). The lines are the best-fit trendlines, based on Eqn 1. Each point on the plots represent the difference in measured source levels for a pair of measurements (i.e., equal to the dB difference between the low-speed and high-speed measurement).

Table 12. Best-fit scaling coefficients of source level versus vessel speed (for Ross power law) calculated from measurements of the same vessels transiting northbound at different speeds over the Haro Strait ULS and Georgia Strait ULS. The uncertainty (±) indicates the 90% confidence interval of the fit. The coefficient of determination is the fraction of data variance explained by the fitted model. 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, note n=98 for MSL15+kHz)				
C_v	3.75 ± 0.50***	5.10 ± 0.56***	3.35 ± 0.47***	6.52 ± 0.75***
Coefficient of determination (r^2)	0.677	0.755	0.653	0.752
Bulker (n = 63, note n=59 for MSL15+kHz)				
C_v	3.10 ± 1.00***	6.05 ± 1.15***	1.91 ± 0.89***	4.78 ± 1.52***
Coefficient of determination (r^2)	0.385	0.646	0.232	0.405
Containership (n = 23, note n=19 for MSL15+kHz)				
C_v	4.17 ± 0.78***	4.96 ± 0.71***	3.97 ± 0.55***	6.93 ± 0.94***
Coefficient of determination (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**
Coefficient of determination (r^2)	0.429	0.706	0.151	0.490

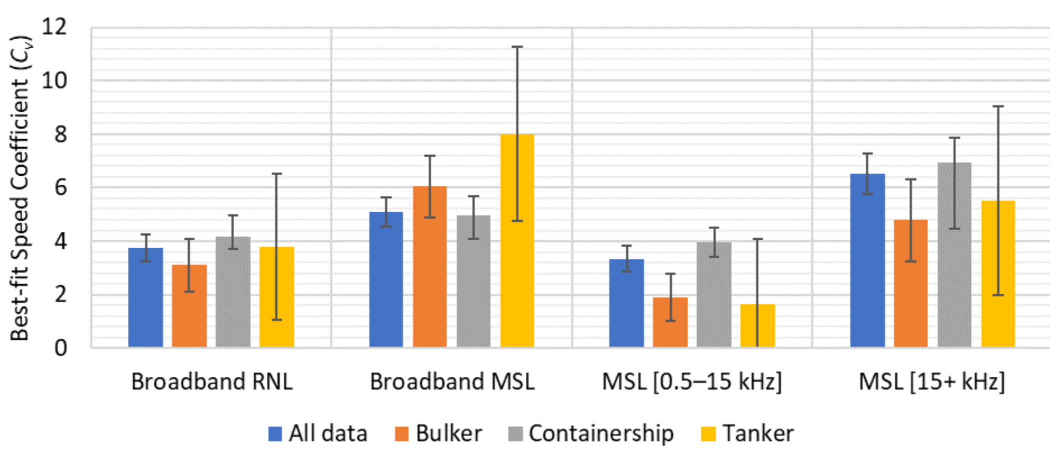


Figure 20. Barplot of best-fit speed scaling coefficients calculated from measurements of the same vessels transiting northbound at different speeds over the Haro Strait ULS and Georgia Strait ULS (Table 12). Error bars show 90% confidence intervals.

3.6. Trends of Source Level versus Vessel Speed by Category

We performed a trend analysis of source levels versus speed through water for each vessel category (Figures 21–24), using all measurements from both Haro Strait and Georgia Strait (i.e., for the combined trial and control periods). All accepted measurements were included in this analysis, regardless of participation status. Trends of source level versus speed were also analyzed in 1/3-octave-bands (Appendix C). This trend analysis did not control for other factors that may have influenced vessel noise emissions, such as draft, RPM, ship design, or ship size.

We found that higher speeds were associated with increased noise emissions (i.e., the best-fit coefficients were positive) for all categories that had sufficient measurements to establish a statistically significant trend. As with the analyses of the trial groups (Section 3.3) and the repeated vessel measurements (Section 3.5), the source level versus speed trends were generally strongest in the SRKW echolocation band (>15 kHz) and weakest in the SRKW communication band (0.5–15 kHz).

The results of the trend analysis were expected to be most reliable for those categories that had substantial slowdown participation (i.e., bulker, containership, tanker, vehicle carrier, cruise, and naval). This is because vessels in these categories changed their speeds between the control and trial periods, which provided some degree of experimental control. For the remaining vessel categories (tug, recreational, fishing, passenger100m-, government/research, and other), which were not clearly divided into participants or non-participants, trends of source levels with speed through water could not be directly attributed to changes in speed, since other factors correlated with speed (e.g., such as vessel size or draft) may have driven the observed trends.

The trends of source level versus speed obtained from this analysis were weaker than those calculated in Section 3.3 by directly comparing source levels in the participant and control groups (i.e., the speed coefficients in Figures 21–24 were generally smaller than those in Table 8). Put another way, the per-category speed trend analysis underestimated the actual source level reductions that were observed during the trial. This was particularly true for bulkers and tankers, which were the two categories with the smallest speed reductions for participant vessels. We expect the estimates based on comparing the trial groups (i.e., Table 8) to be more reliable than the trend analysis, since the former method explicitly controlled for other influential factors whereas the latter did not. This result underscores the benefit of using controlled measurements for investigating the effect of speed reductions on vessel noise emissions.

We examined how noise emissions varied with frequency by calculating mean source spectrum levels in 2 knot speed bins for each vessel category, using all measurements from Haro Strait (Figure 25). The spectrum analysis showed a similar result to the band level analysis (see Figure 15), where the greatest differences between faster and slower vessels were at the upper and lower end of the measured frequency range. The spectrum analysis also showed that some vessels categories (cruise, fishing, government/research, passenger100-) contained tonal noise emissions above 10 kHz. Tonal noise emissions are likely emitted by sonars (e.g., depth sounders) that are in use on some vessels.

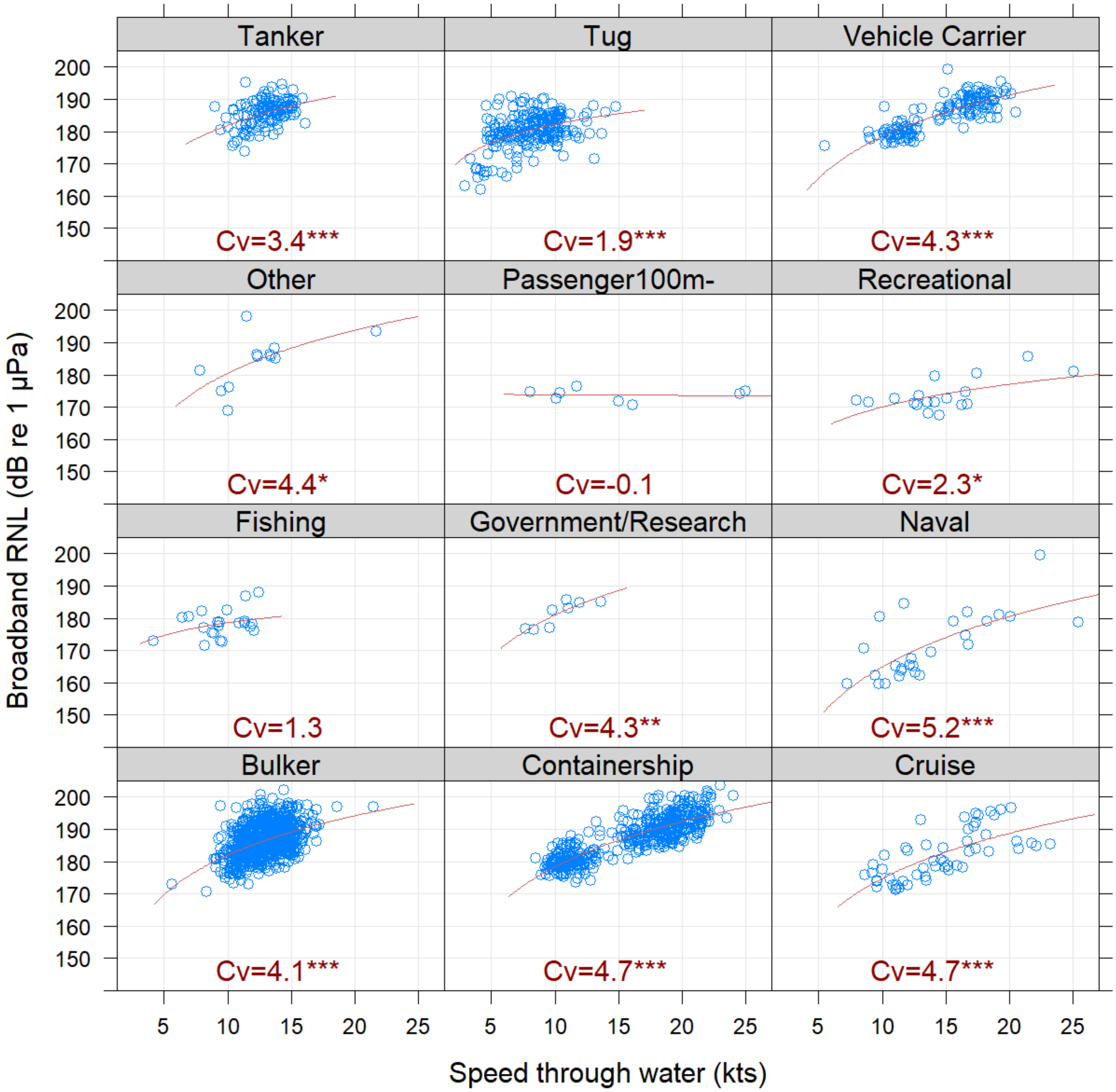


Figure 21. Broadband RNL versus vessel speed for all categories, based on ULS measurements from Haro Strait and Georgia Strait (accepted measurements only). The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v). The asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

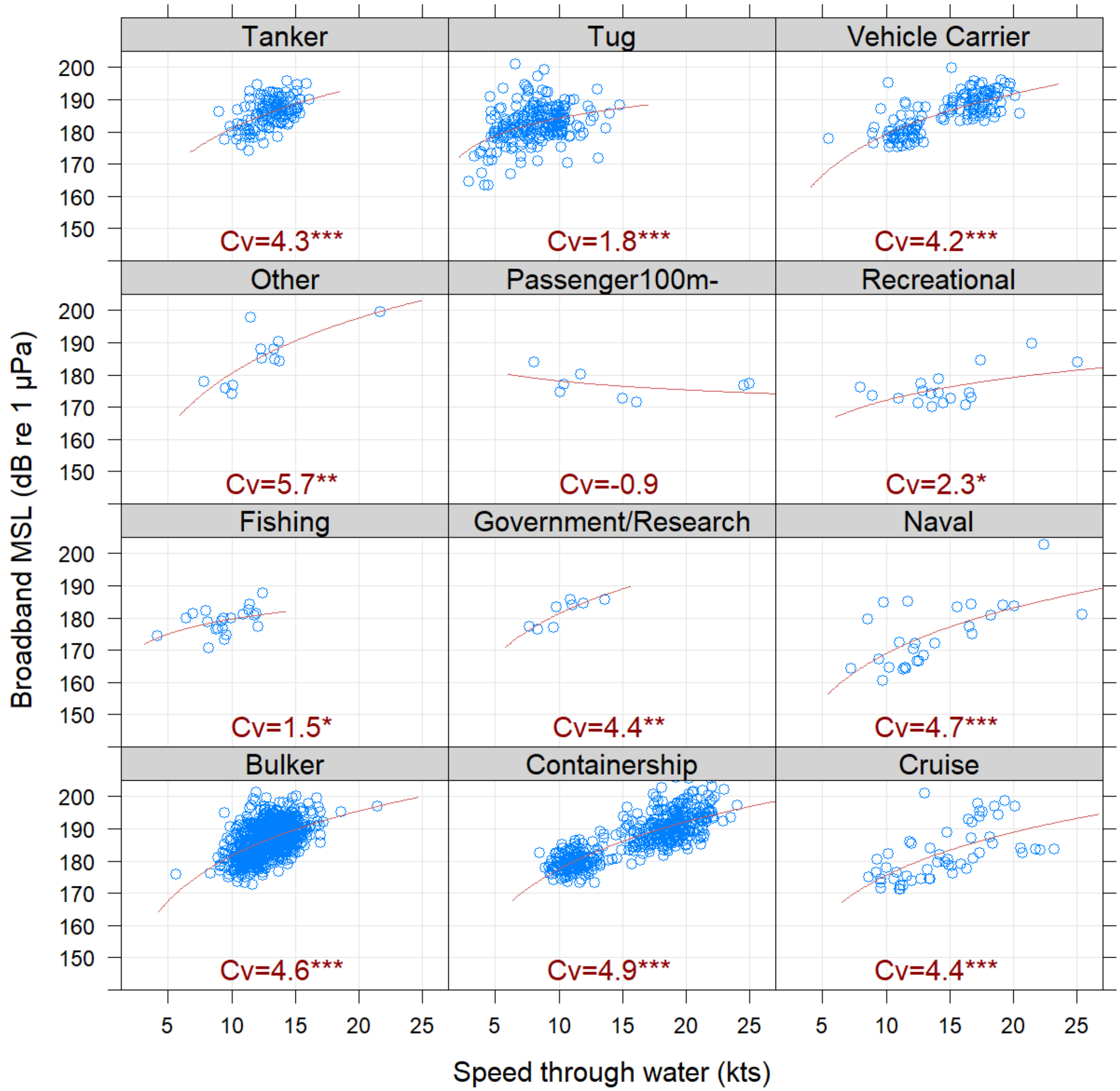


Figure 22. Broadband MSL versus vessel speed for all categories, based on ULS measurements from Haro Strait and Georgia Strait (accepted measurements only). The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_V). The asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

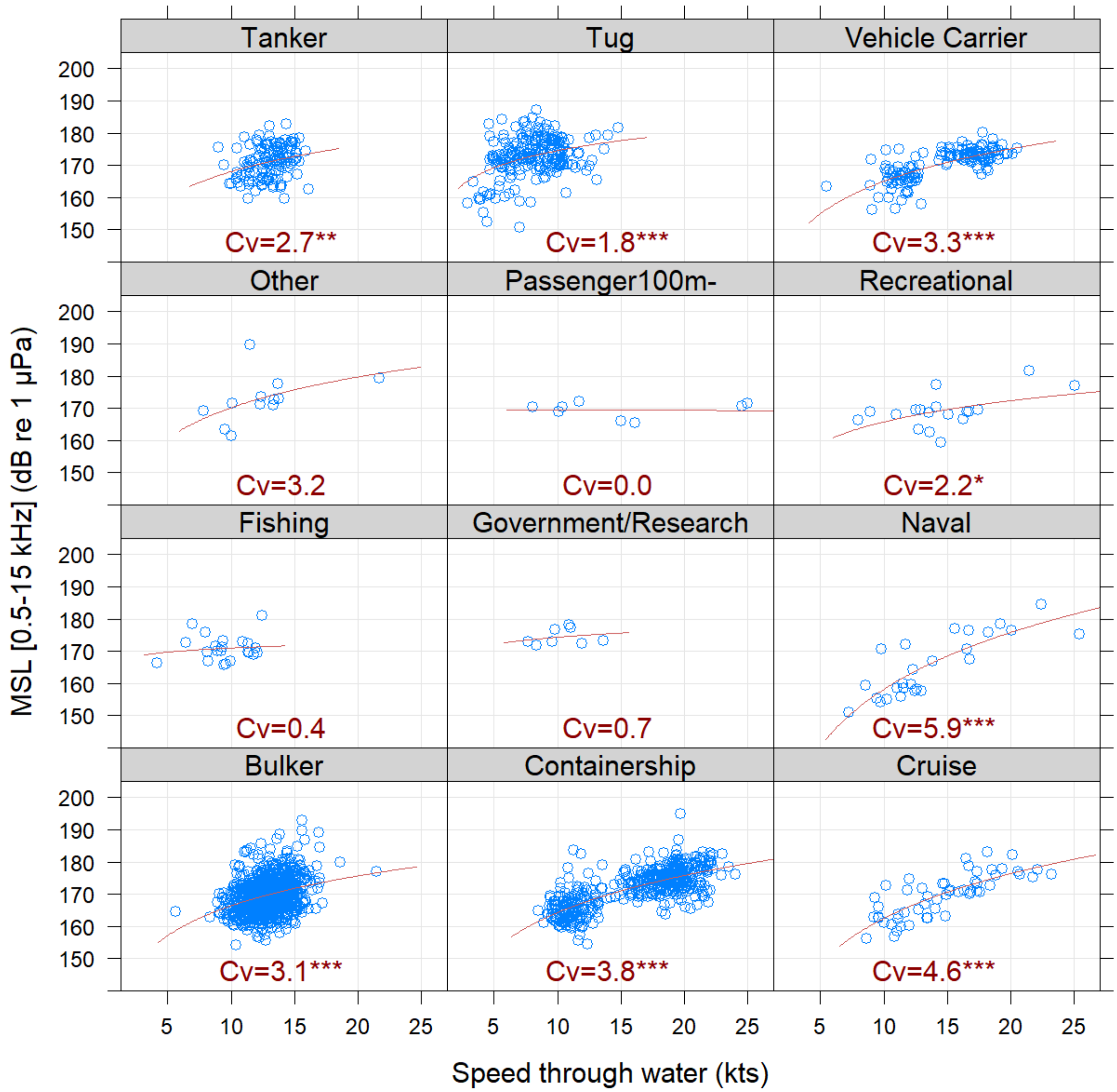


Figure 23. MSL [0.5–15 kHz] versus vessel speed for all categories, based on ULS measurements from Haro Strait and Georgia Strait (accepted measurements only). The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v). The asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

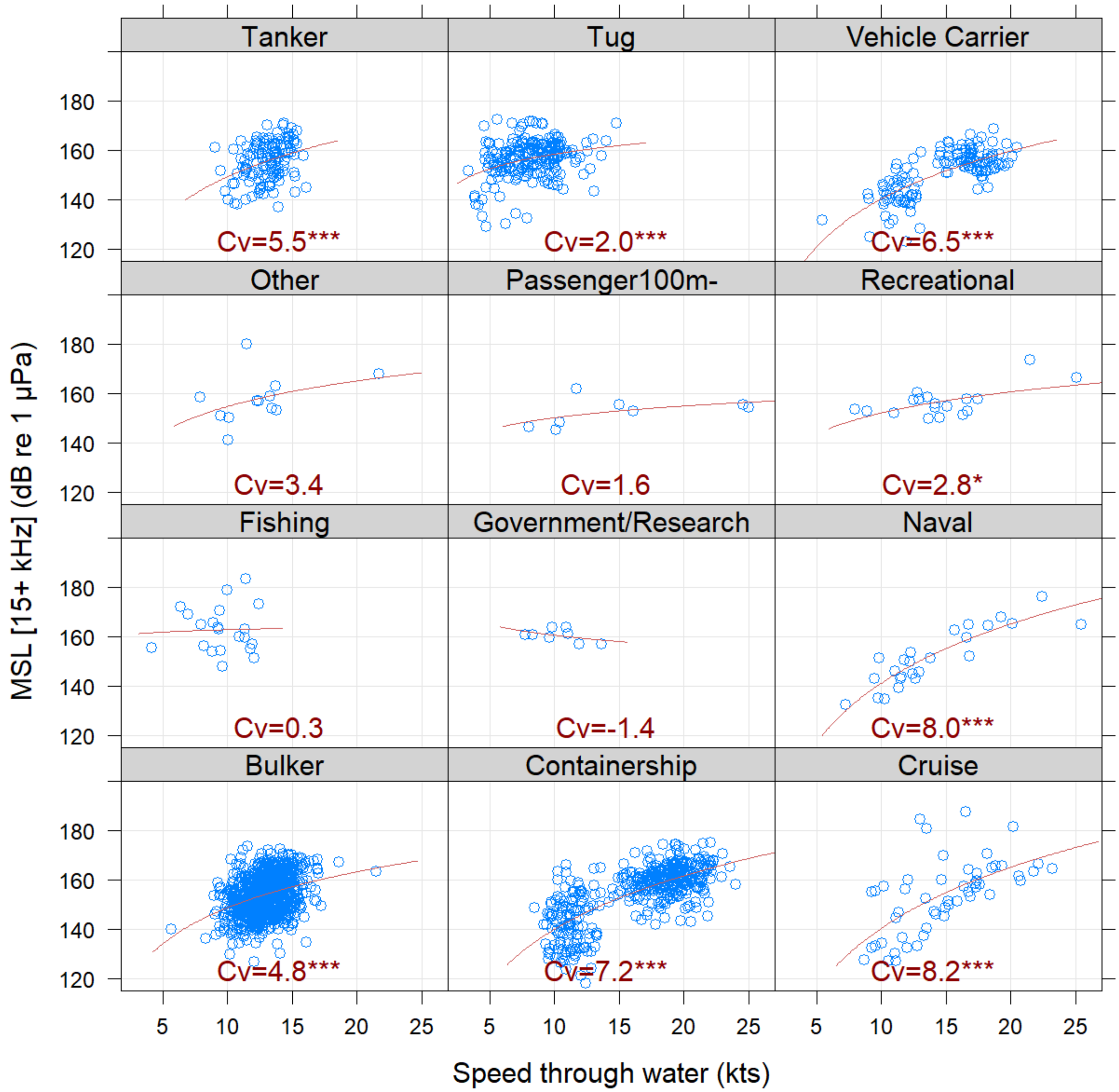


Figure 24. MSL [15+ kHz] versus vessel speed for all categories, based on ULS measurements from Haro Strait and Georgia Strait (accepted measurements only). The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_V). The asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

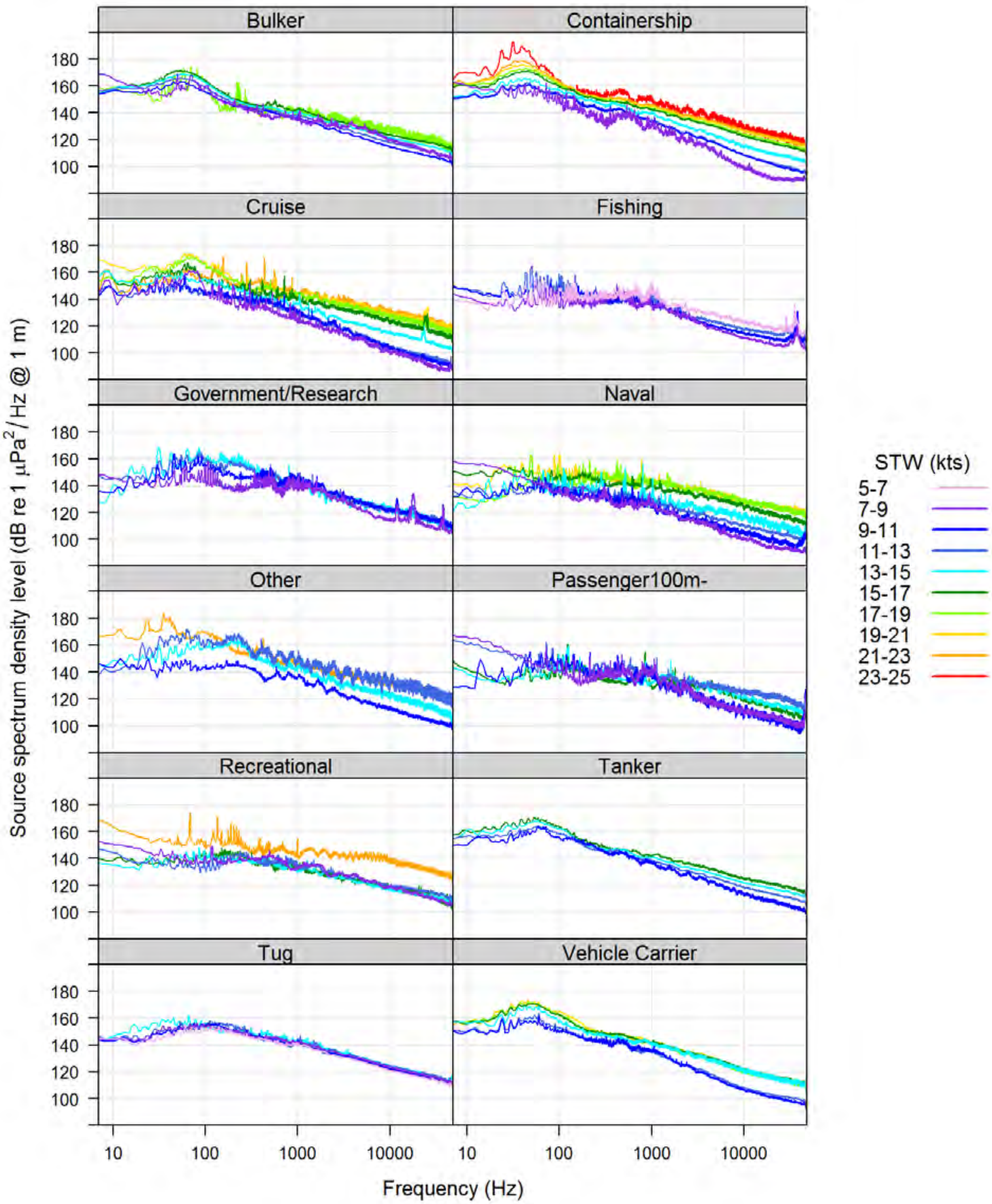


Figure 25. Mean source spectrum density level vs. frequency for all categories, averaged in 2 knot speed bins, based on ULS measurements from Haro Strait (accepted measurements, only). Source spectrum density level is equal to received pressure spectrum density level, scaled to 1 m range (i.e., according to $20\log_{10}(r)$, where r is slant range). Source spectrum levels presented in this figure have not been corrected for background noise at the time of measurement (i.e., unlike the 1/3-octave-band source levels).

4. Discussion and Conclusion

Analysis of acoustic data collected during the Haro Strait slowdown trial showed that slowing speed is an effective method for reducing underwater noise emissions from commercial vessels. We found statistically significant reductions in source levels for five categories of piloted vessels recorded on two underwater listening 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.

Approximately 60% of piloted vessels in Haro Strait participated in the trial by following the voluntary slowdown protocol. Examining non-participating vessels was nonetheless valuable, because comparing the trial and control periods for non-participants provided a means to check for confounding factors that might have influenced the results. For example, whether slower vessels were more likely to have participated in the trial or whether vessel speeds were changing over time in Haro Strait. For piloted vessels, comparisons of non-participants during the control and trial periods showed that speeds and source levels were unchanged for three of five analyzed vessel categories (containerships, tankers, and vehicle carriers). Non-participant bulkers appeared to have been travelling slightly slower (0.4 kn) during the trial period than during the control period, but it is unknown whether this was due to changes in pilot practices, transcription errors in the pilot logs, or some other reason. There were insufficient measurements of non-participant cruise vessels to compare against the control period.

Analysis of 1/3-octave-band source levels for piloted vessels showed that noise reductions associated with slowdown participation were frequency-dependent, with the largest reductions measured at the low and high end 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 affected the various noise generating mechanisms that contribute to the radiated noise spectrum of marine vessels.

Of the twelve vessel categories measured during the control and trial periods, limited information on trial participation was available for seven categories of non-piloted vessels. Noise emissions and speeds in the naval category appear to have been reduced during the trial, which is consistent with the reported participation of RCN vessels. The mean MSL for RCN vessels was 6.3 dB lower during the trial than during the control period, but this was not a high-confidence estimate because the typically-low source levels of naval vessels were often masked by background noise, which resulted in a high percentage of rejected measurements in this category. For the six remaining categories of non-piloted vessels (fishing, government/research, recreational, tug, passenger vessels under 100 m), there was no strong evidence that vessels changed their speeds or reduced their noise emissions during the trial, compared to the control period.

A trend analysis of source levels versus change in speed, based on 107 repeated measurements between Haro Strait and Georgia Strait, showed that slowing speed by 40% reduced broadband MSL of individual vessels by approximately 11.3 ± 1.2 dB. The trend was even stronger at southern resident killer whale echolocation frequencies (>15 kHz), where slowing speed by 40% reduced MSL above 15 kHz by 14.5 ± 1.7 dB. The number of repeated measurements was too small to derive separate source level versus speed trends for different vessel categories (to within the limits of the experimental uncertainty).

The classical power law model of Ross (1976) was used to calculate trends of source levels versus speed for different vessel categories, based on measurements collected during the trail period. We calculated Ross speed scaling coefficients using two different methods: (1) according to mean differences in source levels between the trial groups in Haro Strait, and (2) according to trends of source levels versus speed for all measurements. The second method was found to underestimate mean source level reductions for piloted vessels (particularly for bulkers and tankers), because it did not control for other factors that may have influenced vessel noise emissions. Thus, the first method was preferred for estimating speed scaling coefficients for the Ross model, although it could not be applied to the non-piloted vessel measurements. Speed scaling coefficients for broadband noise emissions (MSL), calculated using the first method, ranged from C_v = 5.1 for containerships to C_v = 8.1 for bulkers, which encompassed the nominal value of C_v = 6 originally proposed by Ross (1976). Furthermore, the calculated speed scaling coefficients were found to be frequency-dependent, with C_v = 4.1–5.4 for the SRKW communication masking band (MSL 0.5–15 kHz) and C_v = 7.6–12.1 for the SRKW echolocation masking band (MSL >15 kHz). For non-piloted vessels, the derived speed trends based on the second method were weak or inconclusive because observed trends of source levels for measurements at different speeds could not be attributed to changes in vessel speed alone.

5. Acknowledgments

A large team of highly-skilled technical experts contributed to the success of this study. JASCO's hardware engineering team designed, assembled, and shipped the underwater listening stations, which performed flawlessly during the trial. JASCO's software engineering team provided expert support for the PortListen software, which was integral to the data analysis. Héloïse Frouin-Mouy, Caitlin O'Neill, Graham Warner, and Jennifer Wladichuk (JASCO) safely and successfully carried out the mooring deployments and retrievals of the underwater listening stations in Haro Strait. Mitch Herron and the crew of R/V Richardson Pt. (Seaward Engineering) provided safe and professional vessel support during the fieldwork. Edward Chapin and his colleagues at the Herzberg Institute of Astrophysics (NRC) generously permitted JASCO's AIS receiver station to be installed at Observatory Hill. Xavier Mouy (JASCO) decoded the AIS data and provided additional software support for PortListen. Jason Wood (SMRU) provided additional AIS data from Lime Kiln to fill in gaps in coverage from the Observatory Hill receiver. Katherine Williams and Karen Hiltz (JASCO) performed editorial review of this report. The ECHO Program's Advisory Working Group worked with the ECHO Team to establish the concept and parameters of the slowdown trial, with further refinements by the ECHO Program's Vessel Operators Committee. The ECHO team worked together with the Pacific Pilotage Authority and BC Coast Pilots to establish a system that allowed pilot data to be collected during the trial. Krista Trounce (VFPA) provided substantial technical feedback on this report. This study would not have been possible without the tireless efforts of Krista Trounce, Orla Robinson, and the rest of the VFPA ECHO team.

Glossary

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

automated identification system (AIS)
A radio-based tracking system whereby vessels regularly broadcast their identity, location, speed, heading, dimensions, class, and other information to nearby receivers.

absorption
The reduction of acoustic pressure amplitude due to acoustic particle motion energy converting to heat in the propagation medium.

Acoustic Current Doppler Profiler (ADCP)
An active sonar system for measuring ocean currents, much like the weather Doppler systems used to map atmospheric winds and rain. It consists of multiple acoustic transducers projecting upwards into the water column. It can measure the currents at many depths, thus providing a profile of the ocean currents.

background noise
Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI S1.1-1994 R2004). Ambient noise detected, measured, or recorded with a signal is part of the background noise.

bandwidth
The range of frequencies over which a sound occurs. Broadband refers to a source that produces sound over a broad range of frequencies (e.g., seismic airguns, vessels) whereas narrowband sources produce sounds over a narrow frequency range (e.g., sonar) (ANSI/ASA S1.13-2005 R2010).

box-and-whisker plot
A plot that illustrates the centre, spread, and overall range of data from a visual 5-number summary. The ends of the box are the upper and lower quartiles (25th and 75th percentiles). The horizontal line inside the box is the median (50th percentile). The whiskers and points extend outside the box to the highest and lowest observations, where the points correspond to outlier observations (i.e., observations that fall more than 1.5 × IQR beyond the upper and lower quartiles, where IQR is the interquartile range).

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

cavitation
A rapid formation and collapse of vapor cavities (i.e., bubbles or voids) in water, most often caused by a rapid change in pressure. Fast-spinning vessel propellers typically cause cavitation, which creates a lot of noise.

cetacean
Any animal in the order Cetacea. These are aquatic, mostly marine mammals and include whales, dolphins, and porpoises.

Coordinated Universal Time (UTC)
A high precision atomic clock time standard that replaces the historic Greenwich Mean Time. It is 7 hours ahead of British Columbia local time during Pacific Daylight Saving Time (PDT), and 8 hours ahead during periods of Pacific Standard Time (PST).

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

ECHO
Enhancing Cetacean Habitat and Observation Program.

fast Fourier transform (FFT)
A computationally efficiently algorithm for computing the discrete Fourier transform.

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

Global Positioning System (GPS)
A satellite based navigation system providing accurate worldwide location and time information.

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

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

interquartile range (IQR)
A measure of statistical dispersion, being equal to the difference between 75th and 25th percentiles, or between upper and lower quartiles. In other words, the IQR is the first quartile subtracted from the third quartile. The IQR is a measure of variability, based on dividing a data set into quartiles.

masking
Obscuring of sounds of interest by sounds at similar frequencies.

median
The 50th percentile of a statistical distribution.

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

multiple linear regression
A statistical method that seeks to explain the response of a dependent variable using multiple explanatory variables.

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

pairwise *t*-test
A statistical procedure used to determine whether the means of different groups of observations are different, with corrections for multiple testing.

parabolic equation method
A computationally-efficient solution to the acoustic wave equation that is used to model transmission loss. The parabolic equation approximation omits effects of back-scattered sound, simplifying the computation of transmission loss. The effect of back-scattered sound is negligible for most ocean-acoustic propagation problems.

power spectrum density
The acoustic signal power per unit frequency as measured at a single frequency. Unit: μPa^2/Hz, or μPa^2·s.

power spectral density level
The decibel level ($10\log_{10}$) of the power spectrum density, usually presented in 1 Hz bins. Unit: dB re 1 μPa^2/Hz.

probability density function (PDF)
A function whose value at any given sample (or point) in the sample space (the set of possible values taken by the random variable) can be interpreted as providing a relative likelihood that the value of the random variable would equal that sample.

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

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

received level
The sound level measured at a receiver.

rms
root-mean-square.

shear wave
A mechanical vibration wave in which the direction of particle motion is perpendicular to the direction of propagation. Also called secondary wave or *S*-wave. Shear waves propagate only in solid media, such as sediments or rock. Shear waves in the seabed can be converted to compressional waves in water at the water-seabed interface.

ship draft
The vertical distance between the waterline and the bottom of the hull (keel), including the thickness of the hull.

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

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

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

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

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

source level (SL)
The sound level measured in the far-field and scaled back to a standard reference distance of 1 metre from the acoustic centre of the source. Unit: dB re 1 μPa @ 1 m (sound pressure level) or dB re 1 μPa^2·s (sound exposure level).

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

speed over ground (SOG)
The speed of a vessel relative to the surface of the earth.

speed through water (STW)
The speed of a vessel relative to the water.

SRKW
Southern Resident Killer Whale.

transmission loss (TL)
The decibel reduction in sound level between two stated points that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also called propagation loss.

ULS
Underwater Listening Station.

Victoria Experimental Network Under the Sea (VENUS)
An observatory in the Salish Sea, comprised of installations in Saanich Inlet and Strait of Georgia. Instruments range in depth from near-surface to 300 m. Operated by Ocean Networks Canada.

VFPA
Vancouver Fraser Port Authority.

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Appendix A. Discarded Measurements

Table A-1. Vessel trips that were discarded from the trial groups, due to likely transcription errors recorded in the pilot participation logs.

Job ID	Category	Order time	First pilot debark	First pilot start bridge watch	First pilot stop bridge watch	Pilot answer	Pilot answer notes	ULS station	STW (kts)	Broadband RNL (dB re 1 µPa)	Broadband MSL (dB re 1 µPa)
176756	Containership	9/18/2017 15:00	9/18/2017 20:42	9/18/2017 15:00	9/18/2017 20:38	No	a) Master refused	Southbound	9.8	179.8	180.7
176962	Containership	9/24/2017 1:00	9/24/2017 8:00	9/24/2017 0:55	9/24/2017 8:00	No	b) Schedule issue	Northbound	9.9	179.1	178.2
177201	Containership	9/29/2017 10:00	9/29/2017 14:40	9/29/2017 10:00	9/29/2017 14:30	No	NA	Northbound	10.3	178.2	178.2
176403	Containership	9/18/2017 2:30	9/18/2017 8:30	9/18/2017 2:30	9/18/2017 8:24	No	NA	Northbound	10.4	178.6	177.0
176843	Containership	9/19/2017 9:30	9/19/2017 16:00	9/19/2017 9:37	9/19/2017 15:50	No	NA	Northbound	10.7	181.2	178.5
176477	Containership	9/23/2017 8:00	9/23/2017 13:05	9/23/2017 8:00	9/23/2017 13:00	No	NA	Southbound	11.2	185.0	182.7
176935	Containership	9/21/2017 1:00	9/21/2017 7:05	9/21/2017 2:35	9/21/2017 7:00	No	a) Master refused	Southbound	11.4	182.9	182.2
174959	Containership	8/13/2017 1:00	8/13/2017 3:50	8/13/2017 0:40	8/13/2017 3:45	Yes	NA	Southbound	19.8	192.1	195.0
176771	Containership	9/18/2017 6:00	9/18/2017 10:15	9/18/2017 6:00	9/18/2017 10:12	Yes	NA	Southbound	19.1	187.9	186.5
175672	Containership	8/27/2017 8:00	8/27/2017 11:35	8/27/2017 7:45	8/27/2017 11:32	Yes	NA	Southbound	18.6	189.9	186.8
176295	Containership	9/15/2017 6:30	9/15/2017 11:48	9/15/2017 8:20	9/15/2017 11:45	Yes	NA	Southbound	17.4	189.1	191.8
175227	Containership	8/24/2017 8:00	8/24/2017 11:40	8/24/2017 7:30	8/24/2017 11:37	Yes	NA	Southbound	16.7	187.3	185.9
174946	Containership	8/14/2017 6:00	8/14/2017 11:40	8/14/2017 6:00	8/14/2017 11:35	Yes	Did not record RPM in Haro of Georgia	Southbound	16.3	186.4	185.3
174812	Containership	8/17/2017 1:00	8/17/2017 5:16	8/17/2017 1:00	8/17/2017 5:12	Yes	NA	Southbound	16.2	194.6	194.7
174587	Containership	8/8/2017 6:00	8/8/2017 11:18	8/8/2017 5:50	8/8/2017 11:15	Yes	NA	Southbound	15.8	180.8	179.1
175323	Tanker	8/20/2017 5:15	8/20/2017 10:57	8/20/2017 5:05	8/20/2017 10:55	No	d) Tidal/current issue 60% CP wheel	Southbound	9.0	187.8	186.3
176045	Tanker	9/5/2017 4:00	9/5/2017 12:50	9/5/2017 4:05	9/5/2017 12:45	No	b) Schedule issue	Northbound	11.0	188.3	187.7

Job ID	Category	Order time	First pilot debark	First pilot start bridge watch	First pilot stop bridge watch	Pilot answer	Pilot answer notes	ULS station	STW (kts)	Broadband RNL (dB re 1 µPa)	Broadband MSL (dB re 1 µPa)
176893	Tanker	9/19/2017 13:45	9/19/2017 20:54	9/19/2017 13:36	9/19/2017 20:48	No	b) Schedule issue	Southbound	11.7	178.5	178.0
176990	Tanker	9/22/2017 19:30	9/23/2017 3:00	9/22/2017 19:05	9/23/2017 2:48	Yes	*NA*	Northbound	14.5	184.7	182.9
177367	Vehicle carrier	10/1/2017 23:59	10/2/2017 4:20	10/2/2017 0:00	10/2/2017 4:15	No	d) Tidal/current issue	Northbound	10.2	176.1	175.1
176968	Vehicle carrier	9/21/2017 22:00	9/22/2017 4:20	9/21/2017 23:50	9/22/2017 4:15	Yes	*NA*	Southbound	15.0	185.2	185.9
174576	Vehicle carrier	8/10/2017 14:00	8/10/2017 19:25	8/10/2017 15:25	8/10/2017 19:20	Yes	*NA*	Southbound	15.0	186.1	186.8
168456	Cruise	9/25/2017 22:15	9/26/2017 8:05	9/25/2017 22:15	9/26/2017 7:55	No	b) Schedule issue	Southbound	11.2	171.5	171.2

Appendix B. Summary Statistics

B.1. Speed Through Water

Table B-1. Statistics of speed through water (knots), by vessel category and trial group.

Vessel category	Bulker	Containership	Cruise	Tanker	Vehicle Carrier
Participant					
5%	9.8	9.5	9.1	9.9	10.1
25%	10.7	10.5	9.6	10.8	10.7
Median	11.4	11.2	10.7	11.4	11.4
Mean	11.4	11.2	10.6	11.4	11.4
75%	12.0	11.9	11.4	12.0	12.0
95%	12.8	13.1	12.2	12.8	12.7
Non-participant					
5%	10.9	15.2	13.5	12.4	13.2
25%	12.3	17.4	14.2	12.8	15.3
Median	13.2	19.0	15.1	13.6	16.5
Mean	13.1	18.7	15.1	13.6	16.2
75%	14.0	19.6	16.0	14.3	17.2
95%	15.1	21.6	16.7	15.0	18.1
Control					
5%	11.4	15.8	13.3	11.5	14.5
25%	12.7	17.7	14.3	13.0	16.6
Median	13.4	19.1	16.9	13.9	17.4
Mean	13.5	18.9	16.8	13.7	17.3
75%	14.4	20.2	18.0	14.5	18.3
95%	15.4	21.9	21.2	15.2	19.7

B.2. Vessel Source Levels

Table B-2. Source levels statistics for the participant group, by vessel category (dB re 1 µPa @ 1 m).

Vessel category	Bulker	Containership	Cruise	Tanker	Vehicle Carrier
Broadband RNL					
5%	176.3	175.8	171.8	176.6	176.6
25%	179.8	178.6	172.6	179.5	178.2
Median	182.1	180.1	174.3	181.6	179.1
Mean	182.6	180.3	175.4	181.7	179.6
75%	184.8	181.6	176.7	184.3	180.5
95%	191.0	185.6	182.5	186.8	183.4
Broadband MSL					
5%	176.1	174.8	171.4	175.9	175.8
25%	178.6	177.4	173.1	179.0	177.8
Median	181.0	179.2	174.7	180.7	179.2
Mean	181.9	179.5	175.8	181.1	180.2
75%	184.6	181.3	176.7	183.4	181.6
95%	190.5	185.1	183.2	186.5	188.4
MSL [0.5–15 kHz]					
5%	161.4	159.9	156.7	162.4	159.1
25%	164.5	162.5	160.1	164.8	164.6
Median	167.6	165.2	162.3	167.5	166.1
Mean	167.9	165.7	162.9	167.7	165.8
75%	170.5	167.9	164.5	170.6	167.7
95%	176.6	172.5	171.5	174.1	170.2
MSL [15+ kHz]					
5%	139.6	127.2	127.3	138.9	129.6
25%	146.4	133.4	132.3	144.1	139.0
Median	150.3	141.7	133.8	150.4	141.7
Mean	150.9	142.2	139.0	149.7	141.8
75%	155.8	150.2	146.1	153.9	146.7
95%	162.8	158.9	156.6	160.0	151.0

Table B-3. Source levels statistics for the non-participant group, by vessel category (dB re 1 µPa @ 1 m).

Vessel category	Bulker	Containership	Cruise	Tanker	Vehicle Carrier
Broadband RNL					
5%	180.9	184.2	178.1	182.0	185.5
25%	184.7	187.6	179.1	185.6	187.0
Median	187.5	190.5	180.4	186.8	189.0
Mean	187.9	190.8	180.4	186.4	188.7
75%	190.7	193.9	181.7	187.3	191.2
95%	196.0	198.9	182.7	190.2	192.1
Broadband MSL					
5%	180.0	183.6	177.6	182.7	184.0
25%	184.3	185.8	178.2	184.8	187.4
Median	186.4	189.9	179.0	186.3	189.1
Mean	186.8	189.9	179.0	186.4	188.7
75%	189.5	193.3	179.8	187.9	189.8
95%	193.4	197.5	180.5	191.4	193.1
MSL [0.5–15 kHz]					
5%	163.4	169.0	167.1	164.8	169.5
25%	168.0	172.3	167.9	171.3	171.8
Median	170.7	175.0	168.8	174.4	173.0
Mean	170.4	174.8	168.8	173.2	173.2
75%	173.0	176.9	169.8	176.5	174.4
95%	176.8	181.1	170.5	177.3	175.9
MSL [15+ kHz]					
5%	143.7	150.8	138.0	144.0	151.2
25%	151.6	157.6	141.2	153.1	154.3
Median	156.6	161.1	145.2	159.0	157.8
Mean	156.0	160.7	145.2	157.5	157.7
75%	161.3	164.4	149.2	162.6	160.3
95%	166.4	169.5	152.4	166.1	166.2

Table B-4. Source levels statistics for the control group, by vessel category (dB re 1 µPa @ 1 m).

Vessel category	Bulker	Containership	Cruise	Tanker	Vehicle Carrier
Broadband RNL					
5%	181.9	185.3	176.6	182.2	183.8
25%	185.2	188.6	180.2	185.4	186.2
Median	187.9	191.5	184.4	187.8	188.9
Mean	188.1	191.5	186.1	187.5	188.8
75%	190.8	194.0	193.7	189.5	191.4
95%	195.5	199.9	195.5	192.7	193.5
Broadband MSL					
5%	181.9	183.8	175.5	182.3	183.6
25%	185.3	187.8	180.2	184.7	186.5
Median	187.7	190.7	182.9	187.1	190.2
Mean	187.8	191.0	186.3	187.2	189.4
75%	190.2	194.0	194.6	190.0	192.0
95%	193.9	199.1	198.3	192.4	195.2
MSL [0.5–15 kHz]					
5%	163.3	168.3	164.5	163.3	169.0
25%	167.8	172.4	170.6	166.8	172.6
Median	171.0	174.9	172.6	171.8	173.4
Mean	171.0	175.0	173.7	171.3	173.3
75%	173.7	177.5	177.5	175.0	174.3
95%	179.5	181.5	182.4	179.0	176.3
MSL [15+ kHz]					
5%	144.4	148.8	146.6	145.0	148.4
25%	150.6	156.5	153.6	151.2	153.6
Median	156.3	160.5	159.7	158.7	155.4
Mean	156.0	160.0	163.0	157.6	155.7
75%	161.7	164.1	169.4	164.0	158.5
95%	167.1	170.3	185.5	170.0	162.8

B.3. Source Level Reductions

Table B-5. Statistics of reductions in vessel source levels that resulted from slowdown participation (control vs. participant groups), by vessel category (dB).

Vessel category	Bulker	Containership	Cruise	Tanker	Vehicle Carrier
Broadband RNL					
5%	5.7	9.6	4.8	5.6	7.2
25%	5.5	10.0	7.7	5.9	8.0
Median	5.8	11.4	10.1	6.1	9.7
Mean	5.6	11.2	10.7	5.8	9.2
75%	6.1	12.4	17.0	5.2	10.9
95%	4.5	14.3	13.0	5.9	10.1
Broadband MSL					
5%	5.7	9.0	4.0	6.4	7.8
25%	6.6	10.4	7.0	5.7	8.7
Median	6.7	11.5	8.2	6.5	11.0
Mean	5.9	11.5	10.5	6.1	9.3
75%	5.6	12.7	17.9	6.7	10.4
95%	3.4	14.0	15.1	5.8	6.8
MSL [0.5–15 kHz]					
5%	1.9	8.4	7.7	0.9	9.9
25%	3.3	9.9	10.5	2.0	8.0
Median	3.4	9.6	10.3	4.3	7.3
Mean	3.1	9.3	10.8	3.6	7.4
75%	3.2	9.7	13.0	4.4	6.6
95%	2.9	9.0	10.9	4.9	6.1
MSL [15+ kHz]					
5%	4.8	21.6	19.3	6.2	18.8
25%	4.2	23.1	21.2	7.1	14.6
Median	6.0	18.8	25.9	8.3	13.7
Mean	5.1	17.8	24.0	7.9	13.9
75%	5.9	13.9	23.3	10.1	11.8
95%	4.4	11.4	28.9	10.0	11.8

Appendix C. Trends of 1/3-Octave Band Source Levels with Vessel Speed

The plots below show measured 1/3-octave-band source levels (MSL) versus speed through water, by vessel category.

C.1. Bulker

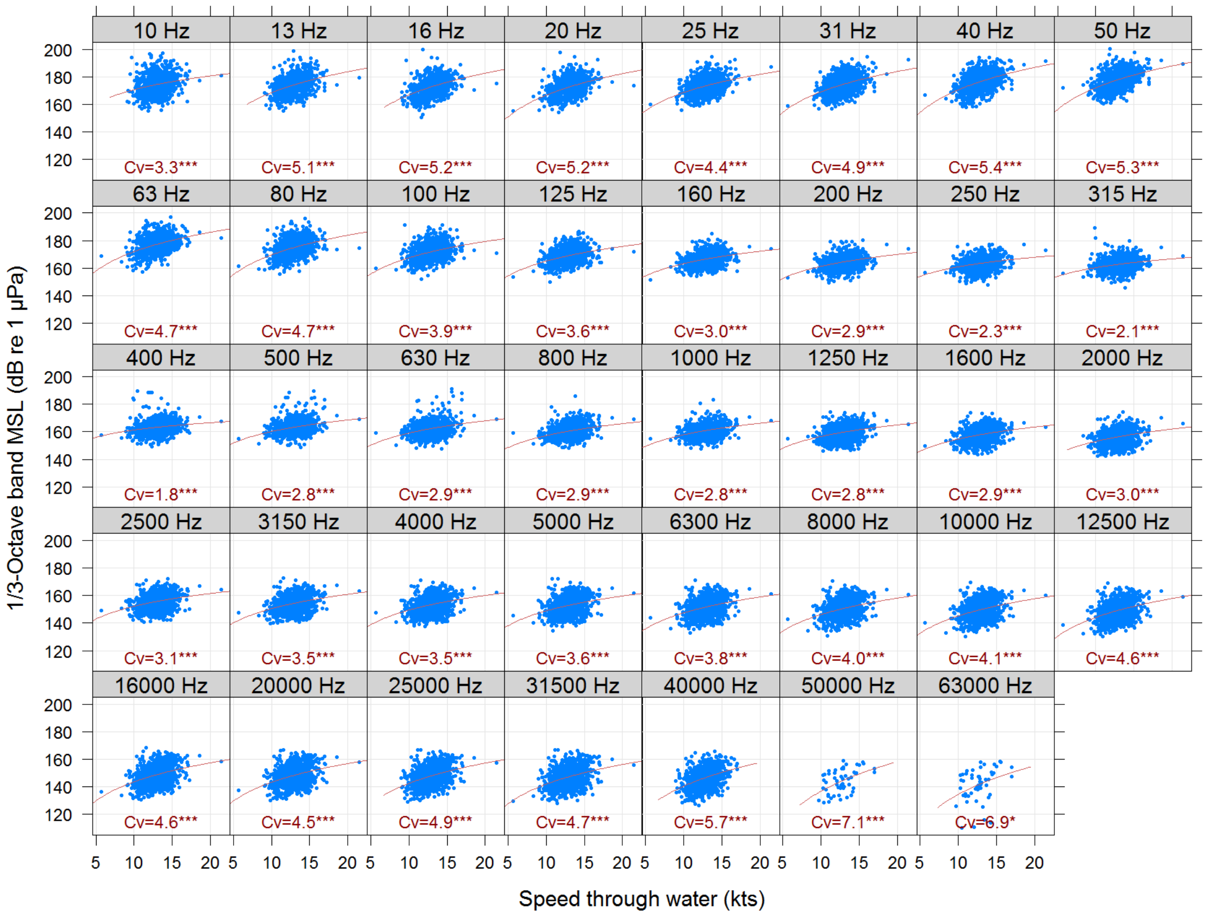

Figure C-1. Bulker: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

C.2. Containership

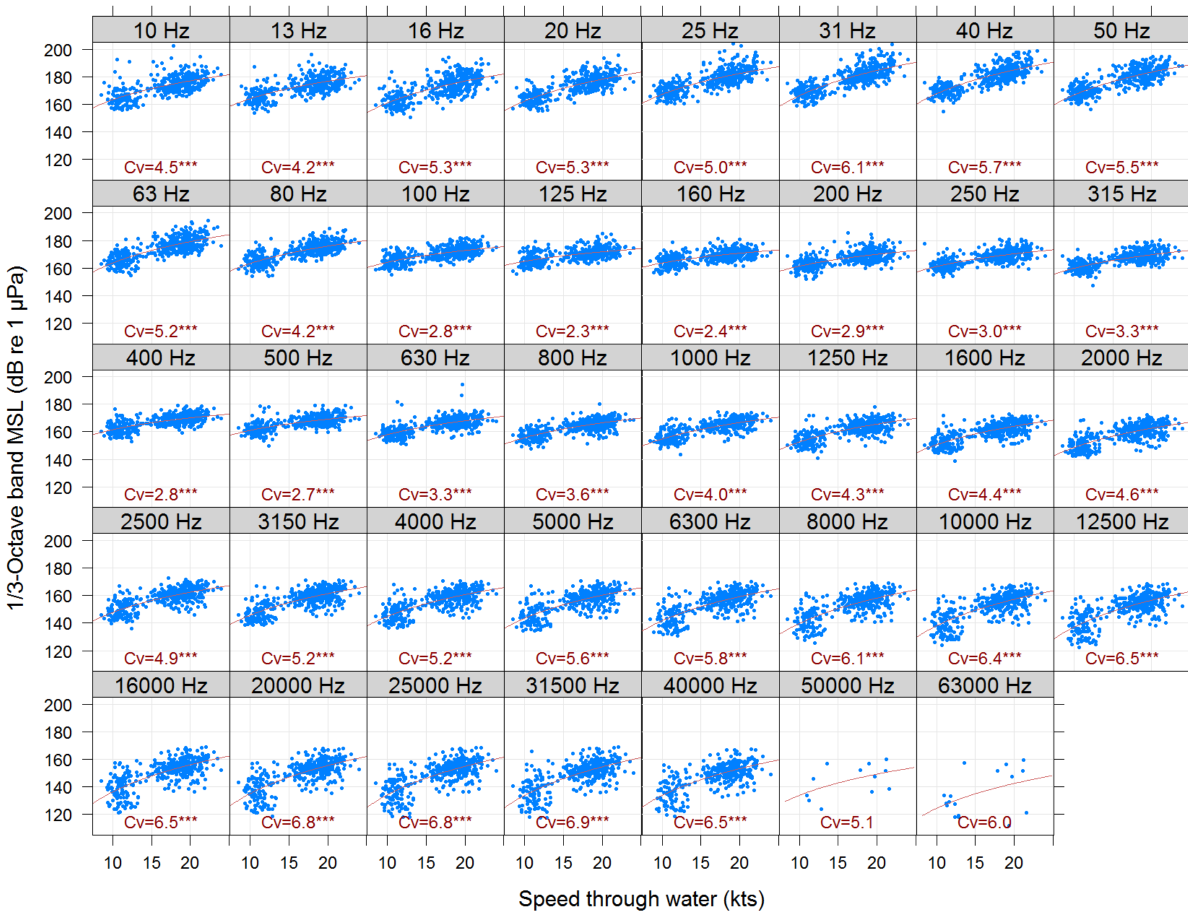

Figure C-2. Containership: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (*Cv*) and the asterisks indicate the statistical significance of the trend (* = p < 0.05, ** = p < 0.01, *** = p < 0.001).

C.3. Cruise

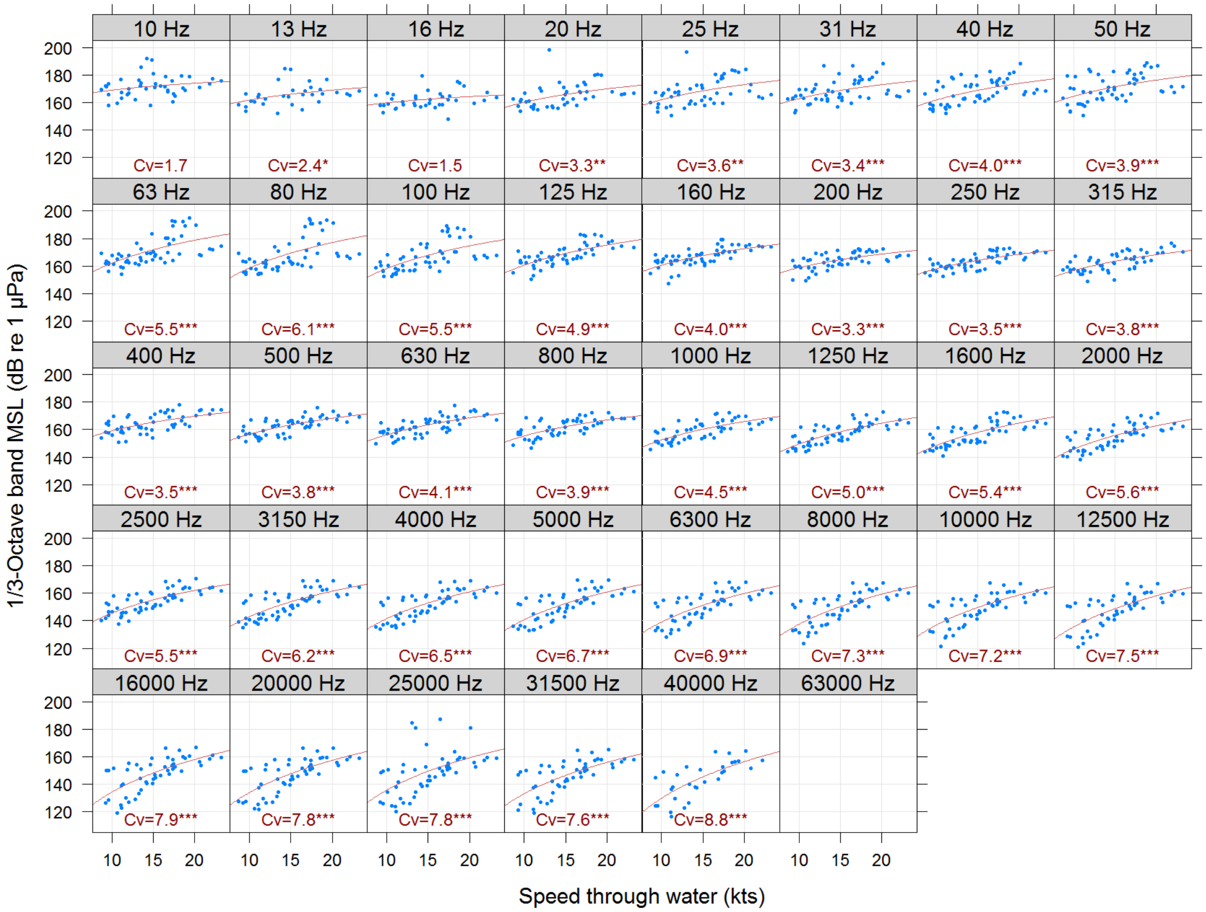

Figure C-3. Cruise: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (*Cv*) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

C.4. Fishing

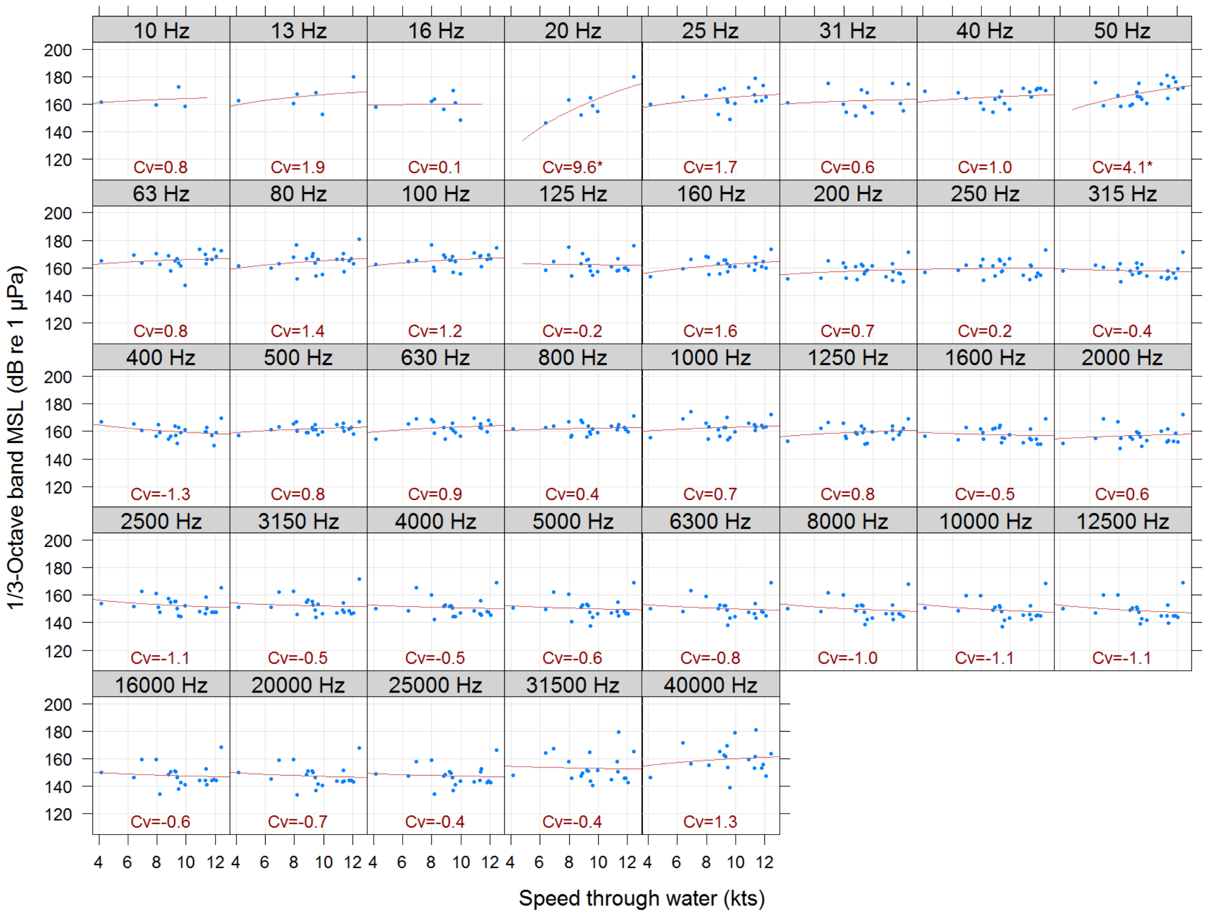

Figure C-4. Fishing: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

C.5. Government/Research

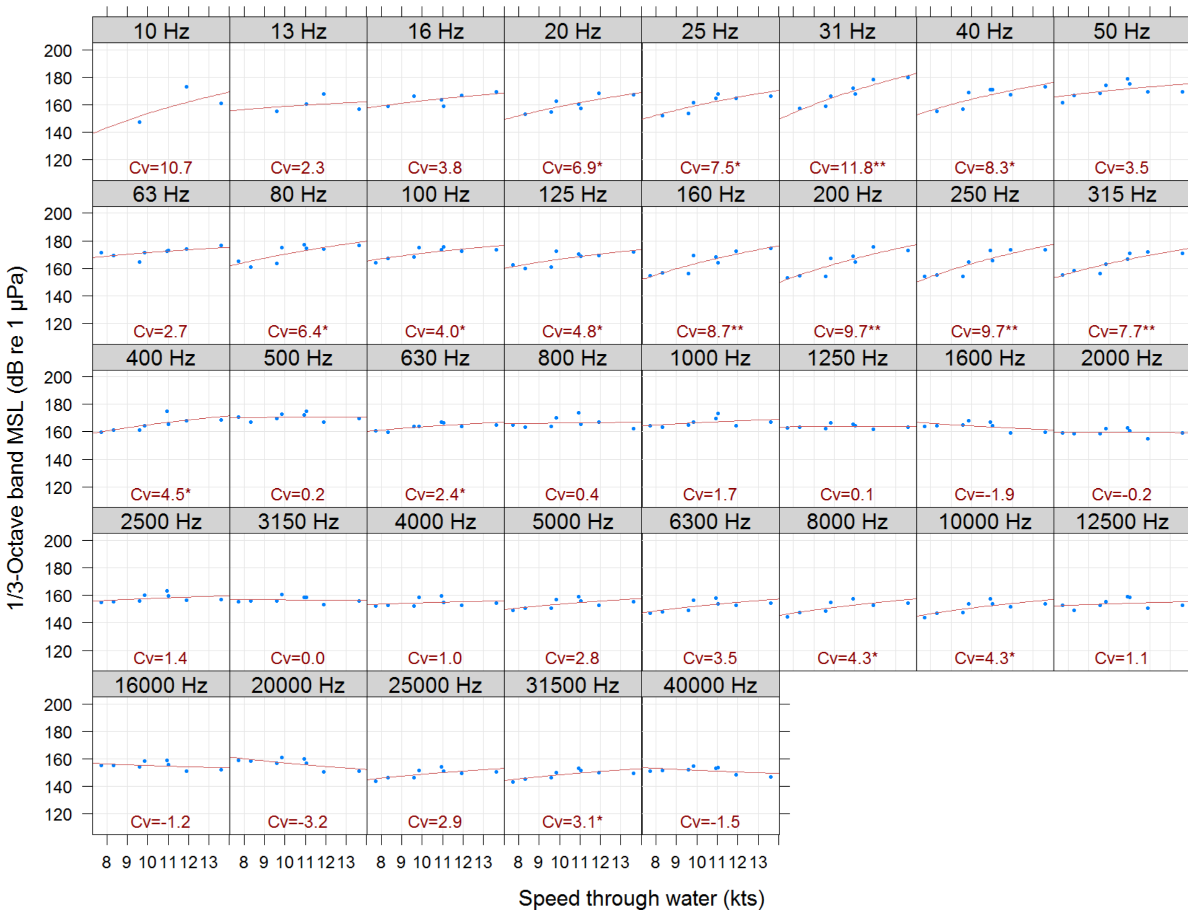

Figure C-5. Government/Research : 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v) and the asterisks indicate the statistical significance of the trend (* = p < 0.05, ** = p < 0.01, *** = p < 0.001).

C.6. Naval

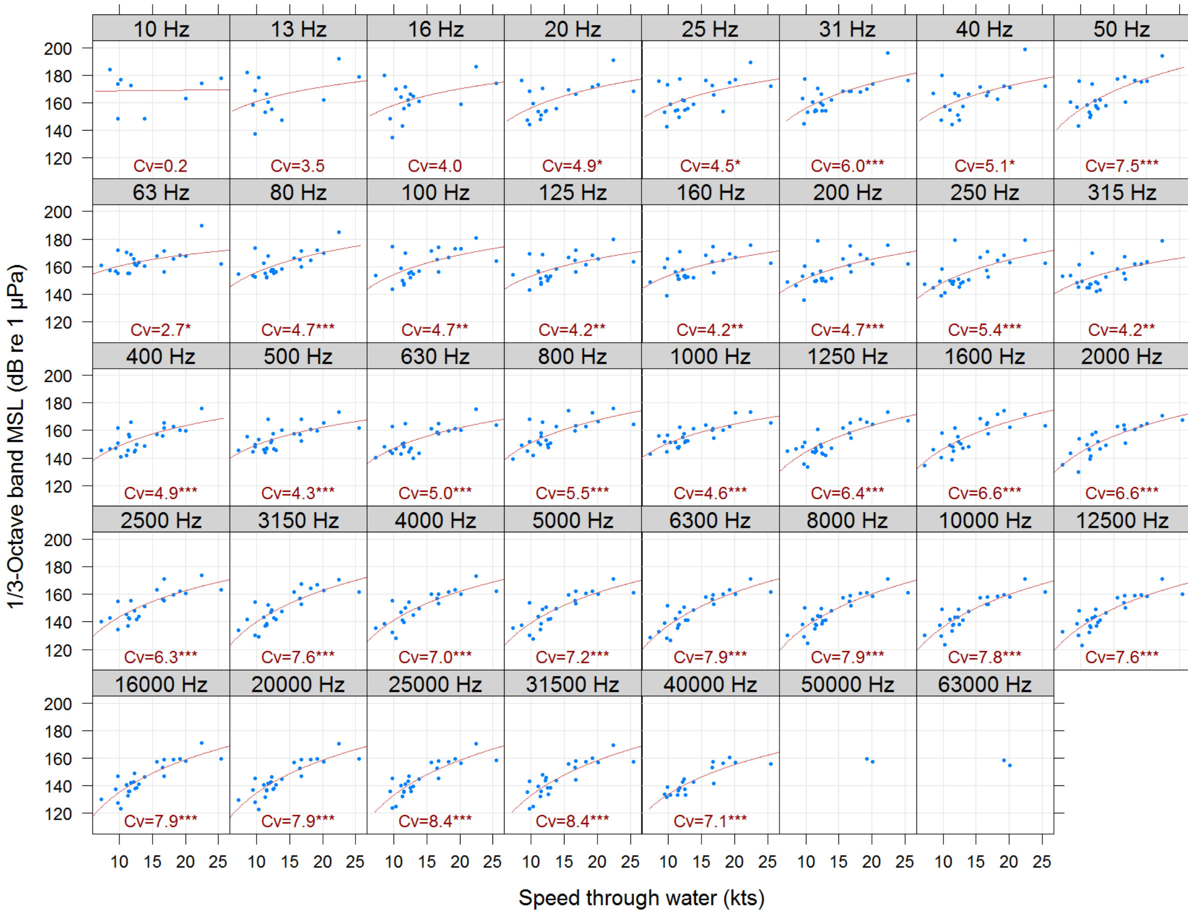

Figure C-6. Naval: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

C.7. Other

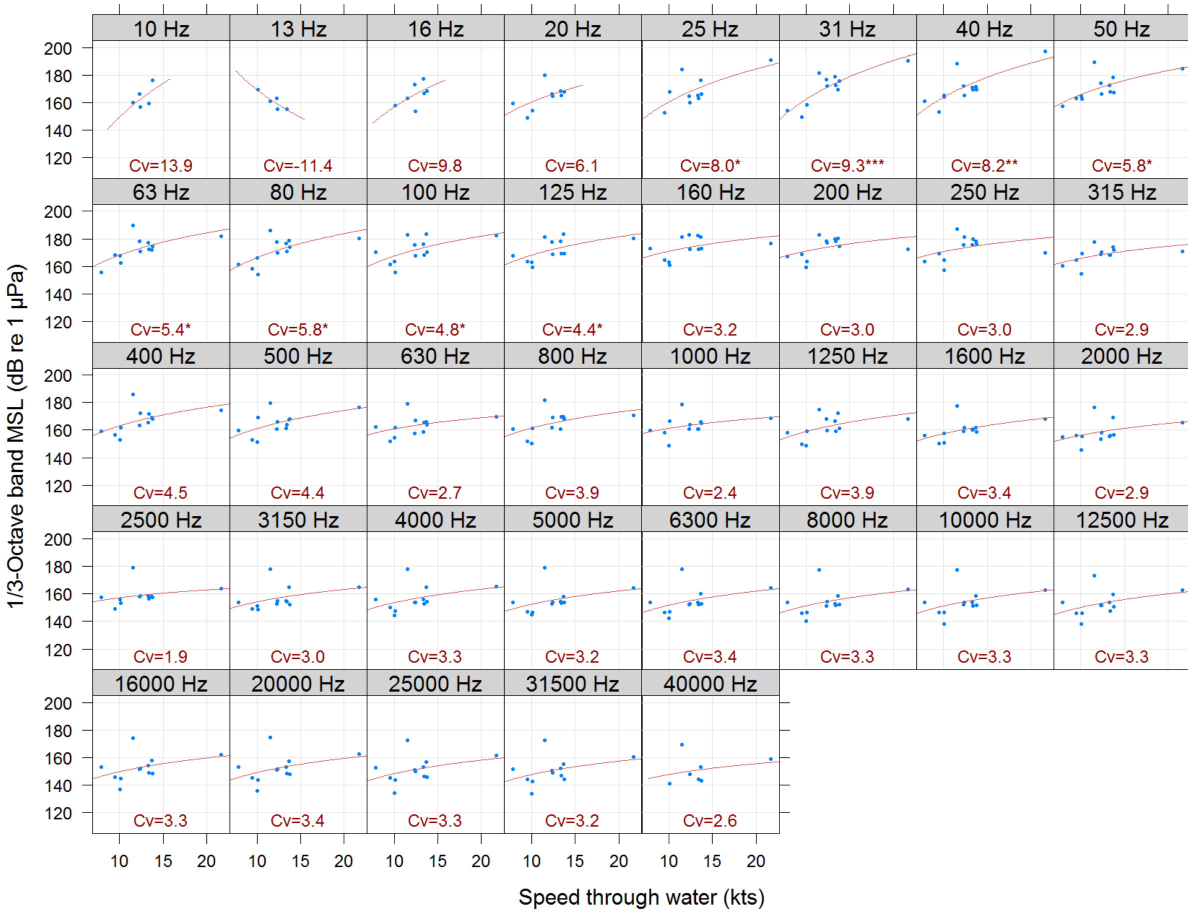

Figure C-7. Other: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

C.8. Passenger100m-

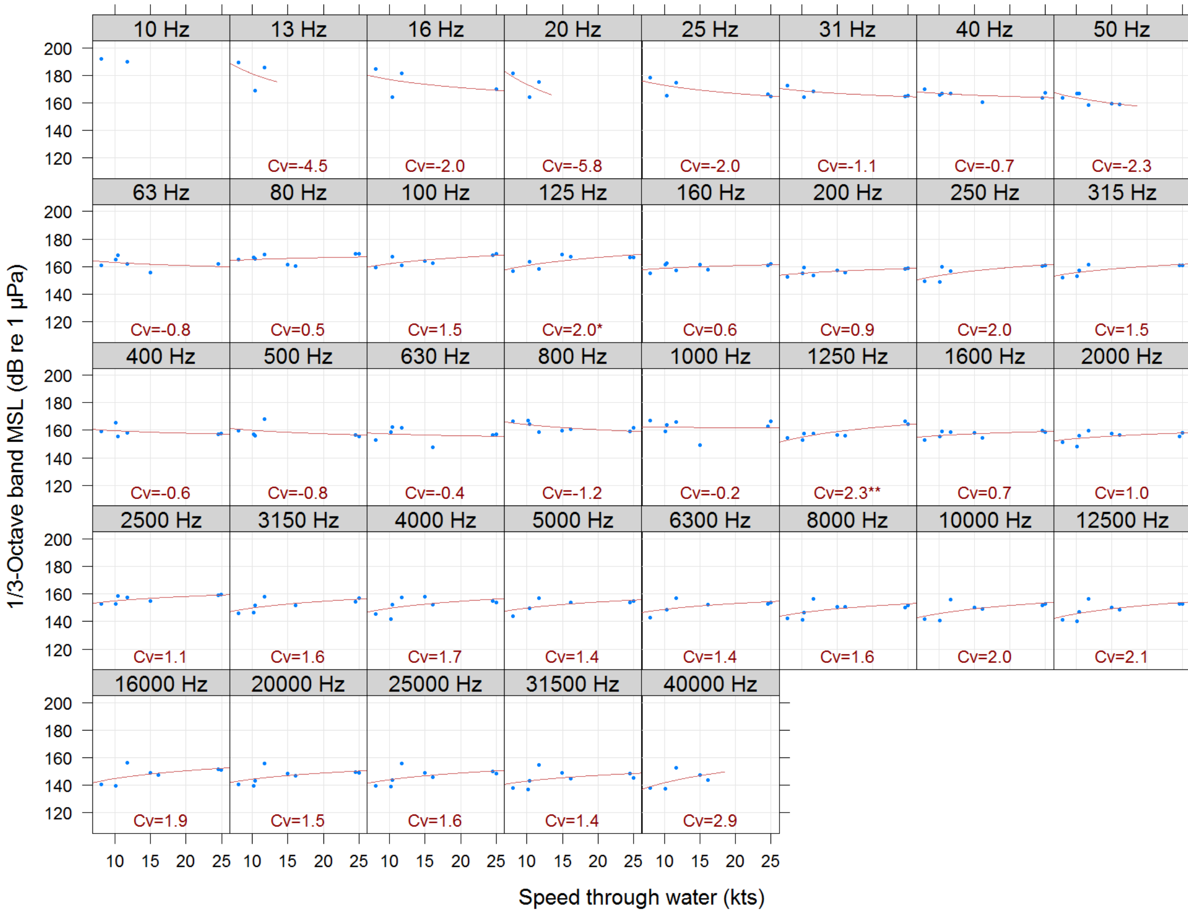

Figure C-8. Passenger100m-: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_V) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

C.9. Recreational

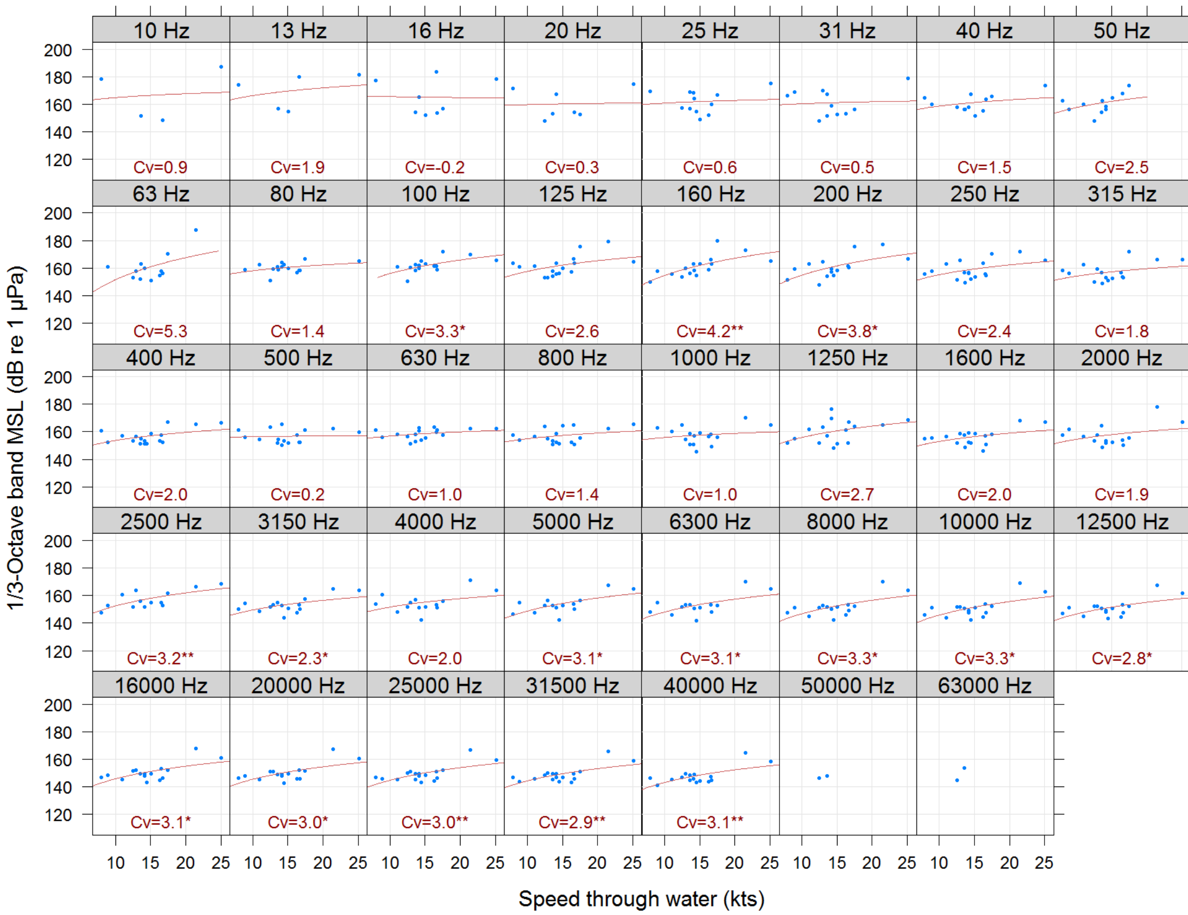

Figure C-9. Recreational: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_V) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

C.10. Tanker

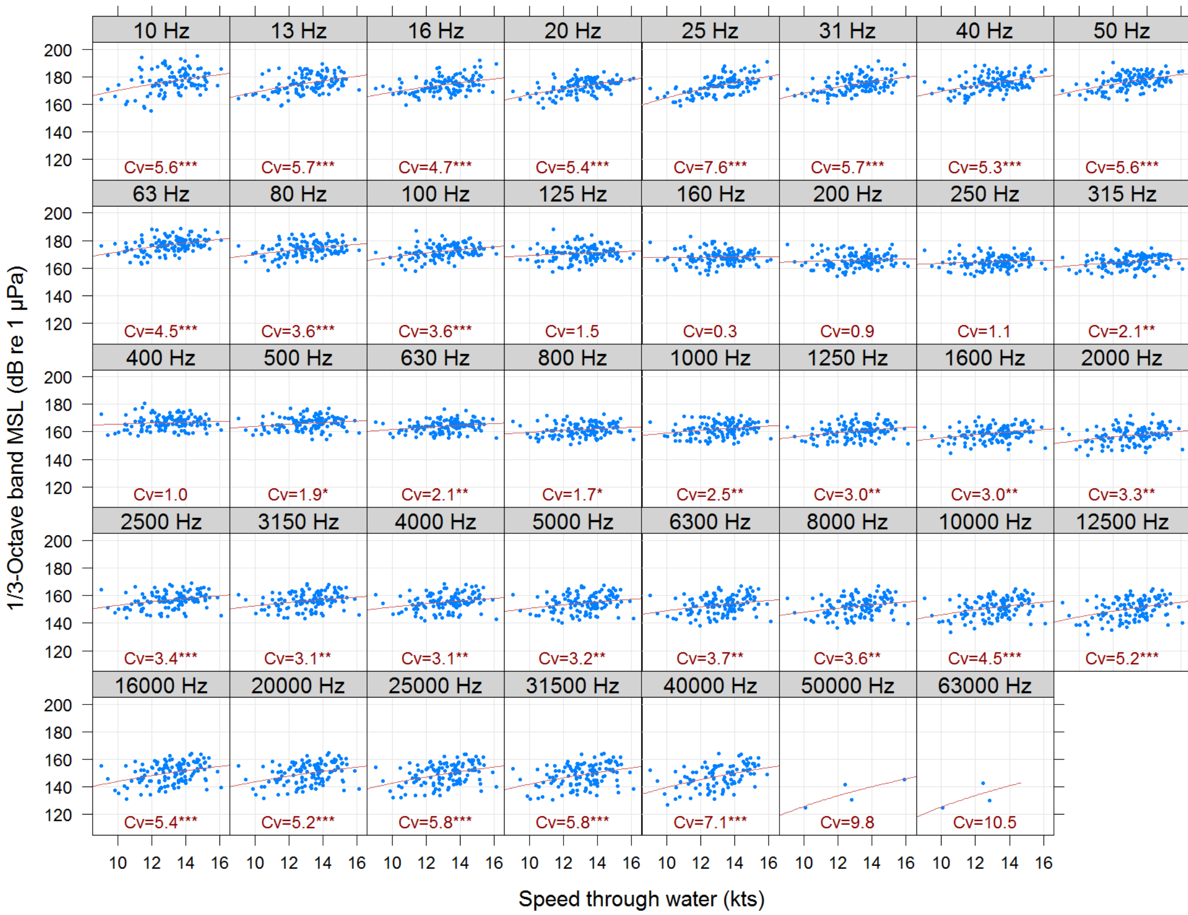

Figure C-10. Tanker: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

C.11. Tug

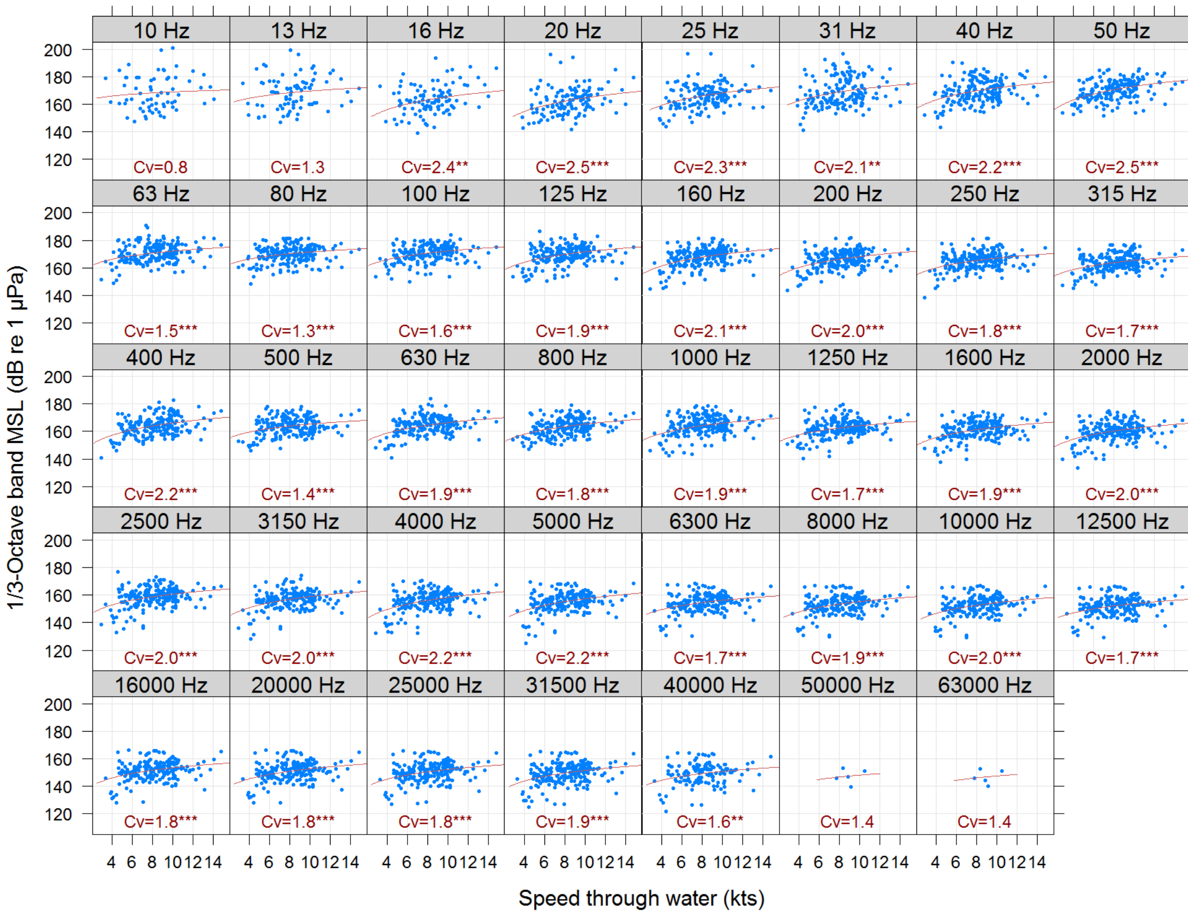

Figure C-11. Tug: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v) and the asterisks indicate the statistical significance of the trend (* = p < 0.05, ** = p < 0.01, *** = p < 0.001).

C.12. Vehicle Carrier

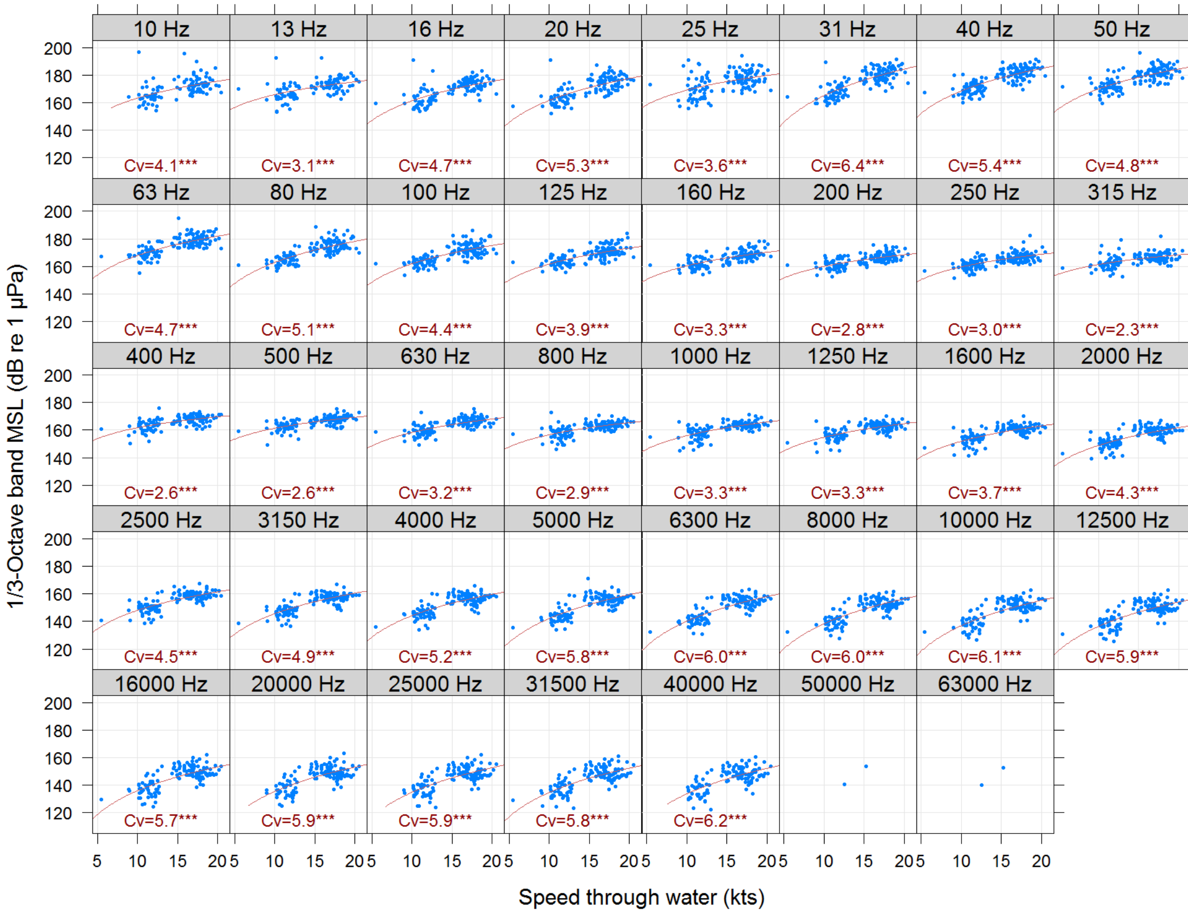

Figure C-12. Vehicle Carrier: 1/3-octave-band MSL versus vessel speed, based on ULS measurements from Haro Strait and Georgia Strait. The red line is the best-fit trendline, based on Eqn 1. The annotation indicates the best-fit coefficient (C_v) and the asterisks indicate the statistical significance of the trend (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

Appendix B

Ambient noise and SRKW detections report - SMRU Consulting North America

ECHO Slowdown Trial: Ambient Noise and SRKW Acoustic Detections – Final Report

SMRU Consulting

[January 2018]

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ECHO Slowdown Trial: Ambient Noise and SRKW Acoustic Detections – Final Report

25 January 2018

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Executive Summary

An ECHO Program led assessment of the potential mitigation measures that would help reduce vessel related underwater noise in Southern Resident killer whale habitat and the potential implications to industry, determined that a vessel slowdown study in Haro Strait would be worth undertaking. This Slowdown Trial took place from August 7 to October 5, 2017 and we report our findings here. As a comparison period we chose a lunar month from August 18 to September 16, 2016 and July 9 to August 7, 2017 as our Baseline period. During Baseline and Slowdown, we **a)** analyzed noise levels and their changes on a lunar scale, **b)** analyzed noise levels and their changes on a fine (1-minute) scale using several approaches, and **c)** ran acoustic detectors of killer whale calls, whistles and echolocation clicks to determine when killer whales were present at Lime Kiln. We found the following.

- When compared to the Baseline period, a significant reduction in vessel speed through water was observed during the Slowdown period. For example, bulker, general cargo and tanker vessels slowed by approximately 2 knots from median speeds on the order of 13-13.6 knots to 11.4-11.8 knots, container vessels slowed from median speeds of 18.6 knots to 11.4 knots, while car carriers slowed from 17.1 to 11.5 knots.
- Lunar month variability was not explained by the number of piloted large commercial vessel or the Slowdown. Further assessment of the consequences of other vessel presence, tidal effects, as well as Fraser River discharge effects on propagation is required. It is clear analyses of noise trends relevant to killer whales needs to focus on finer time scales, appropriate frequency ranges and incorporate covariate data.
- Using cumulative distribution functions when vessels were within a 6 km detection range, and consistently filtering for confounding effects of high wind and currents, as well as small boat noise, we observed a 2.5 dB median reduction (116.9 to 114.4 dB re 1 µPa) in the Slowdown period compared to Baseline - the equivalent of a 44% reduction in acoustic intensity or 16% reduction in loudness.
- Decade band cumulative distribution function SPL analysis indicate ambient noise reduction (L50) in the Slowdown period is highest between 10-100 Hz (3.1 dB) and lowest between 10-100 kHz (0.3 dB). The majority of vessel acoustic energy is in the lower frequency bands (<1,000 Hz). Comparison to the recently developed CORI metrics of SRKW communication (500-15,000 Hz) and echolocation (15-100 kHz) frequency bands show a reduction of 2 dB in the communication band but a 0.4 dB increase in the echolocation band. The lack of high frequency difference found in these analyses is due to high frequency attenuation at the ranges we measured ship noise and potentially system limitations at very high frequencies.
- Comparison of "quiet times" (using both <110 and <102.8 dB re 1 µPa) during Baseline and Slowdown periods indicated no statistical difference in distributions, with a maximum interval highest in the Baseline period, similar medians, but with the Slowdown period having ~3% more time below either threshold.
- Statistical analysis using a Generalized Additive Mixed Model (GAMM) of co-variates affecting received SPL at Lime Kiln to a range of 15 km described 39% of the variability in noise levels, with range to vessel by vessel type, small boat presence and extreme current speed likely most important, followed by Slowdown period and speed through water by vessel type, and wind

speed. At a range of 2.3 km, the GAMM predicted a 1.5 dB reduction for the Bulk vessel type and a 2.3 dB reduction for the Containerized vessel type as a result of the Slowdown.

- Acoustic detections of SRKW calls, whistles and clicks recorded SRKW present on just 9 days (10 transit events, total ~17 hours) during the Slowdown period, far less than that found in 2016. All six visual observations made at Lime Kiln during the Slowdown period were also recorded acoustically and all additional acoustic detections were made during periods when no observations were being undertaken.
- All analysis completed indicated the Slowdown trial was successful in reducing the received broadband sound pressure levels at the Lime Kiln hydrophone.

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1 Introduction

In 2016, the Enhancing Cetacean Habitat and Observation (ECHO) Program's Advisory Working Group conducted a desktop assessment of a variety of potential mitigation measures to help reduce underwater noise in the Salish Sea. Through a screening level assessment considering the potential benefits of reducing vessel-generated underwater noise in Southern Resident killer whale (SRKW) critical habitat, and the potential implications to industry, the group settled on conducting a research trial to slow down vessels through Haro Strait. The Slowdown Trial requested piloted vessels transiting an approximately 16 nautical mile corridor of Haro Strait to voluntarily slow down to 11 knots, speed through the water, from August 7 to October 6, 2017 (covering two full lunar months). One of the key questions to be answered through this study was "How does reduced ship speed change the total underwater ambient noise received at a specific location (Lime Kiln State Park on San Juan Island) of importance to Southern Resident killer whales?"

SMRU Consulting has been funded by the ECHO Program to conduct continuous passive acoustic monitoring (PAM) of ambient underwater noise at the Lime Kiln State Park hydrophone since February 2016 and will continue through to February 2018. As the waters of Haro Strait on the western side of San Juan Island are an important foraging area for the SRKW, analysis of received levels of noise at the Lime Kiln hydrophone site can serve as an indicator of potential received levels by whales feeding in the area.

The data obtained from the Lime Kiln hydrophone allows for provision of the following deliverables:

1. a) Ambient noise analysis for the Slowdown trial lunar months (August 7 – October 5, 2017) providing monthly, daily and weekly plots of received Sound Pressure Levels (SPLs) at the Lime Kiln hydrophone.
   b) An ambient noise comparison of Slowdown trial months to equivalent non-trial or "Baseline" months (i.e. months with similar sound propagation characteristics, vessel composition and counts, and weather conditions) to assess differences in received SPLs at the Lime Kiln hydrophone.
2. A fine-scale ambient noise analysis of the received SPLs at the Lime Kiln hydrophone, taking into consideration vessel type, small boat presence, vessel speed, proximity of vessel passes to the receiving hydrophone, and weather and tidal conditions. This provides a more detailed statistical analysis of the ambient noise reduction, and identifies the important factors affecting received noise at Lime Kiln. Assessment of received SPLs was also used to assess change in "quiet time" durations due to the Slowdown trial.

3. Documentation of acoustic SRKW presence in Slowdown trial months and two equivalent non-trial months using acoustic detections of calls, whistles and echolocation clicks. These data complement land-based observations made during daylight periods at Lime Kiln State Park.

Results of a pre-trial noise-SRKW behavioural response simulation model scenario analysis have been previously provided to the ECHO Program, as well as a summary of visual observations made by observers at Lime Kiln of SRKW transits. Vessel speed compliance datasets during the Slowdown trial have also been provided to the ECHO Program.

2 Methods, Results and Conclusions by Deliverable

Due to the disparate nature of some of the deliverables reported herein, methods, results and conclusions for each deliverable are reported separately by section.

2.1 Ambient Noise: Lunar Month Summary

Ambient noise SPL (dB re 1 µPa, root mean square (rms)) data have been collected for the ECHO Program at the Lime Kiln hydrophone since February 2016 providing summary monthly, weekly and daily analyses across 20 lunar months.

2.1.1 Ambient Noise Lunar Month Summary - Methods

The Reson TC4032 hydrophone used throughout the monitoring period was calibrated both by Reson (frequencies from 5 to 100 kHz) and at low frequencies (10 Hz to 2 kHz) by the Naval Undersea Warfare Center (Rhode Island) before deployment in 2016. The hydrophone was installed at a water depth of 23 m, ~70 m from the shoreline in front of the Lime Kiln State Park light house at 48.5155N, 123.15291W and cabled to shore. An additional spot calibration (at 250 Hz) was performed in the field in June 2017 highlighting that no drift in calibration had occurred.

Data were digitized with a high-quality data acquisition board (St. Andrews Instrumentation Ltd. http://www.sa-instrumentation.com/) at a sample rate of 250 kHz, 16-bit depth and stored by PAMGuard as 1-minute wav files. These files were post-processed with custom Matlab scripts modified from Merchant et al. (2015) with a 1 second Hanning window, 50% overlap and Welch's averaging to average across each 1-minute file.

Analysis of standard metrics across lunar month periods were recommended by the ECHO Program's Acoustic Technical Committee (ATC). Use of lunar months aimed to minimize the effects of low frequency flow noise due to temporal variability in current flow patterns. A full dataset of standard metrics is reported in Appendix 1 for the Slowdown and comparative Baseline time periods. A full year of ambient noise reporting has been provided previously to the ECHO Program. These standard metrics are also utilized when reporting ambient noise at the Strait of Georgia Underwater Listening Station and other ECHO Program supported hydrophones.

The standard ambient noise reporting metrics include;

a) Broadband and decade band SPL versus time plots, showing the hourly variability of the ambient noise over the lunar month. The broadband plot is the total SPL for the frequency range of 10 Hz to 100 kHz (Appendix 1). The four, decade band plots show the SPL integrated from the 10 to 100 Hz, 100 to 1,000 Hz, 1 to 10 kHz, and 10 to 100 kHz frequency bands, noting most of the energy associated with commercial traffic is within the first two decades (i.e., < 1,000 Hz), though energy does extend into higher frequencies (e.g., Veirs et al. 2016).

b) The spectrogram for the lunar month, showing the power spectral density variability on an hourly basis. Figure 1 depicts the spectrogram at 1-hour increment resolution of ambient noise for the two Slowdown lunar months. Higher intensity noise (depicted by red bands) is largely below 100 Hz, but noise also extends to higher frequencies, as might be expected close to a busy shipping lane (see Appendix 1.1 and 1.2 for Baseline period spectrograms).

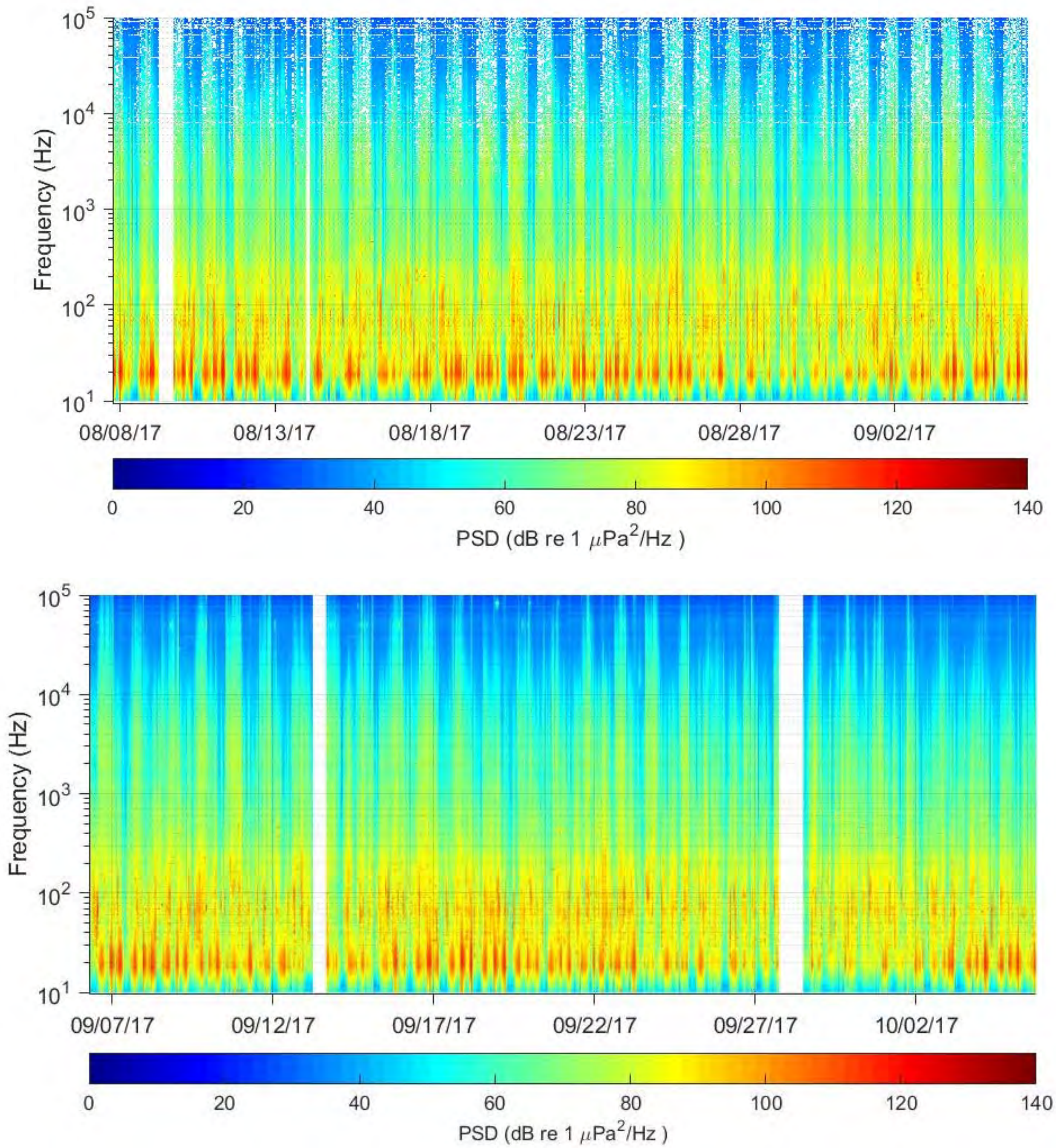


Figure 1. Spectrogram (Power Spectrum Density, PSD, at 1-hour increment resolution) of ambient noise for two Slowdown lunar months. Gaps represent periods of data loss.

c) 1/3-octave band levels and spectral levels for the lunar month at various percentile levels (5th to 95th, see ISO 1996-1:2003), minimum, maximum and arithmetic mean (Leq). These statistics are computed from 1-minute SPL averages throughout the lunar month (Appendix 1). The percentiles represent the percentage of time the ambient noise is greater than the SPL (in dB re 1µPa or dB re 1µPa^2/Hz, as appropriate) at that frequency over the course of the lunar month. The L50 values are commonly referred to as the median or 50th percentile. The L5 (5th percentile) values represent sound levels which are only exceeded 5% of time. Spikes in L5 plots are indicative of high intensity short duration tones such as a very noisy vessel and this metric was recently recommended by Heise et al. (2017) as the appropriate metric to detect trends in vessel traffic. The L95 is the sound level at which 95% of 1-minute intervals exceed this noise level. Merchant et al. (2012) reported that mean SPL averaged in linear space (termed Leq, or the arithmetic mean), though susceptible to strong bias from outliers, are most relevant to cumulative impact assessment metrics. The ECHO Program's ATC recommended reporting both a range of percentiles and Leq levels. Very high intensity but short duration sounds such as vessel transits affect the mean level whereas the median level tends to minimize transient signals and enhance the visibility of long duration sound levels. Since vessels typically emit high underwater noise at low frequencies, the mean level will typically be above the median at low frequencies in areas with significant vessel traffic (Merchant et al. 2015). Differences between the arithmetic mean and median are thus a measure of variability and skewness (i.e., lack of symmetry) of received SPL.

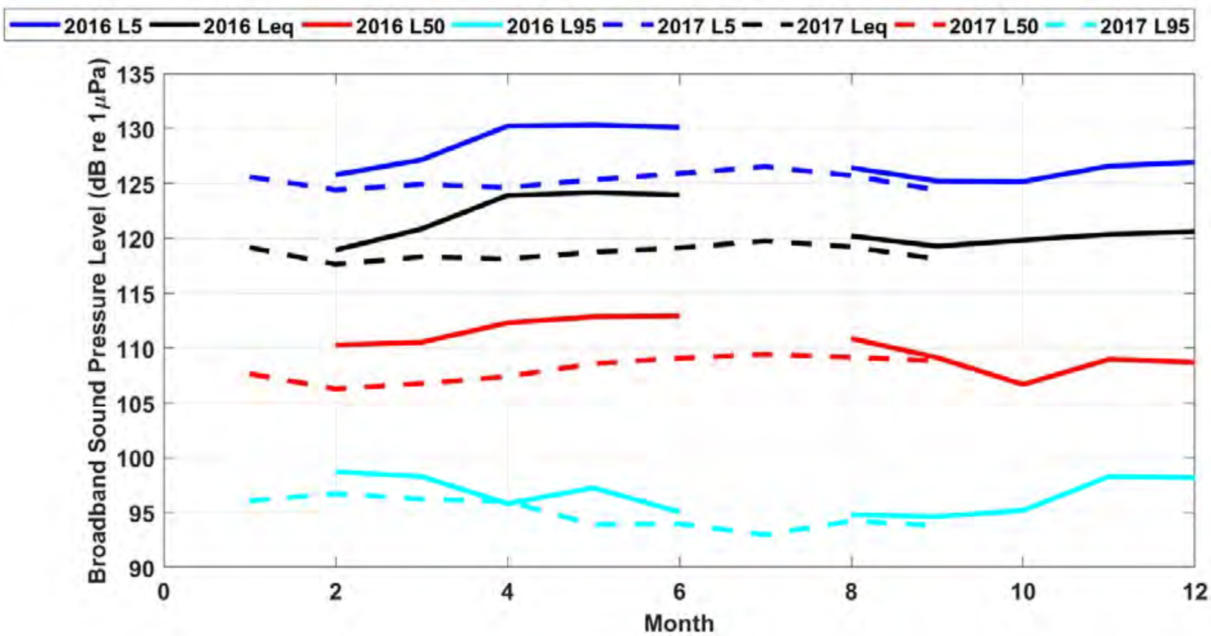
d) A daily rhythm plot of ambient noise using lunar monthly median SPL for each period of the local day (Appendix 1). This is used to identify daily repeating sound levels. The medians are plotted for broadband noise as well as the contribution from the four, decade frequency bands. Plotting the daily cadences can reveal patterns associated with human activity such as ferries or other regular vessel passages.

e) A weekly rhythm plot of ambient noise is similar to the daily rhythm plot, but the median SPL is presented for each period of a 7-day week (Appendix 1). Plotting the weekly cadences can reveal patterns associated with human activity that varies according to a weekly schedule.

f) An rms SPL box plot and table of the noise for the broadband and decade bands (Appendix 1).

2.1.2 Ambient Noise Lunar Month Summary - Results

A summary of broadband SPL metrics across the 20-month monitoring period is provided in Figure 2, together with the number of piloted vessel transits of Haro Strait that occurred, based on Pacific Pilotage Authority (PPA) databases accessed in November 2017. Monthly SPL metrics for each of the four, decade frequency bands is provided in Appendix 2. An interesting pattern emerges, whereby broadband SPLs are consistently higher in 2016 than 2017. This effect is most notable in spring and appears dominated by low frequency noise (< 100 Hz, Appendix 2). Despite consistent calibrated hardware and analytical techniques, broadband ambient noise levels were notably higher (~4-5 dB) April through June 2016 (lunar months 4-6) than in similar months in 2017. Summer 2016 broadband ambient noise levels (lunar months 8-9) were ~1-2 dB higher than in summer 2017. This is consistent with more detailed comparative analyses in Section 2.2.2 and Appendix 1. Lunar month variability was not simply explained by the number of piloted large commercial vessel, which on average were higher in spring and summer 2017 than in 2016. As well as speed compliance levels in summer 2017 (reported at ~60% by participating pilots), further assessment of the consequences of tug, motor yacht and small boat presence (i.e., non-piloted vessels) as well as tidal effects (known to especially effect low frequencies) is required.



	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2016	NaN	448	441	425	447	461	422	432	431	449	457	427
2	2017	414	434	464	484	438	469	444	415	495	417	NaN	NaN

Figure 2. Summary broadband ambient SPL across lunar months (February 2016 to October 2017) at the Lime Kiln hydrophone, with an associated table reporting the number of piloted AIS vessels transiting through Haro Strait (Source: Pacific Pilot Authority 3/11/2018). Solid lines represent 2016 and dashed lines represent 2017 data.

Note: Only 6 days of data were collected in lunar month #7, 2016 due to a cable failure and metrics for this period have been omitted. Because we used lunar months, the timing of months from one year to the next are not a complete overlap.

Furthermore, given the higher broadband SPL levels in April through June 2016 were very clearly focused at low frequencies (10-100 Hz. Figure A2.1), and not apparent at higher frequencies (1-10 kHz, Figure A2.3) and the timing (April – June), we hypothesize that another plausible explanation is variability in freshwater discharge from the Fraser River, with knock on effects to salinity and sound speed profiles in Haro Strait, changing low frequency propagation. Peak Fraser River discharge occurs in late spring and varies dramatically year to year (see https://wateroffice.ec.gc.ca/report/historical_e.html?stn=08MH126). If our hypothesis is correct, this would indicate a clear need to collect CTD (Conductivity, Temperature, Depth) data on a regular basis at or near acoustic monitoring locations as important covariate data to explain fluctuations in ambient noise levels.

In conclusion, given this significant source of monthly variability, and the clear need to take into account temporal variability in the number and duration of vessel and small boat transits and shorter-term environmental conditions (current, wind, etc.) that may affect received SPLs, we conclude that analyses of noise trends relevant to killer whales need to focus on finer time scales and include covariate data. To do this, we have used three fine-scale analytical approaches (cumulative probability functions, time below threshold and Generalized Additive Mixed Modelling (GAMM)) on the 1-minute acoustic data collated for two Slowdown lunar months and two comparable Baseline lunar months in the next section. Baseline months were selected primarily to minimize potential differences in Haro Strait sound speed profiles and secondarily to minimize differences in vessel number/composition.

2.2 Ambient Noise: Fine-scale comparison of Slowdown and Baseline lunar months

The Slowdown trial period encompassed 2017 lunar months #8 and #9 (7 August to 6 September 2017 and 6 September to 5 October 2017). The selected Baseline period included the 2017 lunar month prior to the Slowdown trial (month #7; 9 July to 8 August 2017) and lunar month #8 for the year previous (18 August to 16 September 2016). Short-term power failures occurred in both Slowdown and Baseline datasets resulting in a small loss of acoustic data (Appendix 1).

2.2.1 Ambient Noise: Vessel speed comparison of Slowdown and Baseline months

Received SPLs and PSD were calculated for each 1-minute period (see Section 2.1). To undertake a comparative analysis, we used AIS data in 1-minute bins matching the acoustic data to record vessel transit information. Overall, these data represent 165,182 ambient noise monitoring minutes (or the equivalent of ~115 days) for both the Slowdown and Baseline periods. Lunar month broadband median and mean SPLs were lower in Slowdown trial months compared to Baseline months (Section 2.2.2, Appendix 3), but this initial perspective using all the data does not take into account differences in the number of vessel transits (the Slowdown period had more piloted vessel transits than the Baseline period), the speed compliance level observed, nor the effect of weather, tidal currents or the influence of small boat presence.

To enable a robust comparative analysis of ambient noise levels, we collected or acquired additional (covariate) data that might contribute to ambient noise levels at Lime Kiln (Table 1). These were combined on a matching minute by minute interval with the acoustic data collected at Lime Kiln. We started our fine-scale comparisons with a cumulative distribution function (CDF) analysis of received SPLs at a resolution of 1-minute (Section 2.2.2). This approach uses data only when AIS enabled vessels were reliably present and known to contribute to the soundscape (i.e. clearly audible) at Lime Kiln (a 6 km detection zone), as well as a larger 15 km zone that encompasses the Slowdown trial acoustic monitoring area (Figure 3). This focus on periods of vessel presence coupled with a CDF approach controls for vessel number effect across comparative time periods. More focused analyses were also undertaken to assess change in quiet time (Section 2.2.3) and a GAMM to control for the effect of other covariates (including trial versus non-trial periods, speed of vessels through the water, range of the vessels, key vessel types, presence of small boats, wind and tidal conditions) potentially affecting ambient noise levels (Section 2.2.4). Unless otherwise noted, data analysis was conducted with custom Matlab scripts.

Table 1. Sources and description of covariate data.

Covariate	Description	Source
Range	Distance to closest AIS enabled vessel	SMRU
SOG	Mean speed over ground during 1-minute for closest AIS enabled vessel (ƚ)	SMRU
Vessel Number	Number of AIS enabled vessels during that 1-minute	SMRU
Vessel Type	Class of AIS enabled vessel	PPA (some corrected from www.marinetraffic.com)
Small Boat	Acoustic detector of small non-AIS enabled vessels	SMRU
Wind	Wind velocity as recorded at the Hein Bank buoy (*)	NOAA (http://www.ndbc.noaa.gov/station_history.php?station=46088)
Current	Current velocity as modelled in Haro (#)	NOAA (https://tidesandcurrents.noaa.gov/noaacurrents/Annual?id=PCT2246_1)

ƚ SOG converted to speed through water for use in analyses by combining SOG with current.

* Data recorded every 30 minutes and linearly interpolated to match the acoustic 1-minute resolution.

Data modelled at peak flood/ebb and slack times and cubic spline interpolated to match the acoustic 1-minute resolution.

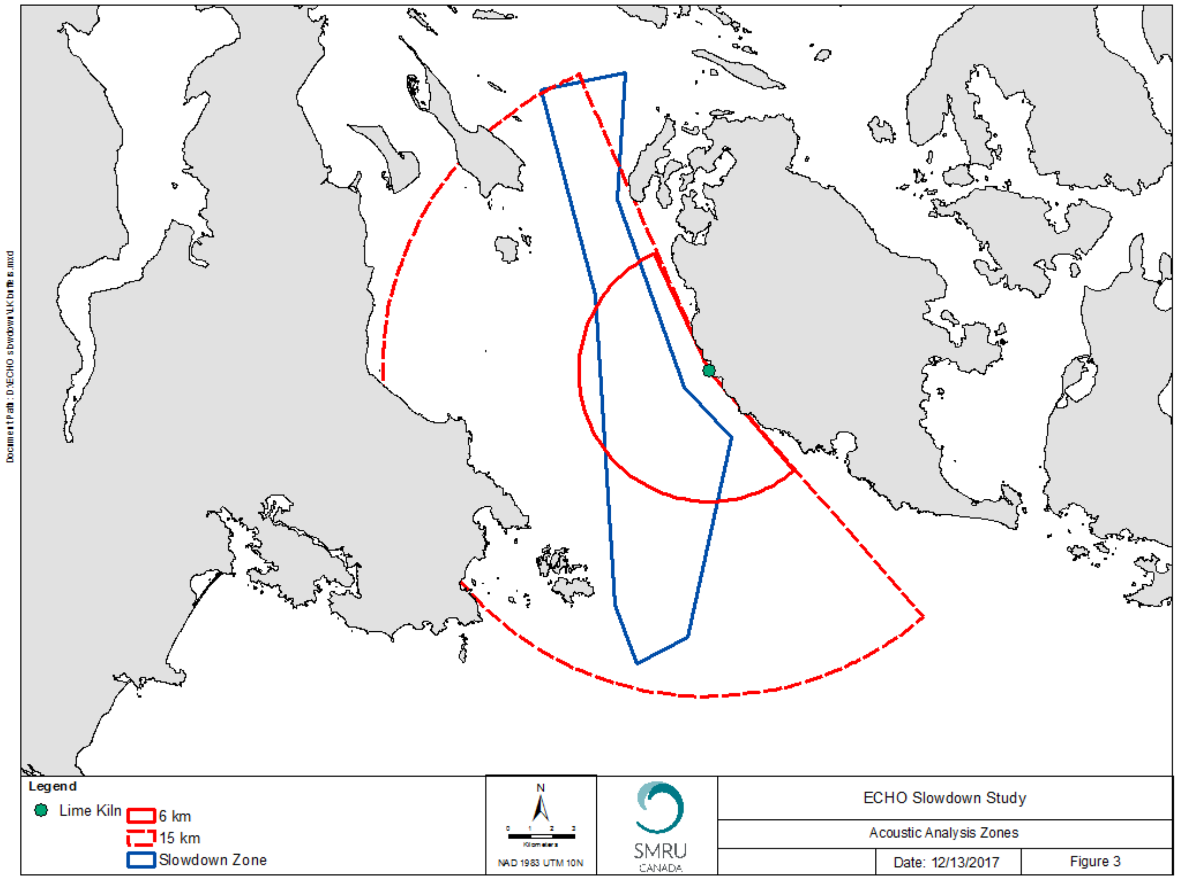


Figure 3. Study area depicting 15 km and 6 km acoustic analysis zones around the Lime Kiln hydrophone

Vessel type composition based on the closest vessel to the Lime Kiln hydrophone in each 1-minute increment within the acoustic 15 km monitoring area was similar (typically within 1-3% across vessel types) between Baseline and Slowdown periods (Figure 4), with Bulk carriers (26-27%), tugs (20-23%) and container vessels (11-14%) the most frequently identified vessel types in both periods. Car carriers, general cargo, passenger (cruise ships and smaller passenger ships together) and tankers each contributed approximately 4-6% of the total minutes. The 'Other' vessel category includes Coastguard, search and rescue, fishing tenders, fishing vessels, heavy lift, a few B.C. Ferries on relocation transits and any other vessel that did not fit into the categories depicted in Figure 4.

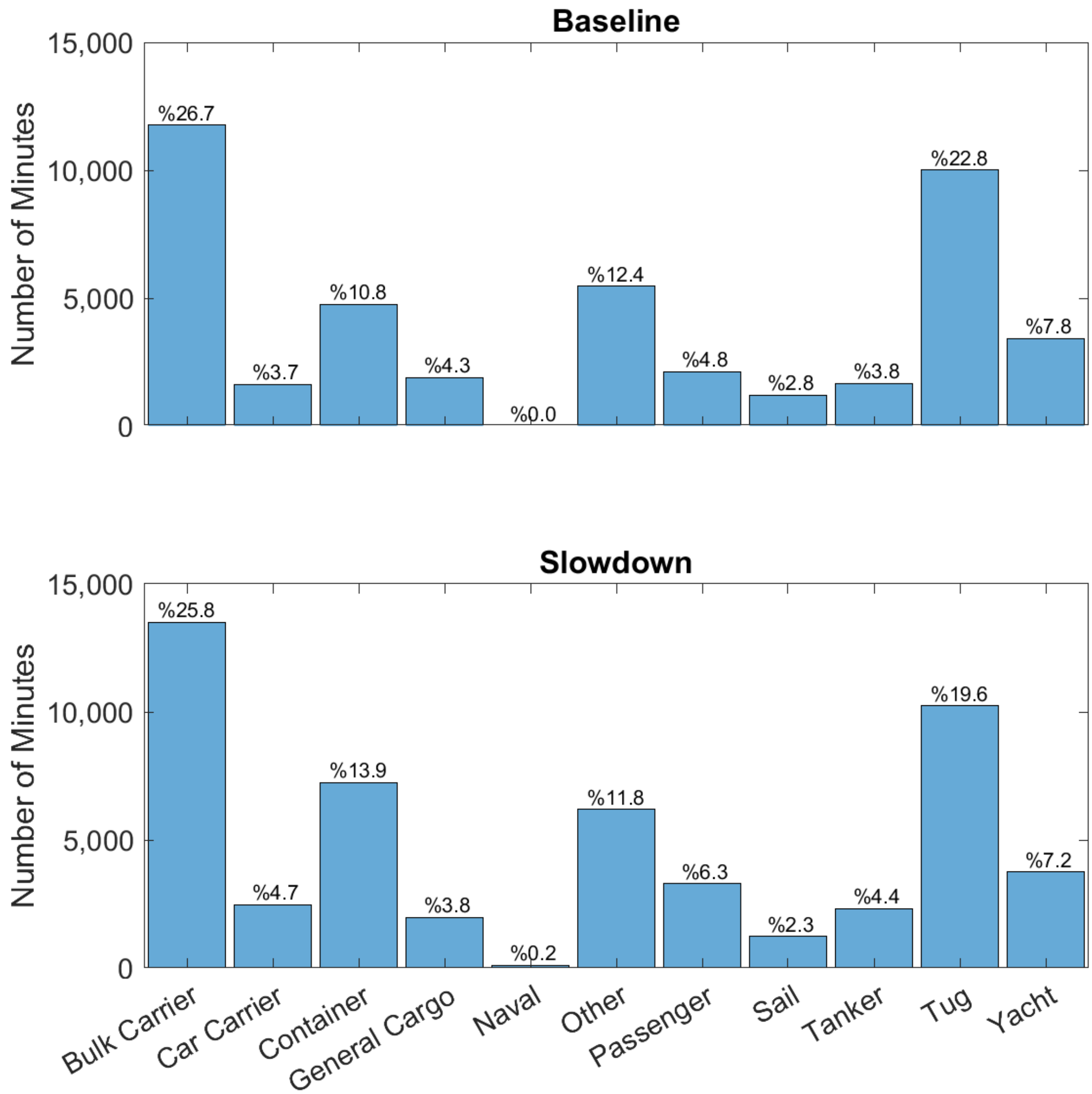


Figure 4. Vessel type composition for Baseline and Slowdown periods as recorded by AIS within a 15-km acoustic monitoring radius of the Lime Kiln hydrophone. Data are depicted as the accumulated number of minutes each vessel type was the closest to Lime Kiln, with associated percentage (%) calculated, for each period.

Speed through water (AIS-derived speed over ground corrected for tidal current effects) of the closest vessel was calculated for each minute of data. For each vessel type, the median speed through water was calculated during the Baseline period. This median speed through the water was subtracted from each 1-minute measure of speed through the water to estimate a vessel type specific difference in speed from Baseline. Figure 5 shows the distribution of the difference in speed for Baseline and Slowdown periods. As expected, the Baseline period shows an even distribution around zero (shown with a red dashed line), i.e., half the differences in speed are negative, half are positive. The Slowdown period shows a clear shift in distribution to the left of the Baseline median speed (red dashed line at zero) and thus a clear reduction in speed during the Slowdown. There is a bimodal nature to this leftward shift. This is due to some vessels slowing down considerably (between 6 and 8 knots) while others slowed down by a few knots. By plotting the distribution of speed through water for key vessel types during Baseline and Slowdown (Figure 6), we can clearly see which classes of vessel slowed down the most, noting that pilots reported to the ECHO Program that ~60% of all piloted vessel complied with the slowdown.

Based on median speed through the water, the types of vessel that slowed down a few knots are: bulk (from 13 to 11.7 knots) and general cargo (from 13.6 to 11.8 knots) carriers, as well as tankers (from 13.6 to 11.4 knots) (see Figure 6). The vessel types that slowed down 6-8 knots were: container vessels (from 18.6 to 11.4 knots) and car carriers (from 17.1 to 11.5), both of which normally transit at higher speeds than the other vessel types (Figure 6). Therefore, the difference in slowdown speeds is related to the typical speed of different vessel types. Those with slower typical speeds did not need to slow down by much to meet the 11 knot target. Data for the category passenger showed less than a knot reduction in median speed through the water between Baseline and Slowdown periods. However, a few caveats are required when interpreting this result. The passenger vessel type includes cruise ships, passenger ferries such as the Victoria Clipper and the larger whale watch vessels. This disparate grouping of vessels and a lower sample size in the Baseline period result in a distribution that has three peaks. During the Slowdown period a larger sample size and some speed change results in a single peak at 10 knots.

A bimodal distribution clearly observed in the Slowdown period for both container vessels and car carriers highlights that a proportion of these vessel remained at typical (Baseline) speeds while transiting Haro Strait (i.e., Slowdown trial non-compliance). This is consistent with pilots reporting a compliance rate of ~60% across the Slowdown trial period. Tugs are typically transiting through Haro Strait very slowly (below the suggested trial speed of 11 knots) and showed an inconsequential change in speed (from 7.3 to 7.1 knots) but contributed ~20% of the presence minutes. Typically, tugs have no pilots. Vessel categories known to have pilots make up 52.8% of the total Slowdown period minutes, plus a proportion (cruise ships) of the 6.3% within the passenger vessel type grouping.

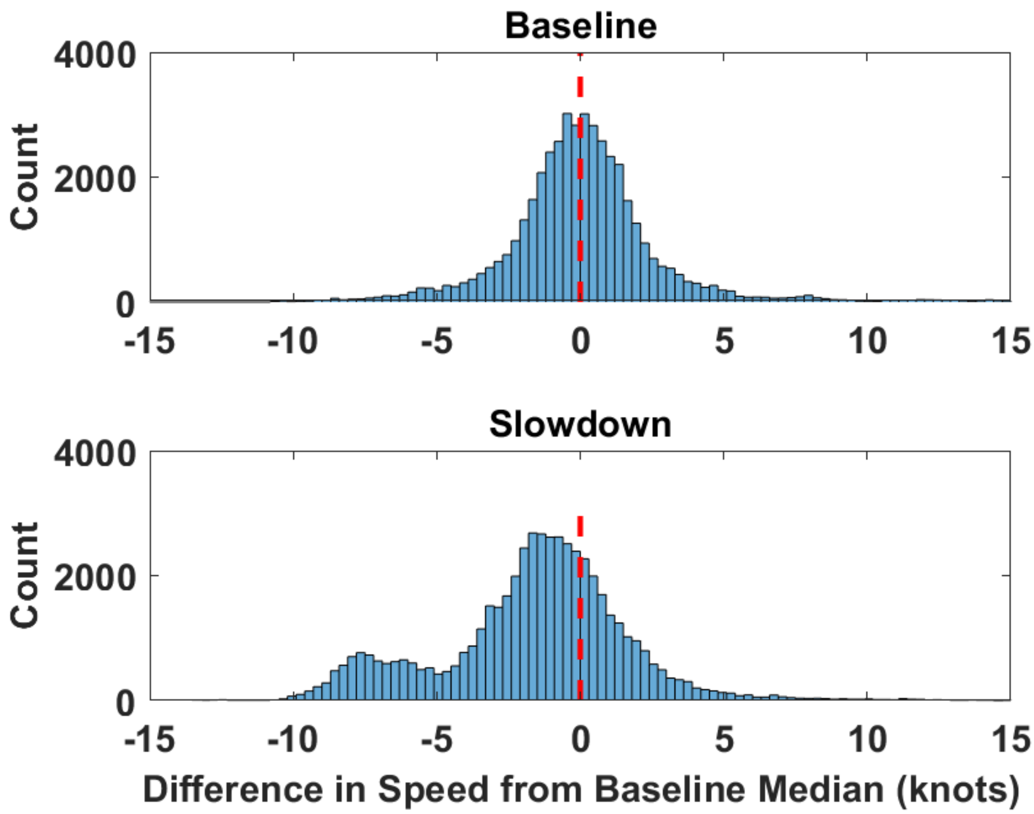


Figure 5. By minute distribution of the difference (by vessel type) between Baseline median speed through water (knots) and vessel speeds recorded during Baseline and Slowdown periods.

Note: Differences in speed are calculated subtracting the median Baseline period speed of each vessel type from the speed of each vessel for every minute they are the closest vessel within the acoustic monitoring zone. The red dashed line represents no difference in speed.

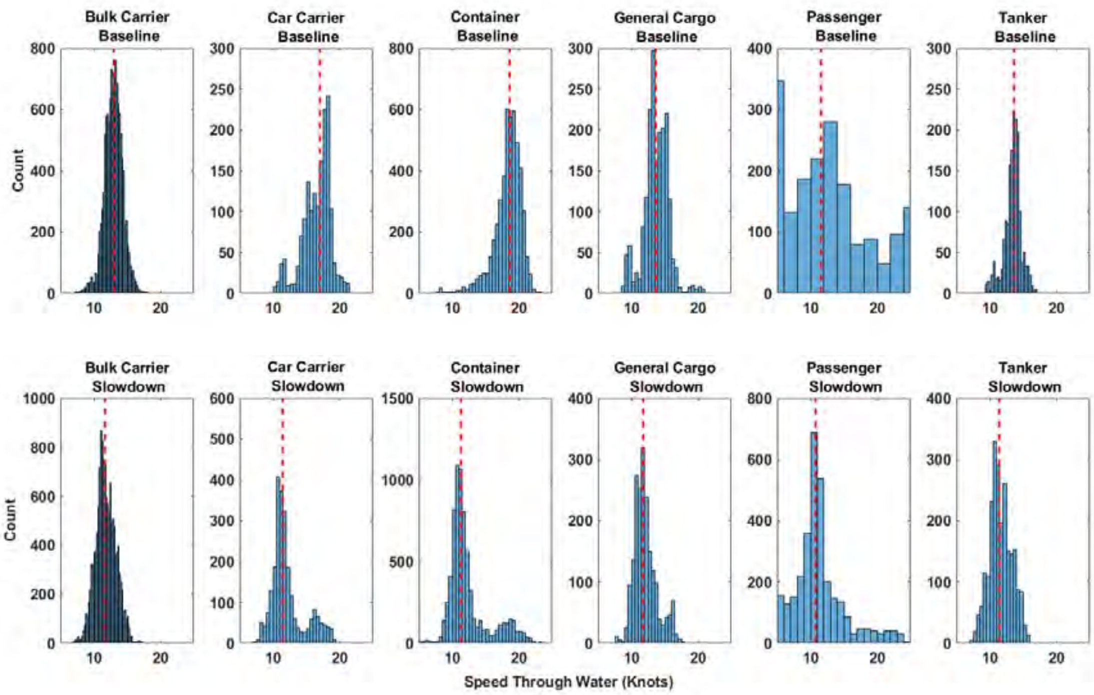


Figure 6. By minute distribution of vessel speed through water (knots) for key vessel types across Baseline and Slowdown periods. The vertical dashed red line represents the median speed for the vessel type in each period.

2.2.2 Ambient Noise: Cumulative Distribution Functions to compare Baseline and Slowdown noise metrics

CDFs provide an ideal method to compare ambient noise levels across different time periods. The CDFs calculate the cumulative probability for a given value of x (in this case dB). With a CDF plot one can read off the probability of exceeding (being above) or below a particular value, or of being within, or outside, a particular range. The use of exceedance CDFs were recommended by the ECHO Program's ATC to detect trends in ambient noise and were recently used in a similar slowdown noise assessment in Glacier Bay National Park (Frankel and Gabriele 2017) as well as being used in the DFO CSAS noise mitigation working paper (see CSAS 2017/041). Not only do CDFs visually synthesize all the available received SPL data, they provide a mechanism to control for the number of vessel transits and account for variability in noise exposure time versus noise amplitude. We sequentially selected specific time periods of data to minimize any effect from known confounding covariates (see Table 1). In other words, we created CDFs for periods with low current and wind velocity, no small boats, and/or AIS-enabled vessels within a 6 km range, etc. to explore the change in CDFs between Baseline and Slowdown periods.

The effects of key confounding covariates were minimized by excluding times when **a)** small boats were detected by a bespoke acoustic detector **b)** current speed was high (values above 25 cm/s) and **c)** wind speed was high (values above 5 m/s). Rainfall for both time periods was found to be infrequent and not considered confounding, with just a handful of days of trace or infrequently low (all <6.5 mm) amounts in both periods[1]. Exceedance CDF were plotted for each month and then combined across Slowdown and Baseline periods to compute differences in L5, L50, L95 and Leq broadband SPL metrics. The most robust dataset for this approach used data only when AIS enabled vessels were reliably present and known to contribute to vessel signal noise excess at Lime Kiln (a 6 km detection zone, Figure 7), but we have also calculated SPL metrics for the 15-km acoustic monitoring zone and all lunar month data with no time periods removed (Table 2, Appendix 3).

In addition to these broadband SPL metrics, we calculated for the 6 km detection zone (Table 2);

a) CDFs by each of the four, decade bands (Figure 8).
b) CDFs by new SRKW-related frequency bands proposed by Heise et al. (2017). These were 0.5-15 kHz (communication masking band) and 15-100 kHz (echolocation click masking band) (Figure 9).
c) CDFs for key piloted vessel types with sufficient sample size; specifically, bulkers and cargo carriers combined and container vessels (Figure 9).

For median (L50) and mean (Leq) noise metrics, in all broadband comparisons (6 km, 15 km, all data), ambient noise levels were lower in Slowdown months compared to Baseline months (Table 2, Appendix 3).

For >90% of the time, there was a clear, quantifiable benefit (noise reduction) during the Slowdown period, as indicated by the divergent CDFs, during periods with vessels within the 6 km detection zone and periods with high covariate levels excluded. At low ambient noise levels (e.g., L95) there was little to no noise reduction (Table 2, Figure 7). Median (L50) broadband SPL for the Slowdown period was 114.4 dB re 1 µPa, 2.5 dB quieter than for the baseline period (116.9 dB re 1 µPa). The mean (Leq) was 2.0 dB quieter (114.6 vs 116.6 dB re 1 µPa). At L5 (noise exceeding this level 95% of the time) the Slowdown period was 1.4 dB quieter than baseline (125.4 vs 126.8 dB re 1 µPa) and at L95 (noise only exceeding this level 5% of the time), noise levels for the Slowdown period were 0.3 dB quieter than Baseline (102.1 vs 102.4 dB re 1 µPa) (Table 2, Figure 7). A similar pattern but with less pronounced differences occurred for the larger 15 km detection zone (Table 2).

These results highlight that the Slowdown trial (with ~60% reported compliance) resulted in a quantifiable noise reduction at ambient noise levels above the L95 quantile and at frequencies < 10 kHz, due to reduced source level amplitude of slower transiting vessels. At ambient noise levels below L95 and at frequencies above 10 kHz, the Slowdown period SPLs were similar to the Baseline period (Figure 7 and Figure 8). At a finer lunar month scale, it can be observed that in fact, at these lower noise levels, the Slowdown months were noisier than the month previous (Figure 7, left panel).

[1] Source: https://victoria.weatherstats.ca/charts/precipitation-daily.html

The reduction in the amount of time that high (>110 dB re 1 µPa) SPL noise levels occur will lead to lower numbers of behavioural responses predicted to occur using broadband dual dose-response SRKW-noise exposure approaches (SMRU 2014a, 2014b). Underlying the dual dose-response relationship is the concept that at higher received noise levels, there is a higher probability of a behavioral response or disruption and that this disruption has the potential to last longer than the time period of the dose (e.g., through a switch in behaviour). In other words, the nearer an SRKW is located to a noise source, the higher the likelihood a behavioural response occurs. Frankel and Gabriele (2017) found that cruise ships traveling at 13 knots produced cumulative Sound Exposure Levels three times lower than those traveling at 20 knots and that maximum SPL levels also decreased. They also concluded that slower vessels have a positive effect on total noise output.

To put these results into perspective, a noise reduction of 2.5 dB is the equivalent of a 44% reduction in acoustic intensity or a 16% reduction in perceived loudness. A noise reduction of 2.0 dB is equivalent to a 37% reduction in acoustic intensity or a 13% reduction in loudness. A noise reduction of 1.5 dB is equivalent to a 28% reduction in acoustic intensity or a 10% reduction in loudness. A noise reduction of 0.3 dB is equivalent to a 7% decrease in acoustic intensity or a 2% decrease in loudness.

Decade band analysis (Figure 8) showed that Slowdown noise reduction at L50 was highest in the 1st decade band (reduction of 3.1 dB), and lowest (0.3 dB reduction) in the highest decade band. Reductions were 2.3 dB in the 2nd decade band and 2.2 dB in the 3rd decade band. The Leq showed a 2-2.1 dB reduction in the first three, decade bands and a noise increase in the 4th decade (0.7 dB). The lack of any notable difference between Slowdown and Baseline periods at frequencies above 10 kHz is expected given high frequency attenuation and the distance between the shipping lanes and Lime Kiln hydrophone. Frequency dependent absorption adds little additional attenuation at 1kHz (0.06 dB/km), but at 10, 50 and 100 kHz, frequency dependent absorption adds another 1.0, 15.7, and 32.1 dB/km of attenuation, respectively (i.e. there is a lot more attenuation at very high frequencies). The center of the north bound shipping lane is 2.3 km from Lime Kiln while the south bound shipping lane is 5 km. By the time ship noise at high frequencies reaches the Lime Kiln hydrophone, sound levels are near the noise floor of the acoustic system. The noise floor is the quietist sound an acoustic system can record (below this, internal noise in the acoustic system dominates). There is also more electronic interference in the recording system above ~50 kHz, which can be seen as spikes in power spectral density plots (e.g. Figure A1.1.2), which make it harder to quantify differences in ship noise at high frequencies.

It can also be observed that at each ascending decade band the median and mean SPLs decrease, reflecting the fact that the majority of vessel acoustic energy is in the lower frequency bands. For example, L50 is 113.5 dB re 1 µPa in the first decade, 111.2 dB re 1 µPa in the second, 104.2 dB re 1 µPa in the third and just 90.4 dB re 1 µPa in the fourth (Figure 8).

CDF analysis of newly recommended (Heise et al. 2017) communication and echolocation masking bands also showed a very clear frequency dependence on Slowdown benefits (Figure 9, upper panels), noting Heise et al. 2017 also recommend using broadband measures, as also presented here. When integrating across 0.5-15 kHz (the communication masking band), there was a clear Slowdown period benefit at all assessed metrics (for example L50 reduced from 104.6 to 102.6 dB re 1 μPa). However, at the higher frequency echolocation masking band (15-100 kHz), there was an observed noise increase at L50 (0.4 dB), Leq (0.4 dB) and L95 (1.2 dB), with a small noise decrease observed at L5 (-0.2 dB). Overall, the acoustic energy is low within this echolocation masking band with L50 below 86 dB re 1 μPa, when compared to lower frequency bands.

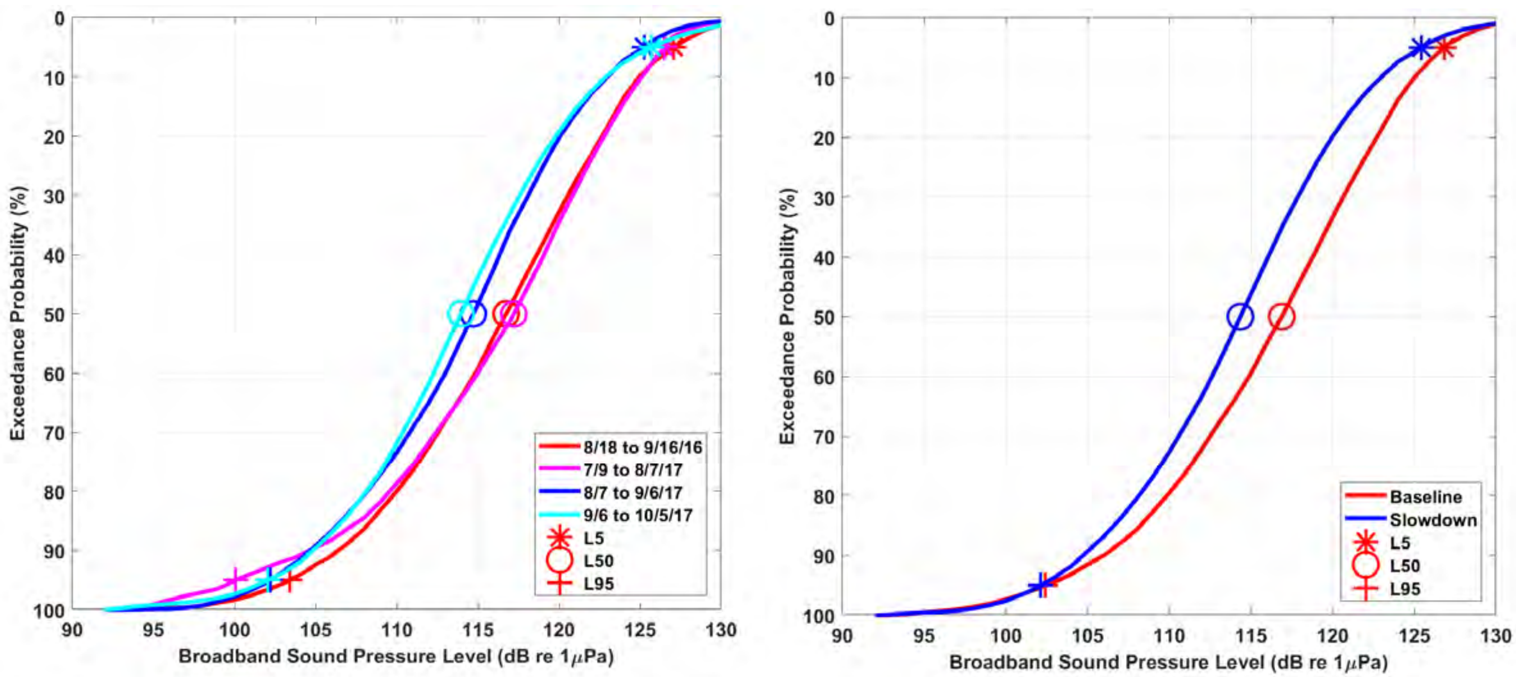
Sample size allowed for the isolated CDF analysis of bulk and general cargo carriers (combined) as well as container vessels (Figure 9, lower panels). Median (L50) and Leq during the Slowdown period were 6.1 dB and 5.2 dB lower for container vessels than for the Baseline period, and 1.5 dB and 1.2 dB respectively for bulk and general cargo carriers. This reflects the larger absolute reduction in average speed for container vessels compared to bulkers and cargo carriers in order to reach the 11 knot Slowdown trial speed goal. At L5, for the bulk and general cargo carriers, noise levels were 0.6 dB higher during the Slowdown (Figure 9) which may result from their longer proximity to Lime Kiln during the Slowdown.

To attempt to put these values into wider (global) context, in parts of the North Pacific Ocean, low frequency underwater noise has been increasing by ~3 dB per decade (doubling in intensity) every decade for the past 60 years (Hildebrand 2009), largely thought due to commercial vessel noise. A meeting of stakeholders and experts in the shipping industry proposed international targets to reduce the contribution of shipping to ambient noise levels in the frequency range 10 Hz to 300 Hz by 3 dB in 10 years and by 10 dB in 30 years relative to current levels (Wright 2008). The noise reduction levels measured during the Slowdown trial compare favorably with these reported noise increases and reduction targets.

Table 2. Comparison of Slowdown versus Baseline period ambient noise exceedance CDF at four select SPL metrics (L5, L50, L95 and Leq). A negative value denotes that the Slowdown period was quieter than the Baseline period. The 6 km detection zone (shaded grey) is considered the most reliable to compare noise levels across periods.

Note: Ambient noise data from this detection zone has been partitioned into the four frequency decade bands, by two new frequency bands reflecting potential masking of SRKW communication and echolocation proposed by Heise et al. (2017), as well as for bulk/cargo carriers and container vessels alone.

Frequency range	**Vessel presence detection zone and confounding covariate time removed**	**SPL (dB) difference between CDFs for Slowdown and Baseline periods**			
		Median (L50)	**Mean (Leq)**	**Upper 5% L5**	**Lower 5% L95**
Broadband 10 Hz – 100,000 Hz	All raw data, no time excluded	-1.2	-1.1	-1.3	+0.2
Broadband **10 Hz – 100,000 Hz**	15 km zone, wind and current speed, small boat presence removed	-1.1	-1.2	-1.3	-0.4
Broadband **10 Hz – 100,000 Hz**	6 km zone, wind and current speed, small boat presence removed	-2.5	-2.0	-1.4	-0.3
1st Decade **10 Hz – 100 Hz**	As above	-3.1	-2.1	-1.1	+0.1
2nd Decade **100 Hz – 1,000 Hz**	As above	-2.3	-2.0	-2.3	-0.1
3rd Decade **1,000 Hz -10,000 Hz**	As above	-2.2	-2.0	-1.3	-1.9
4th Decade **10,000 Hz-100,000 Hz**	As above	-0.3	+0.7	-0.4	+0.7
Communication Band **500 Hz – 15,000 Hz**	6 km zone, wind and current speed, small boat presence removed	-2.1	-1.9	-1.8	-1.1
Echolocation Band **15,000 Hz – 100,000 Hz**	6 km zone, wind and current speed, small boat presence removed	+0.4	+0.4	-0.2	+1.2
Broadband (Bulk/Cargo) **10 Hz – 100,000 Hz**	6 km zone, wind and current speed, small boat presence removed, only bulk and cargo carriers	-1.5	-1.2	+0.6	-1.6
Broadband (Containers) **10 Hz – 100,000 Hz**	6 km zone, wind and current speed, small boat presence removed, only container vessels	-6.1	-5.2	-2.5	-5.8

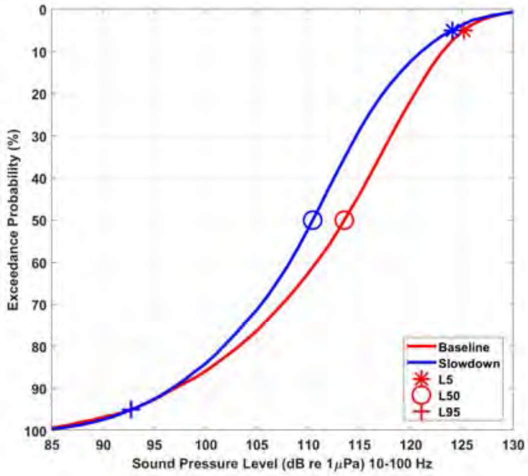


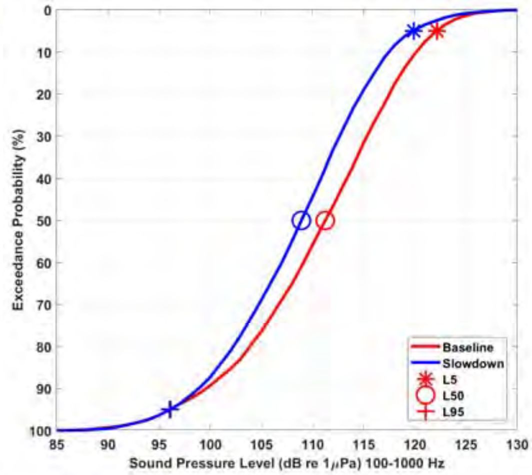
	Metric	Baseline SPL (dB) 8/18 to 9/16/16	Baseline SPL (dB) 7/9 to 8/7/17	Slowdown SPL (dB) 8/7 to 9/6/17	Slowdown SPL(dB) 9/6 to 10/5/17
1	L5	127.1	126.5	125.3	125.7
2	L50	116.8	117.2	114.7	114.0
3	L95	103.4	100.1	102.2	102.1
4	Leq	116.7	116.4	114.8	114.4
5	Minutes	6792	3073	5343	4786

	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	126.8	125.4	-1.4
2	L50	116.9	114.4	-2.5
3	L95	102.4	102.1	-0.3
4	Leq	116.6	114.6	-2.0
5	Minutes	9865	10129	

Figure 7. Exceedance CDF plots of broadband (10 Hz to 100 kHz) ambient SPL (dB re 1 µPa) by two Baseline months (left panel, red and magenta lines) and two Slowdown months (left panel, blue lines), as well as months combined by periods (right panel). Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files.

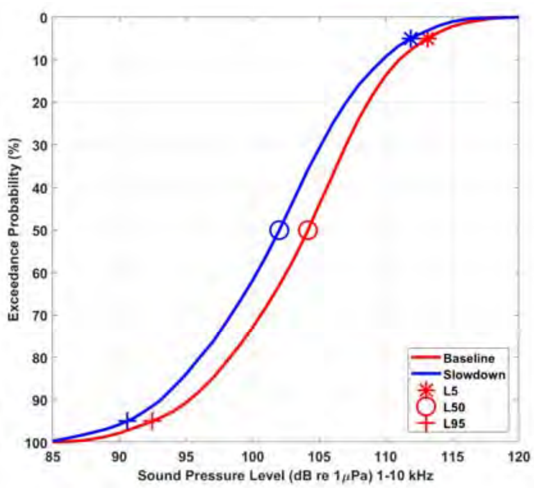
Note: Only minutes with an AIS enabled vessel within a 6km detection zone were included. Times with high wind and current as well as small boat presence were removed. The dB difference between Baseline and Slowdown periods has been provided for each metric (right panel). A negative difference means that the slowdown period is quieter (see Table 2).

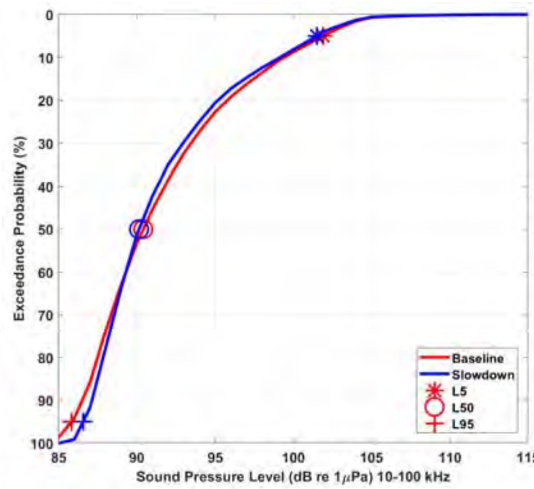




	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	125.2	124.1	-1.1
2	L50	113.5	110.4	-3.1
3	L95	92.7	92.8	0.1
4	Leq	112.2	110.1	-2.1
5	Minutes	9865	10129	

	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	122.1	119.9	-2.3
2	L50	111.2	108.9	-2.3
3	L95	96.1	96.0	-0.1
4	Leq	111.0	109.0	-2.0
5	Minutes	9865	10129	



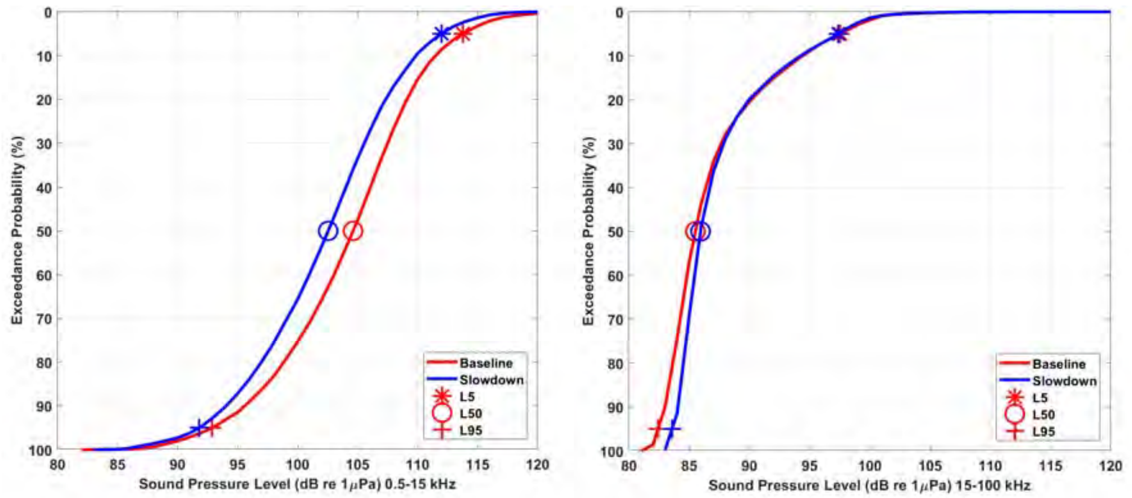


	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	113.2	111.9	-1.3
2	L50	104.2	102.0	-2.2
3	L95	92.5	90.6	-1.9
4	Leq	104.1	102.1	-2.0
5	Minutes	9865	10129	

	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	101.9	101.5	-0.4
2	L50	90.4	90.1	-0.3
3	L95	85.8	86.6	0.7
4	Leq	92.2	92.2	-0.1
5	Minutes	9865	10129	

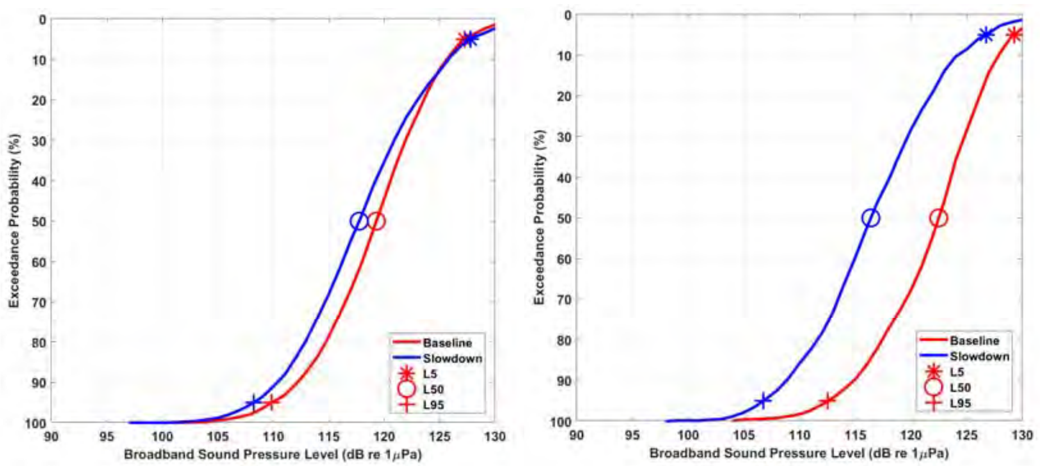
Figure 8. Exceedance CDF plots of ambient SPL (dB re 1 µPa) for each decade band (10 to 100 Hz, 100 to 1000 Hz, 1 to 10 kHz, and 10 to 100 kHz) by Baseline period (red line) and Slowdown period (blue line). Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files

Note: Only minutes with an AIS enabled vessel within a 6 km detection zone were included. Times with high wind and current as well as small boat presence were removed. The dB difference between Baseline and Slowdown periods has been provided for each metric. A negative difference means that the slowdown period is quieter (see Table 2).



	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	113.8	112.0	-1.8
2	L50	104.6	102.6	-2.1
3	L95	92.9	91.8	-1.1
4	Leq	104.6	102.7	-1.9
5	Minutes	9865	10129	

	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	97.6	97.4	-0.2
2	L50	85.5	85.9	0.4
3	L95	82.4	83.6	1.2
4	Leq	87.6	88.1	0.4
5	Minutes	9865	10129	



	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	127.3	127.8	0.6
2	L50	119.3	117.8	-1.5
3	L95	109.9	108.2	-1.6
4	Leq	119.6	118.4	-1.2
5	Minutes	3527	2953	

	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	129.3	126.8	-2.5
2	L50	122.5	116.4	-6.1
3	L95	112.6	106.8	-5.8
4	Leq	122.4	117.1	-5.2
5	Minutes	1235	1591	

Figure 9. Exceedance CDF plots of ambient SPL (dB re 1 µPa) for communication and echolocation bands (top row) and for bulk and cargo carriers (combined) and container vessels alone (bottom row) by Baseline period (red line) and Slowdown period (blue line). Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files

Note: Only minutes with an AIS enabled vessel within a 6 km detection zone were included. Times with high wind and current as well as small boat presence were removed. The dB difference between Baseline and Slowdown periods has been provided for each metric. A negative difference means that the slowdown period is quieter (see Table 2).

2.2.3 Ambient Noise: Comparing quiet time thresholds for Baseline versus Slowdown

As a direct result of a vessel slowdown, the noise exposure duration time will increase, in theory reducing the amount of “quiet time” between vessel transits. The value of quiet time to SRKW is that there is little or no anthropogenic noise interference with acoustic behaviours (see Heise et al. 2017). Clearly, natural environmental conditions (such as waves or rain) can also cause interference to killer whale communication (Miller 2006). There is sparse data on what threshold might represent “quiet time”.

This study assessed variability in two received SPL thresholds (both broadband: 10Hz to 100 kHz). Firstly, 110 dB re 1µPa, below which behavioural dose response curves (SMRU Consulting 2014) predict that no noise related behavioural responses are likely, and secondly 102.8 dB re 1µPa, which is the L5 SPL for the Baseline months of this Slowdown trial. The L5 has been used to represent “natural ambient” and this assumption has been previously confirmed by analysis of acoustic data from Lime Kiln in 2012 that removed periods with no detections of vessels, small boats and associated depth sounders (the three major anthropogenic noise sources at this location) and found a broadband median (L50) SPL at ~101 dB re 1µPa (SMRU Canada, Hemmera, and JASCO 2014).

Received SPL data used in this analysis included all acoustic data and therefore multiple noise sources – both natural and anthropogenic. We calculated the number of minutes (duration) of every quiet period below the two selected thresholds. We used a Kolmogorov–Smirnov test (nonparametric test of the equality of continuous, one-dimensional probability distributions) to compare the distribution of quiet minutes between Slowdown and Baseline periods. For a threshold of 102.8 dB re 1µPa, there was no significant difference between the duration of “quiet time” periods (Figure 10, Test statistic: $D=0.034$, Probability: $p=0.145$). For a threshold of 110 dB re 1µPa, there was no significant difference between the duration of “quiet time” periods (Figure 10, Test statistic: $D=0.026$, Probability: $p=0.176$). The median duration of quiet periods was 3 to 4 minutes with the max duration of quiet periods higher during the Baseline period (328 minutes) compared to the Slowdown period (272 minutes) (Table 3). Considering both the Baseline and Slowdown periods, SPL levels at Lime Kiln were below 102.8 dB re 1µPa ~25% of the time and below 110 dB re 1µPa ~50% of the time. The total percent of time below quiet thresholds (both 10.28 and 110 dB re 1 µPa) increased slightly (~3%) from Baseline to Slowdown periods for both quiet thresholds (Table 3).

The average duration of quiet periods (3-4 minutes) seems low at first thought but makes more sense when observing the 1-minute SPL levels at varying time resolutions (Figure 11). Over short time scales (hours), SPL levels between 102.8 and 110 dB re 1µPa thresholds exhibited a high degree of oscillation. This results in very short duration quiet periods. This high degree of oscillation is related the to the very dynamic ocean soundscape with biological, anthropogenic and physical noise generating processes occurring on their own time scales and combining into a very dynamic pattern. It is also related to the analytical methods used. The acoustic data are averaged within a minute with no overlap between minutes. This will cause a less smooth transition from one minute to the next and add to the oscillating nature of SPL summary results.

All the plots in Figure 11 start at 3:00 AM on 18 August 2016. The general increasing trend seen most clearly in the quarter day panel (top left), is likely due to a transition from a quiet summer night to a summer day with small boat traffic.

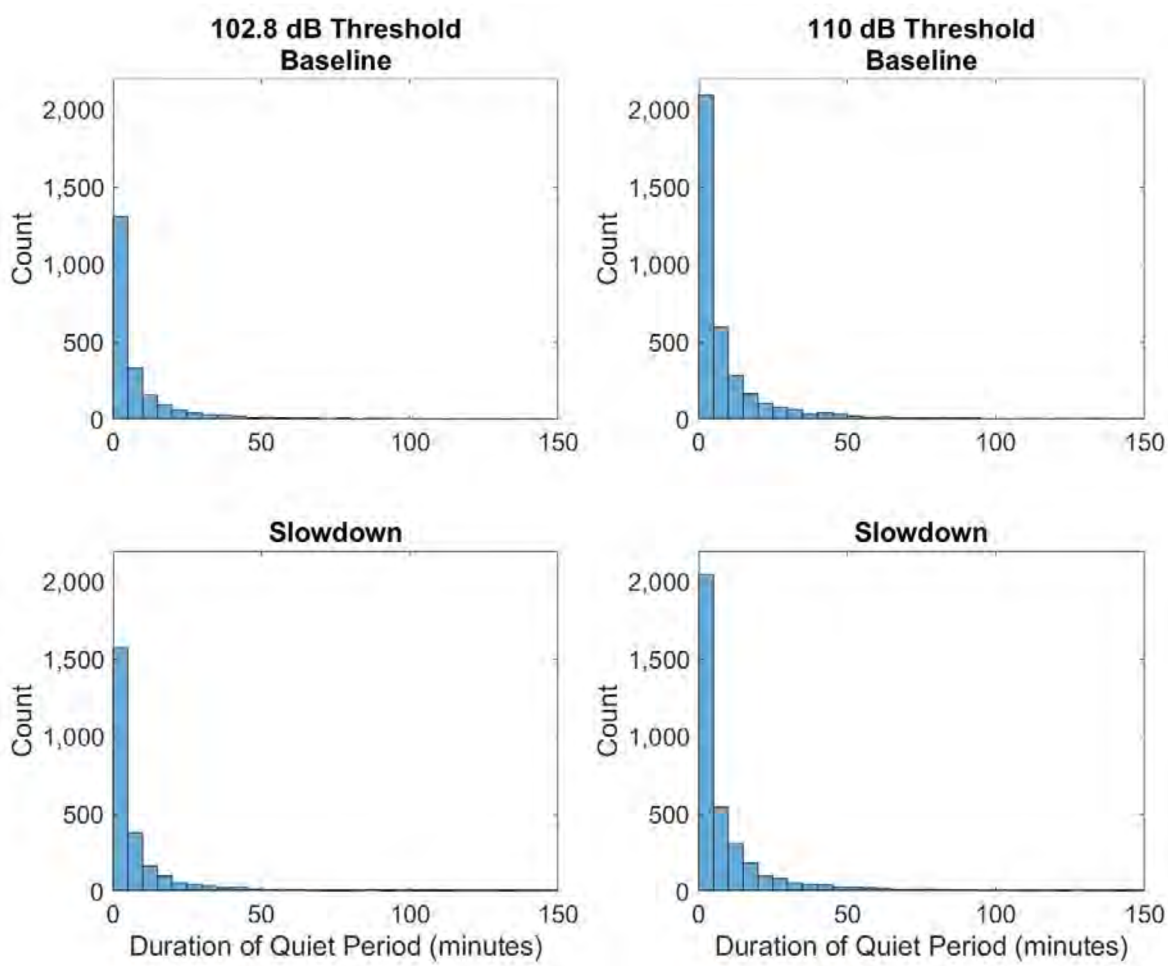


Figure 10. Histogram of the duration of “quiet time” period (minutes) below 102.8 dB re 1µPa threshold (left) and 110 dB re 1µPa threshold (right) for Baseline (top) and Slowdown (bottom) periods.

Note: No significant statistical difference was found between the Baseline and Slowdown distributions. Y-axis is the count of minutes below the threshold.

Table 3. Descriptive statistics of the duration of "quiet time" for two different SPL thresholds. 'Quiet time %' is the total duration of quiet times divided by the duration of the Baseline or Slowdown period.

Quiet Threshold	Statistic	Baseline (minutes)	Slowdown (minutes)
102.8 dB	Median	3	3
102.8 dB	Max	328	207
102.8 dB	Quiet time (%)	24.9%	28.1%
110 dB	Median	3	4
110 dB	Max	334	272
110 dB	Quiet time (%)	49.2%	53.5%

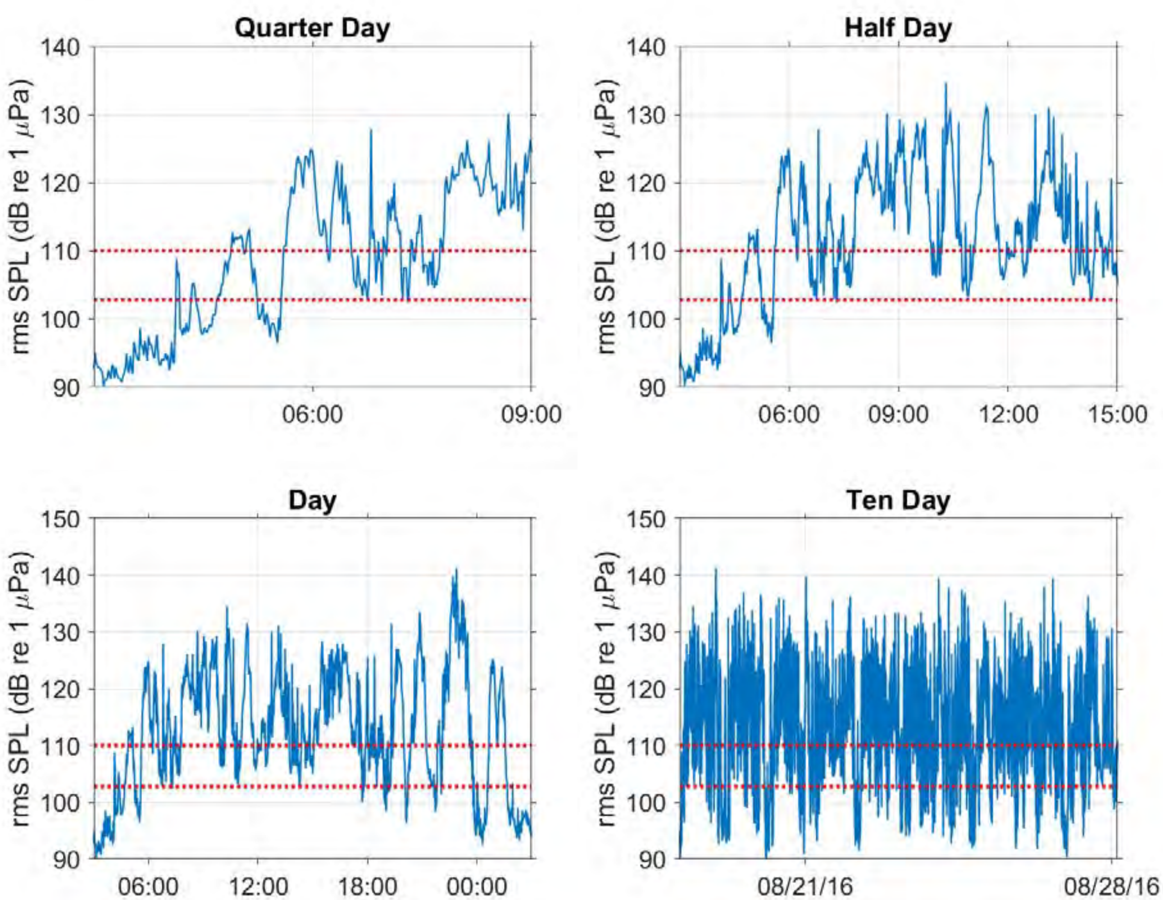


Figure 11. Plots of 1-minute SPLs at Lime Kiln at quarter day (top left), half day (top right), day (bottom left) and ten day (bottom right) resolutions. All plots start at 3:00 o'clock on 18 August 2016. Red dotted lines are the two quiet thresholds used.

Note: Due to the high degree of oscillation in the data, quiet periods do not typically last long.

2.2.4 Ambient Noise: GAMM Analysis Comparing Baseline versus Slowdown explanatory covariates

Statistical analysis of broadband SPL at Lime Kiln was conducted using a Generalized Additive Mixed Model (GAMM) framework to determine which covariates explained changes in noise levels (SPL) at the Lime Kiln hydrophone. A main factor of interest was whether noise levels at Lime Kiln were significantly reduced during the Slowdown period compared to the Baseline period, but the GAMM also provides information on the contributions of other key variables. A GAMM approach was taken for two reasons. Firstly, the relationship between covariates and SPL may not always be linear and therefore a model that also allows for non-linear effects was needed. Secondly, successive SPL measurements at 1-minute intervals are not independent, thus a model that allowed for random effects was needed to account for temporal autocorrelation in the data series. This fine temporal scale analysis used the same data as we used for the CDF analyses (Section 2.2.2), but did not filter out confounding factors, nor restrict the dataset to vessel detections within 6 km. The GAMM analysis was conducted in R (a programming language and software environment for statistical computing) using the mgcv package (Wood 2004).

The statistical analysis included the key co-variate of interest: period of trial (Baseline or Slowdown), and a number of additional regression covariates that would help control for the variation in noise levels received at Lime Kiln. These covariates included (see Table 1 for more info):

- the range to the closest AIS-enabled vessel;
- speed through water of the closest AIS enabled vessel;
- number of AIS enabled vessels within 15 km of Lime Kiln;
- AIS enabled vessel type;
- presence of a small boat (based on an acoustic detector;)
- wind velocity; and
- current velocity

Due to the large number of AIS-enabled vessel types in the original dataset (13), some of these types were condensed into broader categories (reflecting similar speeds and size) so that the GAMM model would run effectively. Container vessels and car carriers were combined into a 'Containerized' category. Bulk carriers, general cargo, and tankers were combined into a Bulk category. Yacht, sail, naval, and heavy lift, ferries and passenger were added to the 'other' vessel type. Tugs had their own category, given their slow speeds but also their large contribution to the soundscape (Figure 4). For each category, we then fit separate estimates for the relationship of range to the closest vessel in that category, and separate estimates for the speed through water for vessels in that category. To deal with the lack of independence of successive 1-minute SPL data, we included an auto-correlation function in the model to down-weight adjacent data and avoid pseudo-replication and the inflation of p-values.

Independence was assumed only after a four-hour time window based on an empirical examination of the data series.

Akaike Information Criterion (AIC) scores were used to select between various GAMMs. A GAMM was initially fit that included only the main effects. These included the period (Slowdown versus Baseline), AIS-enabled vessel presence, small boat presence, wind, current and number of AIS-enabled vessels. Additional covariates were then added to the model to see if the model fit improved as indicated by a drop in the model's AIC score. An iterative approach was used to select and deselect different covariates, to test interaction terms, and to test linear versus non-linear relations such that the final GAMM selected (Table 4 and Table 5) resulted in the model with the lowest AIC score.

Table 4. Results of the best fitting GAMM model. The parametric coefficients include all the categorical covariates, linear fits and any of their interactions included in the model. Non-linear covariates are in Table 5.

Parametric coefficients (i.e. Linear)	Estimate (dB)	Std. Error	t value	p-value
Intercept	111.06	0.28	401.43	<0.001
Period (Slowdown)	-1.17	0.20	-5.80	<0.001
Vessel Type (Containerized)	0.20	0.47	0.42	0.67
Vessel Type (Bulk)	-0.34	0.57	-0.59	0.55
Vessel Type (Tug)	1.64	0.39	4.21	<0.001
Boat Detector (Present)	6.63	0.05	127.89	<0.001
Wind	-0.08	0.03	-2.47	0.01
Speed Through Water by Vessel Type (Other)	0.04	0.02	2.66	<0.01
Speed Through Water by Vessel Type (Containerized)	0.16	0.03	5.91	<0.001
Speed Through Water by Vessel Type (Bulk)	0.20	0.04	4.71	<0.001
Speed Through Water by Vessel Type (Tug)	-0.03	0.04	-0.70	0.48

The best fitting GAMM included the following covariates and interactions. They are not listed in order of their magnitude of effect or importance in the model as ranking the order of their magnitude of effect in this complex model that has non-linear, linear and factor level covariates is not possible.

- Slowdown trial period (as a categorical variable)
- The interaction of range by AIS enabled vessel type (modelled as a smoothed cubic regression spline)
- The interaction of speed through water by AIS enabled vessel type (modelled as a linear variable)
- AIS-enabled vessel type (as a categorical variable)
- Small boat presence (as a categorical variable)
- Current velocity (modelled as a smoothed cyclic cubic regression spline)

- Wind velocity (modelled as a linear variable)

Most of the above terms in the GAMM were statistically significant (i.e. p-values < 0.05) (Table 4 and Table 5) and explained 39% of the variance in the data. Number of AIS enabled vessels within 15km was dropped from the model as it was not significant and did not improve the AIC score of the model.

Table 5. Results of the best fitting GAMM model. The smooth terms are those covariates that were fit with non-linear splines. Linear covariates are in Table 4.

Approximate significance of smooth terms	edf	Ref .df	F	p-value
Range by Vessel Type (Other)	2.91	2.91	168.6	<0.001
Range by Vessel Type (Containerized)	2.96	2.96	463.6	<0.001
Range by Vessel Type (Bulk)	2.97	2.97	711.4	<0.001
Range by Vessel Type (Tug)	2.86	2.86	257.1	<0.001
Current	2.95	3	216.8	<0.001

The interpretation of the GAMM outputs in Table 4 and Table 5 is not simple because of the complexity of the statistical model. This statistical complexity is warranted by the multiple and complicated covariates which explain the large and dynamic fluctuations in the soundscape at Lime Kiln. The best fitting GAMM used both linear (i.e. parametric) coefficients and non-linear (i.e. smooth) terms to model the fluctuations in ambient noise.

2.2.4.1 Interpreting Linear Covariates

Focusing first on the linear coefficients and the 'Estimates' column in Table 4, it is important to note that these are in units of dB and that factor (i.e. categorical) covariates are always compared to a 'reference' of that covariate. For example, the factor of Period in Table 4 is set to Slowdown. Since there are only two Periods (Baseline and Slowdown), the estimate reported in Table 4 for Period is the difference (in dB) between Slowdown and Baseline periods. From the results in Table 4 we can make the following interpretations:

- **Intercept:** This is just the model y-axis intercept as per any simple linear regression.
- **Period:** There is a significant difference in ambient noise from Baseline to Slowdown periods. While there is an estimated 1.17 dB decrease in ambient noise from Baseline to Slowdown, this is not the entire reduction in noise level that occurred from the Slowdown since this does not include other covariates which did change between Baseline and Slowdown periods (namely vessel speed through water and vessel type). In order to estimate reductions in noise levels from the slowdown, we need to add in these other covariates and use the GAMM model to make predictions. This is done below.
- **Vessel Type:** When compared to the vessel type Other, Containerized and Bulk were not significantly different, but Tugs were. This is likely due to the large variety of vessels included in Other which generate a wide range of noise levels at Lime Kiln and from which it is therefore difficult to differentiate noise levels of Containerized and Bulk vessel types. However, the

interaction of vessel type with speed through the water and range were significant, so vessel type was kept in the GAMM model (noting one can't have an interaction term without the main effect). In addition, the main reason for including vessel type in the model was to control for the variance in noise level due to vessel type (and its interaction with other covariates), not to test if there is a difference in noise levels between vessel types. We already know this to be a fact (Veirs et al. 2016).

- **Boat Detector:** There was a significant increase (6.6 dB without including other covariate effects) in noise levels at Lime Kiln when small boats were detected acoustically (when compared to no small boats being detected).
- **Wind:** There is a very small (but significant) negative effect of wind on ambient noise levels at Lime Kiln. This suggests that as wind increases, noise levels decrease. This should not be over interpreted as, a) there were not many windy periods during the Baseline and Slowdown periods, thus not a lot of windy data to draw from, and b) windier conditions could lead to fewer small boats which have a much larger effect on ambient noise levels.
- **Speed through the water by vessel type:** This linear interaction between speed and vessel type had a small but significant relationship with noise levels for all vessel types except tugs. Tugs are probably not significant because their speed did not vary much in this dataset. According to this GAMM, there is a 0.16 dB increase in noise levels at Lime Kiln for every knot increase in speed for containerized vessels. The fact that there is not a larger effect of speed on noise levels at Lime Kiln, especially when other studies report >1 dB per knot increase (Veirs et al. 2016) is due to the large ranges and longer time periods over which we are measuring these vessels rather than just using to point of closes approach (e.g. the closest large AIS-enabled vessels get to Lime Kiln is ~2.3 km and we included data out to 15 km. Median range was 6.1 km. Veirs et al. (2016) included data for 30 seconds, our data can include time periods of ~1-1.5 hours). Transmission loss accounts for this large difference in dB per knot changes between source levels at the vessel and received levels at Lime Kiln. This result of the GAMM should not be over interpreted in isolation of other covariates. Predictions based on the GAMM are provided later which will be more indicative of the combined effect of speed and other covariates.

2.2.4.2 Interpreting Non-linear Covariates

Moving on to the non-linear covariates reported in Table 5, we can see that these are all significant. The first column shows the Estimated Degrees of Freedom (edf). These are not close to one, indicating that these covariates should be modelled as non-linear covariates. We can draw the following interpretation from these non-linear covariates:

- **Range by vessel type:** Range from the vessel to Lime Kiln can have a large effect on noise levels at Lime Kiln. Noise levels are highest when the vessel is closest to Lime Kiln. Noise levels drop more than 10 dB as the vessels move to ~10 km from Lime Kiln, and then noise levels plateau.

- **Current:** Current can have a large effect on noise levels at Lime Kiln regardless of whether currents are ebbing or flooding with noise levels increasing with current velocity. However, the median predicted current velocity at Lime Kiln in this dataset was -38.58 cm/sec (a negative flow is an ebb, a positive is a flood). At this flow, current would add ~1 dB to the noise levels at Lime Kiln. At max flow rates of ±100cm/sec, noise levels would increase by ~6 dB. Flow noise effects on lower frequency ambient noise assessments is well documented. The use of lunar month time period sampling units reflects the desire to minimize the effects of tidal currents (ensuring each sample period has similar number of tidal oscillations). Current velocity effects also justified the removal of high current speeds in the CDF analysis in Section 2.2.2.

2.2.4.3 Select GAMM Predictions

As discussed above, looking at any one covariate in isolation can be misleading when interpreting the GAMM output, especially for such a complex model. We therefore provide some select predictions using the GAMM model. Figure 12 shows the predicted relationship between noise levels at Lime Kiln and the range from Lime Kiln of Bulk and Containerized vessel types for both Baseline and Slowdown periods when no small boats are present and current, and wind are zero. Two trends can be seen. Noise levels drop (in a non-linear way) as the range increases and Slowdown noise levels are lower than Baseline noise levels. At the range of 2.3 km (distance from Lime Kiln to center of northbound shipping lane), the predictions in Figure 12 are 116.5 and 115.1 dB re 1 µPa for Bulk vessel types and 118.2 and 115.9 dB re 1 µPa for Containerized vessel types for Baseline and Slowdown periods, respectively. This is a drop of 1.5 dB for Bulk and 2.3 dB for Containerized vessel types from Baseline to Slowdown. This is not as high of a drop as found in the CDF analysis for container ships on their own (at L50 the drop was 6.1 dB). This may be because of the unexplained variability (61%) the GAMM could not explain.

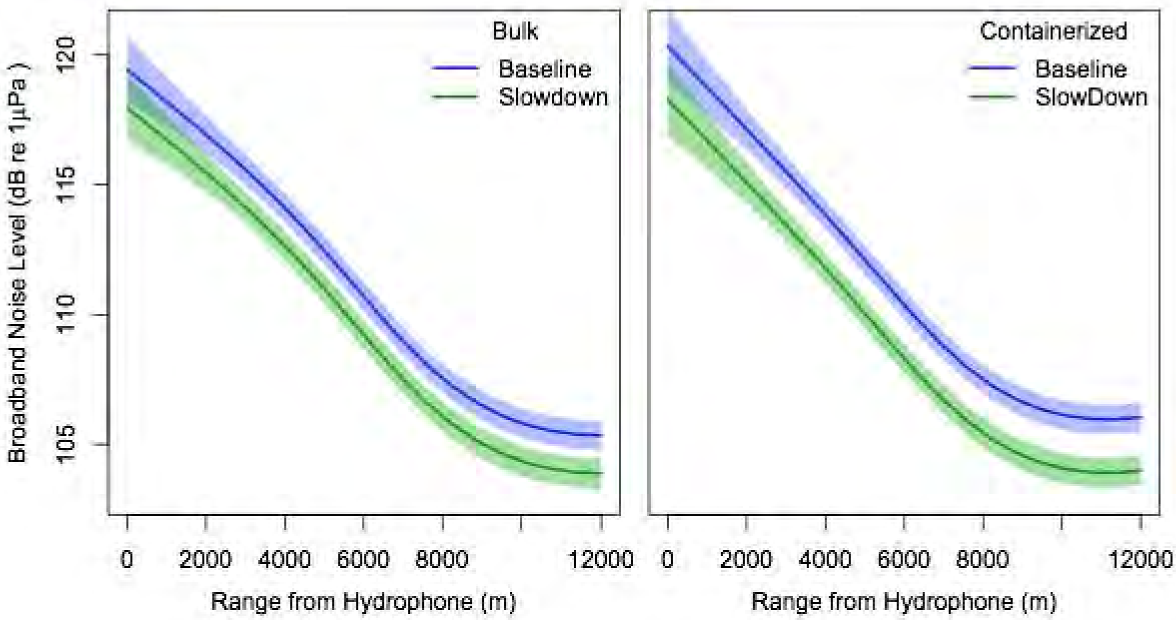


Figure 12. Model predictions for Bulk vessel type (left panel) and Containerized vessel type (right panel) modeled as a non-linear function of distance from the hydrophone. Depicted are the expected values of the model and its 95% confidence regions for Broadband noise levels received at Lime Kiln assuming median vessel speeds through the study area during Baseline (blue) and Slowdown Periods (green). Noise levels contributed from currents, wind and small boats were assumed to be zero in both figure panels.

2.2.4.4 WSDOT

Due to the small number of Washington State Department of Transportation (WSDOT) ferry transits through Haro Strait, and the large distance between Lime Kiln and where they transit Haro Strait (~15 km), we were not able to meaningfully incorporate WSDOT vessels into the CDF or GAMM analyses. They will require a bespoke approach which will involve identifying times when WDOT ferries are the only vessel within 15 km of Lime Kiln and comparing SPL when they were slowed down (the first 2 weeks of the Slowdown period), and when they weren't. The AIS data needed to process this has been requested from JASCO. Because it is beyond the range that they used for their analyses to date, they are having to reprocess their raw AIS data.

2.3 SRKW Vocal Activity: Comparison of PAM detections in Slowdown and Baseline

This deliverable compiled SRKW vocal activity as detected at the Lime Kiln hydrophone during the two Slowdown months as well as two Baseline months (one month prior to the Slowdown trial and one month in the summer of 2016).

2.3.1 Data processing to assess PAM detections of killer whales at Lime Kiln hydrophone

Acoustic detections of killer whales using data from the Lime Kiln hydrophone were assessed across the two trial months (Slowdown) and two non-trial months (Baseline) (see Table 6). Each day of data was initially processed using PAMGuard software (64-bit Version: 1.15.11; Gillespie et al. 2008). PAMGuard was configured with customized click classifiers that were parameterized to classify impulsive signals as porpoise, killer whale, 50 kHz echosounders and vessel noise, as well as a whistle and moan detector to automatically detect tonal signals. This post-processing resulted in 'binary files' (a proprietary PAMGuard filetype) and a populated SQLite database that could be used to further analyze data using PAMGuard's ViewerMode. PAMGuard ViewerMode was then used to identify and log killer whale, porpoise, and anthropogenic events. Events were identified using a combination of the click detection time/bearing display, a scrolling spectrogram and the Data Map (condensed display showing all of the click and whistle and moan detections for the day). An event was defined as a period of time in which the sound type was present continuously with less than a 30-minute inter-detection interval. Event logs were then exported for each day of data and combined by event type for each month of data using a custom R script. Killer whale events were then reviewed a final time to provide a final Ecotype identification (SRKW, Transient, unknown Ecotype), when possible. Vocal event figures for SRKW were produced for each month of data using a custom R Script (see Figure 13-Figure 16).

2.3.2 Killer whale detections using PAM at Lime Kiln hydrophone

During the two-month Slowdown trial period, SRKW were detected on 9 different days across 10 events for a total duration of 17 hours and 7 minutes (Table 6). When summing over both the Baseline and the Slowdown periods, SRKW were detected by PAM on 35 days across 55 unique events. Most of these (21 days and 38 events) were made in the Baseline month in 2016, during which 10 transient killer whale or unknown killer whale ecotype events were also detected (Table 6). Figure 13 and Figure 14 display the date and time of SRKW detections for the Baseline period, while Figure 15 and Figure 16 display data for the Slowdown period. The difference in SRKW detections between 2016 and 2017 is likely due to differences in prey abundance. We compared SRKW PAM detection events made in the summer months of 2017 (July through September inclusive) with those made by local killer whale observers. Table 6 summarizes these results. All PAM detections that occurred while land-based human observers were conducting monitoring were also detected visually. All visual detections made by observers were also detected by PAM (i.e., no silent transits). Seven of the 17 SRKW detection events made in 2017 occurred at night (Table 7), with a total duration of 21 hours 5 minutes across the 3-month summer period. The highest mean transit duration occurred during September 2017.

Table 6. Summary information of PAM detection events of killer whales made at Lime Kiln hydrophone across two Baseline and two Slowdown months.

Date	Number of SRKW days	Number of SRKW events	Mean duration (hr:min:sec)	Total duration (hr:min:sec)	Additional transient KW or unknown KW events
Aug. 14 – Sept. 14 2016 (Baseline)	21	38	1:15:55	48:05:04	10
July 5 – Aug. 6 2017 (Baseline)	5	7	0:34:01	3:58:09	0
Aug. 7 – Sept. 6 2017 (Slowdown)	3	3	1:33:05	4:39:16	0
Sept. 7 – Oct. 6 2017 (Slowdown)	6	7	1:46:54	12:28:17	0

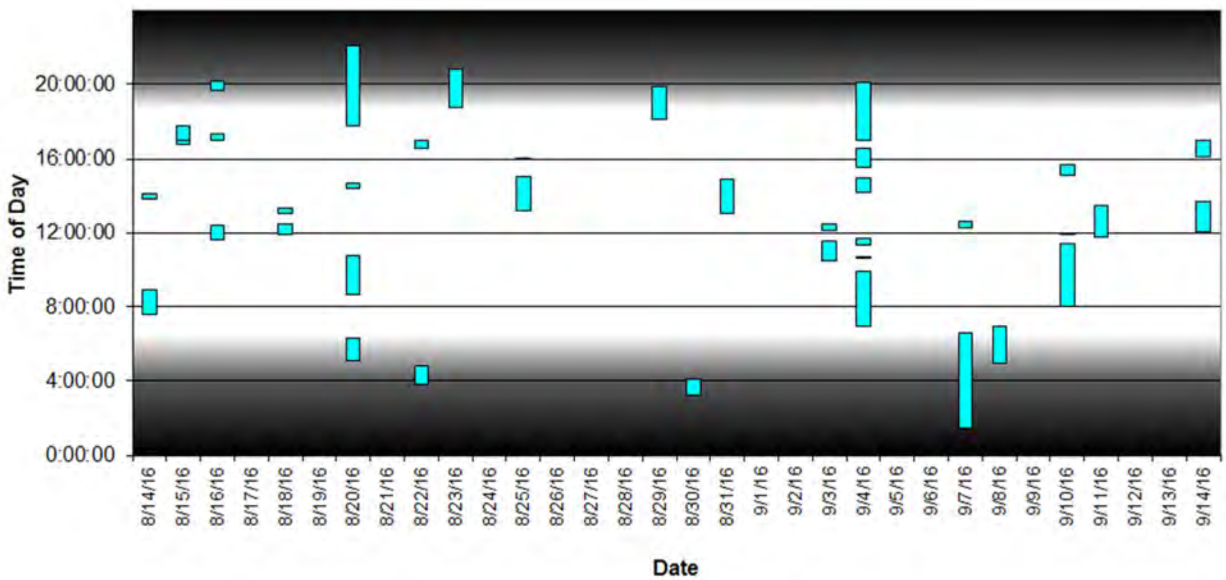


Figure 13. Date, time and duration of SRKW PAM detections made at Lime Kiln (Baseline = August 14 – September 14, 2016).

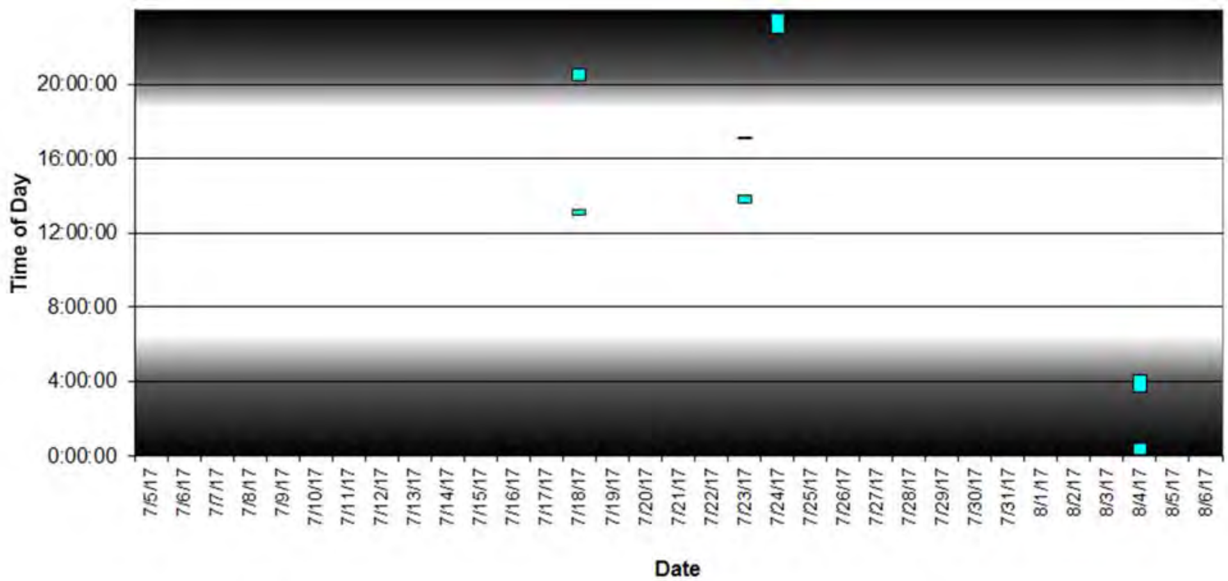


Figure 14. Date, time and duration of SRKW PAM detections made at Lime Kiln (Baseline = July 5 – August 6, 2017).

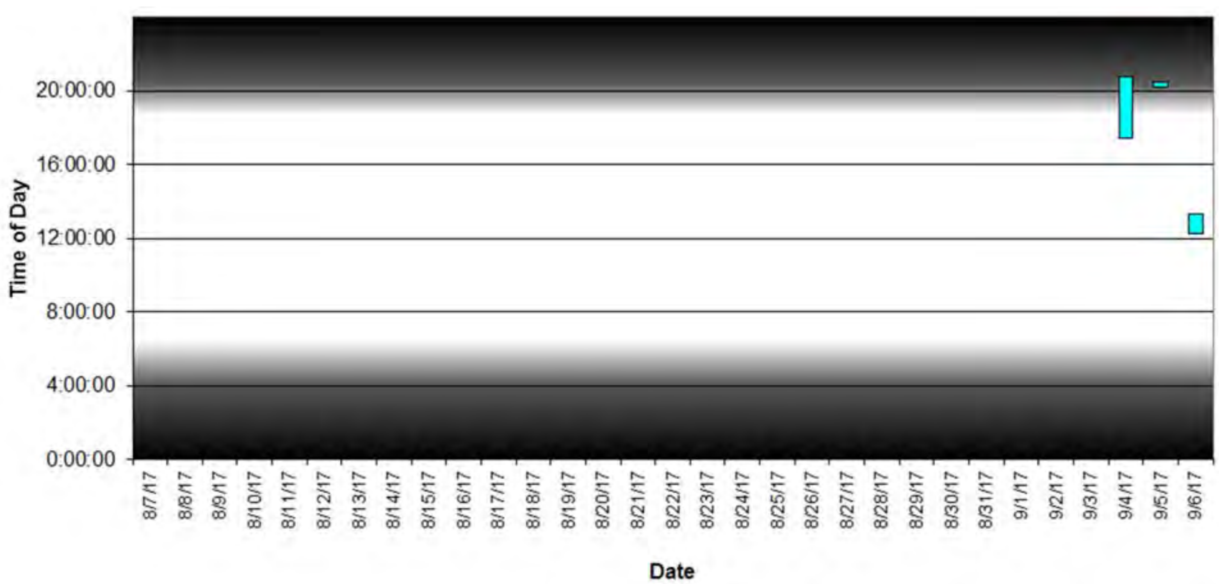


Figure 15. Date, time and duration of SRKW PAM detections made at Lime Kiln (Slowdown = August 7 – September 6, 2017).

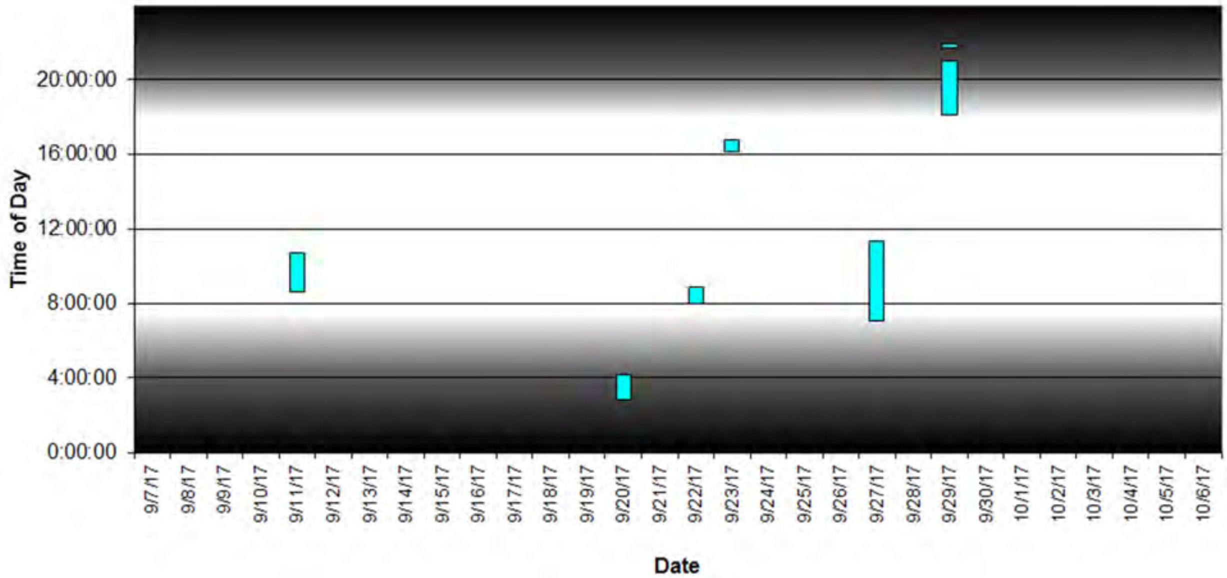


Figure 16. Date, time and duration of SRKW PAM detections made at Lime Kiln (Slowdown = September 7 – October 6, 2017).

Table 7. Summary of SRKW PAM events made in 2017 compared with those made by killer whale observers at Lime Kiln State Park.

Date	Start time (Local PDT)	Event Duration (hr:min:sec)	SRKW also observed by killer whale observers stationed at Lime Kiln State Park (consistently 9 am – 5 pm)
07/18/17	12:57:50	0:17:23	Y
07/18/17	20:12:55	0:37:26	N (no observer present)
07/23/17	13:35:18	0:28:06	Y
07/23/17	17:05:25	0:05:29	Y
07/24/17	22:46:44	1:02:54	N (no observer present)
08/04/17	0:06:31	0:33:31	N (no observer present)
08/04/17	3:25:16	0:53:20	N (no observer present)
09/04/17	17:28:00	3:17:16	Y
09/05/17	20:11:55	0:19:18	N (no observer present)
09/06/17	12:16:53	1:02:43	Y
09/11/17	8:34:08	2:07:36	Y
09/20/17	2:47:12	1:22:07	N (no observer present)
09/22/17	7:59:10	0:52:04	Y
09/23/17	16:07:50	0:38:08	Y
09/27/17	7:01:06	4:20:38	Y
09/29/17	18:07:27	2:54:34	N (no observer present)
09/29/17	21:42:29	0:13:10	N (no observer present)
Overall		**21:05:41**	**All 8 non-observed PAM events were at night**

3 Overall Conclusions

Based on the information presented in this report, the following generalized conclusions are provided:

- Broadband (10 Hz – 100 kHz) median ambient noise levels at Lime Kiln hydrophone in Haro Strait summarized at lunar monthly timescales can vary by ~4-5 dB, with levels typically higher in 2016 than 2017. This variability was largely due to changes in the 10-100 Hz frequency band, with far lower variability at 1-10 kHz.
- Lunar month variability was not simply explained by the number of piloted large commercial vessel. Further assessment of the consequences of tug, motor yacht and small boat presence, tidal effects, as well as differential Fraser River discharge effect on low frequency propagation is required. It is clear analyses of noise trends relevant to killer whales needs to focus on finer time scales, appropriate frequency ranges and incorporate covariate data.
- Monthly scale spectrograms show the regular passage of large vessels through Haro Strait with daytime increases in higher frequency sound pressure level (SPLs), driven by the presence of small boats near Lime Kiln during daylight hours.
- A fine-scale analysis of 1 minute average level SPLs compared the two lunar months of the ECHO Program Slowdown trial period (n=82,441 minutes) with two months of a Baseline period (n=82,741 minutes), considered to have similar acoustic propagation conditions (August 18 to September 16, 2016 and July 9 to August 7, 2017).
- When compared to the Baseline period, a significant reduction in vessel speed through water was observed during the Slowdown period over the designated slowdown area. For example, bulker, general cargo and tanker vessels slowed by approximately 2 knots from median speeds on the order of 13-13.6 knots to 11.4-11.8 knots, container vessels slowed from median speeds of 18.6 knots to 11.4 knots, while car carriers slowed from 17.1 to 11.5 knots.
- Pilots self-reported a speed reduction compliance level of ~60% of all 951 transits during the Slowdown trial. More piloted vessels transited Haro Strait during the Slowdown period than the Baseline period. During the Slowdown period, non-piloted tugs averaging ~7 knots speed through water contributed >10,000 minutes (~20% of all AIS vessel types) to the soundscape.
- Using cumulative distribution functions when vessels were within a 6 km detection range, and consistently filtering for confounding effects of high wind and currents, as well as small boat noise, we observed a 2.5 dB median reduction (116.9 to 114.4 dB re 1 µPa) in the Slowdown period compared to Baseline - the equivalent of a 44% reduction in acoustic intensity or 16% reduction in loudness.
- The Slowdown period also showed a quantifiable broadband noise reduction at the mean (Leq) by 2.0 dB, at L5 by 1.4 dB and at L95 by 0.3 dB. The lesser effect at lower (e.g., L95) noise levels is likely to be a result of the combined effect of reduced source level amplitude of slower transiting vessels and the extended exposure period resulting from slower vessels moving through the detection zone.
- Decade band cumulative distribution function SPL analysis indicate ambient noise reduction (L50) in the Slowdown period is highest between 10-100 Hz (3.1 dB) and lowest between 10-100 kHz (0.3 dB). The majority of vessel acoustic energy is in the lower frequency bands (<1000 Hz). Comparison to the recently developed CORI metrics of SRKW communication (500-

15,000 Hz) and echolocation (15-100 kHz) frequency bands show a reduction of 2 dB in the communication band but a 0.4 dB increase in the echolocation band. High frequency noise transmission loss between the shipping lanes and Lime Kiln (2.3-5 km) will minimize any vessel slowdown effect at higher frequencies. In addition, above ~50 kHz, spikes in electrical system noise and the acoustic system's noise floor may affect robust comparisons across periods.

- Comparison of "quiet times" (using both <110 and <102.8 dB re 1 µPa) during Baseline and Slowdown periods indicated no statistical difference in distributions, with a maximum interval highest in the Baseline period, similar medians, but with the Slowdown period having ~3% more time below either threshold.
- Statistical analysis using a Generalized Additive Mixed Model (GAMM) of co-variates affecting received SPL at Lime Kiln to a range of 15 km described 39% of the variability in noise levels, with range to vessel by vessel type (non-linear), small boat presence and extreme current speed (non-linear) likely most important, followed by Slowdown period (categorical) and speed through water by vessel types, and wind speed. GAMM predictions suggest the Slowdown trial was successful in decreasing noise levels at Lime Kiln. When Bulk vessel types were at 2.3 km from Lime Kiln, the slowdown resulted in a 1.5 dB reduction in noise, as predicted by the GAMM. The corresponding drop in noise levels for the Containerized vessel type was 2.3 dB.
- Acoustic detections of SRKW calls, whistles and clicks recorded SRKW present on just 9 days (10 transit events, total ~17 hours) during the Slowdown period, far less than that found in 2016. All six visual observations made at Lime Kiln during the Slowdown period were also recorded acoustically and all additional acoustic detections were made during periods when no observations were being undertaken.
- All analysis completed indicated the Slowdown trial was successful in reducing the received broadband sound pressure levels at the Lime Kiln hydrophone.

4 Acknowledgements

We'd like to thank VFPAs ECHO Program for funding this study as well as Dr. Robert Otis and Jeanne Hyde for providing observer data at Lime Kiln. We thank Krista Trounce (ECHO Program) for her comments that improved this report.

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Appendix 1: Ambient Noise: Lunar Month Summary

This appendix provides summary lunar month ambient noise reporting for two Slowdown months and two Baseline months.

A calibrated Reson TC4032 hydrophone was used for this project and installed in 23 m of water depth ~70 m from the shoreline in front of the Lime Kiln Point State Park light house at 48.5155N, 123.15291W and cabled to shore. Data were digitized with a high-quality data acquisition board (St. Andrews Instrumentation Ltd. http://www.sa-instrumentation.com/) at a sample rate of 250 kHz, 16-bit depth and stored by PAMGuard as 1-minute wav files. These files were post-processed with custom Matlab scripts modified from Merchant et al. (2015) with a 1 second Hanning window, 50% overlap and Welch's averaging to average across each 1-minute file.

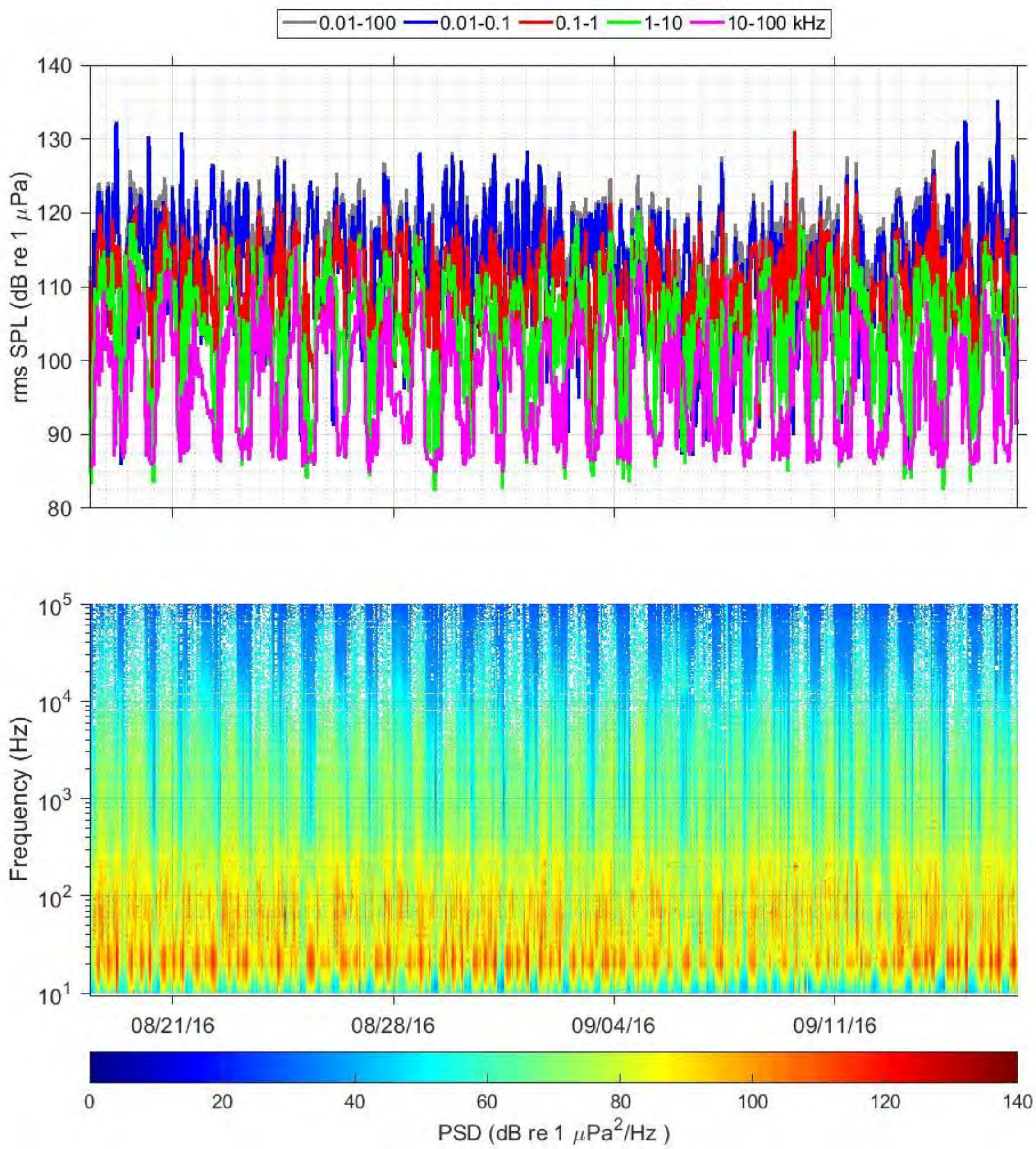
In order to match JASCO's and ONC's ambient noise measurements at the ECHO Program's Underwater Listening Station (ULS) in the Strait of Georgia (for ease of comparison between reference sites), noise summaries at three temporal scales; lunar month, weekly and daily are provided. Lunar months were selected to reduce any potential impact of water current flow noise on low frequency bands. Lunar months began and ended with each full moon; weekly periods began at 0:00 Sunday morning and ended at midnight the following Saturday; daily periods started at 0:00 and ended at 24:00, all in local time. A Year 1 ambient noise report has previously been submitted to ECHO.

A1.1 Lunar Month Aug 18 – Sep 16, 2016 (Baseline)

A total of 42,338 minutes of data, across 30 days, are presented for this lunar month.

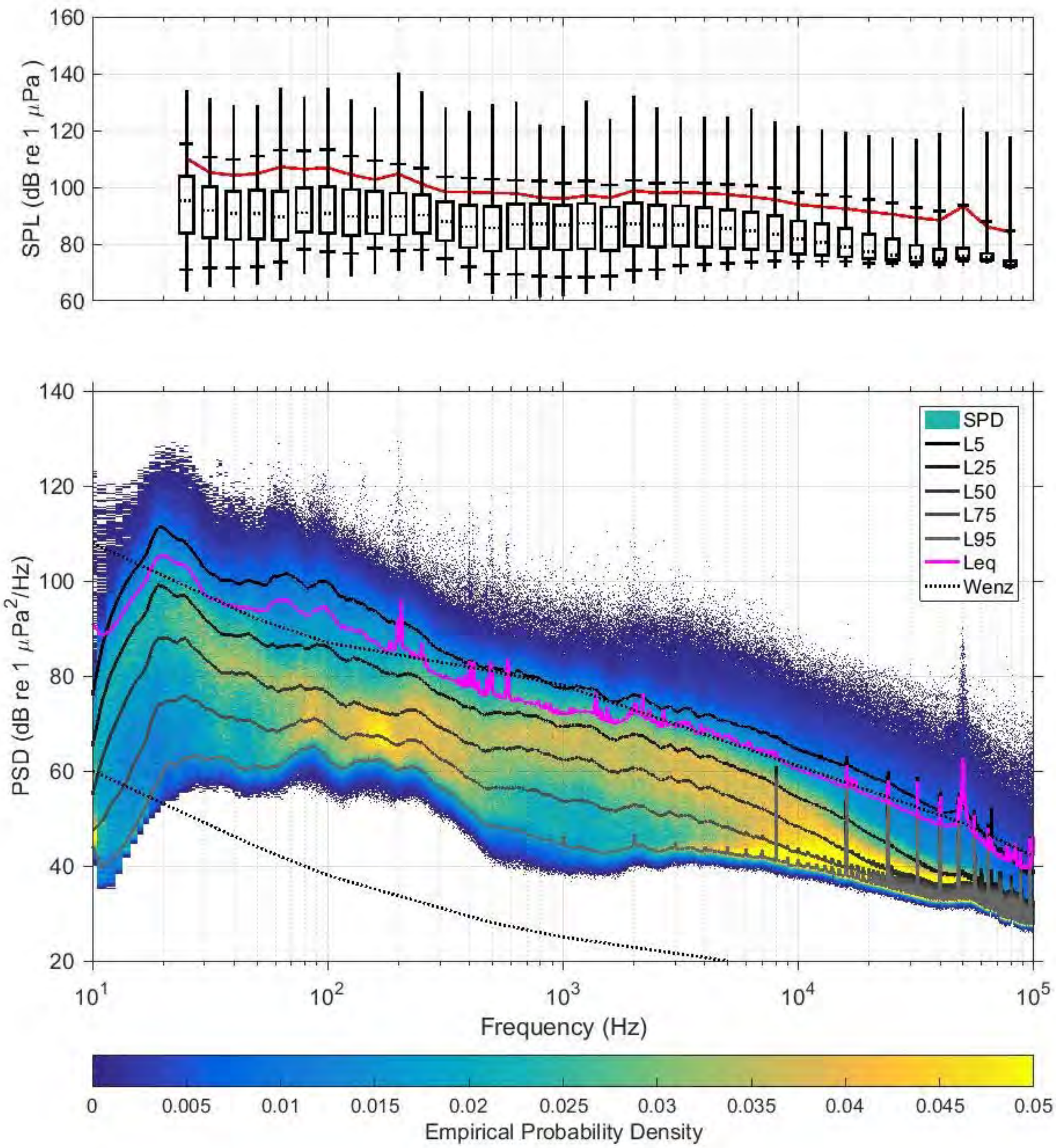
A1.1.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.1.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.

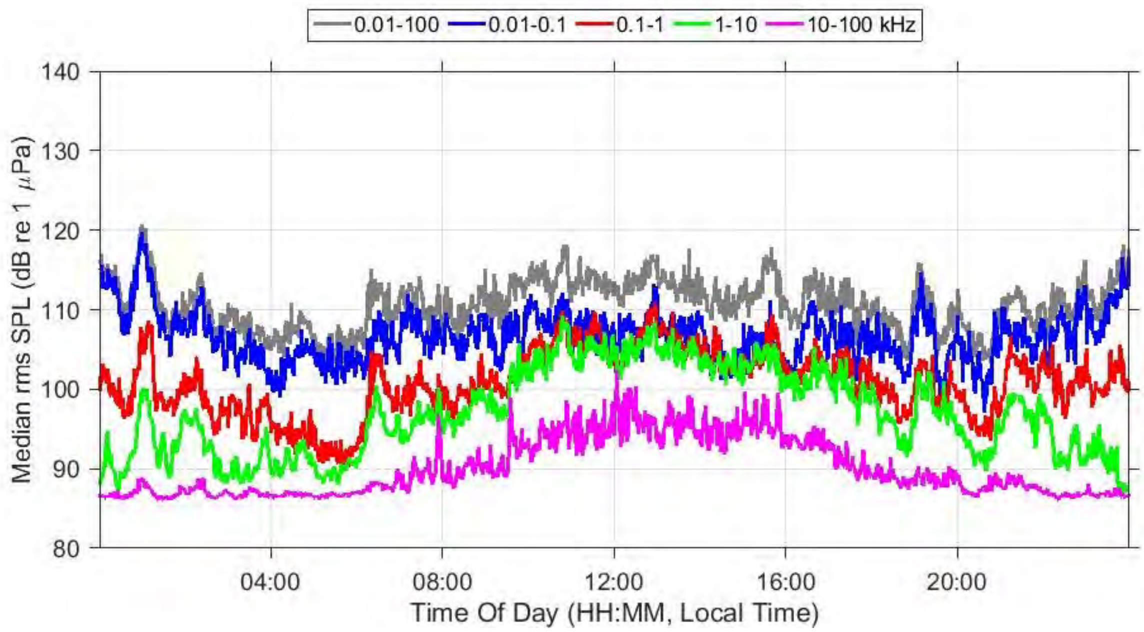


A1.1.3 Table of Broadband and 1/3 Octave SPL Levels

Frequency	95th	75th	50th	25th	5th
Broadband	94.8	103.8	110.9	118.2	126.4
25.1	71.1	83.8	95.2	104.0	115.2
31.6	71.6	82.2	91.8	100.2	110.6
39.8	71.6	81.6	90.7	98.7	109.8
50.1	72.1	81.7	90.8	99.1	111.0
63.1	73.8	81.3	89.5	98.7	113.1
79.4	78.1	84.2	91.1	99.8	112.8
100.0	77.2	83.8	90.9	100.3	113.2
125.9	76.7	83.1	89.7	99.1	111.1
158.5	78.5	83.7	89.5	98.6	109.5
199.5	77.9	83.3	89.9	97.9	108.2
251.2	77.9	83.8	90.2	97.3	106.7
316.2	75.0	81.2	87.9	94.9	103.7
398.1	72.0	78.8	86.2	93.7	103.3
501.2	69.4	77.5	85.8	93.4	102.8
631.0	69.3	78.4	86.9	94.1	102.5
794.3	68.8	78.6	87.2	94.2	102.3
1,000.0	68.3	78.0	86.8	93.6	101.6
1,258.9	68.3	78.4	87.4	94.3	102.2
1,584.9	68.7	77.8	86.1	93.0	100.8
1,995.3	70.9	79.4	87.3	94.4	102.4
2,511.9	71.1	79.0	86.6	93.5	101.5
3,162.3	72.4	79.5	86.8	93.5	101.7
3,981.1	73.0	79.1	86.3	92.9	101.4
5,011.9	73.3	78.7	85.6	92.1	101.0
6,309.6	73.7	78.1	84.6	91.2	100.6
7,943.3	74.2	77.5	83.5	89.9	99.8
10,000.0	73.8	76.5	81.9	88.1	98.2
12,589.3	73.9	76.0	80.7	87.1	97.4
15,848.9	73.9	75.6	79.0	85.5	96.8
19,952.6	73.4	74.8	77.3	83.6	95.7
25,118.9	73.3	74.5	76.3	81.7	94.6
31,622.8	72.9	73.9	75.3	79.6	92.9
39,810.7	72.9	73.9	75.0	78.2	91.5
50,118.7	73.8	74.8	75.7	78.7	93.8
63,095.7	73.9	74.6	75.2	76.8	87.9
79,432.8	72.0	72.5	73.0	74.0	84.6

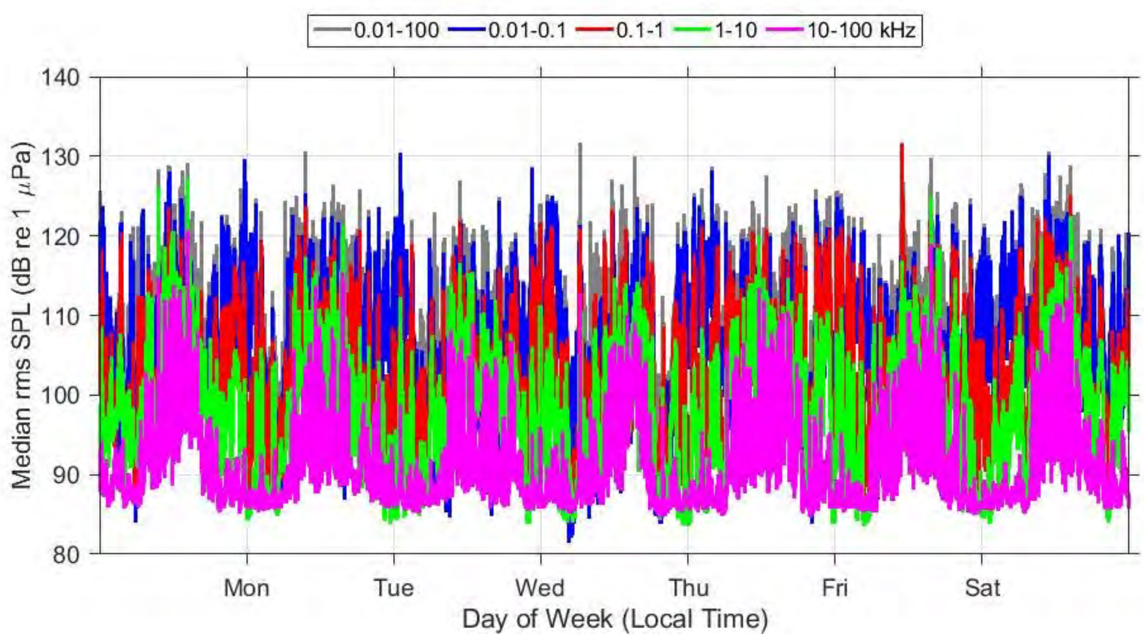
A1.1.4 Daily Rhythm Plot

Median SPL across the lunar month for each hour of the day.



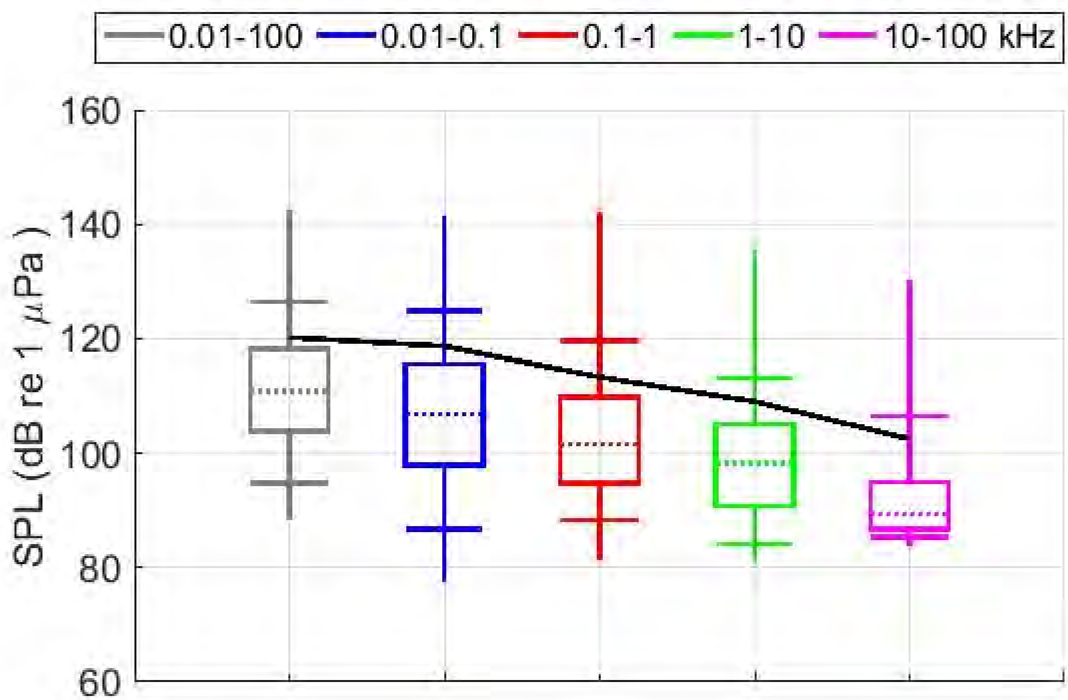
A1.1.5 Weekly Rhythm Plot

Median SPL across the lunar month for each hour of the week.



A1.1.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.1.7 SPL Table of Values

SPL values from the boxplot above.

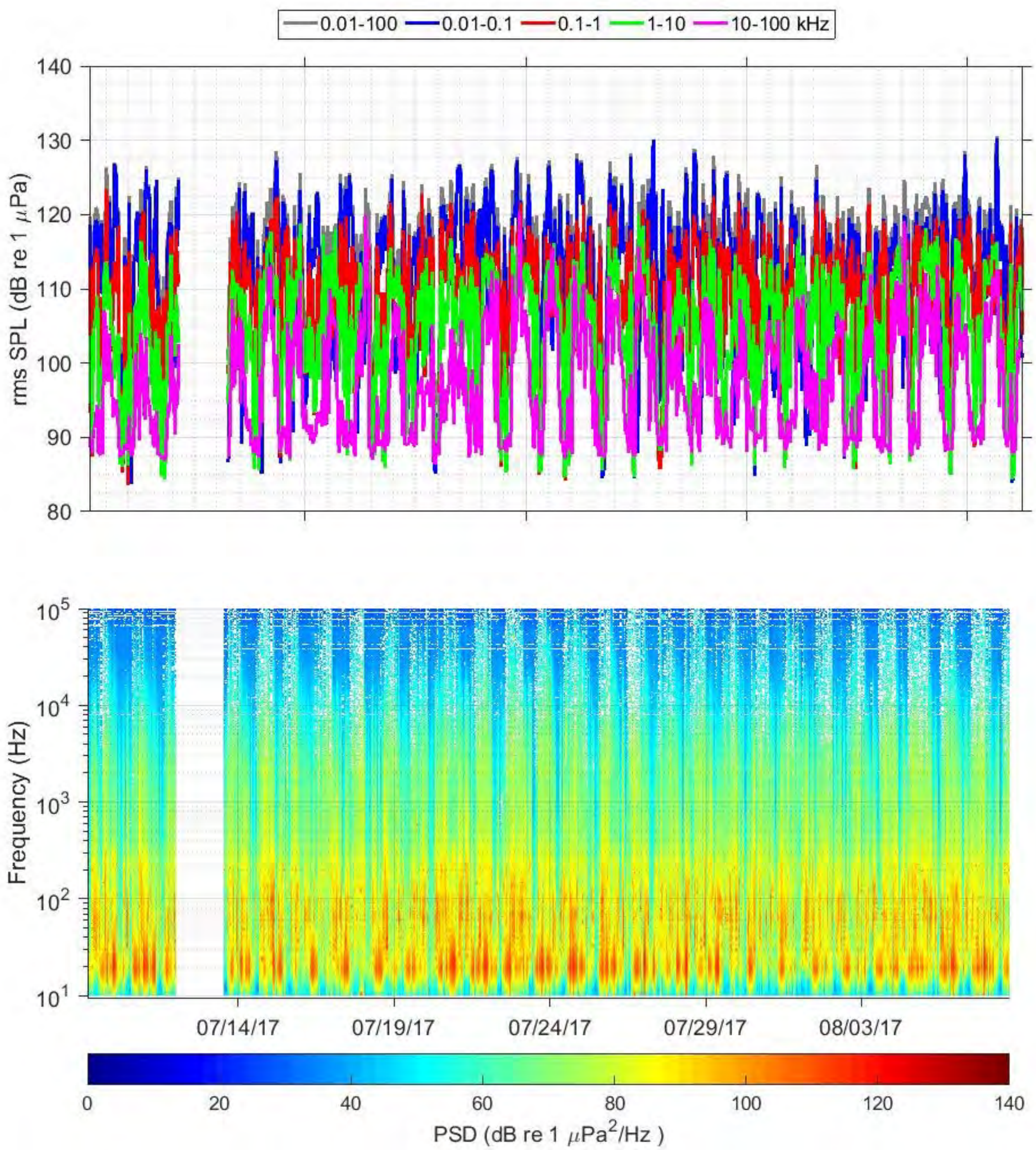
SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	88.3	77.6	81.4	80.9	83.9
L95	94.8	86.9	88.3	84.1	85.4
L75	103.8	98.0	94.8	90.7	86.7
L50	110.9	106.8	101.6	98.3	89.3
L25	118.2	115.6	109.7	105.1	95.0
L5	126.4	124.8	119.7	113.1	106.5
Max	142.5	141.4	142.3	135.5	130.2
Mean	120.2	118.7	113.3	109.1	102.5

A1.2. Lunar Month Jul 8 – Aug 7, 2017 (Baseline)

A total of 40,402 minutes of data, across 30 days, are presented for this lunar month. There was a power outage on 7/11/17 which caused a loss of data until 7/13/17. Where data were averaged, this was done using the data available for this lunar month.

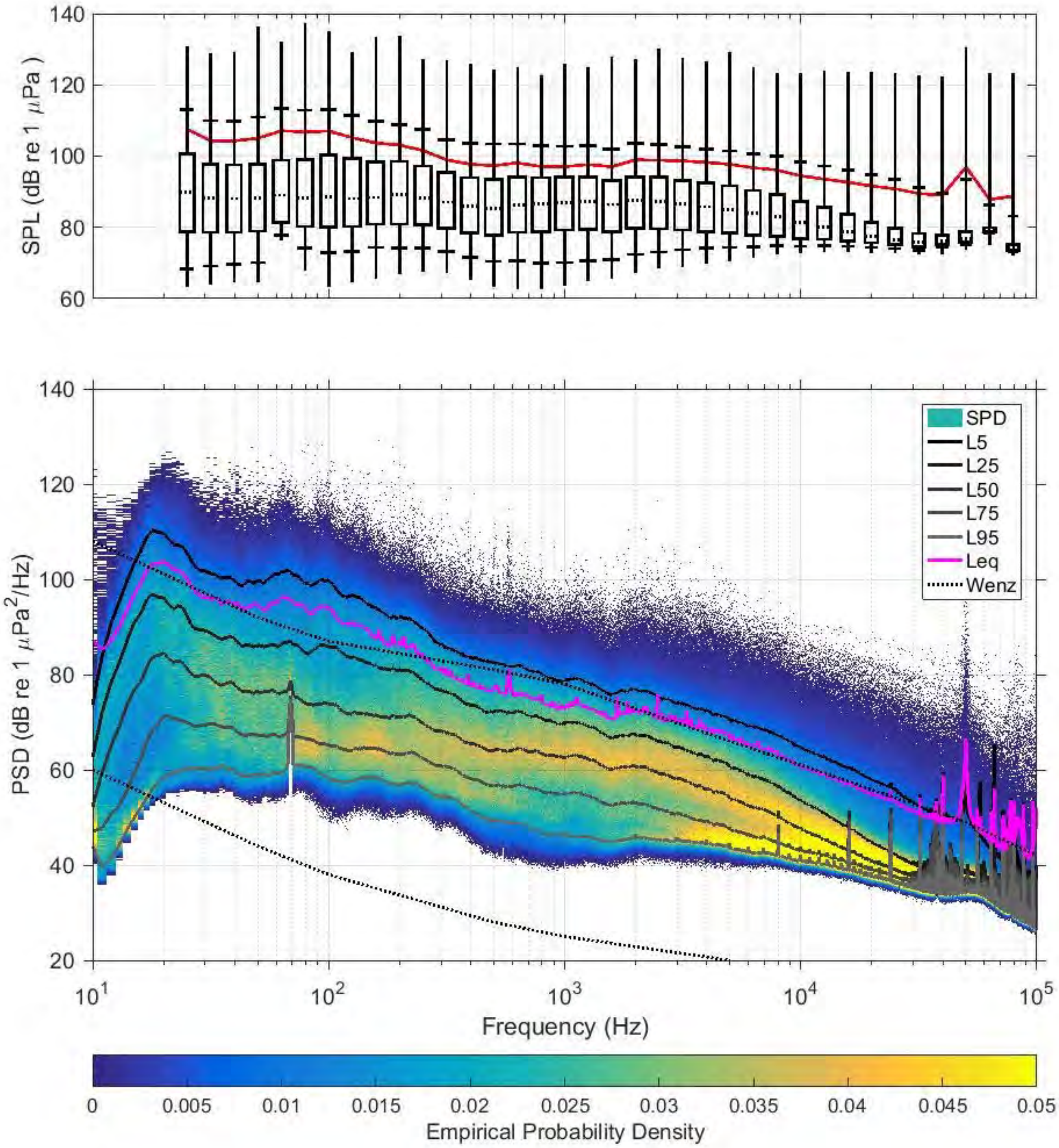
A1.2.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.2.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month* by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



* Partial lunar month of data.

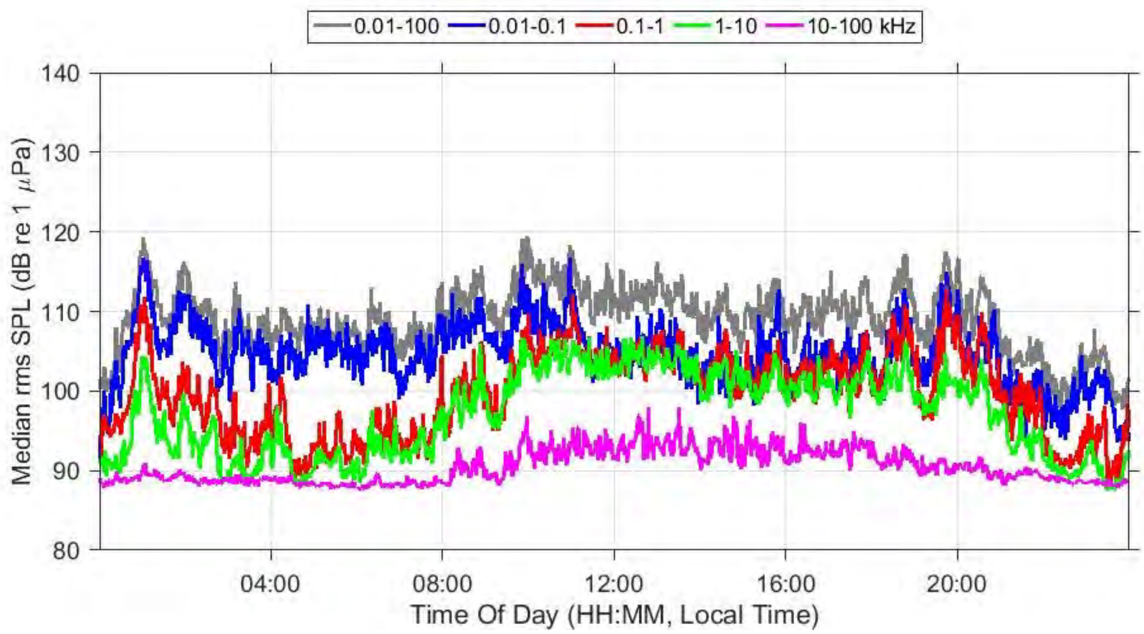
A1.2.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	93.0	101.8	109.4	117.8	126.5
25.1	68.3	78.8	90.0	100.7	113.0
31.6	69.1	78.6	88.2	97.8	110.0
39.8	69.6	78.6	88.0	97.5	109.8
50.1	70.1	78.9	88.2	97.8	110.9
63.1	77.8	81.4	89.1	98.8	113.4
79.4	74.3	80.3	88.3	99.0	113.0
100.0	72.8	80.0	88.6	100.4	113.1
125.9	73.2	80.2	88.1	99.5	111.5
158.5	74.4	80.9	88.4	98.3	109.9
199.5	74.1	80.9	89.2	98.5	108.8
251.2	74.2	80.7	88.3	97.2	107.5
316.2	73.1	79.7	87.1	95.5	104.7
398.1	71.6	78.4	85.9	94.0	103.6
501.2	70.4	77.8	85.4	93.5	103.4
631.0	70.7	78.6	86.3	94.1	103.4
794.3	70.0	78.7	86.7	94.0	103.0
1,000.0	70.2	79.2	87.0	94.1	102.8
1,258.9	70.6	79.4	87.2	94.1	103.0
1,584.9	70.9	78.8	86.4	93.1	102.0
1,995.3	72.4	79.8	87.5	94.1	103.5
2,511.9	73.0	79.6	87.4	94.0	103.2
3,162.3	73.8	79.2	86.7	93.2	102.6
3,981.1	74.3	78.8	85.8	92.5	102.1
5,011.9	74.4	78.4	85.1	91.7	101.4
6,309.6	74.4	77.8	83.9	90.4	100.8
7,943.3	74.8	77.4	83.0	89.3	100.1
10,000.0	74.7	76.8	81.3	87.3	98.4
12,589.3	74.9	76.6	80.0	85.5	97.2
15,848.9	74.7	76.2	78.7	83.6	96.2
19,952.6	74.3	75.6	77.4	81.5	94.7
25,118.9	74.0	75.1	76.5	79.8	93.4
31,622.8	73.6	74.6	75.7	78.3	91.1
39,810.7	74.3	75.1	76.1	77.9	89.6
50,118.7	75.0	75.9	76.9	78.8	93.5
63,095.7	78.4	78.8	79.2	80.0	86.3
79,432.8	73.0	73.6	74.2	75.2	83.2

* Partial lunar month of data.

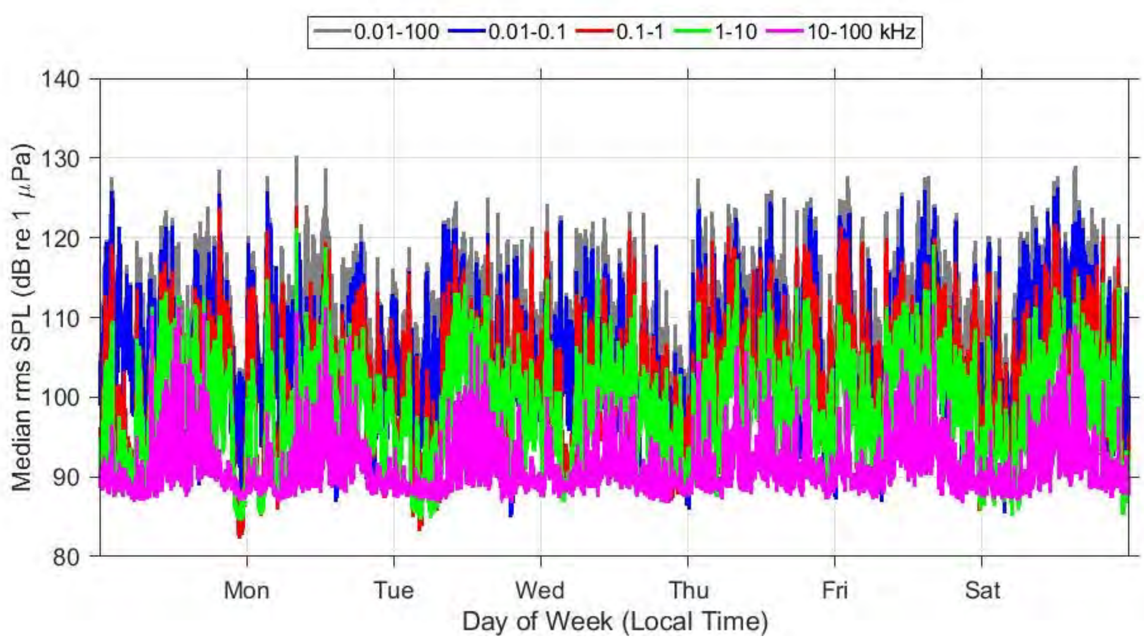
A1.2.4 Daily Rhythm Plot

Median SPL across the lunar month[*] for each hour of the day.



A1.2.5 Weekly Rhythm Plot

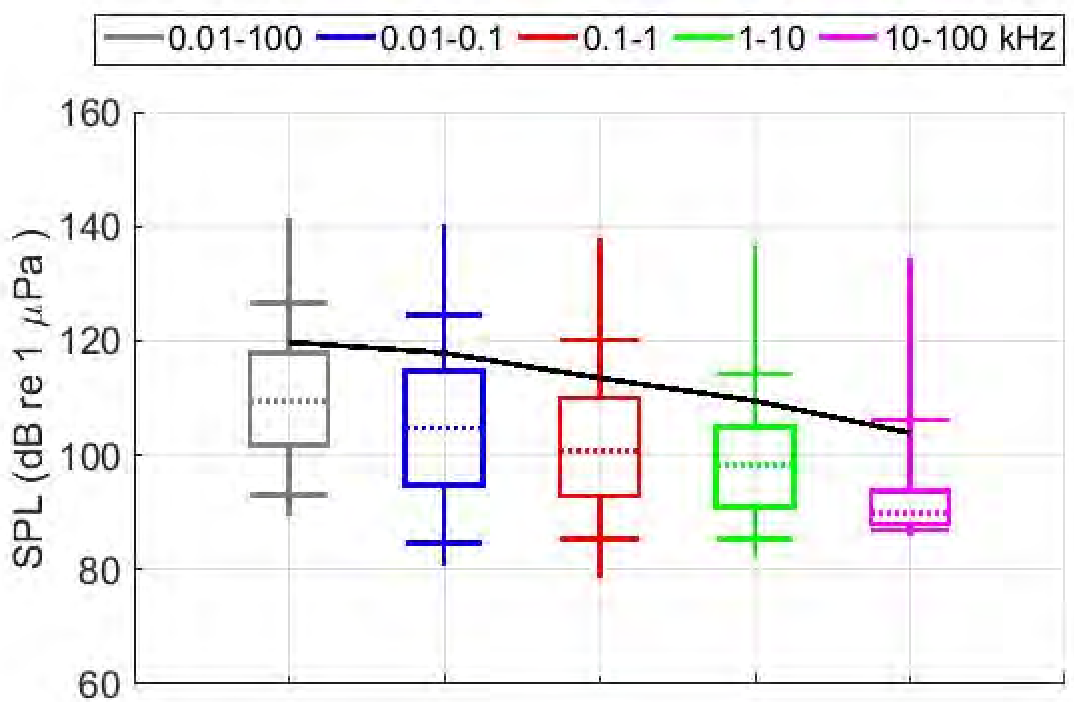
Median SPL across the lunar month* for each hour of the week.



[*] Partial lunar month of data.

A1.2.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month*. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.2.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	89.4	80.6	78.4	82.3	85.8
L95	93.0	84.7	85.4	85.5	86.9
L75	101.8	94.7	92.8	91.1	88.0
L50	109.4	104.8	100.6	98.4	89.8
L25	117.8	114.7	110.0	105.0	93.8
L5	126.5	124.5	120.1	114.2	106.1
Max	141.4	140.3	137.8	136.4	134.6
Mean	119.8	117.9	113.5	109.5	103.9

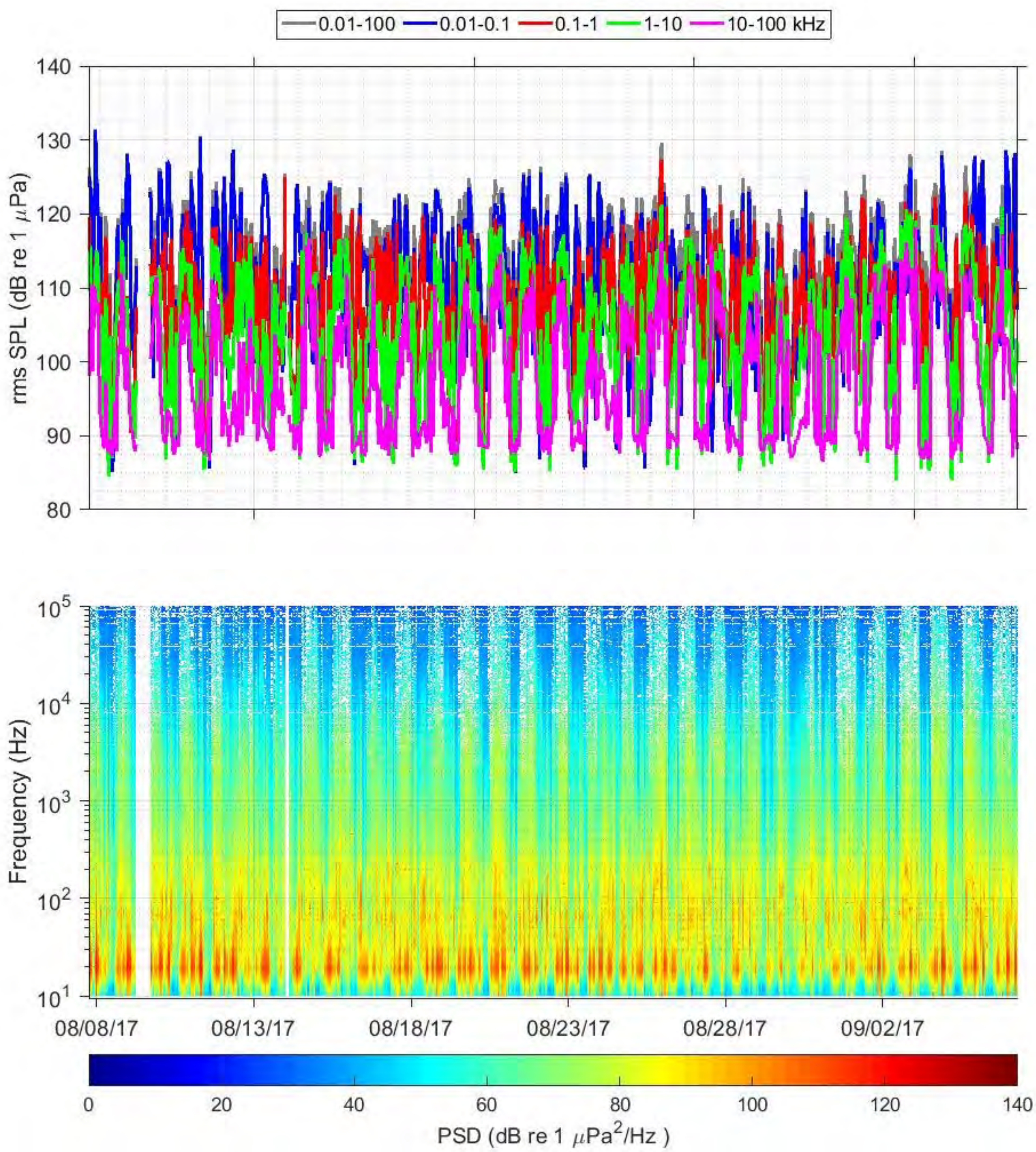
* Partial lunar month of data.

A1.3. Lunar Month Aug 7 – Sep 6, 2017 (Slowdown)

A total of 41,691 minutes of data, across 31 days, are presented for this lunar month. Short periods of lost data were due to Windows updates on the recording computer and for AIS data retrieval. Where data were averaged, this was done using the data available for this lunar month.

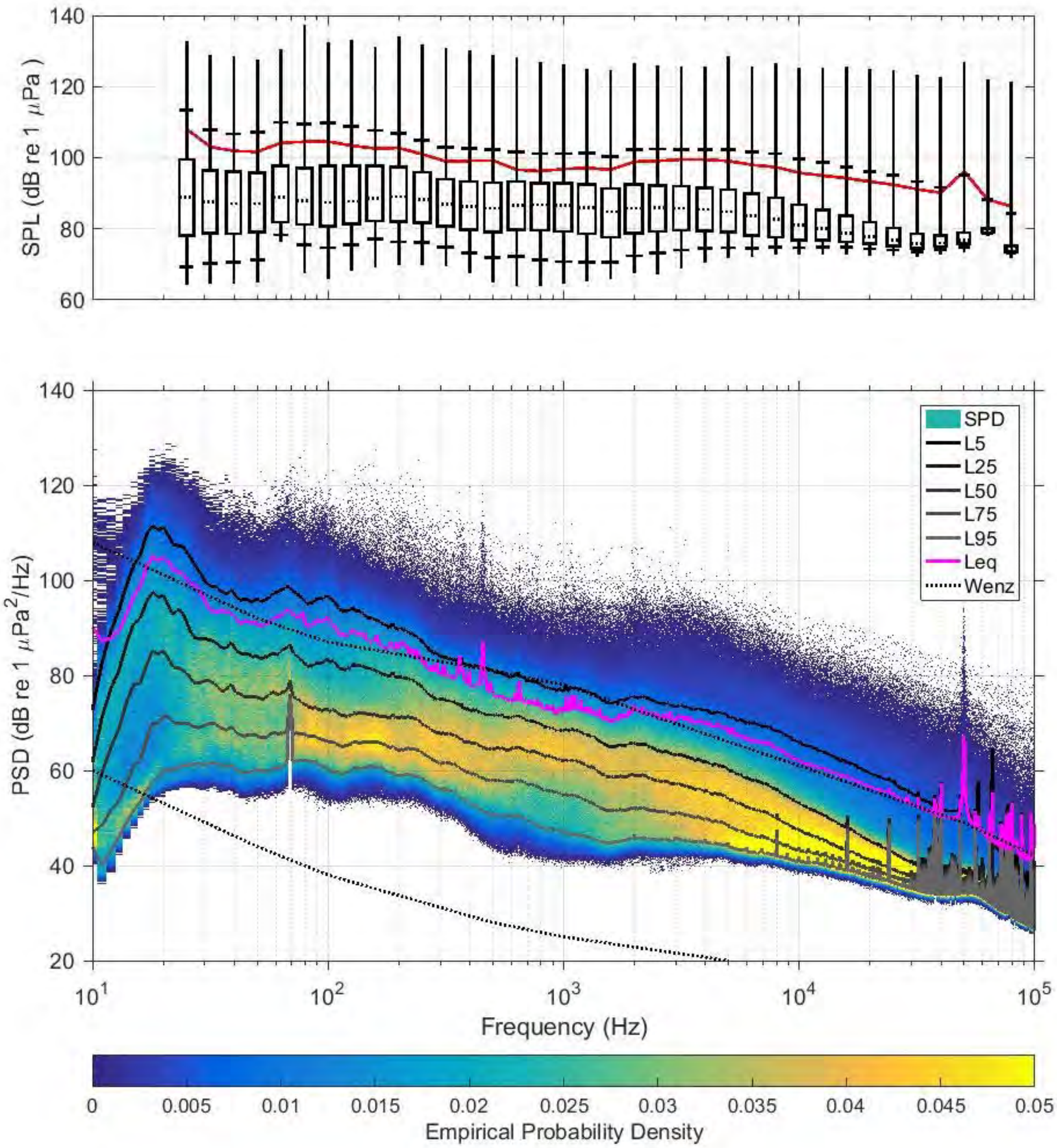
A1.3.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.3.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month* by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



* Partial lunar month of data.

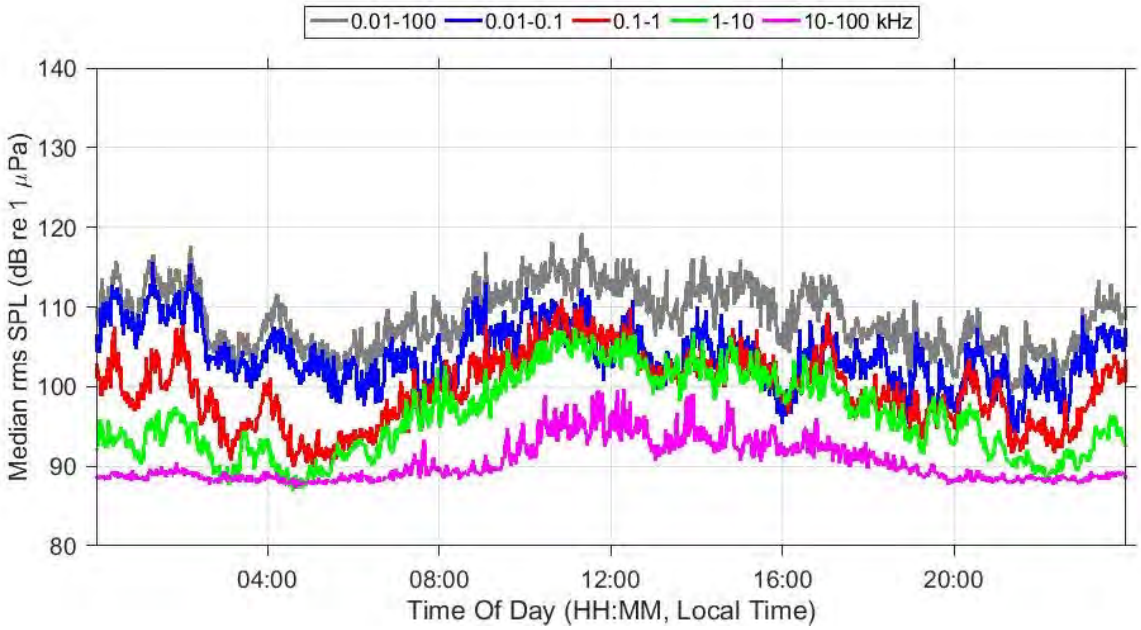
A1.3.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	94.2	102.0	109.2	116.7	125.7
25.1	69.3	78.2	88.8	99.6	113.4
31.6	70.4	78.8	87.5	96.3	107.9
39.8	70.5	78.7	87.1	96.1	106.7
50.1	71.3	79.0	87.2	95.8	107.2
63.1	78.3	81.9	89.0	97.8	110.0
79.4	75.6	81.2	88.0	97.0	109.5
100.0	74.7	80.7	87.4	97.6	109.9
125.9	75.6	81.4	87.8	97.7	108.7
158.5	77.1	82.2	88.5	97.6	107.7
199.5	76.3	82.1	89.1	97.3	106.9
251.2	76.2	81.8	88.3	95.9	105.0
316.2	74.8	80.6	87.0	94.0	102.9
398.1	73.3	79.8	86.3	93.3	102.5
501.2	71.8	79.1	85.8	93.0	102.3
631.0	72.2	79.7	86.7	93.3	101.6
794.3	71.2	79.6	86.7	92.8	101.1
1,000.0	70.8	79.2	86.5	92.7	101.2
1,258.9	70.7	78.6	86.1	92.5	101.4
1,584.9	70.7	77.6	84.8	91.3	100.4
1,995.3	72.4	78.8	85.8	92.4	102.2
2,511.9	73.3	79.3	85.9	92.3	102.4
3,162.3	74.0	79.6	85.8	92.0	102.2
3,981.1	74.5	79.5	85.4	91.6	102.3
5,011.9	74.7	79.0	84.9	91.0	102.2
6,309.6	74.6	78.2	83.7	89.8	101.7
7,943.3	74.9	77.7	82.8	88.7	101.2
10,000.0	74.7	76.9	81.1	86.8	99.7
12,589.3	74.9	76.7	80.0	85.4	98.6
15,848.9	74.8	76.3	78.8	83.7	97.5
19,952.6	74.4	75.8	77.7	81.8	96.2
25,118.9	74.0	75.2	76.7	80.3	95.0
31,622.8	73.6	74.6	75.8	78.6	93.3
39,810.7	74.2	75.1	76.0	78.1	91.7
50,118.7	74.9	75.9	76.9	78.9	95.0
63,095.7	78.6	78.9	79.3	80.0	88.3
79,432.8	73.0	73.6	74.2	75.1	84.3

* Partial lunar month of data.

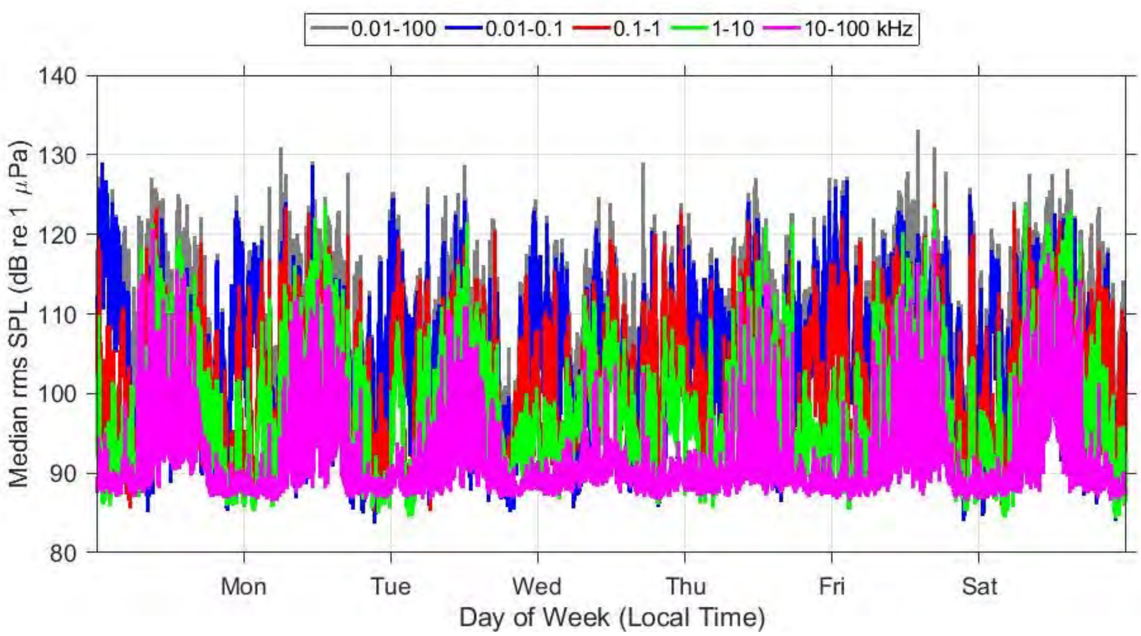
A1.3.4 Daily Rhythm Plot

Median SPL across the lunar month* for each hour of the day.



A1.3.5 Weekly Rhythm Plot

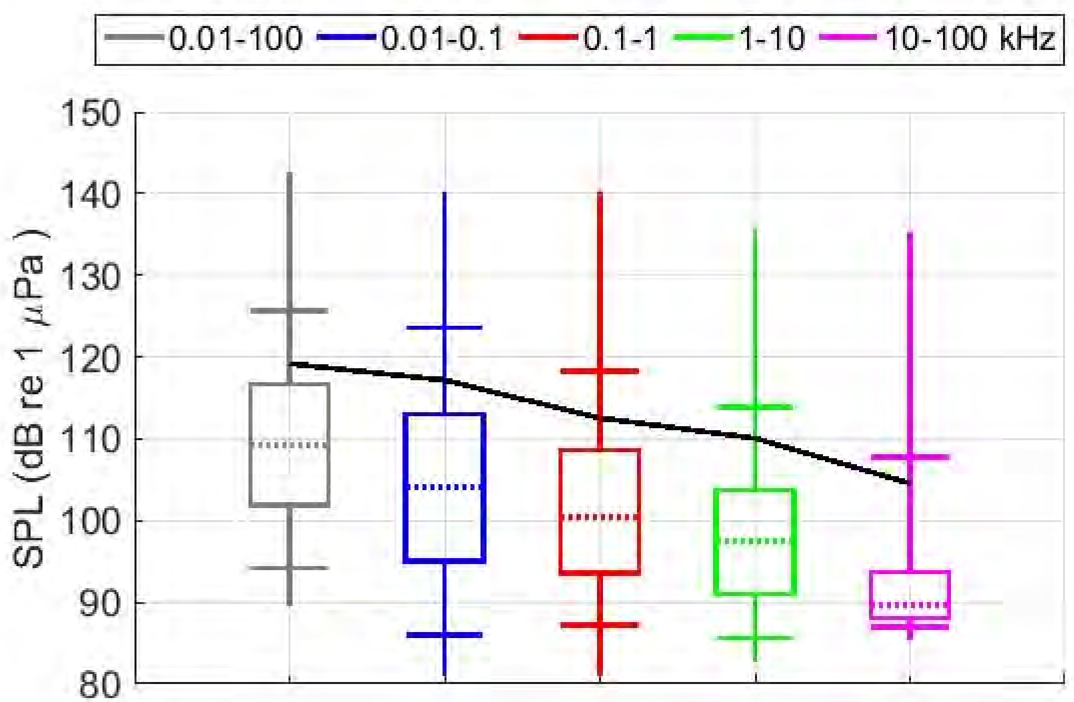
Median SPL across the lunar month* for each hour of the week.



* Partial lunar month of data.

A1.3.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month*. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



A1.3.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	89.5	81.1	80.9	82.6	85.5
L95	94.2	86.0	87.3	85.6	86.9
L75	102.0	95.1	93.6	91.0	88.1
L50	109.2	104.1	100.4	97.5	89.7
L25	116.7	113.0	108.6	103.7	93.7
L5	125.7	123.6	118.2	113.9	107.8
Max	142.6	140.2	140.1	135.6	135.3
Mean	119.2	117.2	112.6	110.1	104.6

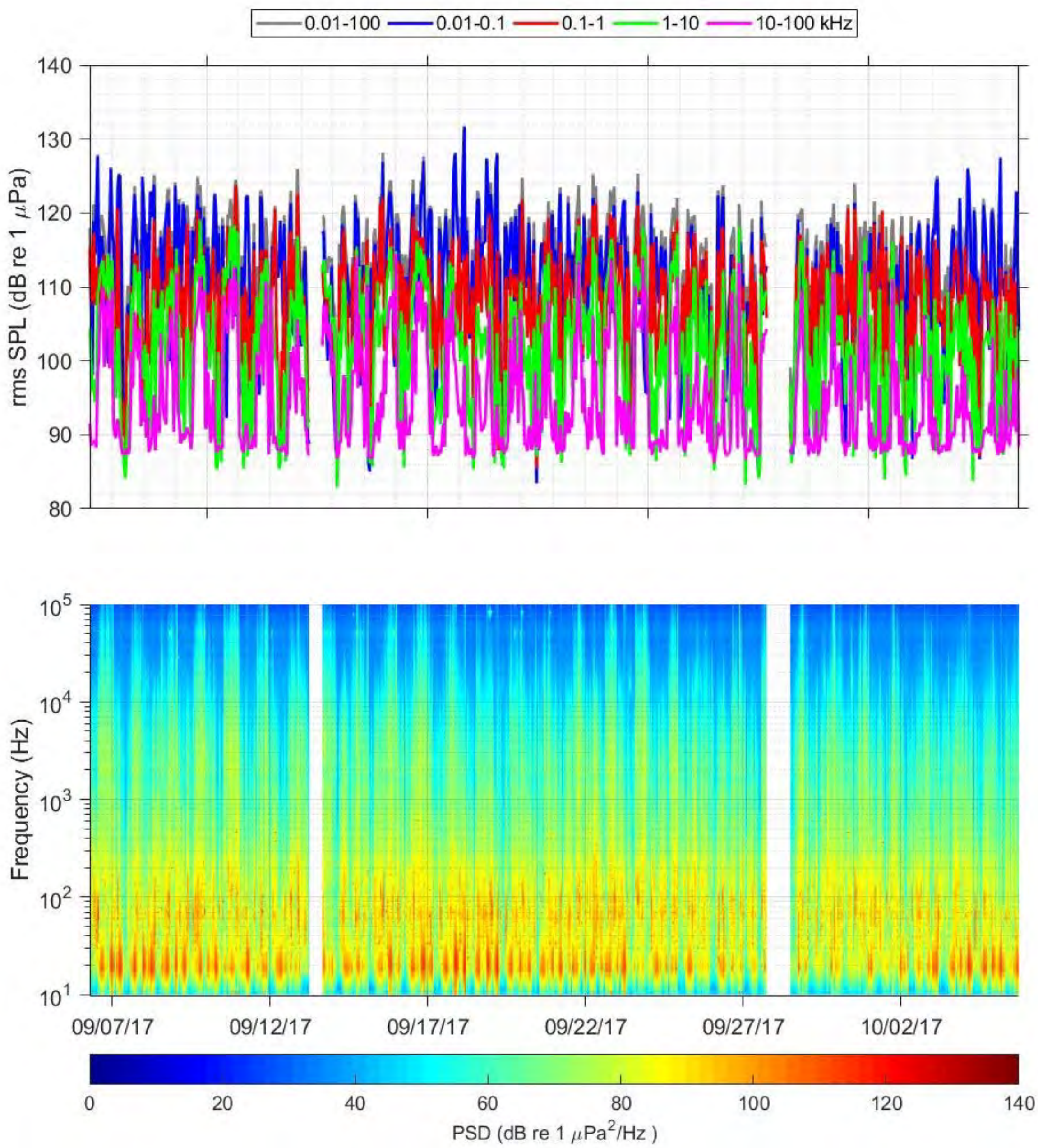
* Partial lunar month of data.

A1.4. Lunar Month Sep 6 – Oct 5, 2017 (Slowdown)

A total of 40,751 minutes of data, across 30 days, are presented for this lunar month. Short periods of lost data were due to Windows updates on the recording computer and for AIS data retrieval. Where data were averaged, this was done using the data available for this lunar month.

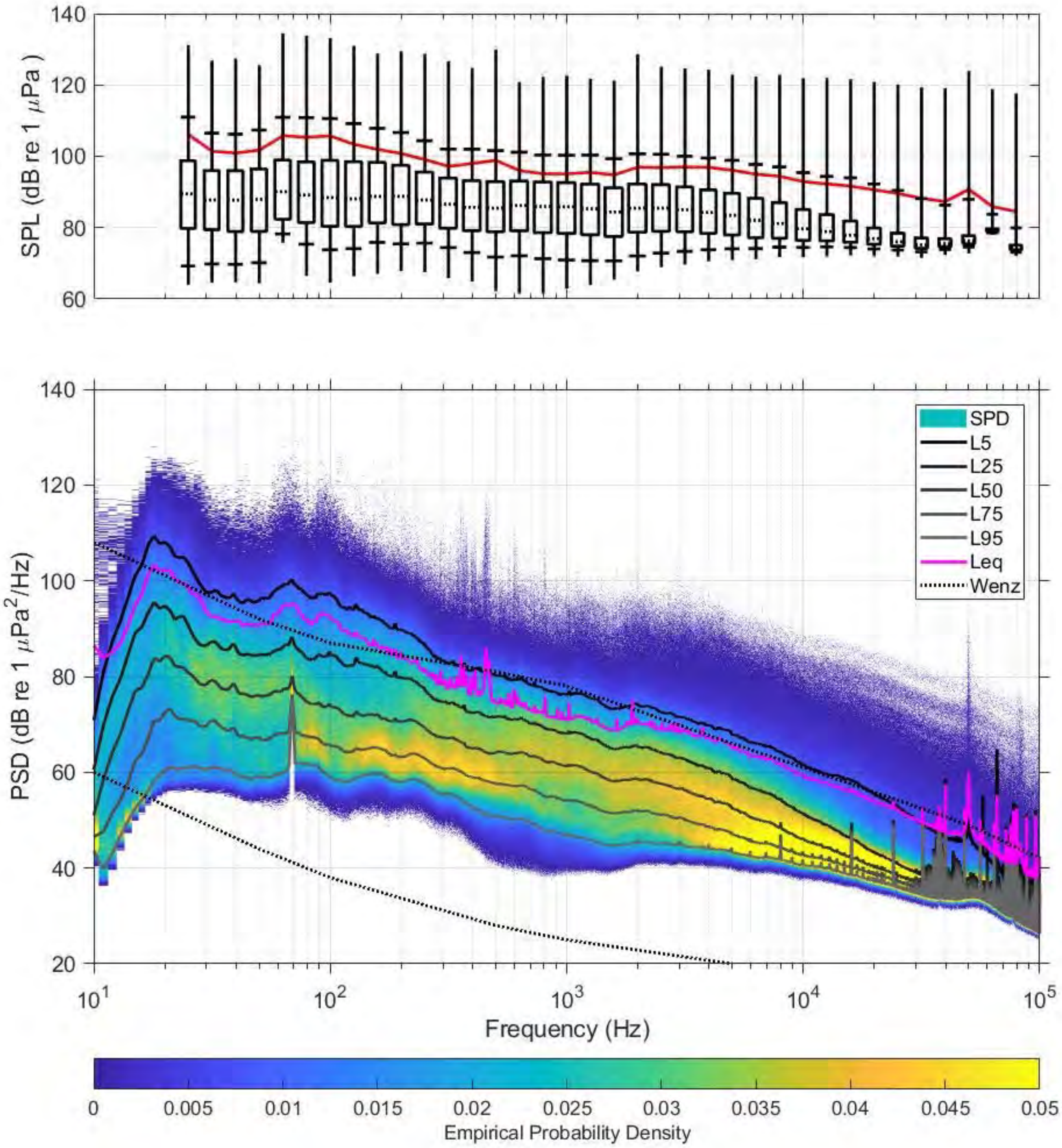
A1.4.1 Ambient Sound Over Time

The following figure shows the broadband (10 Hz – 100 kHz) and decade band SPL (at 1-hour resolution) over time (top panel) and the spectrogram (at 1-hour resolution) over time (bottom panel) for the lunar month.



A1.4.2 1/3 Octave Band and Power Spectral Density Levels

These figures represent the distribution of ambient sound during the lunar month* by frequency. The top plot depicts percentiles and mean of 1-minute 1/3 octave band levels as a box plot. Red line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max. The bottom panel depicts the percentiles and mean of 1-minute power spectral density levels over the lunar month (Solid lines. Percentiles are in the same order as the legend). Dashed lines are the limits of prevailing noise (Wenz 1962). The lines are overlain over the empirical probability density (background color) which further shows the distribution in power spectral density levels during this lunar month.



* Partial lunar month of data.

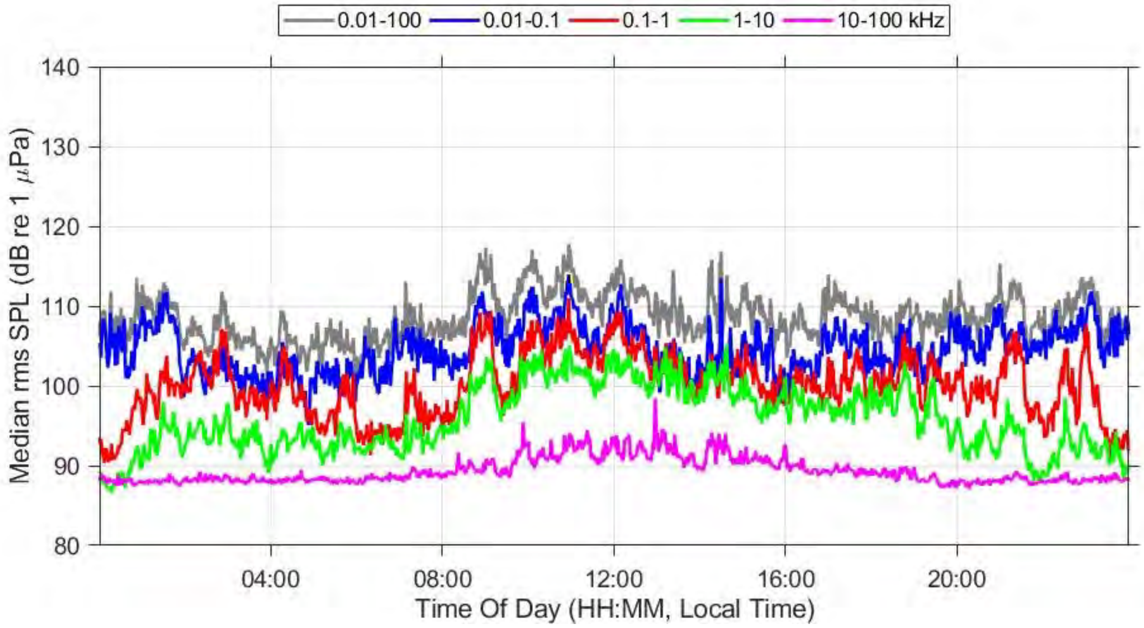
A1.4.3 Table of Broadband and 1/3 Octave SPL Levels*

Frequency	95th	75th	50th	25th	5th
Broadband	93.8	101.6	108.8	115.9	124.4
25.1	69.2	79.8	89.5	98.8	111.0
31.6	69.8	79.4	87.8	96.0	106.5
39.8	69.7	78.9	87.7	96.0	106.2
50.1	70.2	78.9	87.9	96.4	107.4
63.1	78.2	82.3	90.1	98.9	110.9
79.4	75.4	81.4	89.2	98.4	110.8
100.0	73.8	80.4	88.4	98.9	110.6
125.9	74.1	80.3	88.1	98.5	109.2
158.5	75.9	81.3	88.7	98.3	107.8
199.5	75.4	80.8	88.7	97.5	106.7
251.2	75.7	81.0	87.8	95.6	104.4
316.2	74.4	79.8	86.6	93.9	102.0
398.1	73.0	79.1	85.7	93.2	102.0
501.2	71.7	78.8	85.5	92.9	101.6
631.0	72.1	79.1	86.2	93.1	101.1
794.3	71.3	78.6	85.9	92.8	100.3
1,000.0	70.9	78.4	85.9	92.6	100.3
1,258.9	70.7	78.0	85.3	92.2	100.3
1,584.9	70.7	77.5	84.4	91.2	99.3
1,995.3	72.1	78.7	85.4	92.2	100.7
2,511.9	72.9	79.0	85.5	92.0	100.6
3,162.3	73.3	78.8	85.0	91.4	100.0
3,981.1	73.8	78.4	84.3	90.6	99.5
5,011.9	74.1	77.9	83.4	89.7	98.9
6,309.6	74.1	77.2	82.0	88.2	97.7
7,943.3	74.5	77.0	81.2	87.0	97.0
10,000.0	74.4	76.4	79.7	85.1	95.4
12,589.3	74.6	76.3	78.9	83.6	94.4
15,848.9	74.4	75.9	77.9	81.9	94.0
19,952.6	74.0	75.3	76.9	79.9	92.2
25,118.9	73.7	74.8	76.0	78.5	90.4
31,622.8	73.2	74.2	75.2	77.1	88.2
39,810.7	73.9	74.7	75.5	76.9	86.3
50,118.7	74.6	75.5	76.3	77.7	87.9
63,095.7	78.5	78.8	79.1	79.7	83.8
79,432.8	73.1	73.7	74.3	75.1	79.9

* Partial lunar month of data.

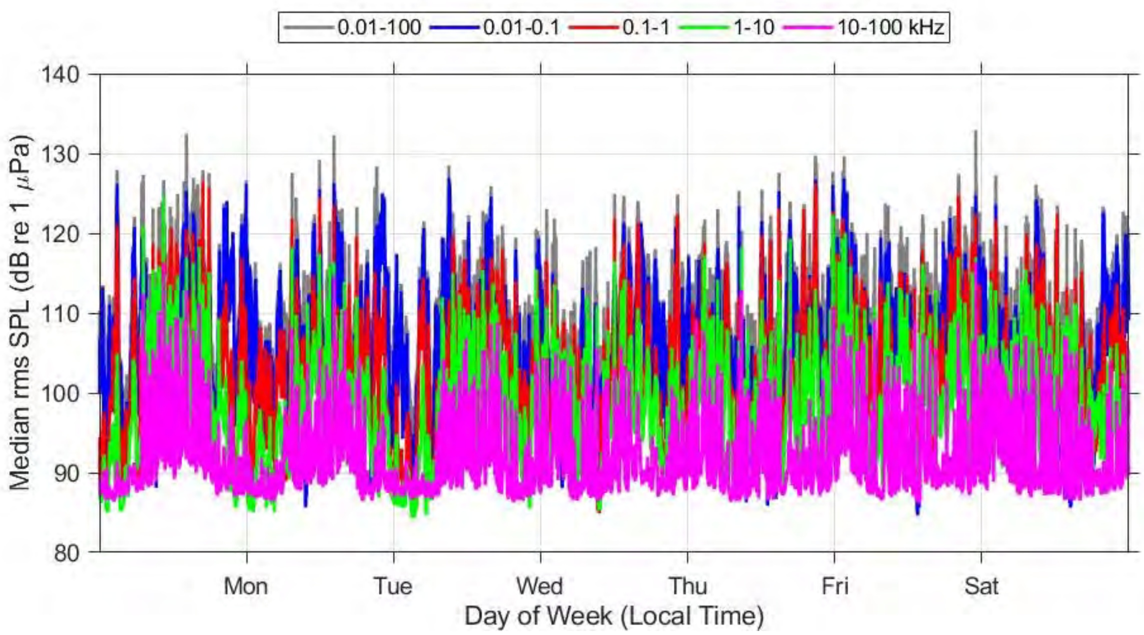
A1.4.4 Daily Rhythm Plot

Median SPL across the lunar month* for each hour of the day.



A1.4.5 Weekly Rhythm Plot

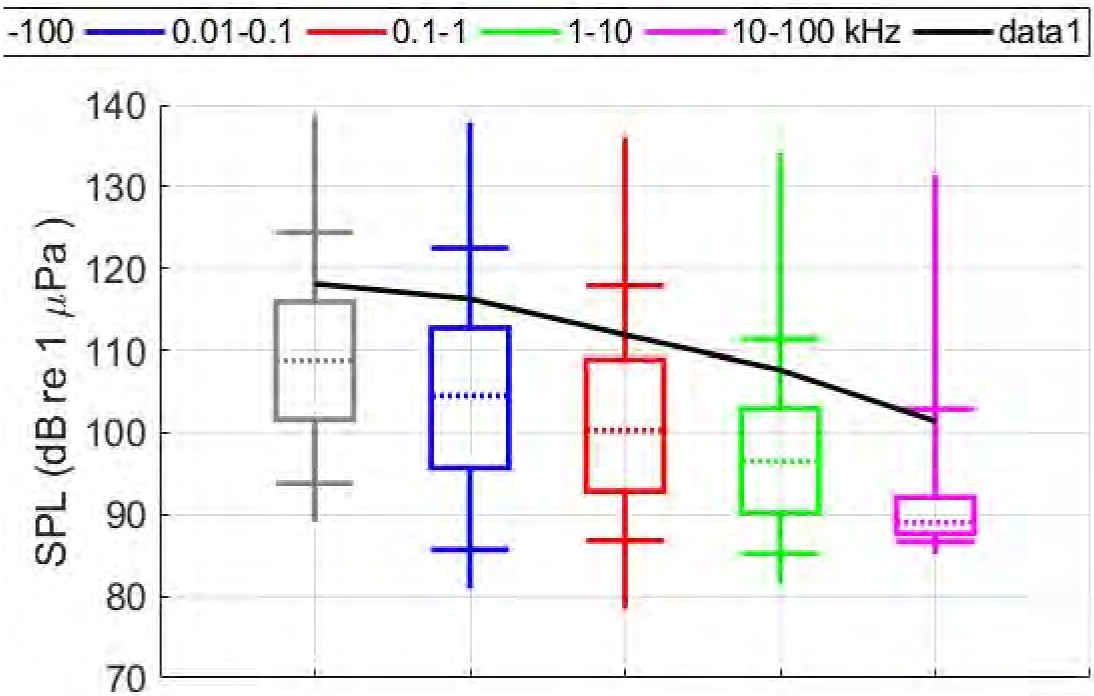
Median SPL across the lunar month* for each hour of the week.



* Partial lunar month of data.

A1.4.6 SPL Box Plot

Boxplot of the SPL over the entire lunar month*. Black line is the rms mean (Leq). Dashed lines are the median values. Boxes are the L25 to L75 values. Horizontal lines are the L5 and L95 values. Vertical lines are the min and max.



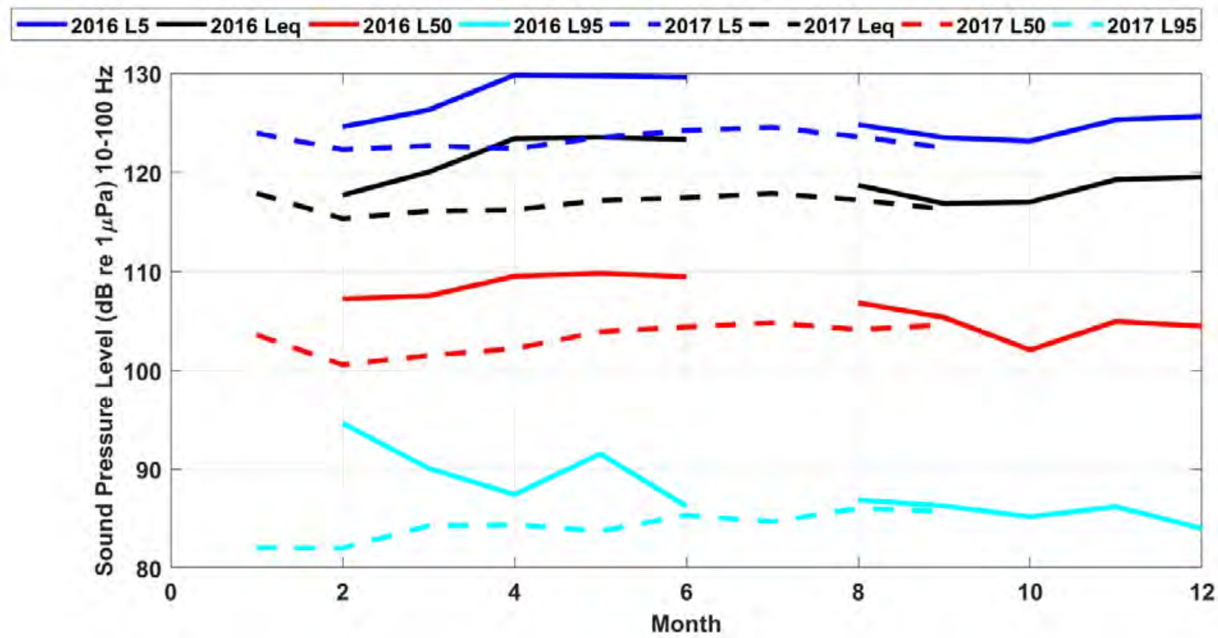
A3.7.7 SPL Table of Values

SPL values from the boxplot above*.

SPL Statistic	0.01-100 kHz	0.01-0.1 kHz	0.1-1 kHz	1-10 kHz	10-100 kHz
Min	89.1	81.0	78.5	81.6	85.2
L95	93.8	85.7	86.8	85.2	86.7
L75	101.6	95.7	92.9	90.2	87.7
L50	108.8	104.6	100.3	96.5	89.0
L25	115.9	112.7	108.9	103.0	92.1
L5	124.4	122.5	117.9	111.3	102.9
Max	138.6	137.8	136.0	134.1	131.4
Mean	118.1	116.3	111.9	107.7	101.4

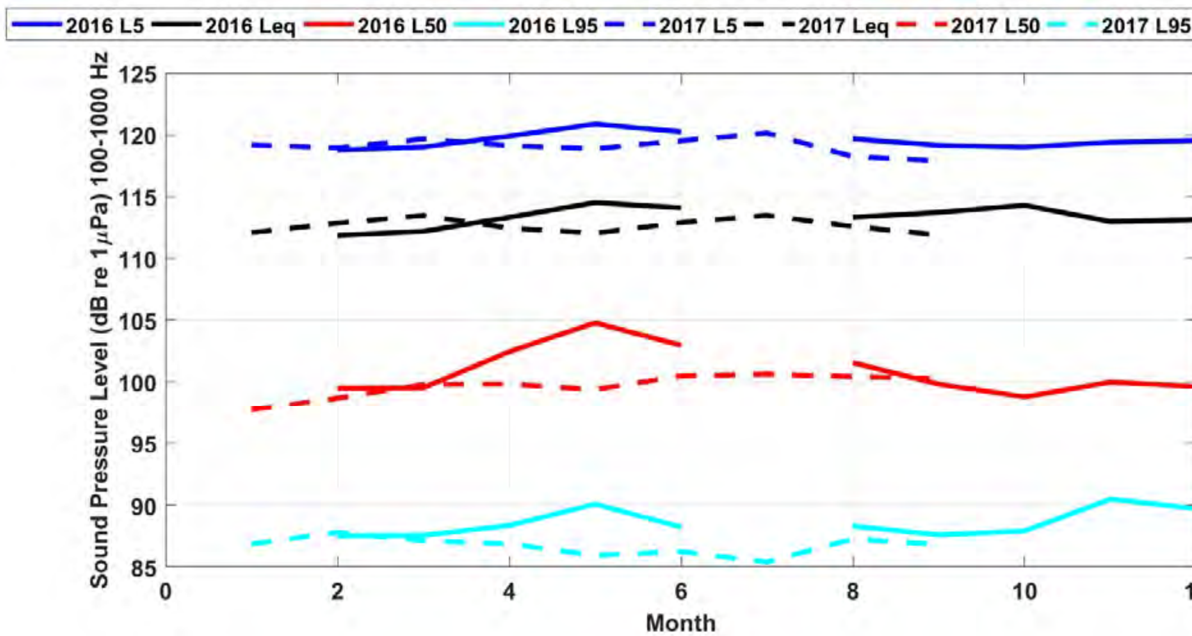
* Partial lunar month of data.

Appendix 2: Monthly summary SPL metrics for four, decade bands



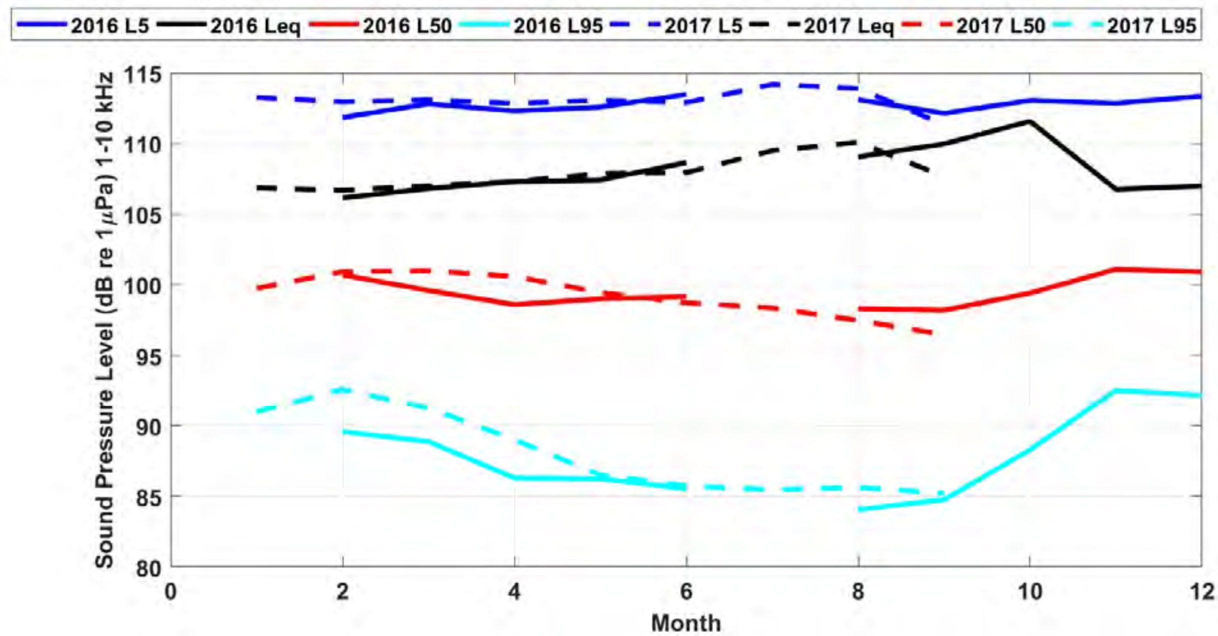
	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2016	NaN	448	441	425	447	461	422	432	431	449	457	427
2	2017	414	434	464	484	438	469	444	415	495	417	NaN	NaN

Figure A2.1 Summary 1st decade (10-100 Hz) SPL metrics across lunar months (February 2016 to October 2017) at the Lime Kiln hydrophone, with an associated table below reporting the number of piloted AIS vessels transiting through Haro Strait (Source: Pacific Pilot Authority). Only 6 days of data were collected in lunar month #7 (July) 2016 due to a cable failure and metrics for this period have been omitted.



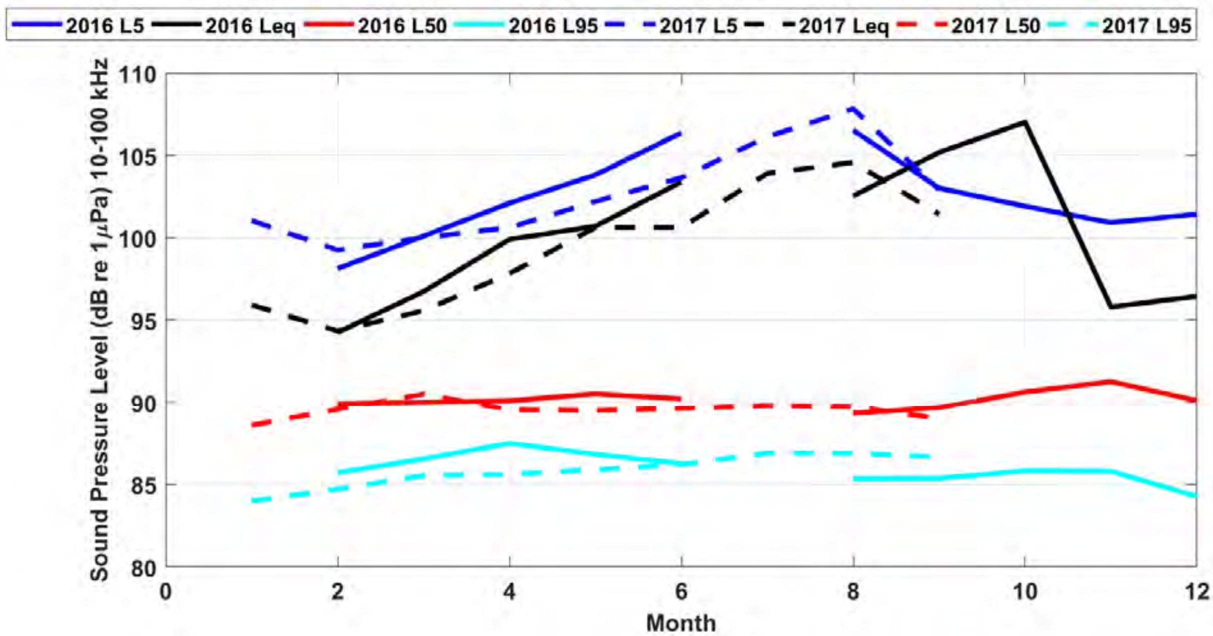
	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2016	NaN	448	441	425	447	461	422	432	431	449	457	427
2	2017	414	434	464	484	438	469	444	415	495	417	NaN	NaN

Figure A2.2 Summary 2nd decade (100-1000 Hz) SPL metrics across lunar months (February 2016 to October 2017) at the Lime Kiln hydrophone, with an associated table below reporting the number of piloted AIS vessels transiting through Haro Strait (Source: Pacific Pilot Authority). Only 6 days of data were collected in lunar month #7 (July) 2016 due to a cable failure and metrics for this period have been omitted.



	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2016	NaN	448	441	425	447	461	422	432	431	449	457	427
2	2017	414	434	464	484	438	469	444	415	495	417	NaN	NaN

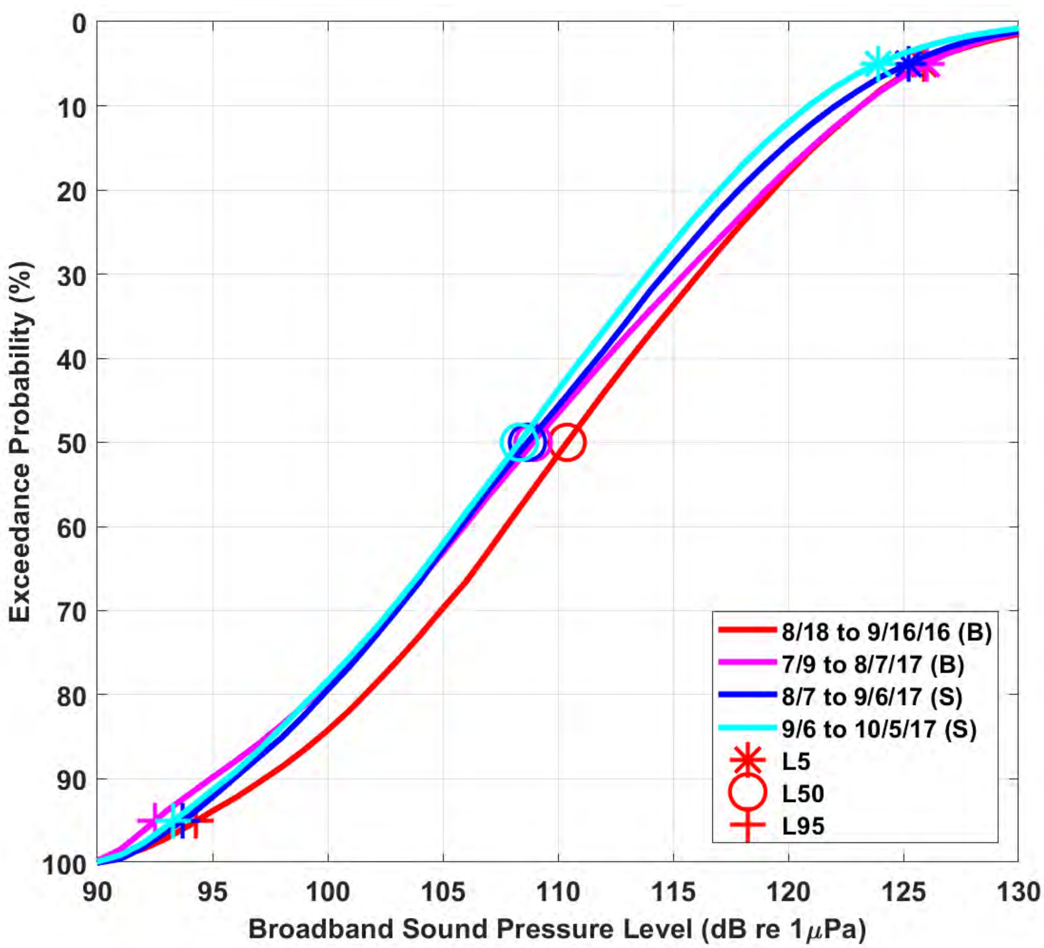
Figure A2.3 Summary 3rd decade (1-10 kHz) SPL metrics across lunar months (February 2016 to October 2017) at the Lime Kiln hydrophone, with an associated table below reporting the number of piloted AIS vessels transiting through Haro Strait (Source: Pacific Pilot Authority). Only 6 days of data were collected in lunar month #7 (July) 2016 due to a cable failure and metrics for this period have been omitted.



	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	2016	NaN	448	441	425	447	461	422	432	431	449	457	427
2	2017	414	434	464	484	438	469	444	415	495	417	NaN	NaN

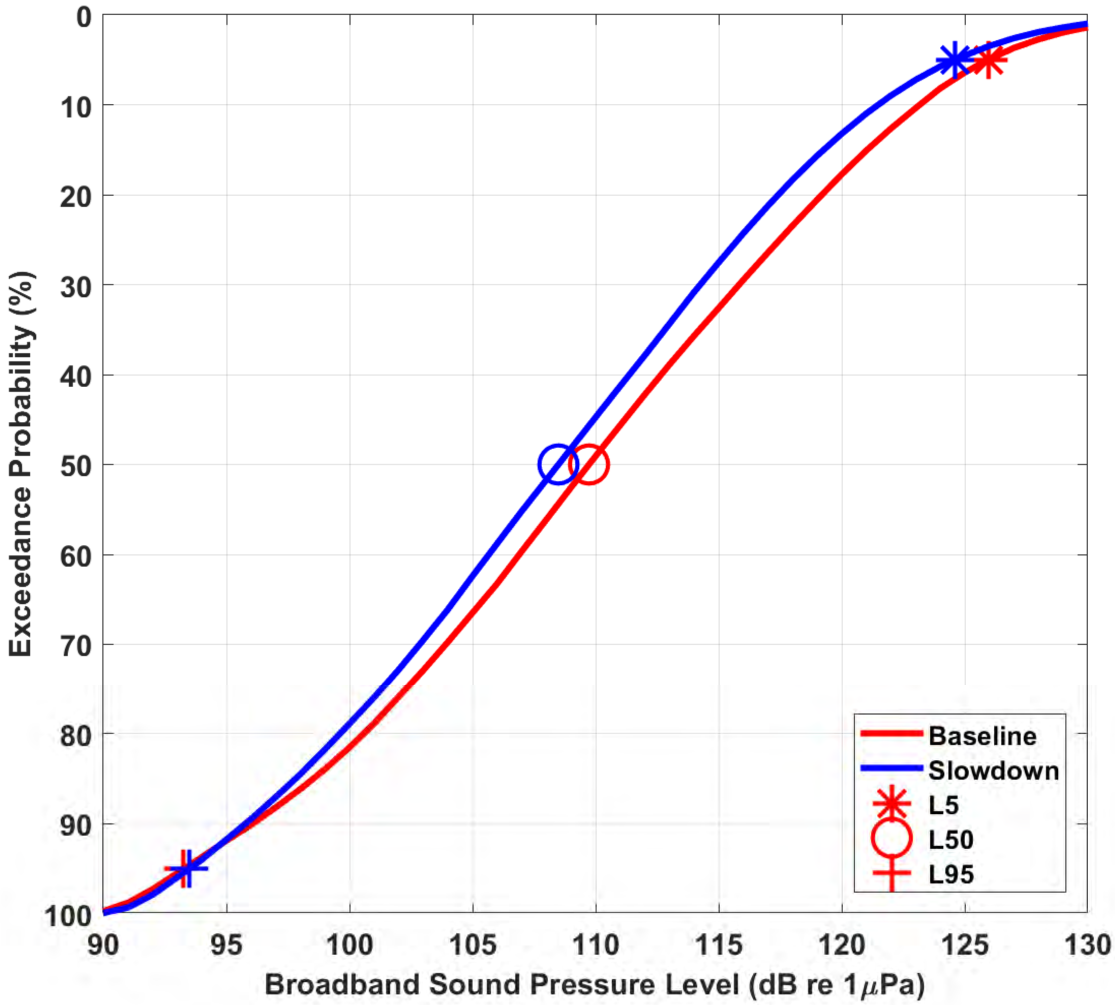
Figure A2.4 Summary 4th decade (10-100 kHz) SPL metrics across lunar months (February 2016 to October 2017) at the Lime Kiln hydrophone, with an associated table below reporting the number of piloted AIS vessels transiting through Haro Strait (Source: Pacific Pilot Authority). Only 6 days of data were collected in lunar month #7 (July) 2016 due to a cable failure and metrics for this period have been omitted.

Appendix 3: Additional CDF plots comparing Slowdown and Baseline periods



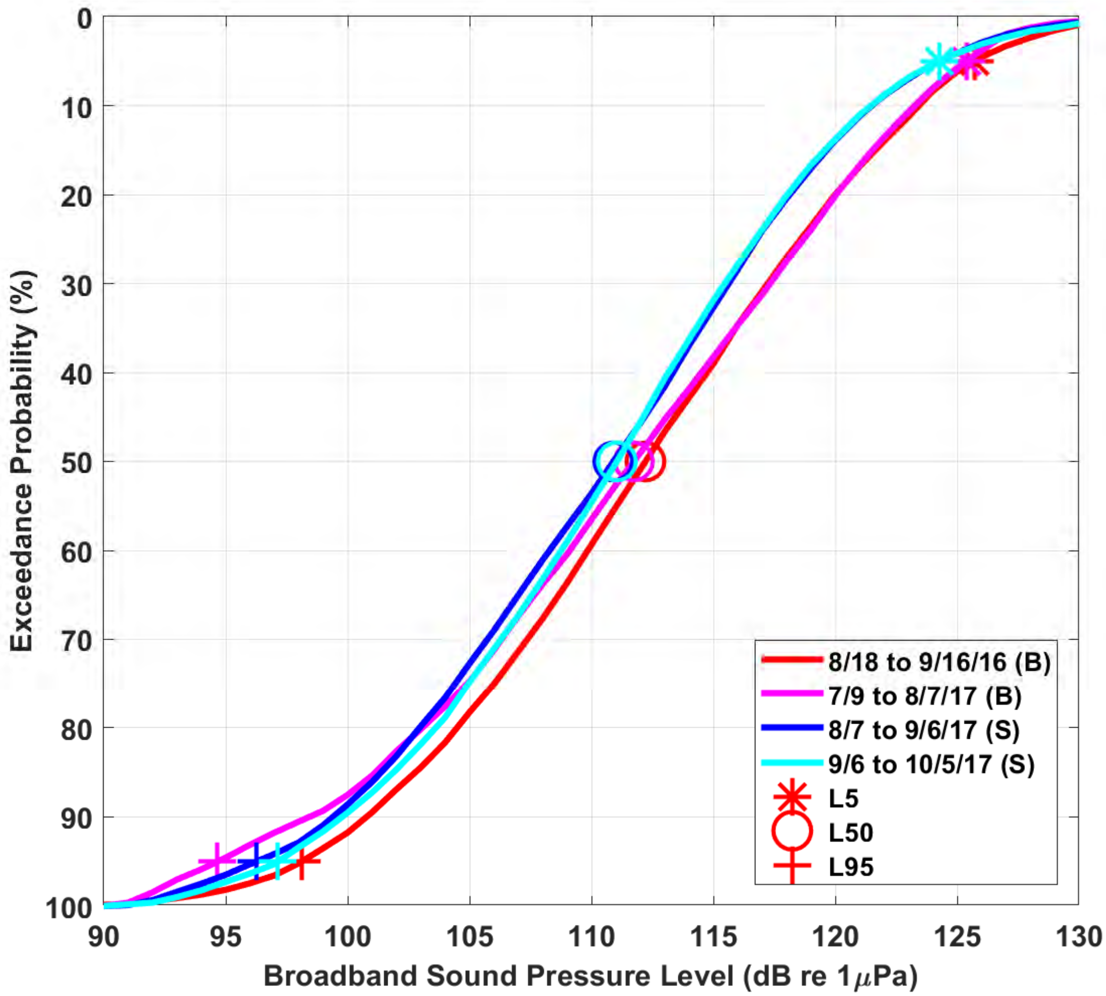
	Metric	Baseline SPL (dB) 8/18 to 9/16/16	Baseline SPL (dB) 7/9 to 8/7/17	Slowdown SPL (dB) 8/7 to 9/6/17	Slowdown SPL(dB) 9/6 to 10/5/17
1	L5	125.9	126.0	125.2	123.9
2	L50	110.4	108.9	108.7	108.3
3	L95	94.3	92.5	93.7	93.3
4	Leq	110.9	109.7	109.5	108.9
5	Minutes	42338	40403	41690	40751

Figure A 3.1. Exceedance CDF plot of broadband (10 Hz to 100 kHz) ambient SPL (dB re 1 µPa) by two Baseline months (red and magenta lines) and two Slowdown months (blue lines). All data – no time periods excluded. Table beneath provides L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files.



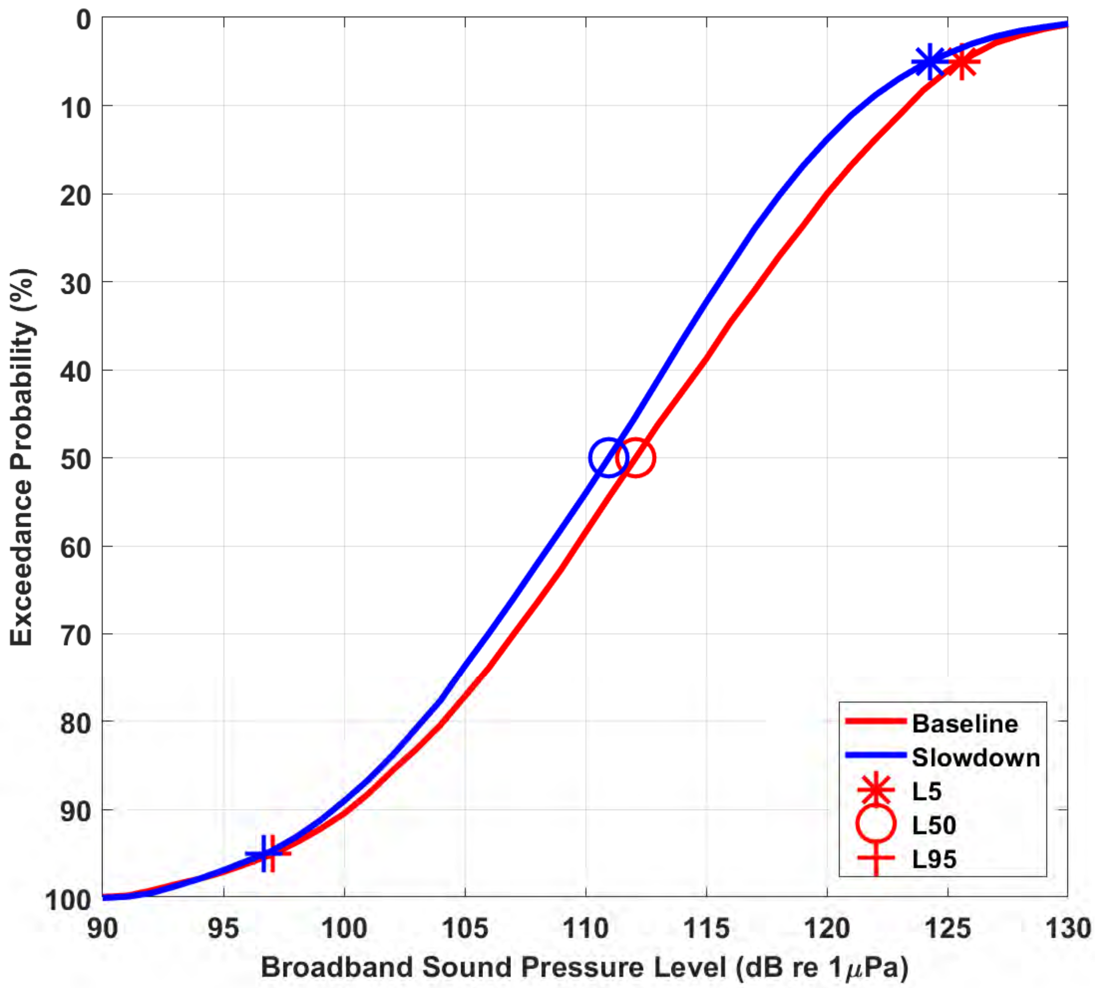
	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	126.0	124.6	-1.3
2	L50	109.7	108.5	-1.2
3	L95	93.3	93.5	0.2
4	Leq	110.3	109.2	-1.1
5	Minutes	82741	82441	

Figure A 3.2. Exceedance CDF plot of broadband (10 Hz to 100 kHz) ambient SPL (dB re 1 µPa) by Baseline (red line) and Slowdown (blue line) periods. All data – no time periods excluded. Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files. The dB difference between Baseline and Slowdown periods has been provided for each metric. A negative difference means that the slowdown period is quieter.



	Metric	Baseline SPL (dB) 8/18 to 9/16/16	Baseline SPL (dB) 7/9 to 8/7/17	Slowdown SPL (dB) 8/7 to 9/6/17	Slowdown SPL(dB) 9/6 to 10/5/17
1	L5	125.7	125.4	124.3	124.3
2	L50	112.2	111.7	110.9	111.0
3	L95	98.1	94.7	96.3	97.1
4	Leq	112.7	111.9	111.1	111.4
5	Minutes	13756	6200	10348	8594

Figure A 3.3. Exceedance CDF plot of broadband (10 Hz to 100 kHz) ambient SPL (dB re 1 µPa) by two Baseline months (red and magenta lines) and two Slowdown months (blue lines). Only minutes with an AIS enabled vessel within a 15-km detection zone were included. Times with high wind and current as well as small boat presence were removed. Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files.



	Metric	Baseline SPL (dB)	Slowdown SPL (dB)	Difference (dB)
1	L5	125.6	124.3	-1.3
2	L50	112.1	111.0	-1.1
3	L95	97.0	96.7	-0.4
4	Leq	112.4	111.2	-1.2
5	Minutes	19956	18942	

Figure A 3.4. Exceedance CDF plot of broadband (10 Hz to 100 kHz) ambient SPL (dB re 1 µPa) by Baseline (red line) and Slowdown (blue line) periods. Only minutes with an AIS enabled vessel within a 15-km detection zone were included. Times with high wind and current as well as small boat presence were removed. Tables beneath provide L5, L50, L95 and Leq noise metric SPL values and the number of associated 1-minute noise files. The dB difference between Baseline and Slowdown periods has been provided for each metric. A negative difference means that the slowdown period is quieter.

Appendix C

Economic, environmental and cultural analysis report - Seaport Consultants Canada

Vancouver Fraser Port Authority

Economic, Environmental & Cultural Analysis of 2017 Voluntary Vessel Slowdown Trial

Final Report

May 2017

Project No. 17001

Seaport Consultants Canada Inc.

In association with Colledge Transportation Consulting Inc.

Vancouver Fraser Port Authority

Economic, Environmental & Cultural Analysis of 2017 Voluntary Vessel Slowdown Trial

Final Report

May 2017

Project No. 17001

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Appendix I: Economic Impact Analysis of Proposed Voluntary Vessel Slow Down Trial Phase 1 Final Report

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1 Executive Summary

1.1 Study Background and Purpose

Haro Strait is located within a Critical Habitat and feeding grounds for the Southern Resident Killer Whales (SRKW) that are listed as endangered under Canada's *Species at Risk Act.* The legislation identifies ways for governments to work together to preserve and protect wildlife species and empowers them to establish penalties for failure to comply with the law.

The critical habitat of the remaining 78 orcas directly overlaps with busy international shipping routes, a U.S. ferry route and the operations of a sizeable whale watching industry. Existing scientific research indicates that underwater noise from vessels masks the whales' echolocation clicks which interferes with their ability to hunt for Chinook salmon, their main food source. Underwater noise from vessels can also affect the whales' ability to navigate and communicate with each other. In 2008, Fisheries and Oceans Canada (DFO) published a Recovery Strategy for Resident Killer Whales which identifies acoustic disturbance from vessels as a key threat. In 2017, DFO published an Action Plan including several measures to better understand and reduce vessel noise. In 2016, the Government of Canada announced the Oceans Protection Plan and in March 2017, Transport Canada officials indicated that they have been tasked to develop a strategy to reduce underwater noise levels in the Salish Sea by 2019 as part of a long-term commitment for recovery of SRKWs.

In 2014, the Vancouver Fraser Port Authority (VFPA) launched the Enhancing Cetacean Habitat and Observation (ECHO) Program, a collaborative initiative aimed at better understanding and managing the impact of shipping activities on at-risk whales throughout the southern coast of British Columbia. A key goal of the ECHO program is to develop voluntary mitigation measures to reduce threats to whales resulting from commercial shipping activity. As part of the program's research to explore vessel noise mitigation solutions, a voluntary vessel slowdown Trial is planned for August 7th to October 6th of 2017. The Trial will focus on understanding the relationship between slower vessel speeds, underwater noise levels and the potential effects on SRKW.

This report evaluates the economic, environmental and cultural implications of the two-month vessel slowdown Trial ('the Trial'). Given the potential implications for the shipping industry and other users of Haro Strait, the ECHO program felt it important to proceed with some analysis prior to commencing the Trial itself. To this end, a two-phased approach was employed.

Phase 1, prepared by Seaport Consultants Canada, estimated the financial implications of the Trial from a shipping industry perspective (see Appendix I). Phase 2, completed by Colledge Transportation Consulting, used a Multiple Account Evaluation (MAE) framework to document the implications of the Trial from several broad perspectives, or "Accounts", the results of which are presented in this Economic, Environmental and Cultural Analysis report. Both of these reports are based on a detailed analysis of 898 actual one-way transits of Haro Strait between August 7 and October 6, 2015 as a proxy for the anticipated shipping activity during the same months as the 2017 Trial.

1.2 Findings and Conclusions

Based on the research and analysis carried out for this study the main findings are as follows.

- During the Trial, the slowdown for vessels transiting Haro Strait while navigating to/from the Port of Vancouver is expected to add 30 to 60 minutes per vessel to the one-way sailing time depending on the vessel type.
- Although the net incremental costs of the Trial to the shipping industry appear modest in comparison with the overall costs of trans-Pacific voyages accessing the Port of Vancouver which run into the millions of dollars, the added costs come at a time when the industry is under significant pressure to reduce costs. The Port is also seeking to maintain/increase its market share in a highly competitive maritime industry where reliable on-time performance and cost efficiency are competitive advantages.
- The estimated impact of the two-month Trial with respect to vessel operating costs (pilotage costs, ship time, fuel consumption) varies by type of vessel, and could range as follows (Canadian $ per ship transit in/out of Haro Strait):

	Cost per Ship (C$)		
Ship Type	Average	Minimum	Maximum
Bulk Carrier	$160	-$166	$2,683
Car Carrier	363	178	453
Container	1,420	210	4,371
General Cargo	236	-42	2,095
Passenger	1432	0	3,526
Tanker	327	-46	3,706

- If all 898 vessels that transited Haro Strait for the same time period in 2015 participated in the two-month Trial, the estimated aggregate industry cost of the Trial by cost category is (all figures in Canadian $): pilotage, $180,882; ship time, $149,909; Haro Strait fuel savings, $438,315; makeup fuel required to maintain sailing schedules, $630,244. Total cost, $522,720.
- There are several port-related costs that could be affected by the Trial such as longshore labour, tug costs, line handling costs, demurrage and safety and security costs for cruise ships. The key determining factor for port costs is the ability of a ship to arrive within its designated berth window. The scheduling and use of berth windows is also critically important to port terminal operations and efficiency, as well as meeting rail and truck connections for the inland distribution of goods in the supply chain. The potential cost impact and decision by a ship owner/operator/agent to participate in the Trial would be on a case by case basis. Because the level of participation is, a priori, unknown, a case study approach is used to illustrate the potential port cost impacts for different types of ships. For example, if the longshore labour for a container ship was delayed for one hour due to the vessel slowdown, the minimum additional cost would be $11,000 or $90 per container based on day shift labour rates (see Section 3.3).
- In the short term, the Trial is not expected to have a material impact on trade traffic calling the Port of Vancouver because of the short duration of the Trial and because the Trial is voluntary. Vessel operators can elect not to participate if they believe their sailing schedule, pilotage hours, port related costs, etc.

are going to be significantly impacted on a particular transit. However, a more permanent slowdown where all vessels had to participate would have a greater potential adverse impact on trade traffic.

- A more permanent vessel slowdown in the Haro Strait area, if applied only to Canadian waters, could create a significant competitive disadvantage for the Port of Vancouver relative to competing west coast ports. This could impact both cargo and passenger shipping and also have major cost and customer service implications for ferry companies that operate in the area 100% of the time.
- The Trial provides an important opportunity to inform federal policy and related future conservation approaches with science-based evidence regarding the most effective measures that might contribute to the recovery of SRKW, while minimizing the adverse effects on the shipping industry and maritime commerce than would otherwise be the case under a “do nothing” scenario that is not informed by a full scientific assessment and confirmation of costs and benefits.
- SRKW are of tremendous cultural importance to coastal Aboriginal peoples and the Trial provides a positive opportunity to demonstrate potential ways and means to protects the species.
- The Trial is an opportunity to raise industry and public awareness of the cultural significance of SRKW to Aboriginal peoples – an iconic species of importance to all British Columbians – and the purpose and importance of reducing threats such as underwater vessel noise.
- The Trial will contribute to the protection of Critical Habitat by gathering evidence regarding the impacts of noise to reduce threats from commercial vessel-related activities on at-risk whales.
- The Trial calls for vessels to slow down to 11 knots which could result in at source sound intensity reductions of 78% and 40%, for containers and bulkers respectively. The scale of these noise reductions should reduce the number of behavioral disruptions to SRKW, as well as reduce the scale of SRKW echolocation click and call masking. The Trial dates encompass a period of typical high inshore presence of the SRKW in a key location known for foraging and other activities and as such the Trial is anticipated to have overall positive effects on SRKW.
- Air emissions analysis indicate that impacts range from a decrease in emissions of 8% (if no makeup of lost time as a result of the trial is required) to +8% if all vessels participate in the Trial and have to make up lost time within the North American Emissions Control Area (ECA)..

2 Introduction

The Vancouver Fraser Port Authority (VFPA) engaged Seaport Consultants Canada Inc. (Seaport) in association with Colledge Transportation Consulting Inc. (CTC) to evaluate the economic, environmental and cultural implications of a proposed voluntary vessel slowdown Trial (the "Trial") planned for the summer of 2017 in Haro Strait.

The objective of the Trial is to understand the relationship between reduced vessel speed, underwater noise levels and the potential effects on southern resident killer whales (SRKW). During the two-month Trial, commercial piloted vessels are being encouraged to reduce their speed to 11 knots through the water for a distance of approximately 16 nautical miles while transiting Haro Strait. Slowing down through the trial area could result in delays of 30 to 60 minutes per vessel depending on the vessel type. The ECHO program (the "program") encourages participating companies to adjust their planned arrival time to minimize potential schedule impacts. The program also encourages companies to evaluate participation on a transit by transit basis and to consider participating only when it is operationally and economically feasible to do so. During the Trial, hydrophones will monitor ambient and vessel underwater noise, as well as the presence of whales, and automated vessel tracking systems (AIS) will be used to monitor vessel speeds.

Phase 1 of this two-phase study estimated the financial impacts of the Trial on the shipping industry and was completed by Seaport in May 2017. Phase 2, prepared by CTC, incorporates the main findings of the financial analysis into a broader Multiple Account Evaluation (MAE) framework to document the costs and benefits of the Trial from several different perspectives.

2.1 Multiple Account Evaluation Framework

Multiple Account Evaluation is an integrated planning tool commonly used by the provincial government and Crown agencies to evaluate transportation initiatives. The purpose of the MAE is to identify and evaluate the implications of the vessel slowdown from several different perspectives or "accounts". As such, it provides an objective assessment of the trade-offs associated with changes in vessel operations. It also provides some overall perspective regarding the merits of scientific research made possible by the Trial compared with a "do nothing" scenario (i.e., no scientific research) that could result is less informed decisions needed to balance financial, economic, environmental and cultural values.

Within the MAE framework, it is important to recognize not only the direct costs borne by vessel operators due to the Trial, but also any indirect costs to the industry, and potential impacts on local/regional economies and the implications for environmental and social values. MAE involves three basic steps:

1. Specification of the evaluation accounts and analytical measures;
2. Assessment and documentation of implications under each account using key measures; and
3. Interpretation and presentation of results.

The MAE comprises five accounts as noted below. Each account is structured to address the main interests and concerns of various stakeholders that may be affected by or would have interests in or concerns about the Trial. The measures used within each account are indicated in the following sections of this report which is organized by account.

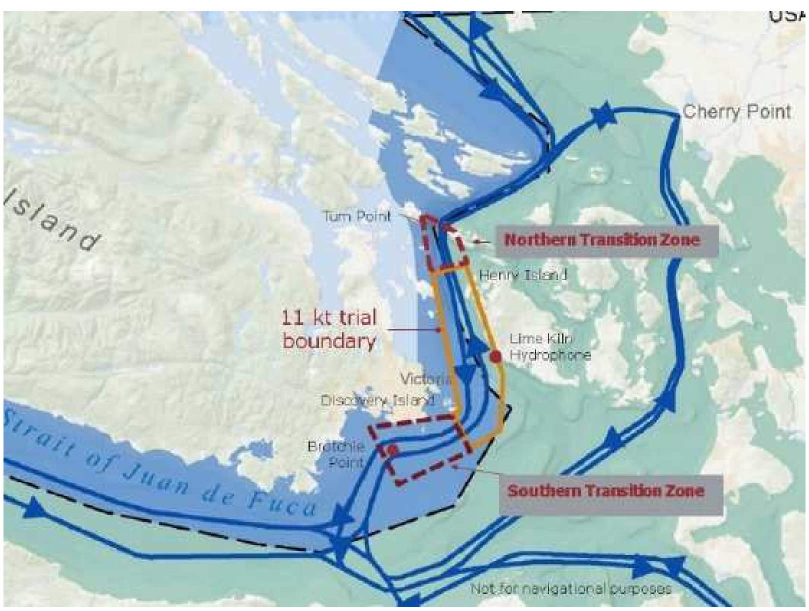
- **FINANCIAL ACCOUNT** – Identifies the potential cost implications of the Trial on cargo and cruise ship operators.

- **CUSTOMER SERVICE ACCOUNT** – Identifies the nature, magnitude and significance of potential impacts of the Trial on commercial users of Haro Strait and their customers.
- **ECONOMIC ACCOUNT** – Identifies the nature, magnitude and significance of anticipated trade-related implications of the Trial.
- **CULTURAL ACCOUNT** – Identifies the benefits and implications of the Trial for Coastal Aboriginal Peoples' cultural interests, values and objectives.
- **ENVIRONMENT ACCOUNT** – Identifies the nature, magnitude and significance of the Trial on the SRKW critical habitat associated with underwater noise reduction, as well as the implications of the vessel slowdown on air quality.

2.2 Affected Environment

Haro Strait is an important feeding area for SRKW, considered by the WWF-Canada as the most endangered group of marine mammals in Canada. SRKW are listed as endangered under Canada's *Species at Risk Act (SARA)* and the U.*S. Endangered Species Act*.[1] Under these Acts, critical habitat has been designated for SRKW in both Canadian and U.S. waters, as shown by the blue and green shaded areas respectively in Figure 1. Also shown in the figure are the international shipping lanes that transit directly through these areas of critical habitat, and the Trial boundaries and speed transition zones in Haro Strait (shown in yellow and red). As of May 2017, the population of SRKW dwindled to just 78 orcas and the species has shown little recovery since the 1980s. Although most SRKW sightings occur between May and November, the August to September period is typically when the whale population peaks in Haro Strait.

Figure 1 – SRKW Habitat and Haro Strait Trial Boundaries



Trial zone = 16.6 nautical miles (inbound); 14.9 nautical miles (outbound)

[1] SARA is federal legislation that became law in December 2002. The goal of the Act is to protect endangered or threatened organisms and their habitats. It identifies ways for governments and organizations to work together to preserve species at risk and establish penalties for failure to comply with the law. The U.S. Act was passed by Congress in 1973.

In 2008, Fisheries and Oceans Canada (DFO) published a Recovery Strategy for Resident Killer Whales which identifies acoustic disturbance from vessels as a key threat. In 2017, DFO published an Action Plan including several measures to better understand and reduce vessel noise. In 2016, the Government of Canada announced the Oceans Protection Plan and in March 2017, Transport Canada officials indicated that they have been tasked to develop a strategy to reduce underwater noise levels in the Salish Sea by 2019 as part of a long-term commitment for recovery of SRKWs.

Existing research indicates that underwater noise from vessels can mask SRKW echolocation clicks which interferes with their ability to hunt for Chinook salmon, their main food source. Underwater noise from vessels can also affect SRKW's ability to navigate and communicate with each other. Projected increases in human population and marine traffic have the potential to further increase vessel traffic and related underwater noise, particularly because much of SRKW critical habitat directly overlaps with international shipping routes, ferry routes and other marine traffic in the Salish Sea.[2]

2.3 ECHO Program Leadership and Interest Groups

In 2014, the Vancouver Fraser Port Authority (VFPA) launched the Enhancing Cetacean Habitat and Observation (ECHO) Program, a collaborative initiative aimed at better understanding and managing the impact of shipping activities on at-risk whales throughout the southern coast of British Columbia. A key goal of the ECHO program is to develop mitigation measures to reduce threats to whales resulting from commercial shipping activities. As part of the program's research to explore vessel noise mitigation solutions, a voluntary vessel slowdown Trial is planned for August 7th to October 6th, 2017.

The voluntary Trial is being planned and coordinated under the auspices of the ECHO Program with the assistance of a Vessel Operators' Committee (VOC). The VOC includes representatives from BC Coast Pilots, BC Ferries, Canadian Coast Guard (DFO), the Chamber of Shipping of British Columbia, Cruise Line International Association North West and Canada, Hapag-Lloyd, Holland America Group, Pacific Pilotage Authority, Shipping Federation of Canada, Transport Canada, the VFPA and Washington State Ferries.

Other parties that may have interest in the Trial include: shipping companies; cruise lines and their customers; U.S. Coast Guard; Royal Canadian Navy; ships' agents; marine terminal operators; stevedore companies; British Columbia Maritime Employers Association (BCMEA); maritime labour; coastal First Nations; recreational boaters; whale watching organizations such as the Pacific Whale Watching Association (PWWA); environmental organizations; marine scientists and the public.

Although not part of the VOC itself, DFO and the U.S. National Oceanic and Atmospheric Administration (NOAA) are both long standing members of the ECHO Program's Advisory Working Group and have also been engaged in the development of the Trial.

[2] The Salish Sea is a network of coastal waterways that includes the southwestern portion of British Columbia and the northwestern portion of Washington State. The major bodies of water included this network are the Strait of Georgia, Strait of Juan de Fuca and Puget Sound, and their connecting channels such as Haro Strait, Rosario Strait, Bellingham Bay and Hood Canal.

2.4 Current International Shipping Context

The fundamental purpose of the Trial is to assemble science-based evidence to inform decisions regarding the most effective steps that should be taken to reduce acoustic disturbance from vessels and help support the recovery of a critically endangered species. The international shipping industry recognizes the importance of the marine environment within which it operates. However, it is extremely important that the industry has input to the development of any measures to reduce or eliminate acoustic disturbance.

The international container shipping industry entered 2017 after five straight years of major financial losses. The industry has seen several high-profile mergers and acquisitions and the bankruptcy filing of Hanjin Shipping in August 2016 caused a massive disruption in the trans-Pacific market that sent shock waves rippling through the industry. Although some sectors such as tankers have recently experienced better financial conditions, the dry bulk sector had one of its worst years on record in 2016, despite a recovery in the Baltic Dry Index towards the end of the year. In this context, and when ship owners are looking to increase efficiency and reduce costs wherever possible, any initiative that adds costs will come under intense scrutiny.

2.5 Users of Haro Strait

Haro Strait is a critical part of the sea route forming the international boundary between Canada and the United States. It is a major shipping channel utilized by international vessels to access the Port of Vancouver.

Apart from port-related traffic, a wide range of other commercial and recreational vessels use the Strait. It is a favourite locale for whale watching tours based out of Greater Victoria and the San Juan Islands. Washington State Ferries also traverses the northern end of the trial boundary on its Anacortes-San Juan Islands- Sydney, BC service. Haro Strait is part of the Coast Salish peoples' larger traditional territory. The Strait is also an important location affecting the regional commercial fishery because the bulk of the Fraser River salmon run uses Haro Strait to enter the river.

2.6 Study Approach

The approach for this report is based on industry consultations with the following parties to understand the existing operational, environmental, cultural and port customer context and the implications of the proposed vessel slowdown:

- BC Coast Pilots
- BC Ferries
- Chamber of Shipping of British Columbia
- Cruise Lines International Association (CLIA) – Northwest & Canada
- Coastal Aboriginal Peoples
- Pacific Northwest Ship & Cargo Services
- Pacific Pilotage Authority
- Pacific Whale Watching Association
- Port terminal operators
- Shipping Federation of Canada
- Shipping lines
- Sea Mammal Research Unit (SMRU) Canada (marine mammal specialists)

- Washington State Department of Transportation
- Vancouver Fraser Port Authority (Marine Operations and Air Quality specialists)
- ECHO Program Vessel Operators Committee

The analysis and findings of this study are presented in the following sections of this report by account. In each case, the evaluation begins with a brief description of the analytical measures and situational context, followed by the main analysis, findings and implications. Where possible, the implications of the Trial are quantified. In cases where quantification is not possible or insufficient data is available, a qualitative assessment is provided.

3 Financial Account

Objective	Measures
Identifies the potential cost implications of the Trial on cargo and cruise ship operators.	• Vessel operating costs • Port costs • Supply chain disruption costs

The purpose of the financial account is to estimate the cost implications of the Trial on commercial vessel operators. This includes cargo and cruise ships calling at the Port of Vancouver.[3] Other directly affected parties include shipping agents, BC Coast Pilots and the Pacific Pilotage Authority (PPA). For the purposes of this study, the key financial metrics are: vessel operating costs (fuel, pilotage and vessel time); port costs (e.g., longshore labour, cruise ship security); and the potential costs of supply chain disruption that could impact the competitiveness of the Port of Vancouver as a gateway for international trade. It should be noted that the financial analysis does not address the impacts of the major vessel schedule changes that container carriers are introducing in Q2 2017.

3.1 Operating Context

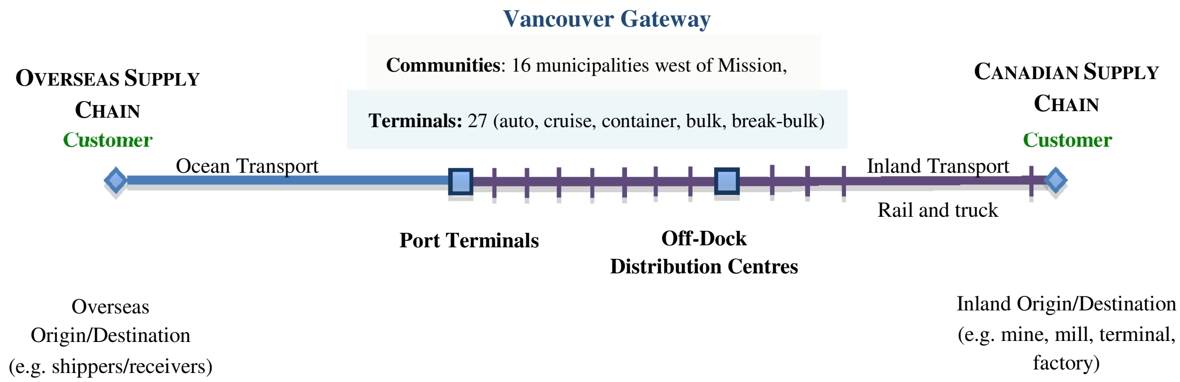
3.1.1 Macro Perspective: Global Supply Chain Environment

Vessels calling at the Port of Vancouver are part of a complex and highly competitive global distribution network. The import/export supply chain serving the gateway shown in Figure 2 makes possible the movement of export resources to world markets and import goods to consumers and industrial users in North America. The Port of Vancouver's integrated logistical system includes 27 major marine terminals and more than 50 off-dock freight facilities serving five business sectors: automobiles, cruise, containers, bulk and break-bulk.

The port facilitates access to 160 global economies and is the interface between marine and landside operations. In such a complex and inter-related system, the actions of any one supply chain participant can impact the operation and performance of any other participant, as well as the collective performance, profitability and reputation of the entire network, not to mention the many thousands of customers using the port. Therefore, while vessel operating and port costs are the primary focus in the financial performance account, the potential shipping costs associated with any disruption in the supply chain must also be considered in the analysis.

[3] Washington State Ferries traverses Haro Strait for a short distance on its Anacortes to Sydney service. Discussions with representatives of the ferry service indicated that their participation in the Trial for a two-week period would have no material impact on this service.

Figure 2 – Vancouver Gateway Import/Export Supply Chain



3.1.2 Local Perspective: Port of Vancouver Operating Environment

The *Pilotage Act (1978*) legally requires international vessels of 350 gross tons or larger to use a Canadian marine pilot while operating in Canadian waters. The Pacific Pilotage Authority (PPA), a federal Crown corporation, administers this service for the British Columbia coast to provide safe, reliable and efficient marine pilotage. PPA's jurisdiction extends about two nautical miles from every major point of land, including the Fraser River and south to Washington State. BC Coast Pilots (BCCP), a private company with 105 licensed professional marine pilots, contracts its services to the PPA. BCCP provides safe navigation for vessels operating in coastal waterways to ensure no damage to ships, crews, the public, or the marine environment. In short, its role is to ensure commercial interests co-exist with the preservation of marine habitat. The PPA is responsible for dispatching pilots to/from ships in close coordination with ships' agents.

The Captain of a foreign flag ship may not be familiar with the specifics of each port where his vessel calls and thus requires the local expertise of a marine pilot. With respect to Port of Vancouver, the pilot boarding/disembarking stations are located at Fairway Buoy, off Brotchie Ledge near Victoria, off Sand Heads at the mouth of the Fraser River, and at a range of Vancouver port terminals and anchorages. With respect to cross-border traffic, if the vessel is Canada bound, the Canadian pilot joins the vessel in the U.S. at Port Angeles. For U.S. bound vessels, the handoff between Canadian and U.S. pilots occurs at Patos Island in Washington State. Pilots are also required for movements to/from anchorages. The master, owner or agent of a ship requiring the services of a licensed pilot must provide notice to the PPA of the estimated time of the ship's arrival at the boarding station at least 12 hours before arrival in the case of Brotchie and 48 hours prior to arrival at Sand Heads. For both boarding stations, the estimated arrival times are then confirmed or corrected within tighter windows of 4 hours for Brotchie and 12 hours for Sand Heads.

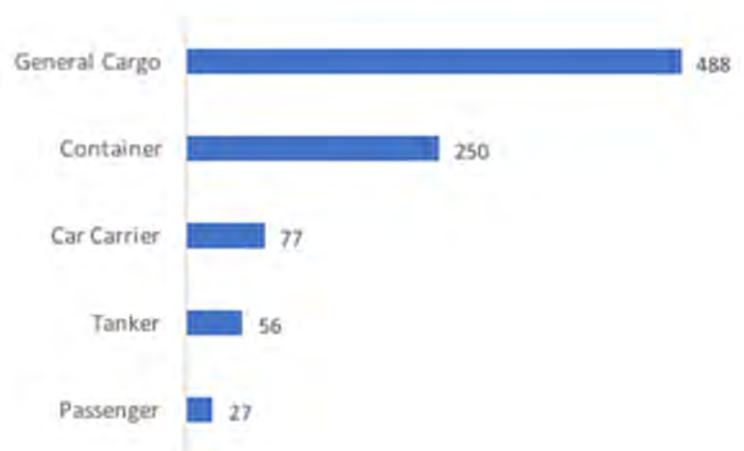
A key component of pilotage costs is bridge watch time. A bridge watch begins at the earlier time for which the pilot is booked, or when the pilot reports on the bridge of a ship and takes conduct thereof.[4] A bridge watch ends when the pilot leaves the bridge to disembark at a station, or when the pilot is relieved by another pilot (for transfers between U.S. and Canadian waters, e.g., ships going to Puget Sound). In most cases, only one pilot is needed aboard a ship. Two pilots are required when bridge watch time exceeds eight hours, for distances exceeding 105 nautical miles and for large tankers.

[4] Bridge watch time drives one component of pilotage charges. The other components are fixed charges based on ship size characteristics and other costs such as pilot transportation to/from boarding stations.

3.2 Vessel Operating Cost Analysis

The vessel operating cost analysis draws from the Phase 1 financial analysis completed in May 2017 (see Appendix) which is based on a detailed analysis of 898 *actual* one-way transits (in or out) of Haro Strait from August 7 to October 6, 2015 from PPA data as a proxy for the 2017 Trial. The breakdown of these transits by vessel type is shown in Figure 3. General cargo vessels include bulk carriers used for the transport of dry bulk cargoes, as well as break-bulk ships used for forest products, steel and project cargo, etc. Passenger refers to all cruise ships serving the port and includes some repositioning voyages in the Vancouver to Alaska cruise market.

Figure 3 – 2015 Haro Strait Transits by Vessel Type (Total - 898 ships)



Direct **vessel operating costs** are estimated based on the three main components of ship related costs *with* and *without* the vessel slowdown in Haro Strait:

Fuel + Pilotage + Ship Time = Operating Cost

Fuel: Fuel is the largest variable cost item for a ship operator. The cost for a trans-Pacific voyage to Vancouver is in the order of $1 million at today's fuel prices. For the purposes of this analysis, the fuel cost is captured in two components: 1) **Cost in Haro Strait** which reflects lower fuel consumption rates at the slowdown speed of 11 knots through the water, versus consumption at regular service speeds; and 2) **Makeup fuel cost** for scheduled service container and cruise ships to recover lost time in Haro Strait by sailing faster on remaining voyage legs to maintain schedules. Fuel consumption rates reflect different vessel and engine types, as well as a 2017 price of **US$550/tonne** for ultra-low sulphur marine gasoil consumed within North American emission control areas (ECA). This is an average price reflecting different local and international fuel prices and purchases. The price for high-sulphur marine fuel oil consumed in international waters is assumed to be **US$300/tonne**.

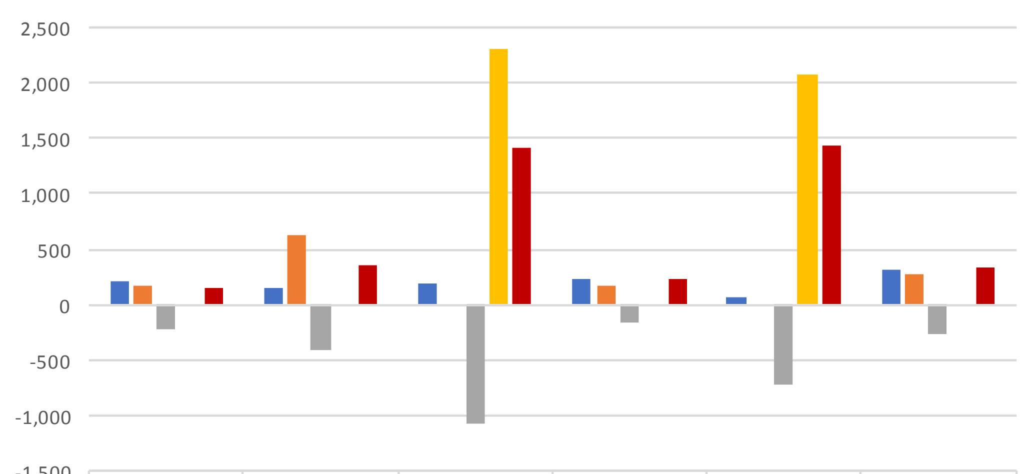
Pilotage: Pilotage costs for the 898 ships were estimated from the PPA Tariff of January 2017 for the actual 2015 situation and the case with the Trial in Haro Strait. The main variable component of pilotage cost is the charge per bridge watch hour, plus other fixed charges (e.g., pilot transportation charges such as taxis). The time for bridge watches begins at the earlier of the time for which the pilot is ordered and when the pilot commences the bridge watch. The time ends when the pilot disembarks the ship. The bridge watch time charge is **C$208.75/hour**, or part thereof for the first 8 hours at which point the rate scale becomes non-linear and additional time charges come into effect. If a single pilot's bridge time were to extend into a 9th hour on a voyage, the charge would be for that 9 hours, plus an additional charge of three times the base amount: (9 x $208.75 = $1,878.75) + (3 x $1,878.75 = $5,636.25) = C$7,515.00. Based on an evaluation of 2015 piloted vessel transits through Haro Strait, it is anticipated that about 47% of ships would experience no pilotage cost increase from the Trial because bridge watch times would be less than 8 hours. About 46% of ships would incur an increase of one hour of bridge time ($208.75) and the remaining 7% of ships would incur greater pilotage costs because of additional charges for bridge times that in total exceed 8 hours (average cost of $1,440.69 per hour).

Ship Time: The cost of ship time is based on current average time charter rates for bulk carriers, general cargo ships and tankers to capture the costs of time gained or lost by such ships. The costs vary by type of ship and are in the range of **US$8,000 to $12,000** per day for bulk carriers and **US$13,000 to $14,000** per day for tankers. Since time-based costs do not reflect the cost structure of the container and cruise trades that are fixed once an operator establishes the service, there is no time-related cost for container vessels.

Operating Cost: Based on the foregoing assumptions, an estimate of the additional cost per ship transit as a result of the Trial is provided in Figure 4.

Table 1 provides the range of total costs per ship. Cruise and container ships exhibit the highest cost because of the relatively greater incidence of vessel rotations to/from Puget Sound and California ports. In this case, the correspondingly short voyage distances available to compensate for lost sailing time and make up time to maintain schedules requires greater fuel consumption.

Figure 4 – Estimated Average Cost of the Trial by Sector (C$/ship transit)



	Bulk carrier	Car carrier	Container	General cargo	Passenger	Tanker
Pilotage	209	157	185	233	62	313
Ship Time	180	620	0	167	0	270
Haro Str. Fuel	-229	-414	-1,061	-163	-709	-256
Makeup Fuel	0	0	2,296	0	2,079	0
Total	160	363	1,420	236	1,432	327

Source: Seaport estimates based on actual 2015 Haro Strait ship transit data.

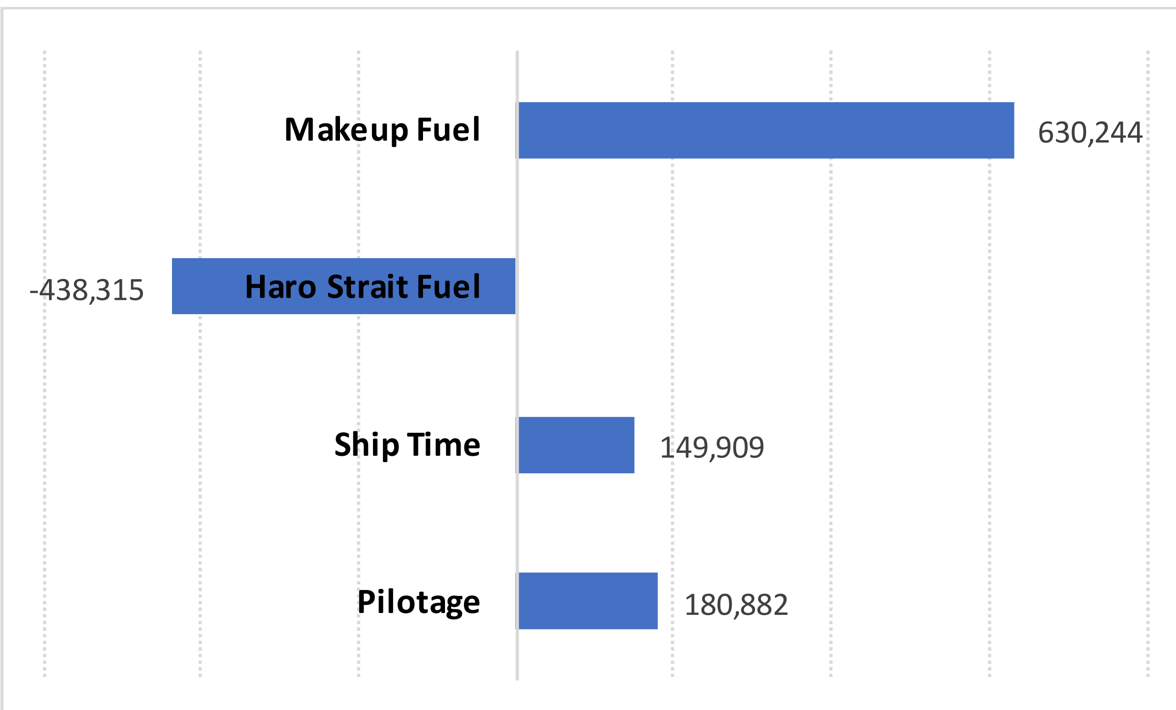
Table 1 – Range of Costs per Ship

Ship Type	Cost per Ship (C$) Average	Minimum	Maximum
Bulk Carrier	$160	-$166	$2,683
Car Carrier	363	178	453
Container	1,420	210	4,371
General Cargo	236	-42	2,095
Passenger	1432	0	3,526
Tanker	327	-46	3,706

Source: Seaport estimates based on actual 2015 Haro Strait ship transit data.

The composition of vessel operating cost impacts is further illustrated in Figure 5. Makeup fuel consumed to compensate for lost sailing time in Haro Strait is the largest component of vessel costs followed by pilotage and ship time costs. The incremental costs are partially offset by the reduced cost of fuel consumed while ships operate at slower speeds in the Haro Strait slowdown zone.

Figure 5 – Composition of Industry Cost Impacts (C$)



3.2.1 Discussion

Container Ships (28% of ship transits). The most significant impact of the Trial for the container sector is the cost of makeup fuel because of the need to maintain schedule integrity. Although container vessels would realize fuel cost savings by slowing in Haro Strait, the added cost of makeup fuel—if required to make up for lost time to maintain schedule—is considerable and far outweighs the savings. The magnitude of makeup fuel costs, however depends on voyage distance. The largest impact involves voyages between Vancouver and Seattle/Tacoma where only a short distance is available for faster steaming. Other time constraints also come into play such as the requirement for vessels to reduce speed on approaches to a port terminal, slow transits through First Narrows to/from Vanterm and Centerm, as well as time for Canadian-U.S. pilot exchanges. Consequently, vessels would have to operate at significantly higher speeds between Vancouver and Puget Sound ports to compensate for lost time. Since the Trial is voluntary, a container ship, or any other type of ship faced with higher costs, can simply choose to opt out of the Trial.

In contrast, trans-Pacific voyages involve much longer distances over which to make up lost time. As a result, makeup fuel costs would be lower because vessels only need relatively small increases in speed spread out over vast distances to compensate for lost time. The sequence of port calls is also important given that more than 50% of the ships calling at Vancouver in the 2015 data set involve voyages to/from Puget Sound ports. However, as of Q2 2017 the itineraries associated with new vessel alliances reduce the number of direct Vancouver-Puget Sound container port calls, giving relatively greater prominence to long-haul voyages which would reduce the impact of makeup fuel costs. To this extent, the 2015 data tends to overstate the fuel cost estimates of the Trial.

Bulk Carrier and General Cargo Ships (60% of transits). Vessels in this sector, which includes tankers, have much slower operating speeds (i.e., 11-13 knots versus 18 knots for container ships) and frequently use anchorages. As a result, these slow ships experience long-duration voyages. Based on industry consultations, it already takes 7 to 7.5 hours to transit from Inner Harbour terminals such as Neptune, Lynnterm and Cascadia to Brotchie. It is difficult therefore, for bulk and general cargo vessels to make up lost sailing time and the slower operating speeds for this class of vessel risk triggering significant additional pilotage costs if the bridge watch time exceeds 8 hours. Yet based on 2015 data, only 63 of 544 bulk and general cargo/tanker ships (11.6%) would be in the situation where the slowdown pushes bridge watch time over 8 hours.

The same is true when *all* vessel types are considered. It is estimated that about 47% of ships would experience no pilotage cost increase from the Trial because bridge watch times are less than 8 hours. About 46% of ships would incur an increase of one hour of bridge time ($208.75) and the remaining 7% of ships would incur greater pilotage costs because of additional charges for bridge times that in total exceed 8 hours (average cost of $1,440.69/hour).

Car Carriers (9% of transits). Since the average service speed of car carrier vessels is 16.3 knots, pilotage costs and makeup fuel are less of an issue. For these vessels, ship time costs dominate the cost impacts.

Passenger Ships (3% of transits). Discussions with Cruise Line International Association (North West & Canada) indicated that ships on some voyages between Vancouver and Victoria would not be affected by the Trial since they have transit times of 14 hours and can operate at speeds as low as 5 knots, well below the slowdown speed limit of 11 knots. The biggest concern is the ability to meet sailing schedules because on-time sailing is a major factor in customer satisfaction. The most significant impact of the Trial is expected to be on repositioning sailings between California and Vancouver and some itineraries from Vancouver to Honolulu because of the makeup fuel required to maintain schedules.

Washington State Ferries only plans to participate in the Trial for a two-week period. Port engineers for the company advise that ferries entering Haro Strait would reduce speed from 15 or 16 knots down to 11 knots while traversing the Trial zone. Upon exit from Haro Strait, they would return to full speed without expending any extra fuel to compensate for the relatively short transit distance of 2.5 miles.[5]

3.3 Port Cost Analysis

There are several disbursements associated with every port call that could be affected by the vessel slowdown Trial including longshore labour, tugs, ships' line handling and safety and security costs for cruise ships.[6] The key determining factor for port costs is the ability of a ship to arrive within its designated **berth window**. The scheduling and use of berth windows is also critically important to port terminal operations and efficiency, as well as meeting rail and truck connections for the inland distribution of goods in the supply chain.

The arrival of vessels in port is governed by the **British Columbia Maritime Employers Association (BCMEA) Vessel Forecasting System.** The system is designed to give priority to vessels using the system and to those arriving on time. If a vessel is behind schedule, it will normally speed up to meet its berth window and comply with BCMEA's gang allocation rules and regulations in order to gain "A" priority vessel arrival status. Priority arrival status is important because it provides the best available labour dispatch to work a ship and expedite its turnaround at the port. Under this system, gangs are allocated based on vessel priority as determined by the arrival time and type of ship. Passenger vessels receive top priority, followed by container and then general cargo vessels. If multiple vessels have "A" priority status, BCMEA dispatch allocates labour in Vancouver based on arrival times at Brotchie.

The potential cost impact and decision by a ship owner/operator/agent to participate in the Trial would be on a case by case basis. Because the level of participation in the Trial is, a priori, unknown, a case study approach is used below to illustrate the potential port cost impacts for container, bulk/general cargo and cruise ships.

3.3.1 Container Ships

Under normal circumstances, the arrival of a container vessel at a port terminal is timed to coincide with longshore labour based on three daily shifts: Day Shift (08:00 to 16:30), Night Shift (16:30 to 01:00) and the Graveyard Shift (01:00 to 08:00). Carriers under commercial contract with terminal operators normally target vessel arrival alongside berth 8 hours prior to shifts. This allows time to complete customs and cargo clearance procedures required to ready the ship for work, as well as qualifying for VFPA's Container Vessel On Time Incentive program. Under this program, wharfage discounts are available for container vessels only for on time arrival within 8 hours of the start of the scheduled terminal berth window. The main port cost factors associated with a vessel delay are: longshore labour, missed berth windows, container demurrage and foregone discounts for on-time vessel arrivals. Each of these factors is discussed below.

Longshore Labour Costs. Every International Longshore and Warehouse Union (ILWU) gang includes several different categories of workers—foremen, quay crane operators, checkers, yard equipment operators, mechanics, electricians and others—who work aboard the ship and at dockside. Estimates of the associated labour delay rates for vessel operations by shift are as follows:

[5] The transit distance is shorter than for other commercial vessels because the ferry route runs perpendicular to the Trial zone.

[6] Many port charges are independent of the Trial and would not change if a vessel arrived late at the port. For example, berthage fees are based on the physical size of the vessel, as well as the vessel's length of stay at the berth. Similarly, wharfage is based on the weight or measurement of the cargo and varies by commodity.

Estimated 2017 Vancouver ILWU Delay Rates for Vessel Operations by Shift						
	Day Shift (Base)	Night Shift	Graveyard	Saturday (Day)	Sat/Sunday (Other)	Holidays
$/hour/gang	2,195	2,694	3,305	2,738	3,369	4,136
$/8-hour shift	17,560	21,552	26,440	21,904	26,952	33,088

Source: Based on 2015 Collective Agreement rates indexed to 2017 at 3% a year; includes markup for delay. Costs were confirmed with terminal operators.

A typical larger container vessel loading and discharging 8,500 twenty-foot-equivalent container units (TEU) would require five shifts with five gangs per shift to discharge/load the vessel, assuming productivity of 25 containers/hour (i.e., 25 containers x 8 hours = 200 containers/gang/shift x 5 gangs x 5 shifts = 5,000 containers or about 8,500 TEU).

If a carrier had ordered gangs for say an 08:00 start time and the vessel is delayed an hour because of the Trial, the minimum cost would be about $2,200/hour x 5 gangs = $11,000 based on day shift labour rates because the vessel operator must pay for the complete labour complement that is ordered (known in the industry as No Work Provided, NWP). If the vessel delay affected a Saturday shift, the minimum cost would be $2,700/hour x 5 gangs = $13,500. These costs equate to $90.00/container (day shift) and $110.00/container (Saturday shift). **This is a potentially significant additional cost relative to the total stevedoring charge in Vancouver which was about $325/container in 2015**.[7] A NWP situation also impacts the container terminal operator because of the lost capacity and could contribute to terminal congestion and spillover effects for connected rail and truck operations.

Delays getting in/out of Vancouver could impact the next leg of a vessel rotation. However, outbound vessels for Seattle/Tacoma can compensate for the slowdown by arriving at the pilot transfer station earlier to avoid missing a berth window. Based on consultations with a major container carrier calling at both Vancouver and Puget Sound, slowing the vessel is expected to increase pilotage costs by US$200/vessel per transit on average which compares favourably with the estimates provided above in Figure 4.

Missed Berth Window Costs. A rare, but worst-case scenario may occur if a carrier were to miss its berth window entirely. In this case, the vessel would have to wait for the next available time slot. Based on consultations with carriers, the related costs would include time chartering costs, seaman salaries, daily maintenance and additional tug and pilotage charges if the vessel needed to be moved to/from an anchorage. Although there is a limited time-charter market for larger container ships, carriers still track vessel time and cost for planning purposes. Ship time-charter costs are highly variable and depend on market demand and supply conditions, but would be in the range of US$13,000 to $50,000 per day should a missed berth window result in an additional day of chartering.

Demurrage Costs. Demurrage is a charge payable to the owner of a ship in respect of failure to load or discharge the ship within an agreed/contracted time. Vessel delays would affect export container demurrage

[7] Derived from Port of Vancouver Container Traffic Forecast Study, 2016, Ocean Shipping Consultants. Basic container handling charge of C$260 per container plus additional charges of 25% or C$325.

charges levied by terminal operators that are in place as an incentive to minimize container dwell time and terminal congestion. If a ship is delayed past midnight into the next day, it would place the export containers that have already been received at the terminal into a status of being on dock before the allowable export earliest receiving date (ERD) free time for the intended vessel. All containers that are bumped into that status would incur demurrage charges of $37.95 to $39.06 per TEU per day.[8] The total cost incurred would be unknown until such a case occurs and is a function of the total number of containers involved and delay days.

On-Time Berthing. Apart from VFPA's container vessel on-time incentive program, it is common practice for some container terminal operators to provide on time arrival incentives for carriers (i.e., +/- 2 hours) by offering a discount on the container throughput charge. This type of incentive program is designed to promote operational efficiency. Delays because of the Trial could put the on-time discount at risk, effectively increasing the carriers' costs.

3.3.2 Bulk Carrier & General Cargo Ships

The main concern with respect to the bulk/general cargo trade from a port cost perspective is the time a ship spends in port which potentially impacts demurrage costs and vessel shifting costs. Ship time depends, in part, on the time of tendering the Notice of Readiness (NOR) which is the document used by the captain of the ship to notify that the ship is ready to load and/or unload. The NOR is important because it causes laytime to commence and marks the time at which the ship owner/operator starts the demurrage/dispatch clock.[9] Laytime is the contracted period of time within which vessel loading/discharging must occur. If laytime is exceeded, the charterer must pay the ship owner compensation (demurrage).

Demurrage Costs. In general, a NOR must be tendered at port in writing at the offices of shippers/receivers or their agents in Vancouver between 0800 hours and 1600 hours Monday to Friday. If NOR is filed before noon, laytime would begin at 1600 hours that same day. If it is filed after noon, the laytime would be delayed until 0800 the following day. A worst-case scenario could occur if a delayed ship arrives at 1700 hours on a Friday and is unable to tender the NOR until Monday morning. The cost to the charterer at prevailing time-charter rates would be in the range of US$8,000 - $15,000 per day depending on the type of ship.

Vessel Shifting Costs. Vessel shifting costs include tugs, pilotage and longshore labour for handling a ship's lines.[10] If a delayed vessel misses its berth window or anchorage slot it would require an additional move between the anchorage and the terminal. Although tugs can typically be canceled at no cost, the same is not true for pilots and longshore labour. The incremental cost for launching a pilot to an anchorage including the lines cost is approximately $6,000 per occurrence for Inner Harbor terminals. For a facility such as Pacific Coast Terminals which is located to the east of the Second Narrows bridge and where all vessel arrivals use Indian Arm anchorages, the additional shifting cost could be as much as $20,000.[11] The delayed vessel could also have upstream (landside) consequences as well. For example, inbound cargo

[8] Source: GCT Canada Limited Partnership Terminal Services Tariff, April 2017; DP World Vancouver Terminal Services Tariff, April 2017

[9] NOR is also affected by third-party inspection of a ship's holds to ensure they are washed, clean and a protective coating applied in some cases to ensure cargo quality. Until the vessel has passed the inspection and the NOR has been filed, the ship cannot be moved to a terminal in readiness for loading.

[10] Except to prevent imminent hazard to a vessel or its crew, no vessel which is subject to the Pilotage Act is permitted to reposition itself within the port without having a pilot onboard.

[11] Source: Pacific Northwest Ship & Cargo Services and Pacific Coast Terminals.

arriving by rail may not have room to unload at the port terminal if vessels are delayed lifting product from storage.

A related concern for bulk and general cargo vessels is the limited number of anchorages in English Bay and in the Inner Harbour that are already under pressure from growing demand. If a vessel misses an anchorage due to the slowdown, a competing carrier could take an anchorage which is allocated on a first come, first serve basis.

3.3.3 Cruise Ships

Sailing schedule integrity is particularly important for cruise lines from a customer experience perspective (see Section 3.2.1), as well as from the perspective of costs associated with safety and security. Vessel delays could trigger additional labour and/or overtime costs for Canada Border Services Agency (CBSA) and longshore labour personnel.

4 Customer Service Account

Objective	Measures
Identifies the nature, magnitude and significance of potential impacts of the Trial on commercial users of Haro Strait and their customers.	• Sailing schedule reliability • Navigation conditions • Customer satisfaction

The customer service account assesses the anticipated impacts of the Trial on commercial users of Haro Strait. The users of Haro Strait include a broad interest group made up of vessel operators and their customers across many commodity sectors that pay the costs of transportation services, cruise lines and their passengers from around the world, as well as whale watching tour operators and their customers. The key measures used to analyze the customer service account are sailing schedule reliability, navigation conditions (adverse tidal windows and currents) and customer satisfaction.

4.1 Commercial Users of Haro Strait

Haro Strait is a major shipping channel utilized by some 15 cruise lines, 20 container shipping lines and more than a dozen general and specialized cargo shipping companies calling at the Port of Vancouver (e.g., bulk, break-bulk, car carriers).[12] In 2016, a total of 3,105 foreign vessels called at the port. The majority of international vessels calling at the port navigate a route through Haro Strait.

The other main interest group is whale watching tour operators. The commercial whale watching industry has developed into one of the fastest growing wild-life based viewing industries in the world. One estimate suggests that the marine mammal viewing sector of the BC tourism industry has grown at a rate of about 4.2% per year.[13] The Pacific Whale Watching Association (PWWA) estimates there were about half a million whale watch customers in 2016, up from 400,000 in 2014. Whale watching is an important educational experience because it allows people to better understand the issues related to endangered and threatened species.

In 1998, there were a total of 164 charter and cruise operators in British Columbia offering wildlife viewing as part of their product and 120 of these focused primarily on whale watching. The majority of whale watching is undertaken from Vancouver Island in three areas: Haro Strait, Johnstone and Queen Charlotte Straits on northeastern Vancouver Island and near Ucluelet and Tofino on the west coast of Vancouver Island. Victoria has the most whale watching operators with some 45 operators and a fleet of about 80 vessels. Most of the operators are small entities. Today, the PWWA has 35 member companies in the U.S. and Canada focused in Victoria, Sydney, Vancouver, San Juan Islands, the Olympic Peninsula and as far south as Seattle.

With respect to customer experience, Haro Strait, the Gulf Islands and the San Juan Islands in Washington State are considered among the best and most accessible areas of the world to watch killer whales. The most popular time is between May and October when the whales feed on migrating salmon. Apart from the 78

[12] A number of tug and barge operators also use the shipping channel but would typically already be operating at speeds of less than 11 knots.
[13] Source: O'Connor, Campbell, Cortez & Knowles, 2009 special report from the International Fund for Animal Welfare.

resident whales, there is also a transient population of approximately 300 whales that can be seen year-round along the Pacific Coast.[14]

4.2 Sailing Schedule Reliability Analysis

Sailing schedule reliability is critical for ship owners, agents and terminal operators. Any delays or uncertainty associated with a vessel's arrival/departure has serious repercussions and the potential to disrupt an entire supply chain. Agents representing ship owners want to minimize vessel time in port and reduce costs. Vessel owners are particularly concerned with sailing schedules because delays impact their ability to keep ships utilized and generate revenue. One of the most important considerations is the ability for a vessel to meet the scheduled berth window arrival time, as well as securing an anchorage in the case of bulk carriers. In the cruise sector, delays could have major impacts on passenger satisfaction and the broader tourism sector in Vancouver.

VFPA's Container Vessel On Time Incentive program is designed to encourage vessel operators to arrive on schedule to contribute to overall supply chain reliability. Vessel on-time arrival is measured within +8 hours of berth window start. The port also reports on-time performance within +24 hours in recognition of industry standard metrics. However, many carriers are unable to meet schedules due to factors beyond their control such as delays at a foreign port. On-time performance varies significantly by carrier and container terminal. The average on-time vessel performance for the gateway was 58.8% in 2016 versus 39.7% in 2015.

Vessel delays resulting from participation in the Trial are not anticipated to have a major impact on sailing schedules because operators can make up lost sailing time by operating at faster speeds outside Haro Strait, and in some cases due to built-in buffers in sailing schedules.

4.3 Navigation Conditions Analysis

Two factors may impact navigation during the Trial: adverse currents in Haro Strait and tidal windows. The latter primarily affects vessels transiting Second Narrows and when navigating the Fraser River.

4.3.1 Haro Strait Currents

The Trial requests vessels to transit at 11 knots through the water. Depending on the prevailing tidal conditions, the current may either be in the same or an opposite direction relative to a vessel's sailing direction (i.e., flood or ebb tide). A 2-knot adverse current means that a vessel operating at 11 knots through the water would be traveling at 9 knots over ground and would incur additional sailing time over and above the time lost because of the slowdown. If the 2-knot current provides an assist, the vessel operating at 11 knots through the water would gain time since it effectively is moving at 13 knots over ground.

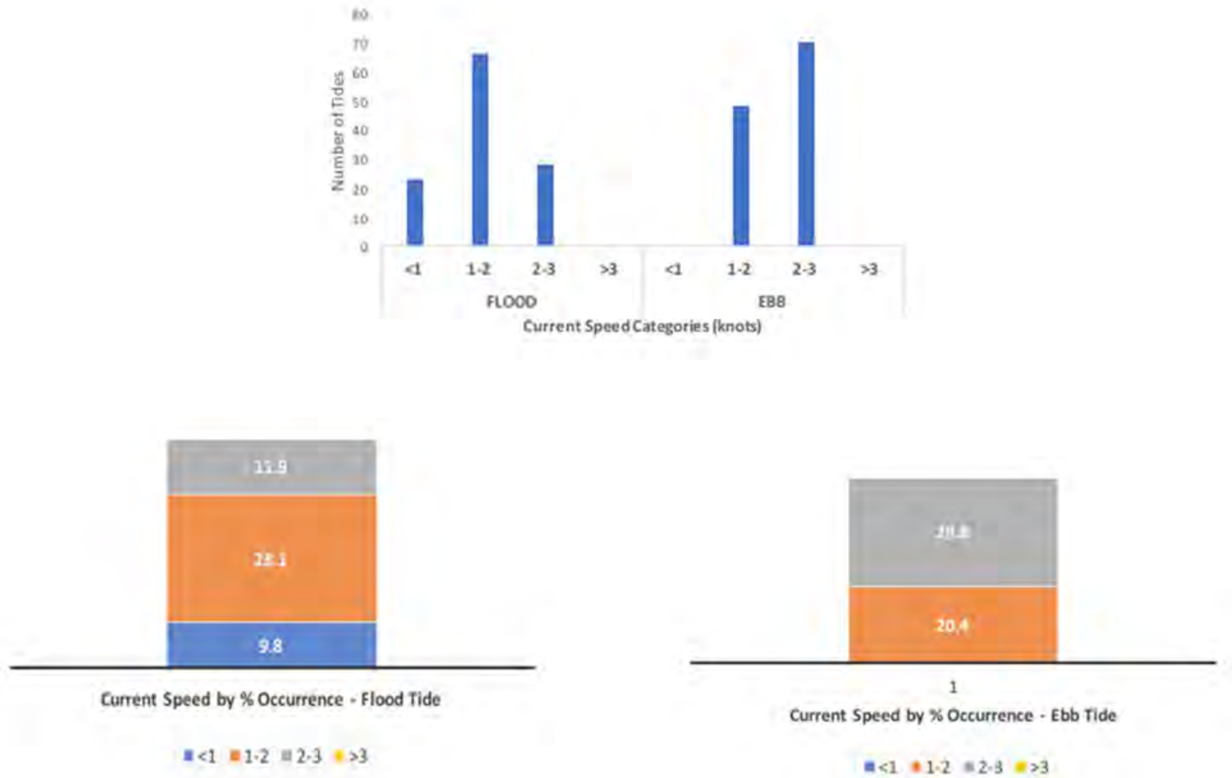
Figure 6 shows the predicted incidence and strength of currents between August 7 and October 6, 2017 based on readings at Kellet Bluff at the north end of Haro Strait.[15] During the 60-day trial period, it is expected there will be about 70 flood tides between 1 and 2 knots and 70 ebb tides between 2 and 3 knots (top chart). Of the total flood tides, 56% are anticipated to be between 1 and 2 knots and 59% of the ebb

[14] Source: Backgrounder on Whale Watching in Pacific Canada. Although this publication is somewhat dated, it provides an idea of the size of the industry in British Columbia. http://www.dfo-mpo.gc.ca/library/329592.pdf

[15] Kellet Bluff is the station used by the ECHO program for measuring tidal flows. It records higher tidal variation than Discovery Island at the southern entrance of Haro Strait.

tides between 2 and 3 knots. Overall, 28.1% of the flood tides (bottom left chart) and 20.4% of the ebb tides (bottom right chart) are expected to be between 1 and 2 knots.

Figure 6 – Incidence & Strength of Haro Strait Currents (Predicted for 2017 Trial Period)



Given the fact that vessels navigate the channel in two directions (inbound to port and outbound from port) and tide conditions alternate from flood to ebb, it is anticipated that the adverse/assist currents will tend to even out over the course of the Trial. The implication is that vessel delays due to transiting at the reduced slowdown speed of 11 knots are expected to normalize in the range of 30 to 60 minutes as follows: approximately 30 minutes delay for bulk, general cargo and tanker vessels; and up to 60 minutes delay for car carriers, container and cruise ships.

4.3.2 Tidal Windows

At Second Narrows, deep-sea vessel transits are restricted to (or close to), periods of slack water (low current speed) which occurs three times a day. In addition, some vessels may also be subject to a window established by the height of the tide. If a vessel is empty and concerned about the overhead clearance under the Ironworkers Memorial Bridge then it may be restricted to the slack water transit window at low water.[16] If a vessel is loaded and sitting deep in the water, it may be restricted to the slack water transit window at high water. In general, however, the main concern for a transit window is current speed.

With respect to the Fraser River, every deep-sea vessel is required to transit during a window that is based on the tidal height, especially near Steveston Bend where the tidal assist provides additional under keel clearance. These windows may also take into consideration current flow in the river and channel condition.

[16] The clearance for the bridge is beam dependent, but can vary around the 42-metre mark.

The windows for the river are provided to the vessel operator by the Fraser River pilots. There are also several other instances where a transit window may apply to a ship but they are less common and predictable:

- Rare cases at First Narrows where very large container ships or cruise ships may require a transit window at low water because of overhead clearance;
- Terminals located in First or Second Narrows may have a berthing window limited to 2 knots of current which would apply to Kinder Morgan, Vancouver Wharves, Lynnterm, Canexus, Cascadia and Fibreco;
- Neptune Terminal occasionally will have a large vessel that when loaded, requires a tidal assist to transit First Narrows because the draft exceeds 15 metres.

For bulk export terminals located in the eastern parts of Burrard Inlet and to the east of Second Narrows bridge, making the transit window is an important concern. For vessels calling at these terminals, participating in the Trial may result in a missed transit window and thus incurring significant additional costs. On such occasions, a vessel operator could understandably decide to opt out of the Trial.

4.3.3 Customer Satisfaction Analysis

In the cruise sector, on-time vessel performance is a key customer service attribute. Scheduling delays can have a major impact on guest satisfaction by affecting connecting flights, as well as influencing visitors' overall impression of Vancouver as a tourism destination. The worldwide cruise industry is growing. Passenger volumes are increasing by about 7% a year and global cruise ship capacity will expand by 40% within the next decade.[17] British Columbia is well positioned to participate in the growth. However, there are added risks if vessel delays negatively impact guest satisfaction. Seattle is an alternative and is growing its cruise business with plans to double the economic benefits to Washington State within 10 years.[18] For Vancouver to maintain its share of the Alaska cruise business and capitalize on global growth trends it must ensure customer satisfaction. Based on consultations with CLIA, one-half of the expected 30 cruise ship transits expected during the Trial stand to be impacted by the vessel slowdown.

In the freight sector, cargo owners are the customers because they pay the costs of transportation. In the bulk and general cargo trades, the cost impacts of the Trial depend on the charter party terms. For commodities sold on a CIF (cost insurance and freight) basis where the seller pays for transportation, any additional costs such as pilotage would be borne by the exporter. In the case of FOB (free on board) sales, the buyer would bear the transportation costs. In either case there is a risk to the port's reputation, although for the short duration of the Trial the impact is not expected to be material. In some cases, the added time in/out of a terminal caused by the slowdown is not a concern. This is because the transportation costs are factored into the average contractual terminal throughput charge with the customer which is based on average operating conditions. The situation would be similar for container ships where most of the costs of the trades are essentially fixed once the service is set.

The Trial is not expected to have any negative impacts on the whale watching sector and would more likely be beneficial by virtue of less disturbance to the marine habitat (i.e., reduced vessel noise, reduced risk of ship strikes on whales).

[17] Source: Cruise Lines International Association (CLIA).
[18] Ibid.

5 Economic Account

Objective	Measures
Identifies the nature, magnitude and significance of anticipated trade-related implications of the Trial.	• Trade volume & value • Port competitiveness • International reputation

The economic account evaluates the anticipated import/export trade traffic and associated economic impacts of the Trial. The measures used for the analysis are: trade volume and value at stake, port competitiveness (risk of traffic diversion), and the Port of Vancouver's international reputation (corporate social responsibility).

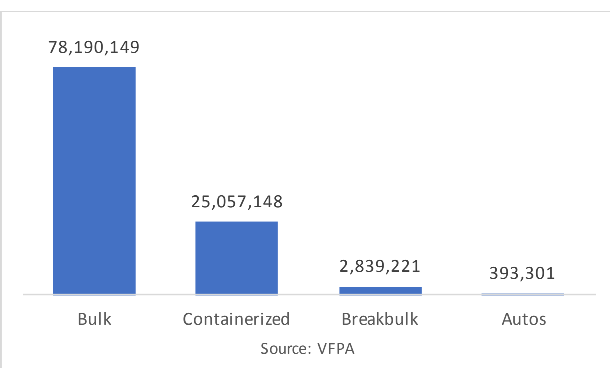
5.1 Economic Context

The Port of Vancouver is Canada's busiest port and the fourth largest port in North America in terms of throughput tonnage. In 2016, the port handled 135.5 million tonnes of international and domestic cargo. Vancouver is also the country's largest cruise port with 827,000 revenue passengers and 228 ship calls. The port is nationally significant as Canada's main trading gateway for the movement goods between North America and the Asia-Pacific region. Port operations provide 38,200 direct person years of employment in British Columbia and $2.3 billion in wages. When associated industries and services are included, the total employment is 76,800 jobs. Other direct economic impacts of the port in British Columbia include $3.5 billion a year in gross domestic product (GDP) and $8.5 billion in economic output.[19]

5.2 Trade Volume & Value Analysis

The Port of Vancouver facilitates trade with more than 160 world economies. About 95% of the port's economic activity is focused on Canadian import/export markets that are largely connected by the international shipping lane running through Haro Strait. Almost three-quarters of overall foreign trade tonnage is in bulk products including coal, grain, potash, petroleum products and liquid chemicals which accounted for 78 million tonnes in 2016. The port's two auto terminals located on the Fraser River serve more than a dozen of the world's top auto manufacturers and handle about 400,000 vehicles a year, including nearly all Asian-made vehicles into Canada.

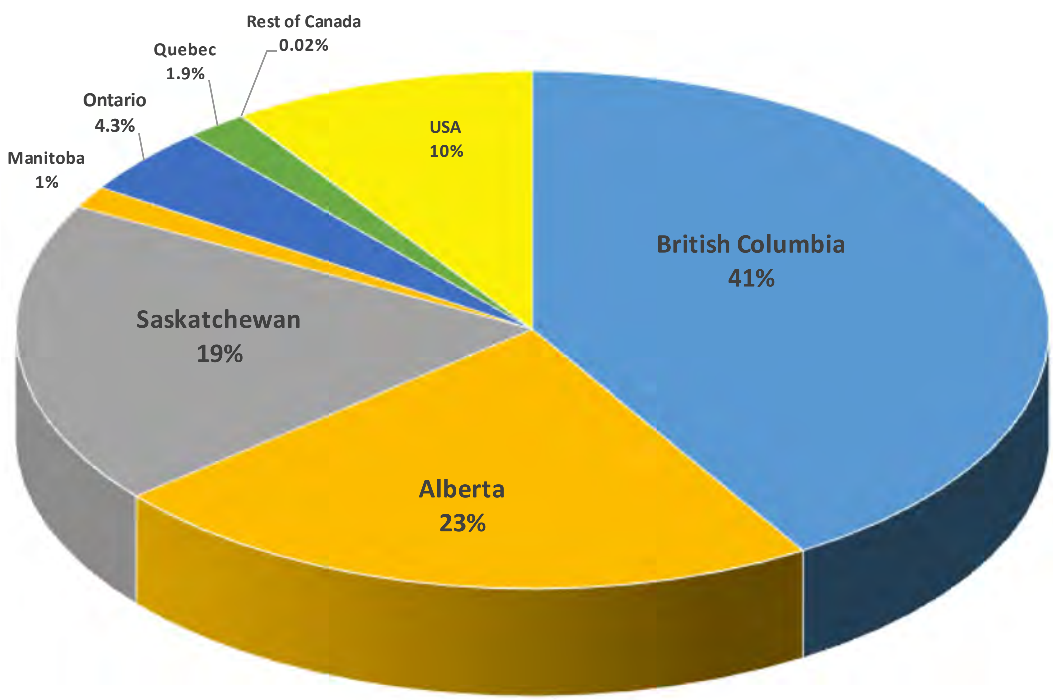
Figure 7 – Port of Vancouver Foreign Trade Volume by Sector (2016, tonnes)



[19] Source: 2012 Port Metro Vancouver Economic Impact Study, Final Report, May 2013.

The importance of the port extends well beyond Vancouver, serving customers across Canada and North America with 83% of the total tonnage to/from British Columbia, Alberta and Saskatchewan and 10% to/from the United States.

Figure 8 – Scope of Vancouver's International Trade (2016, % of Foreign cargo tonnes)



Source: VFPA Analysis

The annual value of foreign cargo trade moving through the port in 2016 is estimated to be $137 billion, the vast majority of which is related to consumer goods, machinery and parts. This latter category provides critical inputs for many other businesses and industries. About $70 billion of the total trade is with British Columbia, Alberta and Saskatchewan. In 2011, the port handled about 19% of Canada's total trade. [20]

In the cruise sector, Vancouver accounted for approximately 60% of the total cruise passenger visits in British Columbia in 2016, the largest share of any port in the province. The economic impact of the cruise industry includes nearly $1 billion of spending in the province by cruise lines (e.g., fuel, business and professional services, vessel maintenance and repair, equipment, supplies), passengers (e.g., transportation, shore excursions, accommodation, food and beverage) and crew (e.g., transportation, retail, food and beverage). [21]

In the short term, the Trial is not expected to have a material impact on trade traffic calling the Port of Vancouver because of the short duration of the Trial and because the Trial is voluntary. Vessel operators can elect not to participate if they believe their sailing schedule, pilotage hours, port related costs, etc. are

[20] Source: All figures from analysis by VFPA Decision Support.
[21] Source: All cruise references from Cruise Lines International Association economic contribution backgrounder.

going to be significantly impacted on a particular transit. However, a more permanent slowdown in Haro Strait, where vessel participation was mandatory, could have a greater potential adverse impact on trade traffic transiting this area. One way of gauging the possible industry response is to look at the significance of costs to the industry as a percentage of total trade value as shown in Figure 9. This methodology has been used successfully in other studies, such as the economic analysis of North Atlantic right whale ship strike reduction rule in work done for NOAA in 2012.[22] Given that the relative cost of the Trial is a small proportion of the total trade value, a large-scale diversion of traffic away from the port during the Trial seems unlikely.

Figure 9 – Estimated Cost of the Trial as a Percentage of Trade Value [23]

	Total Industry Cost of Trial ($)	Trade Value During Trial ($)*	Trial Cost as % of Total Trade Value During Trial
Cargo Vessels	484,064	22,842,000,000	0.0021%
Cruise Ships	38,656	81,000,000	0.0477%

* Cargo value is based on an average of $11.421 billion/month ($137 billion per year/12). The trade value for cruise is estimated based on approximately $3 million per vessel call x 27 vessels in 2015 data set. The $3 million is based on passenger, crew and cruise line spending of $606 million in Vancouver and 207 vessel arrivals, per the most recent economic impact study. The cruise value is somewhat understated due to the exclusion of cruise passenger expenditures on airfare.

5.3 Port Competitiveness Assessment

A port's competitive position in the market is a key factor for entire coastal regions that rely on healthy trade and ships are mobile assets. Shippers and ship owners seeking to optimize returns may have the option of calling at competing west coast ports. In the Pacific Northwest (PNW) region, the ports of Prince Rupert, Seattle, Tacoma and Portland are all vying for business and economic growth.

Cruise ships also call at Seattle, Nanaimo and Victoria that have all seen increases in passengers. While there are relatively fewer alternative export outlets for bulk cargo exporters due to the limited number of port terminals on the coast, the container trade remains fiercely competitive. Prince Rupert has consistently grown its share of PNW container trade from zero when it opened the Fairview Terminal in 2007 to 9.6% by 2015. During this time Vancouver's share increased from about 35% to 37.8% at the expense of Seattle/Tacoma that now have a joint marine cargo operating partnership to win back traffic.[24]

Globalization has fundamentally altered the nature of industry and the role of transportation and logistics in achieving competitive success. Today, business networks and indeed nations compete at a global supply chain level. To be competitive and connected, the Port of Vancouver needs to achieve low cost, high value supply chains to get goods to and from global markets. However, today's ports and terminals face several pressing challenges. Years of losses by global shipping lines have resulted in industry consolidation into three mega-alliances and a trend toward ever-larger vessels that make fewer port calls with higher volumes of containers per call. On the landside, there is pressure to handle the larger volumes of containers and other cargoes and to improve the overall efficiency of the inland rail and road network.

[22] Source: http://www.nmfs.noaa.gov/pr/pdfs/shipstrike/economic_analysis_dec2012.pdf
[23] Source: consultant analysis of data provided by VFPA Decision Support and from VFPA's 2012 economic impact report noted above.
[24] Source: Ocean Shipping Consultants. Also, the Northwest Seaport Alliance is the first of its kind in North America, demonstrating the competitive response of ports that have experienced a loss of traffic in recent years.

The Port of Vancouver's competitive position is primarily a function of the total shipping costs for the major markets it serves. From a cargo owner/shippers' perspective this is viewed as the end-to-end supply chain costs including ocean freight, stevedoring and terminal costs and intermodal rail and truck delivery.

A two-month vessel slowdown Trial is unlikely to impact the overall competitiveness of the Port of Vancouver because of its voluntary nature and short duration. A more permanent vessel slowdown in Haro Strait, if applied to Canadian waters, could however create a competitive disadvantage for the Port of Vancouver relative to competing west coast ports and could result in a future diversion of international trade traffic and cruise passengers from the Port of Vancouver. At stake is $375 million in trade per day flowing through Vancouver and the Canadian economy.

5.4 International Reputation

The most efficient supply chains from NAFTA to Asia run through Canada. From an economic standpoint, the Port of Vancouver's reputation on the world stage is critically important to its continued success as a major North American gateway. The vessel slowdown and related measures present an important opportunity for the port authority and users of the port to demonstrate proactive collaboration to develop scientific evidence in support of any future decisions by Canadian and U.S. federal regulators to protect SRKW and their critical habitat.

Many of the international shipping lines that call Vancouver have strong environmental mandates and have already received recognition for voluntary environmental and ecological protection in other jurisdictions. For example, many shipping lines that call the Port of Vancouver participated in a program to reduce speeds to 12 knots or less within 95 nautical miles of the ports of Los Angeles and Long Beach to reduce the risk of ship strikes with blue, humpback and fin whales. That vessel speed reduction also eliminated more than a thousand tonnes of greenhouse gases and other air pollutants.

In this regard, the work of the collaborative ECHO Program can help enhance the international reputation and social license of the port and ship owners and operators by showcasing their willingness to participate, adapt and manage change during the Trial.

6 Cultural Account

Objective	Measures
Identifies the benefits and implications of the Trial for Coastal Aboriginal Peoples' cultural interests, values and objectives.	• Respect for and preservation of cultural values and practices • Restoration and protection of SRKW and the marine ecosystem • Safety of Aboriginal canoe paddlers and fishers

SRKW are a species of tremendous cultural importance to Aboriginal peoples in coastal British Columbia who are deeply concerned about the decline of SRKW and the marine ecosystem in general in their traditional territories. The cultural account, described in the sections below and prepared by the Fraser Basin Council, captures coastal Aboriginal perspectives on the benefits and implications of the Trial based on interviews undertaken with the two Aboriginal members of the ECHO Program Advisory Working Group (AWG). Although this section of the report focuses on cultural considerations associated with the Trial, it is important to note that in Aboriginal societies, these considerations are inseparable from ecological, economic and social considerations.

6.1 Protecting and Raising Awareness of a Foundation of Coastal Aboriginal Culture

From the perspective of Aboriginal AWG members interviewed, the Trial affords an opportunity to make progress in reducing underwater vessel noise with the hope that it will contribute to the recovery of SRKW populations, assuming that the Trial leads to full-scale implementation of meaningful noise mitigation measures. The Trial also represents an opportunity to raise industry and public awareness of the cultural significance of SRKW to Aboriginal peoples – an iconic species of importance to all British Columbians – and the purpose and importance of reducing threats such as underwater vessel noise.

Although the Trial is generally viewed as a positive undertaking, concern was expressed that through sharing cultural information, such information could be misconstrued or misrepresented by others. Concern was also voiced that Aboriginal support for the Trial could be misrepresented as support for increased vessel traffic.

6.2 Reducing Underwater Noise Impacts on SRKW

One aspect of the Trial that is viewed as a positive by Aboriginal AWG members is its focus on underwater noise, an important threat to SRKW and that the Trial presents an opportunity to learn about what effects slowdowns will have. It was further noted that there is potential for the whales to respond positively to slowdowns during and after the Trial period.

Aboriginal AWG members also see the Trial to be an opportunity to raise awareness of SRKW, their roles in a complex marine ecosystem and the need for more attention on this ecosystem as a whole. The Trial was further viewed as an opportunity to raise awareness within the marine industry, and of British Columbians in general, of an activity that is having an environmental effect.

Concerns include the following:

- Slowing to 11 knots may have little or no effect - if slowdowns to 8 or 9 knots are required to make a difference, this would introduce more economic and safety issues to industry, potentially impeding further progress;
- Vessels may encounter SRKW at any speed and scientists may not be familiar with the behavioural responses to a slower vessel – it could have unexpected consequences (e.g., whales not avoiding vessels as much as they should);
- The Trial is not targeting all vessel types using Haro Strait for participation so not all vessels will be slowing down;
- Other potential noise reduction options (e.g. route adjustments) are not currently being explored through the Trial; and
- Vessel noise reductions alone may not be sufficient to enable SRKW recovery. One example cited in this regard is the importance of Chinook population health. There is a trend towards smaller fish – the average has declined from 25 lbs to 16 lbs due to commercial and sports fisheries taking larger fish. In addition, there is a need for more data on the impacts of human activities (e.g., loss of eelgrass habitat, increasing temperatures and other impacts) on juveniles in the Fraser River estuary. The fact that the prey availability issue is not being addressed through the Trial is a matter of concern.

6.3 Safety Considerations

It was noted that commercial vessels operating at slower speeds in Haro Strait will generate less wake, potentially improving safety for Aboriginal fishers and traditional canoe paddlers if and when they are in the vicinity.

6.4 Industry Participation and Trial Implications

Concern was expressed that because participation in the Trial is voluntary, an insufficient number of vessels may participate, especially if incentives are not clear. Insufficient participation could mean inadequate data collection and delays to developing measures to reduce impacts.

It was further noted that if noise reduction proves to be beneficial, this result could be used to justify increases in vessel traffic (albeit at lower noise levels for each vessel), for example, increased oil tanker transits associated with the TransMountain expansion project, which is of concern.

7 Environment Account

Objective	Measures
Identifies the nature, magnitude and significance of the Trial on the SRKW critical habitat associated with underwater noise reduction, as well as the implications of the vessel slowdown on air quality.	• Critical Habitat protection • Underwater vessel noise • Air quality

The environment account identifies the impact of acoustic disturbance on the SRKW population and by extension its biological habitat. The key values and measures are protection of species at risk (sustainability and benefits to marine habitat), noise levels (ambient and anthropogenic source) and air quality. The following Sections 7.1 and 7.2 are based on research and analysis by SMRU Consulting as inputs to the evaluation. Section 7.3 is based on inputs provided by the VFPA air quality specialists.

7.1 SRKW Critical Habitat

The SRKW population of only 78 individuals has shown little sign of recovery since the 1980s, and currently exhibits a male-skewed sex bias in recent births of calves. Recent analysis suggests that the SRKW population will not rebuild under current environmental conditions (Velez-Espino et al. 2013 and Lacy et al. 2015). Killer whales' use of sound is vital to survival to their survival. They use sound to navigate, communicate and importantly, to locate prey via echolocation.

Both Canadian and US federal regulators have designated SRKW Critical Habitat across most of the southern Salish Sea, offering the species legal protection of vital habitat functions e.g., ability to feed, socialize, rest (National Oceanic and Atmospheric Administration 2008, DFO 2011). Further Critical Habitat designation outside the Salish Sea is presently under review. The distribution of SRKW varies seasonally and across the three matrilineal pods called J, K and L. In general, the inshore waters of the Salish Sea are most important to the SRKW in spring through fall, with all pods ranging more widely in the winter outside the Salish Sea. Peak SRKW sightings usually occur in the Salish Sea between June and September.

The Fisheries and Oceans Canada Recovery Strategy for Southern and Northern Resident Killer Whales (2011) identifies sources of underwater noise including vessel, construction and sonar noise as threats to species recovery, in addition to other threats such as limited availability of prey (primarily Chinook salmon), physical disturbance and contaminants. Critical Habitat directly overlaps with international shipping routes, busy ferry routes and the operations of a sizeable whale watching industry. Fisheries and Oceans Canada's 2016 Species at Risk Action Plan for SRKW Recovery identifies 43 of 94 recovery measures related to noise pollution and vessel disturbance. The vessel slowdown trial will help support a number of these recovery measures by gathering scientific evidence on how vessels sound under different operational conditions. This evidence will inform the development of measures to reduce vessel noise impacts to SRKW, thereby contributing to the protection of Critical Habitat.

7.2 Underwater Noise Analysis

Sound waves travel in water 4.5 times faster than they do in air. Underwater sound is generated across various frequencies (measured in Hertz) by natural sources such as waves, rain and marine life, as well as man-made sources such as vessels and construction activity. Sound levels are most often described in units of decibel (dB), which is reported on a log scale. A 3dB difference translates into a 50% difference in sound intensity. At low frequencies (e.g., 5 to 1,000 Hz), ambient or background noise in coastal environments is typically dominated by shipping. In parts of the North Pacific Ocean, low frequency underwater noise has been doubling in intensity every decade for the past 60 years (Hildebrand 200, Andrew et al. 2011).

An increase in underwater noise has the potential to affect marine mammals through behavioural changes (e.g., switching from foraging to travelling), range displacement, communication interference, decreased foraging efficiency, hearing damage and physiological stress. Vessel noise is also known to disrupt behavior and mask or cover up sounds required for navigation, communication and detecting prey as well as increase stress hormone levels. These effects are likely to compound prey availability limitations. Population models predict that a 5-10% reduction in killer whale prey availability can cause significant population-level effects. (Erbe 2002; Aguilar Soto et al. 2006; Southall et al. 2007; NMFS 2008; Lusseau et al. 2009; Fisheries and Oceans Canada 2011; Vélez-Espino et al. 2013; Wasser et al. 2012; Rolland et al. 2012; Williams et al. 2014a; Williams et al. 2014b; Lacy et al. 2015; Williams et al. 2016).

Most vessel underwater noise is caused by propeller cavitation, with peak frequencies of 30-150 Hz but acoustic power can radiate power beyond 40,000 Hz (Veirs et al. 2015). Other sources of vessel noise include propeller singing, engine and onboard machinery noise and the use of thrusters. Noise levels and peak frequencies vary by vessel type and operating conditions. The killer whales use of sound overlaps with the frequencies produced by vessels. Echolocation clicks used to find prey and navigate range from about 8,000 to 100,000+ Hz (Holt, M.M. 2008), while vocal communication is used for hunting coordination, prey sharing and social interactions via a complex repertoire of whistles and calls that range from 500 to 30,000 Hz.

Many vessel types contribute to underwater noise but large, fast commercial vessels such as container ships are typically the loudest. Recent studies indicate that SRKW are already impacted by existing levels of vessel traffic in the Salish Sea, and projected increases in population and future development projects with marine components will further increase marine traffic and underwater noise. For example, the 2016 National Energy Board Report[25] review of the Trans Mountain pipeline expansion project concluded that there were already significant noise effects on SRKW from commercial shipping.

ECHO Program-funded independent research compared noise effects from whale watch boats to large (AIS-enabled) commercial vessels using a fine-scale SKRW noise-exposure model (SMRU 2014, JASCO 2014) and predicted that overall foraging time may be negatively affected for about 5 hours or 20-23% of every day that SRKW are present in the Salish Sea (SMRU Consulting 2017). Large vessels accounted for 57-64% of the overall predicted noise effects, which focused only on the whale watching months of May to September. The SRKW noise-exposure model also predicted that more than 25% of large vessel noise-exposure effects occurred in Haro Strait, a well-documented SRKW foraging hotspot. During the summer, the bulk of the SRKW diet consists of Fraser River Chinook salmon present in this area, as they return to spawn. The shipping lanes through Haro strait are close to this important foraging area, making the resulting

[25] Accessed here https://www.ceaa-acee.gc.ca/050/documents/p80061/114562E.pdf.

overlap of commercial vessel noise and SRKW summer habitat use relatively high in Haro Strait compared to all other areas of current SRKW Critical Habitat.

7.3 Effects of Vessel Speed Reduction

Vessel speed reductions have been proposed by several organizations including the International Maritime Organization as a means to reduce the effects of underwater noise on marine mammals (IMO 2014). SONIC-AQUO, a European ocean noise consortium, reported: "ship speed reduction is normally the most powerful real-time control of noise radiation" (SONIC-AQUO 2015). Noise output for a particular vessel speed depends on loading and trim, fouling or propeller damage, as well as fixed factors such as propeller type and hull design. A strong relationship between speed and noise levels has been found particularly for containerships that derive a linear relationship with the source level of the vessel increasing by a factor of 1.1 for each knot increase in speed (McKenna et al. 2013).

McKenna et al. (2013) also highlighted the net benefit in sound exposure levels in slowing a vessel down, despite longer periods of time in the area. In a separate study (Veirs et al. 2015), signatures of 2,809 vessels transiting Haro Strait also showed a similar 1.1:1 relationship, although with much variability across vessel types. In a follow up analysis, Veirs et al (2017) estimated that if all vessels transiting Haro Strait reduced to 11.8 knots then this would lead to a 3dB reduction, equivalent to a 50% reduction in noise intensity. Averson and Vendittis (2000) reported for a 173m bulk cargo ship, dramatic increases in noise as speed increased, with a 10dB difference noted between 10 knots and 14 knots representing a 10-fold increase in acoustic power. Overall, there is strong evidence that speed reductions of vessels with fixed pitch propellers will yield source level noise reduction.

Using tracking data from AIS, it is estimated that container ships are transiting on average at 18.1 knots and bulkers and general cargo ships at 13.2 knots through Haro Strait. Container, bulker and general cargo ships can comprise more than 80% of the piloted transits through Haro Strait (Pacific Pilotage Authority Canada, unpubl. data). The underwater noise contribution (percentage of total mean squared sound pressure for July 2015) of these ship categories in Haro Strait was >42% when estimated using a July 2015 Marine AIS dataset that included commercial ships, as well as accounting for tugs, fishing vessels, whale watch and recreational boats (MacGillvray et al. 2016). The Trial calls for vessels to slow down to 11 knots which could result in at source sound intensity reductions of 78% and 40%, for container and bulker vessels respectively. The scale of these noise reductions should reduce the number of behavioral disruptions as well as reduce the scale of SKRW echolocation click and call masking. The Trial dates encompass a period of typical high inshore presence (>60% of all days, SMRU 2014) by all three pods of the SRKW in a key location known for foraging and other activities and as such the Trial is anticipated to have overall positive effects on SKRW.

7.4 Air Emissions Analysis

The estimated impact of the slowdown Trial on emissions that contribute to both air quality and climate change is outlined in Figure 10. Using the same vessel type and composition dataset as summarized in Section 3.2 of this report, the results estimate relative fuel consumed under different slowdown participation and time make up scenarios. Estimates of relative fuel consumed can also be used as approximations for pollutant emissions. The percentage difference in emissions presented in Figure 10 are relative to the normal amount of emissions that would occur over the entire transit distance between the pilot station (Brotchie Point) and the Port of Vancouver under a no slowdown scenario. The transit distance used in calculations assumes that all vessels are going to/from Burrard Inlet in the Port of Vancouver, although some would travel shorter distances, for example to Deltaport.

Using the same vessel voyage/destinations summarized in Section 3.2, the distances and locations over which lost time may have to be made up are used to inform the different air emission scenarios estimated in Figure10. If the future or previous port call of a vessel is located within the North American Emission Control Area (i.e. within 200 nautical miles of the coast of Canada), it is assumed that the vessel will have to speed up considerably in order to make up time over a shorter distance and that fuel consumption rates would be higher than normal. If the future or previous port call of a vessel is located outside of the North American Emission Control Area (ECA), it is assumed that the vessel can make up time over a much longer distance and because of the non-linear relationship between speed and fuel consumption, the difference in overall fuel consumption would be small to insignificant and no increase in fuel consumption is assumed.

Results in Figure 10 indicate that if no vessels make up their lost time, there would be a decrease of 8% in air emissions (both air quality and climate change related) as a result of the Trial. If a portion of vessels make up their time inside the ECA (as described in Section 3.2), and the rest of the vessels make up their time outside the ECA, air emissions are expected to increase by between 1% and 2%. If all vessels that need to make up time do so within the ECA, it is estimated that air emissions will increase by between 4% and 8%.

Figure 10 – Relative Change in Air Emissions as a Result of the Slowdown Trial

Potential Vessel Slowdown Participation Rates	Difference in air emissions if making up lost time not required	Difference in air emissions if making up lost time is partially required within ECA*	Difference in air emissions if making up lost time is required within ECA
50% participation	-	+1%	+4%
75% participation	-	+1%	+6%
100% participation	-8%	+2%	+8%

* Remainder is made up outside Emission Control Area. However, no increase in fuel consumption is assumed for makeup time outside ECA due to the long distance over which to make the time up and the non-linear relationship between speed and fuel consumption.

8 Do Nothing Scenario

The main implication of a “do nothing” scenario—not proceeding with an industry supported vessel slowdown Trial—is the potential for regulations to be developed and implemented in the absence of science-based research regarding the impacts of shipping noise on the southern resident killer whales. The Canadian government has recognized that vessel noise is a key threat to the survival and recovery of the resident killer whale population. Momentum is growing for a government plan and timetable to reduce physical and acoustic disturbance caused by shipping which could include mandatory noise-quieting measures in parts of, or the entirety of the Salish Sea area that is designated as SRKW Critical Habitat under *SARA*.

A group of 20 marine scientists wrote a letter dated April 12, 2017 to Prime Minister Trudeau and the federal ministers of Fisheries, Environment and Transport calling on Ottawa to compel a reduction in shipping noise in line with the recommended initial global target of 3dB within 10 years and a 10dB reduction within 30 years, relative to current levels.[26] The scientists believe an even more precautionary target is necessary in some areas such as the Salish Sea that are more “acoustically degraded and that constitute critical habitat for a noise-sensitive endangered species.” Federal officials in Canada have been tasked to develop a strategy by the fall of 2017 to reduce noise levels by the end of 2019 as part of a long-term commitment to the recovery of SRKWs.

The main implications of “do nothing” are:

- Missed opportunity to test and evaluate the feasibility of vessel slowdowns as a meaningful vessel noise reduction measure;
- Missed opportunity to reduce impacts to SRKW in an important foraging area and demonstrate industry leadership;
- Missed opportunity to inform federal policy and related SRKW protection conservation measures with an evidence-based scientific approach that balances industry and environmental values.

8.1 Experience in Other Jurisdictions

By the late 1990s, the North Atlantic right whale was considered one of the most endangered large whale populations in the world. One of the biggest threats to its survival was collisions with ships. In response, the U.S. National Marine Fisheries Service (NMFS) implemented the Right Whale Ship Strike Reduction Rule on December 9, 2008.[27] The rule requires certain vessels to travel at 10 knots or less in designated areas of right whale aggregation near several key port entrances along the U.S. eastern seaboard.

Years before the Strike Rule came into effect, stakeholders representing environmental groups had urged NMFS to take immediate action with emergency regulations and/or implementation prior to completing an Environmental Impact Statement (EIS). Some stakeholders supported proposed speed restrictions in the

[26] As recommended by the Scientific Committee of the International Whaling Commission. The goal is to reverse the upward trend of +3 dB per decade in deep-water ambient noise pollution during the second half of the 20th Century, largely attributable to commercial shipping. Research has shown that a one knot reduction in vessel speed results in a greater than 1 dB reduction in underwater noise, although the relationship highly depends on the vessel type, speed range and frequency. Because sound levels are reported on a logarithmic scale, a 3-dB reduction can result in a 50% decrease in sound intensity (and a 6-dB reduction, a 75% decrease).

[27] The Commerce Department’s NMFS is responsible for administering the Endangered Species Act, focusing on marine wildlife such as whales, along with the U.S. Fish and Wildlife Service which has primary responsibility for terrestrial and freshwater organisms.

range of 10 to 14 knots based on the best available data. However, others questioned the effectiveness of speed restrictions as a mitigation measure and would not support this measure until further speed and hydrodynamic studies were completed. Industry representatives recommended that the NMFS evaluate the impacts on port operations, local economies and port communities serviced by commercial shipping and ferry vessels, as well as any other indirect economic and environmental impacts.

Subsequently, NMFS signaled their intent to complete an EIS with adequate time for comment and analysis. They received about 350 letters and emails from interested parties. This included inputs from federal agencies, environmental groups and industry representatives with comments on designated management areas, mitigation alternatives, types of vessels that should be involved, vessel operational measures, navigation routes, effectiveness of speed restrictions, etc. The participation of industry and environmental groups shaped the eventual Right Whale Ship Strike Reduction Rule. The proactive approach led to more informed decisions contributing to the recovery and sustainability of the whales, while minimizing the adverse effects on the shipping industry and maritime commerce than would have otherwise been the case if emergency, or non-science based regulations were implemented in the pretext of a “do nothing” scenario.

9 Summary of Results

The main findings of the study for the Trial period are summarized below, first by account and then with respect to the implications of the Trial for different interest groups. The analysis is based on actual vessel transit data from the Pacific Pilotage Authority for Haro Strait from August 7 to October 6, 2015 as a proxy for the anticipated number of transits likely to occur during the same two-month period in the 2017 Trial.

9.1 Summary by Account

<table>
<tr><th>Account/Measure</th><th>Key Findings</th><th>Implication / Comment</th></tr>
<tr><td colspan="3">FINANCIAL ACCOUNT</td></tr>
<tr><td>Vessel Operating Costs</td><td>Cost per ship transit of Haro Strait (C$):*
<table>
<tr><th>Ship Type</th><th>Avg.</th><th>Min.</th><th>Max.</th></tr>
<tr><td>Bulk Carrier</td><td>160</td><td>-166</td><td>2,683</td></tr>
<tr><td>Car Carrier</td><td>363</td><td>178</td><td>453</td></tr>
<tr><td>Container</td><td>1,420</td><td>210</td><td>4,371</td></tr>
<tr><td>General Cargo</td><td>236</td><td>-42</td><td>2,095</td></tr>
<tr><td>Passenger</td><td>1,432</td><td>0</td><td>3,526</td></tr>
<tr><td>Tanker</td><td>327</td><td>-46</td><td>3,706</td></tr>
</table>
* ship transit = movement in or out of Haro Strait
Estimated total additional cost of Haro Strait ship transits for two-month Trial (C$):
<table>
<tr><td>Pilotage</td><td>180,882</td></tr>
<tr><td>Ship time</td><td>149,909</td></tr>
<tr><td>Haro Strait fuel</td><td>(438,315)</td></tr>
<tr><td>Makeup fuel</td><td>630,244</td></tr>
<tr><td>Total</td><td>522,720</td></tr>
</table></td><td>Makeup fuel is the largest cost impact on the marine transportation industry but only affects container and cruise ships primarily because of the need to maintain sailing schedules where the cost of not meeting schedules can be high. The cost impact of makeup fuel is relatively less for long trans-Pacific voyages where vessels only need small increases in speed to make up for lost time due to the slowdown.

Of the 898 ships in the dataset, about 47% would experience no pilotage cost increase from the Trial because bridge watch times would be less than 8 hours. The 8-hour threshold is important because it marks the point where pilotage costs start to increase rapidly. About 46% of all ships would incur an increase of one hour of bridge watch time ($208.75), and the remaining 7% of ships would incur greater pilotage costs because of additional charges for bridge times that in total exceed 8 hours (average cost of $1,440.69 per hour).</td></tr>
<tr><td>Port Costs</td><td>Container Ships (in the case of a missed berth window):

Longshore labour: C$11,000 to $13,500 per hour of No Work Provided ($90 to $110/container)
Ship time: US$13,000 to $50,000 per day
Demurrage: C$37.95 – 39.06 per TEU/day
On-Time Berthing: Risk of losing incentive discount offered by some terminals

Bulk Carrier & General Cargo Ships:

Demurrage: penalty of 16 to 24 hours @ US$8,000 – $15,000 per day depending on type of ship and extent of the delay
Vessel shifting to/from anchorages: C$6,000 – $20,000 per occurrence for missed berth window or transit window at Second Narrows

Cruise Ships:

Delays and/or a missed berth window increases CBSA and longshore labour costs
</td><td>Port disbursements that could be affected by a vessel slowdown include: longshore labour, tugs, ships’ line handling and safety and security costs (cruise). The key determining factor is the ability of a ship to arrive within its designated berth window.

The potential cost impacts and decisions by ship owners/operators/agents to participate in the Trial would be on a case by case basis. Because the level of participation is, a priori, unknown, a case study approach is used to illustrate the potential port cost implications.</td></tr>
</table>

Account/Measure	Key Findings	Implication / Comment
CUSTOMER SERVICE ACCOUNT		
Sailing Schedule Reliability	The Trial is planned to take place over a fixed period of time and for reasonably short duration he vessel slowdown is generally not anticipated to have a major impact on sailing schedules. Through Trial communications, operators should have advance notice and the ability to make up time by operating at faster speeds outside Haro Strait, and in some cases have buffers in their schedules. Because the trial is voluntary, operators will also have the option to opt out if constrained by a sailing schedule on a specific transit.	It is more difficult to make up lost sailing time on shorter Pacific coast multi-port itineraries as opposed to trans-Pacific voyages.
Navigation Conditions	Incidence and strength of **tides/currents** in Haro Strait (August to October 2017 outlook): • Flood tides: 56% between 1 and 2 knots • Ebb tides: 59% between 2 and 3 knots For bulk export terminals located in the eastern parts of Burrard Inlet and to the east of Second Narrows bridge, making the **transit window** during periods of slack tides is an important concern. For vessels calling at these terminals, participating in the Trial may result in a missed window and incur additional costs.	Since vessels navigate Haro Strait in two directions and tide conditions alternate from flood to ebb, it is anticipated that the adverse/assist currents will tend to even out over the course of the Trial with minimal overall impact to navigation.
Customer Satisfaction	Based on industry consultations, about half of the expected 30 **cruise ship** transits expected during the Trial could be impacted by the slowdown. In the **cargo sector**, the short duration of the Trial is not expected to have a material impact on cargo owners who are the ultimate customers.	Scheduling delays can have a significant impact on cruise guest satisfaction affecting their ability to make connecting flights, as well as influencing overall impressions of Vancouver as a tourism destination.
ECONOMIC ACCOUNT		
Trade Volume & Value	In the short term, the Trial is not expected to have a material impact on international trade traffic moving through the Port of Vancouver because of its short duration and because the Trial is voluntary and vessels can choose to not participate if for example, they believe their sailing schedule, pilotage hours etc. are going to be significantly impacted on a particular transit. A more permanent slowdown where all vessels were mandated to participate could however have a greater potential adverse impact on trade traffic transiting this area.	The cost of the Trial as % of estimated trade value during the two-month Trial: • Cargo vessels 0.0021 % • Cruise 0.0477 %
Port Competitiveness	The Trial is unlikely to impact the overall competitiveness of the Port of Vancouver because of its voluntary nature and short duration.	At stake is some $375 million in foreign trade per day flowing through the Port of Vancouver and the Canadian economy.

Account/Measure	Key Findings	Implication / Comment
	A more permanent vessel slowdown in the Haro Strait area, if applied only to Canadian waters, could add cost and supply chain uncertainty and create a significant competitive disadvantage for the Port of Vancouver relative to competing west coast ports, resulting in potential future diversions of international trade traffic and cruise passengers from the Port of Vancouver	
International Reputation	The work of the collaborative ECHO Program can help enhance the international reputation and social license of the port itself, as well as participating ship owners and operators by showcasing their willingness to participate, adapt and manage change during the Trial.	The vessel slowdown and related measures present an important opportunity for the port authority and users of the port to demonstrate proactive collaboration to develop scientific evidence in support of any future decisions by Canadian and U.S. federal regulators to protect SRKW and their critical habitat.
CULTURAL ACCOUNT		
Respect for and Preservation of Cultural Values	The Trial is an opportunity to raise industry and public awareness of the cultural significance of SRKW to Aboriginal peoples – an iconic species of importance to all British Columbians – and the purpose and importance of reducing threats such as underwater vessel noise.	Although the Trial is generally viewed as a positive undertaking, concern was voiced that Aboriginal support for the Trial could be misrepresented as support for increased vessel traffic.
Underwater Noise	Slowing to 11 knots may have little or no effect - if slowdowns to 8 or 9 knots are required to make a difference, this would introduce more economic and safety issues to industry, potentially impeding further progress Vessel noise reductions alone may not be sufficient to enable SRKW recovery.	Aboriginal advisory group members see the Trial as an opportunity to raise awareness of SRKW, their roles in a complex marine ecosystem and the need for more attention on this ecosystem as a whole. The Trial was further viewed as an opportunity to raise awareness within the marine industry, and of British Columbians in general, of an activity that is having an environmental effect.
Safety	Commercial vessels operating at slower speeds in Haro Strait will generate less wake, potentially improving safety for Aboriginal fishers and traditional canoe paddlers if and when they are in the vicinity.	It was noted that if noise reduction proves to be beneficial, this result could be used to justify increases in vessel traffic (albeit at lower noise levels for each vessel), for example, increased oil tanker transits associated with the TransMountain expansion project, which is of concern.
ENVIRONMENT ACCOUNT		
Critical Habitat Protection	The Trial will contribute to the protection of Critical Habitat by gathering scientific evidence regarding underwater noise impacts to SRKW, thereby contributing to the protection of Critical Habitat.	Both Canadian and US federal regulators have designated SRKW Critical Habitat across most of the southern Salish Sea, offering the species legal protection of vital habitat functions (e.g., ability to feed, socialize, rest). Further Critical Habitat designation outside the Salish Sea is presently under review.
Underwater Vessel Noise	Container ships and bulkers/general cargo ships comprise more than 80% of the piloted transits through Haro Strait and the vessel slowdown is	Sound waves travel in water 4.5 times faster than in air. Sound levels are measured in decibels (dB) and reported on a log scale. A 3dB difference equates to a 50% difference in sound intensity.

Account/Measure	Key Findings	Implication / Comment
	estimated to reduce sound intensity by 78% and 40%, respectively for these types of vessel.	
Air Quality	Impacts range from a decrease in emissions of 8% (if no makeup of lost time is required) to +8% if all vessels participate in the Trial and have to make up lost time within the Emission Control Area (ECA).	The relative change in air emissions as a result of the Trial depend upon the participation rate and whether any makeup fuel consumed to make up lost time is consumed within the ECA.

9.2 Summary by Interest Group

Interest Group	Key Findings
Marine transportation industry	The estimated cost implications of the Trial vary by type of vessel as shown above in the Financial Account. Container and cruise ships are expected to have the greatest cost impact due to the high costs of makeup fuel needed to maintain schedules. Opportunity to inform federal policy and related conservation measures with an evidence-based scientific approach that balances industry and environmental values.
BC Coast Pilots/Fraser River Pilots and Pacific Pilotage Authority (PPA)	The Trial will have minimal impacts apart from requiring close coordination between the pilots, PPA and ship captains regarding operational protocols to determine which vessels decide to opt out of the trial for business/economic or safety reasons.
Port Terminals	The Trial is not expected to have a material impact on port terminal operations and efficiency.
Whale Watching Industry	Benefits due to underwater noise reduction which is good for the SRKW habitat and well-being of the remaining 78 whales; similar benefits for transient whales. Overall benefits for ecotourism businesses in the Salish Sea.
Coastal Aboriginal Peoples	Benefits to protect and raise awareness and respect for Coastal Aboriginal culture and practices.
Environment	Benefits of reducing cumulative impacts of vessels on SKRW and their critical habitat.
Vancouver Fraser Port Authority	Benefits with respect to social license regarding a pro-active approach and leadership on environmental and cultural values.
Canada & U.S. Federal Government Agencies	The Trial should provide a valuable body of evidence regarding the impacts of shipping noise on at-risk southern resident killer whales. It will also help inform future federal policy and related conservation measures with a science-based approach that balances industry, environmental and cultural values.

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Appendix I

Economic Impact Analysis of Proposed Voluntary Vessel Slow Down Trial

Phase 1 Final Report

May 2017

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Annexes to Appendix I

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1 Executive Summary

1.1 Summary of Findings

1.1.1 The Trial and the Study

Vancouver Fraser Port Authority (VFPA) engaged Seaport Consultants Canada Inc. (Seaport) in association with Colledge Transportation Consulting Inc. (CTC) to evaluate the economic impact of a proposed voluntary vessel slowdown Trial in Haro Strait. The objective of the Trial is to measure the effect of reducing vessel speed on underwater noise and to predict resulting impacts on the southern resident killer whales.

Phase I of this two-phase study estimates the financial impacts on the shipping industry of the proposed voluntary vessel slowdown Trial, the findings of which are presented in this report prepared by Seaport. Phase II, prepared by CTC, incorporates this analysis into a broader Multiple Account Evaluation (MAE) to document the costs and benefits of the Trial from several different perspectives.

The Trial is planned for August 7 to October 6, 2017; the evaluations of this study are based on vessel data from Pacific Pilotage Authority (PPA) records of 898 Haro Strait ship transits between August 7 and October 6, 2015. The evaluations involve the reduction of vessel speed in Haro Strait from the AIS-measured speeds of the ships to 11 knots (kn). This Study does not address the impacts of the major schedule changes the container carriers will introduce in the second quarter of 2017.

The overall approach to the Study involved:

- Buildup of vessel costs for the following categories:
  - Pilotage.
  - Vessel time in some cases.
  - Main engine fuel.
    - Consumption.
    - Price.
- Estimate of cost impact of trial:
  - Estimates of costs by ship type in total and per transit.
  - Evaluations of cost components.

1.1.2 The Study Dataset

The study used a PPA dataset adapted by a consultant to VFPA. The pilot records included ship name, deadweight tonnage (DWT), gross registered tonnage (GRT), International Maritime Organization (IMO) number, actual draft and type of ship. It also included dates and times of pilot activities such as pilot booking time, and the times bridge watch began and ended. Finally, it included estimates of ship time in Haro Strait with and without the slowdown. The Study added to the dataset additional vessel details of passenger, vehicle, and 20-foot equivalent container unit (TEU) capacity, design speed and, as available, fuel consumption at design speed.

The following table summarizes the average vessel characteristics and numbers of records of the dataset. Of note:

- The main constituents of the dataset are 488 bulk carriers and general cargo ships (treated as one group because the ship characteristics are similar) and 250 container ships. It also included 77 car carriers, 56 tankers and 27 "passenger" ships (in all cases cruise ships).
- Full records were available for DWT, GRT, passenger and container ship capacity, design speed and year of build.
- Only 109 records were available for fuel consumption (12% of the total).

Summary of Vessel Characteristics in Dataset

Vessel Type	DWT	GRT	Vehicles	Passengers	TEU	Main Fuel	Speed	Built
	(Tonnes)	(Tonnes)	(No)	(No)	(No)	(t/d)	(Knots)	
Dry Bulk & General Cargo								
Average	65,236	36,855			Irrelevant	30.5	14.5	2009
Count of Data Entries	488	488			46	37	488	488
Car Carrier								
Average	17,764	53,644	5,090			40.8	19.5	2003
Count of Data Entries	77	77	23			17.0	75.0	77
Container								
Average	75,720	68,890			6,181	175.0	24.6	2005
Count of Data Entries	250	250			250	44	250	250
Passenger (Cruise)								
Average	8,776	83,681		2,446		110.0	21.7	2003
Count of Data Entries	27	27		27		2	27	27
Tanker								
Average	34,541	20,893				29.1	14.7	2008
Count of Data Entries	56	56				9	56	56
Total Count	898	898				109	896	898

Source: Compiled from Table 1.

The following table summarizes ship time from the dataset between the Brotchie pilot station near Victoria and the port terminal origins and destinations with and without the Trial slowdown. The vessel speeds were:

- 11.0 knots with the Trial and
- Without the Trial, measured by an AIS sample
    - Bulk carriers and general cargo, 13.2 kn
    - Car carriers, 16.3 kn
    - Container ships, 18.1 kn
    - Passenger ships, 18.1 kn
    - Tankers, 13.6 kn.

A critical bridge watch time is 8 hours (480 minutes), the time at which additional time charges for pilots begin at non-linear rates.

- Dry bulk carriers, general cargo ships, cruise ships and tankers have average bridge watch times of about 400 minutes without the Trial delay and in most cases times above 400 minutes with the Trial.

- Without the Trial delay, some ships already exceeded 480 minutes and more do so with the trial delay added in. For example:
    - 23 dry bulk carriers fell into this category without the Trial delay and 50 with.
    - 3 tankers without the Trial delay and 9 with.

Summary of Vessel Trip and Bridge Watch (Trip) Times for Haro Strait Ships

	Trip Time (Minutes)		Number of Voyages over 8 Hours	
Vessel Type	Actual 2015	With Slowdown	Actual 2015	With Slowdown
Dry Bulk				
Minimum	160	180		
Maximum	700	720		
Average	396	416	23	50
Car Carrier				
Minimum	195	230		
Maximum	290	322		
Average	223	257	0	0
Container				
Minimum	178	216		
Maximum	486	524		
Average	290	329	1	3
General Cargo				
Minimum	238	259		
Maximum	495	516		
Average	372	394	2	7
Passenger (Cruise)				
Minimum	305	343		
Maximum	482	523		
Average	367	405	1	2
Tanker				
Minimum	315	338		
Maximum	520	542		
Average	413	435	3	9

Source: VFPA consultant estimates.

1.1.3 Buildup of Costs

Pilotage costs:

- Pilotage costs were estimated with the assumption of single pilots and pilot additional time charges for voyages of more than 8 hours per the January 2017 PPA Tariff.
- PPA undertook their own independent analysis of pilotage costs resulting from the Trial and confirmed that their calculations yield numbers that are consistent with those presented in this study

Vessel time costs:

- Spot / short-term market time-charter rates were used for bulk carriers (including general cargo ships) and tankers.
- For car carriers, general period time-charter rates were used for this illiquid market in which ships are often owned by the carriers.
- For container ships, ship time costs were not used:
    - Although it is possible to build up time-charter equivalent costs for container ships and a limited time-charter market exists for larger container ships, time costs do not reflect the cost structure of established container trades such as those to VFPA via Haro Strait:
        - Once established, most costs of such trades are fixed: vessel ownership and operating costs however measured and most fuel.
        - Variable costs include variable port charges, container handing charges and ship fuel to maintain schedules.
    - The cost of extra (makeup) fuel required to maintain voyage schedules was used as the measure of the impact on container ships.
- For cruise ships, ship time costs were also not used:
    - Cruise lines own ships and few if any are time chartered.
    - Schedule maintenance is critical to cruise lines.
    - Makeup fuel costs to maintain schedules were used.
    - Several cruise ship operators provided their estimates of extra voyage speeds or fuel consumptions to meet their planned 2017 repositioning voyage schedules via Haro Strait.

Fuel costs were estimated in two stages:

- Base fuel consumption at ship design speed:
    - Because fuel consumption data was sparse for Haro Strait ships (only 12% of vessels had fuel records), it was necessary to model fuel consumption.
    - Fuel consumption was modeled at design speed by ship type:
        - The model was estimated from register data for as many relevant ships as possible for each type.
        - The following relationship was used to reflect the nonlinear relationships between fuel consumption, and ship size and design speed:

$$\text{Fuel consumption} = a(\text{ship size})^b(\text{design speed})^c$$

- Fuel consumptions at service speeds in Haro Strait and at 11 kn and for other voyages:
    - The norm is that fuel consumption varies with the cube of speed.
    - A formulaic approach that incorporates the basic hydrodynamic properties of a ship was chosen.
    - With this approach, fuel consumption varied with roughly the cube of speed: the exponents ranged from 2.7 to 3.3 and averaged 3.1.

1.1.4 Assumptions

Time-charter rates used are in the following table.

Time Charter Rates Used in the Study (US$ per Day)

Ship Type and Class	Size Range (DWT) Minimum	Size Range (DWT) Maximum	Time Charter
Bulk Carrier & General Cargo			
Handysize		45,000	$8,000
Supramax	45,000	60,000	10,000
Panamax	60,000	80,000	9,000
Capesize	80,000		12,000
Tanker			
Medium Range		50,000	$13,000
Panamax	50,000	80,000	14,000
Car Carrier			$20,000

Sources: Table 4 and Table 6.

The price of fuel:

- The price of ship fuel varies with the region in which it is used:
    - Ultra-low sulphur marine gasoil (0.10% sulphur) within the North American Emission Control Area (ECA).
    - Standard main engine fuel oil (3.5% sulphur) elsewhere.
- Fuel prices at 2017 levels were used:
    - Ultra-low sulphur marine gasoil, US$550 a tonne (blend of local and international prices).
    - Standard main engine fuel oil (IFO380), US$300 a tonne (international prices).

1.1.5 Impact of Trial on Vessel Costs

Impacts in general:

- Increased pilotage costs for all ship types where the Trial delay either triggered an additional hour of bridge time (pilotage costs are rounded up to next hour) or introduced or increased additional time charges for voyages of more than 8 hours.
- Increased ship time costs for bulk carriers, car carriers, general cargo ships and tankers because of the increased time in Haro Strait.
- No ship time costs for container and cruise ships, as noted in Section 1.1.3.
- Fuel cost savings experienced in Haro Strait by all ships because of lower fuel consumptions at lower speeds.
- Makeup fuel impacts for cruise and container ships. These ships need to maintain schedule regularity which sometimes requires them to speed up in other voyage segments to make up the delay due to the Haro Strait Trial. The values in the table for container ships reflect the cost to offset all time lost in Haro Strait during the Trial, a relatively extreme but quite possible scenario.

The following table summarizes the base case evaluation of the additional vessel costs. The net cost is about C$523,000.

Regarding makeup fuel for the container sector:

- Discussions with container carriers indicated that schedule maintenance is an important issue, especially in the relatively short voyages between the Vancouver and Puget Sound container terminals. If a vessel misses its berth windows or arrive late when terminal labour has been ordered, costs are high, typically several tens of thousands of dollars per ship call.
- Not all container vessels are expected to consume makeup fuel because some will have sufficient flexibility within their voyages to avoid it.
- Others will have more schedule issues and must either steam faster to make up time to avoid issues such as missed berth windows or extra expenses in container terminals due to late ship arrival.

Estimate of Additional Costs of 2015 Haro Strait Ship Transits for Two-Month Trial Period (C$)

Ship Type	Pilotage	Ship Time	Cost of Fuel Consumption		Total Cost	Number of Ships
			Haro Strait Reduction	Schedule Makeup		
Bulk Carrier	$89,241	$76,842	-$97,714		$68,369	427
Car Carrier	12,108	47,758	-31,902		27,964	77
Container	46,134	0	-265,254	574,121	355,001	250
General Cargo	14,195	10,198	-9,973		14,420	61
Passenger	1,670	0	-19,137	56,123	38,656	27
Tanker	17,535	15,111	-14,336		18,310	56
Total Cost	$180,882	$149,909	-$438,315	$630,244	$522,720	898

Source: Evaluations in Section 2.3.2.

The following table summarizes the base additional costs per ship by cost component and the next table provides the ranges of total costs per ship.

Estimate of Additional Costs per Ship Transit of 2015 Haro Strait Ships (C$ per Ship)

Ship Type	Cost Component				
	Pilotage	Ship Time	Haro Str. Fuel	Makeup Fuel	Total Cost
Bulk Carrier	$209	$180	-$229	$0	$160
Car Carrier	157	620	-414	0	363
Container	185	0	-1,061	2,296	1,420
General Cargo	233	167	-163	0	236
Passenger	62	0	-709	2,079	1,432
Tanker	313	270	-256	0	327

Source: Evaluations in Section 2.3.2.

Range of Costs per Ship

	Cost per Ship (C$)		
Ship Type	Average	Minimum	Maximum
Bulk Carrier	$160	-$166	$2,537
Car Carrier	363	178	453
Container	1,420	547	5,380
General Cargo	236	-42	2,606
Passenger	1432	0	3.526
Tanker	327	-58	2,641

Source: Evaluations in Section 2.3.2.

The following material presents some supplemental evaluations.

Pilotage costs increase rapidly when bridge watch time exceeds 8 hours. The following table summarizes costs for ships that experience less than and more than 8 hours. If those ships that exceed 8 hours of bridge time did not participate in the Trial, this would reduce the total cost of the Trial by approximately 20% or $100,000.

Bridge Watch Time Greater Than / Less Than 8 Hours (C$)

			Cost of Fuel Consumption			
Circumstance	Pilotage	Ship Time	Haro Strait Reduction	Schedule Makeup	Total Cost	Number of Ships
Bridge Watch						
Less than 8 Hours	$85,796	$137,279	-419,882	$623,338	$426,531	819
More than 8 Hours	95,086	12,631	-18,433	6,906	96,190	69
Unaffected Passenger Ships	0	0	0	0	0	10
Total Cost	$180,882	$149,909	-438,315	$630,244	$522,720	898

Source: Evaluations in Section 2.3.2.

The following table summarizes the effect on pilotage costs if all ships participated in the Trial. For all ships, about 47% would experience no pilotage cost increase, about 46% an increase of one hour of bridge time ($208.75) and about 7% greater charges because of additional time charges for bridge times that in total exceed 8 hours. : The pilotage costs associated with this 7% of ships represent approximately half of the total pilotage costs for the Trial.

Effect of Trial Participation on Pilotage Cost

Ship Type	Total No. Calls	Percent of Ships with Pilotage Situation: No Additional Cost	Additional 1 Hour	More than One Hour
Bulk Carrier	427	60%	29%	11%
Car Carrier	77	25%	75%	0%
Container	250	22%	77%	1%
General Cargo	61	59%	30%	11%
Passenger	27	70%	30%	0%
Tanker	56	64%	20%	16%
Total/Average %	898	47%	46%	7%
Average Cost		C$0.00	C$208.75	C$1,440.69

Source: Evaluations in Section 2.3.2.

The following table summarizes the effect of the Trial on the costs of ship time (time-charter costs) and fuel savings in Haro Strait of bulk carriers, general cargo ships and tankers. The fuel cost savings result from lower consumption at 11 kn than at usual service speeds. The net cost per ship is either negative or minimal.

Effect of Trial Participation on Fuel Cost of Bulk Carriers, General Cargo Ships and Tankers

	Ship Transits		Cost per Ship (C$)		
Voyage	Number	Percent	Ship Time	Fuel Savings	Net Cost
Bulk & General Cargo Ships	488	90%	178	-221	-42
Tankers	56	10%	270	-256	14
Total	544	100%			

Source: Evaluations in Section 2.3.2.

The following table summarizes the effect of the Trial on the fuel costs of container ships by voyage. To some degree, the savings in Haro Strait offset the costs of fuel consumed in other voyage segments to make up time lost in Haro Strait. The makeup fuel costs are for the total recovery of time lost in Haro Strait. Not all ships will have to make up time because of slack in schedules so this reflects a relatively extreme but quite possible scenario. But the consequences to container carriers of schedule issues can be high: if a carrier orders labour for 8 AM but cannot start work until 10 AM because of a delay in berthing, the standby charges for labour are about C$20,000.

Effect of Trial Participation on Fuel Cost of Container Ships (C$)

	Transits		Fuel Cost per Transit		Net
Voyage	Number	Percent	Makeup	Haro Saving	Fuel Cost
To / From Asia	96	38%	$1,876	-$1,061	$815
Out to California	15	6%	2,772	-1,061	1,711
In from Prince Rupert	11	4%	3,350	-1,061	2,289
To / from PNW Ports	128	51%	2,466	-1,061	1,405
Total / Average	250	100%	$2,296	-$1,061	$1,235

Source: Evaluations in Section 2.3.2.

The following table summarizes the effect of the Trial on the fuel costs of cruise ships by voyage. The table uses the number and nature of cruise ship transits planned for the fall of 2017. There is no additional cost to cruise ships between Vancouver and Seattle or Victoria because these ships travel slowly due to long periods between port departure and arrival times. But cruise lines take schedules very seriously for cost and market reasons. One cruise carrier provided an estimate of extra fuel consumption of a repositioning voyage to California and another an estimate of extra speed to Hawaii.

Effect of Trial Participation on Fuel Cost of Cruise Ships (C$)

	Transits		Fuel Cost per Transit		Net
Voyage	Number	Percent	Makeup	Haro Saving	Fuel Cost
Seattle / Victoria	14	47%	$0	$0	$0
West Coast	10	33%	2,079	-709	1,370
Hawaii	6	20%	2,079	-709	1,370
Total / Average	30	100%	2,079	-709	$1,370

Source: Evaluations in Section 2.3.2.

1.2 Conclusions

The conclusions reached in Phase 1 of the study include:

1. The net additional costs to bulk carriers, car carriers, general cargo ships and tankers are generally modest, in all cases less than C$500 per ship transit of Haro Strait.
2. The net costs to additional container and passenger ships are greater, typically C$1,500, where there is the need to maintain schedules.
3. The costs to container and passenger ships of not meeting schedules can be high.

2 Introduction

Vancouver Fraser Port Authority (VFPA) engaged Seaport Consultants Canada Inc. (Seaport) in association with Colledge Transportation Consulting Inc. (CTC) to evaluate the economic impact of a proposed voluntary vessel slowdown trial in Haro Strait ("Trial"). The federal government has identified acoustic disturbance from vessel noise by as a key threat to the recovery of the southern resident killer whale (SRKW). The objective of the Trial is to monitor and measure the impact that reducing vessel speed has on underwater noise, and on the shipping industry and to predict resulting impacts to SRKW.

The Trial is planned for August 7 to October 6, 2017; the evaluations of this study ("Study") are based on data between August 7 and October 6, 2015 provided by VFPA from the Pacific Pilot Authority (PPA) and AIS records. The 2015 data was used as VFPA had previously used this data for its pre-trial (baseline) modeling. VFPA's environmental consultant compared the 2015 data with 2016 data and found no meaningful differences. The container carriers will introduce major schedule changes in the second quarter of 2017. This Study does not take such schedule changes into effect.

The Study is structured in two phases. Phase I estimates the financial impacts to the shipping industry of the proposed voluntary vessel slowdown Trial, the findings of which are presented in this report prepared by Seaport. Phase II incorporates this analysis into a broader framework known as a Multiple Account Evaluation (MAE) which systematically documents the estimated costs and benefits of the Trial from several perspectives (i.e., financial, customer service, economic, First Nations culture, environmental). CTC prepared the Phase II report.

2.1 Quantitative Economic Impact Analysis

Phase I of the Study focused on the Quantitative Economic Impact Analysis (QEA) of the Trial. This work estimates the financial impacts of the Trial on the international ships transiting Haro Strait.

2.1.1 Vessel Traffic

A consultant to VFPA[1] utilized records and information provided by the Pacific Pilotage Authority (PPA) to generate a dataset of international ship transits of Haro Strait between August 7 and October 6, 2015. These 898 transits form the basis of the slowdown trial evaluation. The structure and contents of this dataset were used as the basis for the quantitative economic impact analysis of this report.

Information on ships was added to the dataset, primarily from the 2017 Fairplay register of ships, and supplemented with information from older registers issued by Clarkson Research Services Limited and a variety of online sources. The following fields were added: deadweight tonnage (DWT), gross registered tonnage (GRT), International Maritime Organization (IMO) number, ship name and Fairplay ship type as a cross-check with the Pilots' records for the same fields. The main cross-check was confirmation that the records applied to the same ship because since 2015 several ships have changed name and a few have been scrapped. The types of ships listed in the registers were compared with the type records of the Pilots. There was correspondence in most cases but with some overlaps as discussed below.

New records were added for vehicle capacity for car carriers, passenger capacity for passenger (cruise) ships[2], container capacity in 20-foot equivalent container units (TEU) for container ships and some bulk carriers, main engine fuel consumption, service speed, the year the vessel was built and its flag. Table 1 summarizes some of the information from the dataset. It includes for each ship type the minimum,

[1] SMRU Canada.
[2] PPA used the term "passenger" as a ship descriptor. All these "passenger" ships were cruise ships, virtually all in the Alaska cruise trade or on repositioning voyages from it.

maximum and average values for each record and the number of data entries. Observations by ship type are:

- **Bulk cargo and general cargo ships.** These ships were consolidated into one category of 488 ships because they all transport dry cargoes and there are overlaps between them. In strict terms, bulk carriers transport dry bulk cargoes loaded and discharged in bulk form. General cargo ships typically transport items of dry cargo (such as copper ingots and structural steel) handled in break-bulk form but can at times transport dry bulk cargo. About 10% of the ships are specialized vessels called "open-hatch bulk carriers" (OHBC) with large hatches, squared-off holds and high-capacity cranes that handle forest products such as wood pulp and lumber in break-bulk form, but are otherwise bulk carriers. OHBCs also handle dry bulks in some voyages. The PPA classified some OHBCs as general cargo ships and others as bulk carriers. Of relevance:
  - The bulk carriers are relatively new ships, with about 60% built since 2010.
  - About 60 of the ships are "Capesize" vessels of up to 210,000 DWT that load export coal in Vancouver.
  - 46 of the ships have some container capacity, most of which are OHBCs. Some ships have one cellular hold for containers and routinely transport containers. Many OHBCs operate on a schedule (albeit a somewhat loose schedule) rather than on voyage charters.
  - Only 37 of the 488 records (less than 10%) include fuel consumption data. The range is 19 to 50 tonnes of fuel per day at design speed.
- **Car carriers.** These are roll on – roll off (ro-ro) ships that specialize in vehicle transport. They are called pure car carriers (PCC) and their capacities are often stated in car-equivalent units (CEU).
  - They are relatively small ships with the maximum capacity in the sample about 25,000 DWT.
  - They have a high cubic capacity because of the low density of vehicles. The gross registered tonnage (a cubic measure) of a 25,000 DWT car carrier is typically about 70,000 GRT.
  - Car carriers in the dataset are relatively old ships with only 25% built since 2010, about 50% built before 2005 and some dating back to 1985.
  - Only 17 of the 77 records (about 20%) include fuel consumption data. The range is 30 to 55 tonnes of fuel per day at design speed.
- **Container ships.** These are purpose-built ships with cellular holds to support containers under deck. There were 250 Haro Strait transits of container ships in August – October 2015. The structure of the container ship fleet is in transition because of massive ordering of very-large container ships of up to 20,000 TEU since 2010 and in June 2016 a major change in the dimensions of ships that can transit the Panama Canal. While the very-large container ships will probably not serve the transpacific trade, their use between East Asia and Europe will push smaller but still increasingly large ships into the transpacific and other trades.
  - The Haro Strait container ships are relatively old: about 90% built before 2011. The newest was built in 2014 and the oldest in 1996.
  - About 65% of the ships were post-Panamax under the old definition but all could transit the new Panama Canal[3].

[3] The Panamax ship prior to June 2016 had a maximum beam of 32.3 m, LOA of 290 m, draft of 12.0 m in tropical fresh water (TFW) and a capacity of 4,500 to 5,000 TEU. With the expanded Panama Canal, the "neo-Panamax" ship has a beam of 49 m, LOA of 366 m, a TFW draft of 15.2 m and a capacity of about 12,500 TEU.

    - Only 44 of the 250 records (about 18%) include fuel consumption data. The range is 130 to 230 tonnes of fuel per day at design speed.
- **Passenger ships.** These are all cruise ships and many are on repositioning voyages from the Vancouver – Alaska trade to other locations at the end of the cruise season.
    - They are relatively old ships with none built since 2010 and 60% built before 2006.
    - Only one record includes fuel consumption: 110 tonnes per day for a 1999-built, 2,800-person passenger ship at 21.5 knots.
- **Tankers.** There were 56 tanker transits, with ships ranging from a 12,000 DWT "chemical/products" tanker to a 74,000 DWT "crude/products" tanker (Fairplay designations). In 2015, VFPA handled about 6.5 million tonnes of petroleum cargoes of which about 2 million tonnes were crude oil and the balance mostly distillates such as diesel and gasoline[4].
    - The Haro Strait tankers were relatively new, with about 80% built since 2005.
    - Only 9 of the 56 records (about 16%) include fuel consumption data. The range is 23 to 45 tonnes of per day at design speed.

[4] Vancouver Fraser Port Authority, *Statistics Overview*, 2016

Table 1 – Summary of Vessel Characteristics in Dataset

Vessel Type & Characteristics	DWT	GRT	Vehicles	Passengers	TEU	Main Fuel	Speed	Built
	(Tonnes)	(Tonnes)	(No)	(No)	(No)	(t/d)	(Knots)	
Dry Bulk and General Cargo								
Minimum	10,872	8,059			306	18.6	13.0	1981
Maximum	209,537	107,761			2,118	50.0	17.0	2015
Average	65,236	36,855			Irrelevant	30.5	14.5	2009
Count of Data Entries	488	488			46	37	488	488
Car Carrier								
Minimum	12,282	39,454	4,095			29.5	18.0	1985
Maximum	25,765	71,383	6,658			55.3	20.7	2013
Average	17,764	53,644	5,090			40.8	19.5	2003
Count of Data Entries	77	77	23			17.0	75.0	77
Container								
Minimum	30,007	21,583			2,118	134.3	15.5	1996
Maximum	131,236	131,332			11,356	230.0	27.5	2014
Average	75,720	68,890			6,181	175.0	24.6	2005
Count of Data Entries	250	250			250	44	250	250
Passenger								
Minimum	1,441	10,944		264		110.0	16.0	1993
Maximum	13,294	121,878		3,782		110.0	24.6	2010
Average	8,776	83,681		2,446		110.0	21.7	2003
Count of Data Entries	27	27		27		2	27	27
Tanker								
Minimum	12,601	7,522				22.8	13.5	1997
Maximum	74,329	41,676				44.9	15.5	2015
Average	34,541	20,893				29.1	14.7	2008
Count of Data Entries	56	56				9	56	56
Total Count [1]	898	898				109	896	898

Source: Pacific Pilotage Authority dataset, Fairplay register, 2017, past Clarkson registers, and various online sources, 2017.

Notes: [1] Only 109 of the 898 records (about 12%) had fuel consumption.

2.2 Buildup of Vessel Costs

This section describes the buildup of vessel costs: pilotage, vessel time and fuel consumption.

2.2.1 Pilotage Costs

Pilotage charges vary with the physical characterises of the ship, the time pilots are aboard the ship (bridge watch time) and fixed charges associated with the pilots' movements to and from the ship. The costs are specified in the PPA's January 2017 Tariff Regulations (Tariff)[5]. The main Tariff items are:

- **Fixed pilotage charge.** Fixed pilotage charge. This is the product of a ship's overall length (LOA), beam and maximum draft on the movement under the pilot's guidance divided by 100 (the pilotage unit) and multiplied by the rate in the January 2017 Tariff of $3.6290. There is an additional fixed charge of $0.01060 multiplied by the ship's GRT for vessels equal to or greater than 226 m LOA. For smaller vessels, the fixed charge is $4.1587 times the pilotage unit. The fixed charge also differs if the vessel is a tethered tanker of at least 226 m LOA with a GRT of more than 39,999 tonnes.
- **Time charge for bridge watches.** This begins at the earlier of the time for which the pilot is ordered and when the pilot commences the bridge watch and ends when the pilot can disembark the ship. The bridge time rate in January 2017 is $208.75 per hour or part thereof.
- **Other fixed charges.** These costs are particular to each pilotage ship movement. They include a pilot transportation charge by work area location set out in the Tariff plus other transportation costs such as taxi fares to Squamish, airfares to Prince Rupert and hotel accommodation, fees for launches that take pilots to ships not at berth, often a pilot boat replacement charge, and a launch fuel fee.

Schedule 3 of the Tariff provides for additional time charges if the bridge watch time exceeds eight hours. The components of time charges for bridge watches are in Table 2:

Table 2 – Time Charges for Bridge Watches

Item	Period	Time Charge
1.	Per consecutive hour or part of an hour	$208.75
2.	After 8 consecutive hours, an additional time charge, as follows:	
	a) for not more than 15 minutes	50 percent of the amount payable under item 1
	b) for more than 15 minutes, but not more than 30 minutes	100 percent of the amount payable under item 1
	c) for more than 30 minutes, but not more than 45 minutes	150 percent of the amount payable under item 1
	d) for more than 45 minutes, but not more than 60 minutes	200 percent of the amount payable under item 1
	e) for more than 60 minutes	300 percent of the amount payable under item 1

Source: Pacific Pilotage Authority, "Pilotage Act Pacific Pilotage Tariff Regulations," effective January 1, 2017.

Discussions with industry brought out that in most cases the vessel operator or representative orders one pilot with the expectation that the voyage will be less than eight hours. Exceptions include bulk carriers from Pacific Coast Terminals (located east of Second Narrows) and cruise ships with slow voyages necessary to meet their port call schedules within B.C. waters. Of the sample of 898 ships in the dataset

[5] Pacific Pilotage Authority, "Pilotage Act Pacific Pilotage Tariff Regulations," effective January 1, 2017.

that transited Haro Strait, about 20 bulk carriers, two general cargo ships and three tankers exceeded 8 hours. The durations exceeding 8 hours ranged from four minutes to about four hours.

The approach to pilotage costs for the Trial was as follows:

- Only bridge time was considered in the comparative estimates of pilotage cost. While the fixed pilotage charge estimated from vessel dimensions and sizes will vary for Haro Strait transits, within each transit they will be the same with or without the slowdown and cancel out. The same will be true of transportation and other fixed charges such as launch fees and fuel charges.
- The bridge time costs were estimated for a single pilot with and without the Haro Strait slowdown per the 2015 dataset.
- The cost of bridge time incorporated both the hourly charges of Item 1 in Table 2 and the additional time charges of Item 2 in this table.

This Study uses the estimates of pilotage costs based on the January 2017 PPA Tariff. In parallel, the PPA undertook their own independent analysis of pilotage costs resulting from the Trial and confirmed that their calculations yield numbers that are consistent with those presented in this study.

2.2.2 Vessel Time Costs

2.2.2.1 Overview

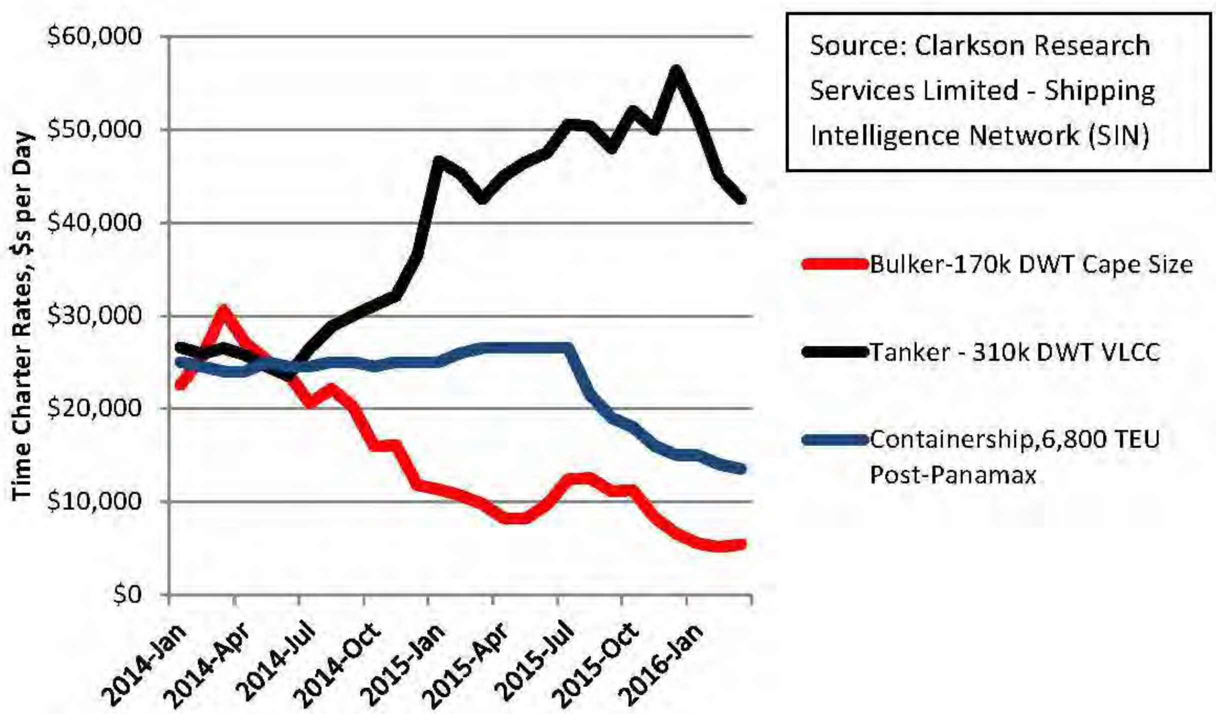
Vessel costs are typically stated in U.S. dollars per day as either time-charter rates (what one pays under a contract for the use of a ship) or time-charter equivalent costs (estimates of daily costs built up by item). The largest cost component of the latter is generally ownership (cost of debt and return on equity), with crew, insurance, and maintenance the larger out-of-pocket cost items.

An extensive study of 2020 world marine fuel demand provided a variety of background information of relevance to the Haro Strait study[6]. Figure 1 presents from this study recent trends in time-charter rates for three kinds of ships:

- A small post-Panamax container ship (with the old definition of "Panamax"). Over this period time-charter rates drifted down because of an oversupply of vessels and a shift to larger ship sizes because of the influence of the new limits of the expanded Panama Canal.
- Dry bulk carriers, represented by a "Capesize" bulker of 170,000 DWT, typical of larger coal ships and smaller ore carriers. Time-charter rates declined considerably due to falling commodity demand, although the commodity market seems to have bottomed in early 2016.
- A very-large crude carrier (VLCC) typical of ships from the Middle East to Asia and Europe. The market for these ships strengthened considerably. Although crude oil prices fell in late 2014, volumes did not change much. In addition, such ships sometimes provide crude oil storage for oil traders when oil prices are in contango (oil prices in futures contracts are above spot prices) and it is attractive to hold crude oil in storage as a speculation.

[6] EnSys Energy with Navigistics Consulting, "Supplemental Marine Fuel Availability Study," MARPOL Annex VI Global Sulphur Cap 2020 Supply-Demand Assessment, July 15, 2016.

Figure 1 – Tanker, Bulk Carrier and Container Ship Time-Charter Rates 2014 – 2016



Source: EnSys Energy with Navigistics Consulting, "Supplemental Marine Fuel Availability Study," MARPOL Annex VI Global Sulphur Cap 2020 Supply-Demand Assessment, July 15, 2016.

Various approaches were used to vessel time costs:

- In the cases of bulk carriers and tankers, ships are typically chartered. These can range from a single voyage to a period such as ten years. The time charter market provides a good measure of the costs to these vessel operators.
- The costs of car carriers were treated as time-charter costs in this study. Nevertheless, the time-charter market for these ships is limited and opaque and they operate on flexible schedules.
- Container ships on major trade routes to the Port of Vancouver are on fixed schedules and are usually owned and financed by the container shipping line rather than chartered. If chartered, such ships are typically under long-term charters from another container carrier or a vessel owner. However measured, the ownership costs of container ships and many operating costs are fixed once a container shipping line establishes a service and allocates ships to it. The time values for container ships were not used in this study. Instead the fuel costs of maintaining schedules with a fixed set of ships were estimated as the impacts of the Haro Strait slowdown on the container sector.
- Passenger ships are generally owned by cruise lines and there is essentially no time-charter market for them. The fuel costs of maintaining schedules were estimated as the impacts of the Haro Strait slowdown on this sector.

2.2.2.2 Bulk Carriers

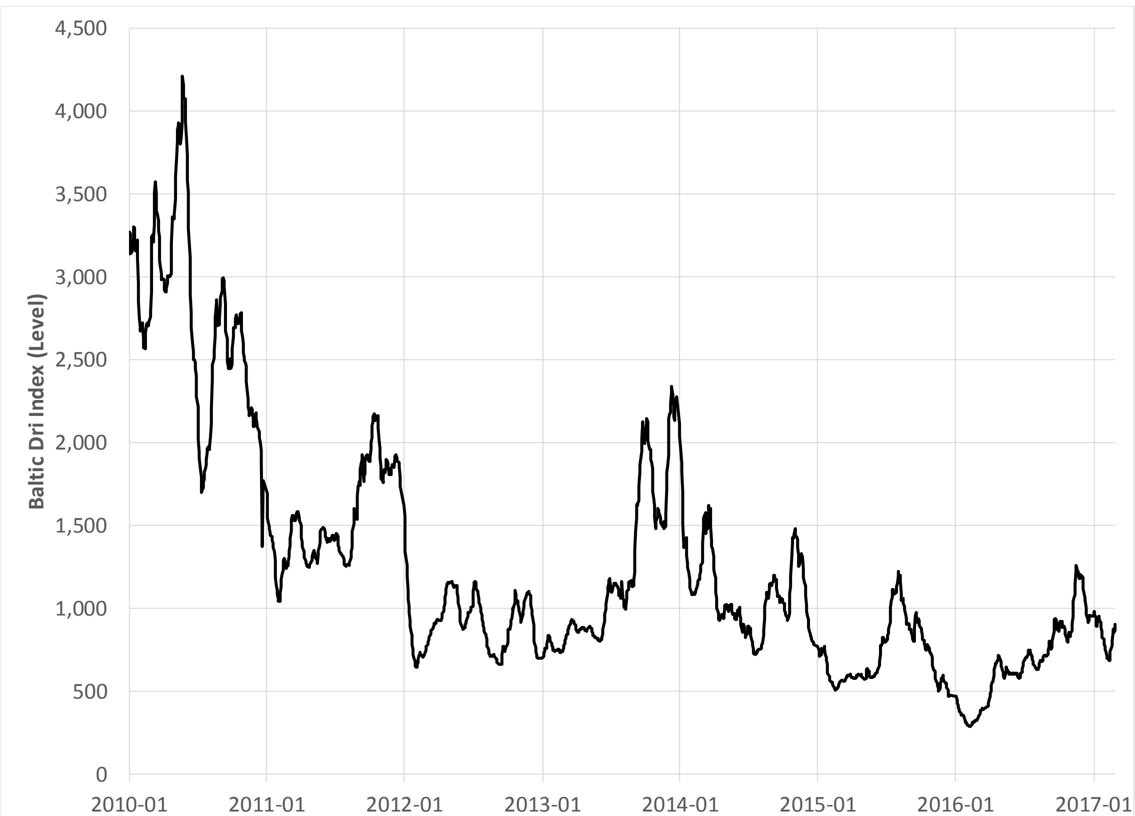
The cost structure of dry bulk ships involves spot and period rates for both cargo transport (a rate per tonne) and the ships themselves (a rate per day). The ships trade both as an asset and in a charter market. A ship owner can commission the construction of a new ship or purchase a used ship and charter it to another party for a daily rate. The charterer may have fixed employment for the ship over the charter period (such as a miner shipping ore from Australia to China) or a fixed contract of affreightment to provide shipping services for several years. The charterer may also play the spot market and fix the ship on a voyage basis.

The most appropriate measure of the cost of ship time due to a delay such as the Haro Strait speed limit is a time charter rate, somewhere between the spot charter market and a period charter of perhaps five years. The charter market is very volatile, especially for shorter-term charters.

One measure of the overall dry bulk market is the Baltic Dry Index (BDI), which averages the spot time-charter rates for defined voyages of four classes of bulk carrier: Capesize (generally over 80,000 DWT), Panamax (60,000 to 80,000 DWT), Supramax (45,000 to 60,000 DWT) and Handysize (15,000 to 45,000 DWT). The spot voyage rates in the index are not actual fixtures but the average opinion of ship brokers as to the market rate at a specified time of each day. The index is an unweighted average of the voyage charters of the four ship categories multiplied by a factor of 0.109078497. It is not equivalent to an average time-charter rate but does provide a guide to overall market conditions.

Figure 2 summarizes the BDI from January 2010 to March 2017. The chart indicates the index's volatility and shows that the August to October period of 2015 was comparable to that of recent months. The BDI reached a recent low in early 2016, generally in parallel with the bottom of commodity market.

Figure 2 – Baltic Dry Index 2010 to 2017



Source: Quandl Inc., Baltic Dry Index, March 3, 2017

[7] Source: The Baltic Index, April 2017.

Table 3 summarizes spot market rates by ship size in August to October 2015 in the upper part, recent spot market rates in the centre, and recent period charters in the lower part. The 2015 time-charter rates are only indications of spot market conditions and most do not represent actual transactions. The recent period charters are based on actual transactions albeit with rounding and generalization.

The time charter market is very volatile. For example, the rate of Capesize ships on one-year charters hit US$160,000 a day in 2008; the trough in 2009 was about US$6,000 a day.

Table 3 – Baltic Dry Index Components: Recent and August - October 2015 (US$ per Day)

Item / Period	Capesize	Panamax	Supramax	Handysize
Size Range (DWT)	80,000 +	60,000 - 80,000	45,000 - 60,000	15,000 - 45,000
Markets 2015				
14-Aug-15	$15,000	$8,500	$12,000	$11,000
21-Aug-15	12,000	10,000	11,000	15,000
28-Aug-15	No Reports	8,500	8,500	13,000
04-Sep-15	7,000	10,000	13,000	No Reports
09-Sep-15	12,000	7,000	10,000	7,000
18-Sep-15	13,000	12,000	15,000	9,000
25-Sep-15	15,000	12,000	14,000	No Reports
02-Oct-15	24,000	10,000	8,500	7,000
09-Oct-15	11,000	9,000	10,000	8,000
16-Oct-15	9,000	12,000	10,000	8,000
Recent Market Activity				
10-Feb-17	No Reports	$8,000	$10,000	$9,000
17-Feb-17	11,000	9,000	9,000	7,000
24-Feb-17	12,000	9,000	9,000	8,000
03-Mar-17	13,000	8,500	11,000	8,000
Recent Period Charters				
1-Year Pacific	$11,750	$9,000	No Reports	No Reports
3 Years	12,500	9,250	“	“
5 Years	12,500	9,250	“	“

Sources: Markets 2015 and 2017, Baltic Briefing, Bulk Reports; time-charter rates, Clarkson Shipping Intelligence Network, March 2017.

Table 4 summarizes the time-charter rates used in the study for bulk carriers and general cargo ships.

Table 4 – Bulk Carrier and General Cargo Time Charter Rates Used in the Study (US$ per Day)

Ship Size Class	Size Range (DWT) Minimum	Maximum	Time Charter
Handysize		45,000	$8,000
Supramax	45,000	60,000	10,000
Panamax	60,000	80,000	9,000
Capesize	80,000		12,000

Source: Consultant estimates.

2.2.2.3 Car Carriers

There is a very limited time-charter market for car carriers as most companies in the car transport field either own their ships or charter them under long-term agreement. Some evidence from Clarkson is that time-charter rates for vessels of the size that call at Vancouver are US$15,000 to US$25,000. A time-charter rate of US$20,000 is used in this study.

2.2.2.4 Container Ships

A considerable amount of information on costs of container ship time was assembled for this study. Because in the end such costs were not used for evaluations, they are appended for reference in Annex A.

2.2.2.5 Passenger (Cruise) Ships

The "passenger ships" in this study are cruise ships. Most major cruise operators own their ships, the cruise industry does not use the concept of the value of ship time in general and there is no time-charter market for cruise ships.

The ships are expensive to build and operate. An example of a new building is the 3,646-passenger *Carnival Dream* built for US$672 million by Fincantieri and delivered to Carnival Cruise Line in 2009.[8] The daily capital charge alone of such a ship would be about US$250,000. To this one would add costs for the marine crew, the hospitality crew and other costs particular to the cruise sector as well as standard out-of-pocket costs such as maintenance and insurance.

The cost of ship time is not meaningful to this sector. The impact of the Haro Strait slowdown is estimated by the fuel costs of maintaining schedule integrity.

2.2.2.6 Tankers

Table 5 provides market information for tankers comparable to that for bulk carriers above. Unlike bulk carriers in the current market, there is a progression in time-charter rates: the larger the tanker, the higher the time-charter rate. The Panamax and Medium-Range period-charter rates are those relevant to the tankers in the dataset for Haro Strait between August and October 2015.

[8] Source: G. P. Wild (International) Limited, 2011.

Table 5 – Tanker Time-Charter Rates (US$ per Day)

Week	VLCC	Suezmax [1]	Aframax [2]	Panamax	Med. Range
Size Range (DWT)	200,000 +	120,000 - 200,000	80,000 - 120,000	60,000 - 80,000	25,000 - 50,000
Spot					
2016	$41,000	$27,500	$23,000		$12,000
2017	33,000	18,000	19,000		10,000
One-year					
2016	$36,500	$27,000	$21,500		$15,000
2017	28,500	21,000	17,000	14,000	13,000

Sources Clarkson Shipping Intelligence Network, March 2017; 2017 Panamax rate for 80,000 DWT tanker per Compass Maritime Weekly Report, March 3, 2017.

Notes: [1] A "Suezmax" tanker can transit the Suez Canal while fully laden.

[2] An "Aframax" (in which "AFRA" means "Average Freight Rate Assessment," a shipping contract term) is a tanker between 80,000 and 120,000 DWT

Table 6 summarizes the time-charter rates used in the study for tankers.

Table 6 – Tanker Time-Charter Rates Used in Study (US$ per Day)

	Size Range (DWT)		Time
Ship Size Class	Minimum	Maximum	Charter
Medium Range		50,000	$13,000
Panamax	50,000	80,000	14,000

Source: Consultant estimates.

2.2.3 Ship Fuel Consumption

2.2.3.1 Fuel Consumption at Design Speed

The fuel consumption of a ship's main engine generally varies with the size of the ship and the speed at which it operates. The fuel consumption in tonnes per day (t/d) is recorded in vessel registers (but only for a selection of ships, not all) along with the ship's design speed to which this consumption applies. Other factors that affect fuel consumption are hull design, engine thermal efficiency and speed, and hull smoothness. As discussed below, fuel consumption varies exponentially with speed.

Since fuel consumption records were available for only a few ships in the August – October 2015 dataset, fuel consumption was modeled as a function of ship size and design speed and applied to register data for each ship type to estimate fuel consumption of the Haro Strait ships at their design speeds. The nonlinear relationship between ship fuel consumption, ship size and speed used in the model is:

Fuel consumption = $a(\text{ship size})^b(\text{design speed})^c$

Where “a” is a constant, b is the power exponent of ship size and c is the power exponent of speed. The measure of ship size varies with the type of ship: TEU in the case of container ships, deadweight tonnes for bulk carriers, tankers and car carriers and GRT for cruise ships. Ship speed is stated in knots (kn).

Annex B summarizes the estimates of the fuel consumption models by ship type.

2.2.3.2 Fuel Consumption versus Speed

This section summarizes the approach to ship fuel consumption as a function of speed. Details are in Annex C.

A general fuel consumption model was needed to extend the fuel consumptions at design speeds down to those of typical service speeds today and 11 knots and to other speeds needed in this study. The norm in the shipping industry is to apply a cubic power relationship for fuel consumption as a function of ship speed: if the speed of a ship doubles, fuel consumption increases eightfold[9]. Further evidence for the variability of fuel consumption with speed came from the study of marine fuel supply and demand cited above in which estimated exponents were typically between 3.25 and 3.50[10]. This supports the information in the literature that fuel consumption generally varies with the third power of speed.

A somewhat more complicated and complete approach to calculate differences in ship fuel consumption with speed was chosen to incorporate the hydrodynamic properties of a ship[11]. The approach involves:

- Calculation of the Froude number (Fn) as a basic hydrodynamic measure, as: (vessel speed in m/s) / ([vessel length in m]) * 9.81$)^{0.5}$ Where 9.81 is a gravitational coefficient and ship length is LOA.
- Calculation of Fuel Indexes for speeds under study from the Froude number with the following formula:

  Fuel Index = $- 0.0664 + 2.4325 * Fn – 24.4453 * Fn^2 + 145.1438 * Fn^3$

- Calculation of fuel consumptions in proportion to the ratios of the Fuel Index applied to the original fuel consumption.

The article cited includes an example of a reduction in the speed of at 332.6 m LOA VLCC from 15.6 knots design speed to 10 knots and fuel consumption from a design 97.1 t/d to 30.2 t/d. The resulting power exponent for this ship was about 2.6.

This approach was adopted for the study:

- Calculate the Froude number for each vessel and speed.
- Calculate the Fuel Index for each vessel and speed.
- Estimate the variation in fuel consumption for a ship operating at two speeds as the ratio of the fuel indexes.
- Calculate the resulting exponents as a crosscheck.

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9 Citations include: Martin Stopford, *Maritime Economics*, 2009, which quotes and applies the cube power rule; The INTERTANKO, Optimum speed calculator, 29 June 2012 states that “The bunker consumption is varying as a function of the speed with an exponent of power of 3…”.
10 EnSys Energy with Navigistics Consulting, op. cit.
11 This was adapted from St. D. Amand., “Optimal Economic Speed and the Impact on Marine GHG Emissions,” Society of Naval Architects and Marine Engineers (SNAME) Transactions, 2012.

2.2.4 Ship Fuel Prices

The price of ship fuel is complicated because it varies significantly with the region in which it is purchased and used:

- The 1997 MARPOL Protocol established four world emission control areas (ECA), one of which was the North American ECA. As of January 1, 2015, the maximum sulphur content of ship fuel for main and auxiliary engines fell from 1.0% to 0.10% for the North American ECA, which extends 200 nautical mile (NM) from the coast.
- The typical sulphur content of standard main engine fuel (such as IFO380) used in non-ECA areas is 3.5% and this fuel is much less expensive than fuel with a 0.10% sulphur content.
- The marine diesel oil used in non-ECA areas also has a relatively high sulphur content, typically 1.5%.

A ship in Haro Strait must consume 0.10% sulphur fuel because it is within the 200-NM limit of the North American ECA. This applies to both main engine fuel and that used in auxiliary engines. While low-sulphur heavy marine fuel oils are available in some parts of the world for main engines, the common fuel in North America is ultralow sulphur gasoil. Outside the 200-NM limit ships can consume 3.5% sulphur main-engine fuel, at least until 2020 when the IMO worldwide requirement for lower-sulphur ship fuel may come into effect.

There are several ways for ships to comply with the sulphur standards of the North America ECA. One is to burn low-sulphur fuel as happens now and the other is to build new ships or retrofit older ships with scrubbing equipment that removes the sulphur dioxide in the exhaust gases (there is also a third: exemptions for some domestic-flag ships that have been granted in the U.S. and Canada).

Few international ships have installed gas scrubbers. One estimate is that about 0.3% of such ships had done so by 2015. For ships that serve the European ECA only (ferries, coastal trade ships, etc.), about 30% have installed scrubbers[12]. Some cruise lines have also installed exhaust-gas scrubbers on some of their ships.

The approach that applies to Haro Strait and environs is the consumption of low sulphur gasoil.

Table 7 summarizes the specifications of the main marine fuels.

[12] EnSys Energy with Navigistics Consulting, op. cit.

Table 7 – Marine Fuel Grades and Specifications

WORLD Model Grade	ISO8217 Grade	Key Specifications Employed							
		density @ 15C - max	wt % sulphur - max	flash point degC - min	viscosity @ 40C (mm2/s) - max	viscosity @ 50C (mm2/s) - max	pour point Summer / Winter average (degC) - max	cetane index - min	micro carbon residue (%m/m) - max
Marine Distillate Fuels									
'Traditional' MGO	DMA	890	1.5/0.5	60	6		0/-6 = -3	40	
ECA MGO	DMA	890	0.1	60	6		0/-6 = -3	40	
Global MDO	DMB	900	0.5	60	11		6/0 = 3	35	0.3
IFO Fuels									
HS IFO180	RMG	0.991	3.5	60		180	30		18
HS IFO380	RMG	0.991	3.5	60		380	30		18
Global IFO 80 / 'Hybrid'	RMD	0.975	0.5	60		80	30		14
Global IFO 380	RMG	0.991	0.5	60		380	30		18

Source: EnSys Energy with Navigistics Consulting, "Supplemental Marine Fuel Availability Study," MARPOL Annex VI Global Sulphur Cap 2020 Supply-Demand Assessment, July 15, 2016.

Table 8 summarizes current prices for marine fuels: intermediate fuel oils at the top and distillate fuels below. The fuels of relevance to this study are the high-sulphur fuel oils and the ultralow sulphur marine gasoils.

Table 8 – Marine Fuel Prices by Fuel Type

Fuel Type and Grade	Sulphur	Price
	(%)	(US$/Tonne)
Intermediate Fuel Oils		
High-Sulphur IFO180 [1]	3.50%	$340
High-Sulphur IFO380 [1]	3.50%	300
Ultra-Low Sulphur Fuel Oil [2]	0.10%	450
Marine Distillate Fuels		
Traditional Marine Diesel Oil [1]	1.50%	$500
Ultra-Low Sulphur Marine Gasoil [3]		
Vancouver Quoted Price	0.10%	600
Estimated International Price	0.10%	500

Sources: IFO180, IFO380, ultra-low sulphur fuel oil and marine diesel oil, Ship & Bunker March 2017 (www.shipandbunker.com); low-sulphur marine gasoil, Marine Petrobulk LP.

Notes: [1] Typical prices in cheaper ports in East Asia, Southeast Asia and West Coast North America.
[2] Rotterdam price only; does not seem to be widely available and the fuel type may not be proven in use at sea.

[3] Quote by Vancouver supplier Marine Petrobulk LP was US$580. International price (Rotterdam, some U.S. Gulf ports) is about US$500, little different than traditional marine diesel oil. There are also such prices in some U.S. Gulf ports.

Discussions with the shipping industry indicate that most international ship operators in the Vancouver trade purchase ultra-low sulphur marine gasoil either in Asian ports offering the best prices or under contracts for local supply. US$550 a tonne was chosen for ultra-low sulphur marine gasoil to reflect local and international fuel purchases. US$300 a tonne was chosen as the international price of high-sulphur marine fuel oil.

2.3 Estimates of Cost Impact

This section estimates the cost impact of the Haro Strait slowdown, first as a base case and then with sensitivities. The vessel speeds used in the evaluations were:

- 11.0 knots with the Trial and
- Without the Trial, measured by an AIS sample[13]
  - Bulk carriers and general cargo, 13.2 kn
  - Car carriers, 16.3 kn
  - Container ships, 18.1 kn
  - Passenger ships, 18.1 kn
  - Tankers, 13.6 k.

2.3.1 Buildup of Costs

Based on the previous review and inputs, three components are used in the cost estimates: pilotage, vessel time and vessel main-engine fuel.

2.3.1.1 Pilotage

As discussed in Section 2.2.1, the pilotage costs were those estimated from the 2017 PPA Tariff for the Haro Strait ships.

2.3.1.2 Vessel Time Costs

The vessel time costs discussed in Section 2.2.2 above were applied.

- For **bulk carriers, general cargo ships and tankers**, current time-charter rates were used. These reflect the opportunity cost of such ships because of the active market for both the ships (represented by the time-charter rates) and the freight market in which these ships operate.
- For **car carriers**, a time-charter rate of US$20,000 a day was assumed. There was very limited information on this illiquid market.

Time costs for **container and cruise ships** were estimated and used in initial evaluations not shown in this report, but these do not reflect the cost structure of these sectors. The costs of ship time are essentially fixed within each region and trade and a more appropriate measure is that of fuel consumption to meet schedules.

2.3.1.3 Fuel Costs

The fuel costs were derived as follows:

[13] Source: SMRU Canada.

- First the models of ship fuel consumption at design speed developed in Annex B by ship type were used. As noted above, fuel consumption as a function of ship size and speed had to be modeled because of the lack of fuel consumption records for the Haro Strait ships. This involved application of the fuel model with inputs of the records of size (DWT, GRT or TEU) and ship design speed.
- The Froude numbers were calculated for all ships at their design speeds [Fn (DS)], actual or estimated service speeds (SS) in Haro Strait [Fn (SS)], the trial speed limit of 11 kn [Fn (11 kn)] and for container and cruise ships the speeds necessary to make up for time lost in Haro Strait with the slowdown.
- The Froude numbers were then used to estimate Fuel Indexes for each ship and speed which in turn were used to estimate fuel consumptions at service speeds and 11 kn for the movements in Haro Strait and for schedule maintenance in other voyages. For example, a bulk carrier of about 60,000 DWT had an estimated design fuel consumption of about 33 tonnes per day at a design speed of 14.3 kn, 26 tonnes per day at the average bulk carrier service speed in Haro Strait of 13.2 kn and 15 tonnes per day at the Haro Strait speed of 11.0 kn.

The results were checked by estimating the relationship between fuel consumption and speed. Fuel consumption varied with roughly the cube of speed: the power coefficient averaged 3.1 and varied between 2.7 and 3.3. This corresponds with the evidence and discussions above.

The fuel consumption of ships transiting Haro Strait was estimated under two scenarios: with and without the vessel slowdown. The speeds were 11.0 kn with the Trial and the measured speeds by ship type without the trial. Fuel costs assumed were US$550 a tonne because Haro Strait is within ECA waters.

To estimate makeup fuel for container ships, 2015 container ship rotations were used to select four typical voyages for VFPA ships: from Prince Rupert, to and from the Puget Sound ports of Seattle and Tacoma, to Southern California and to and from East Asia, represented by Busan. In this case, the Haro Strait delays increased fuel consumption because of the higher speeds required to make up time in other voyage segments. The cost of ultra-low sulphur gasoil was used for all voyages except those to and from Busan, for which the price of 3.5% sulphur IFO380 was used.

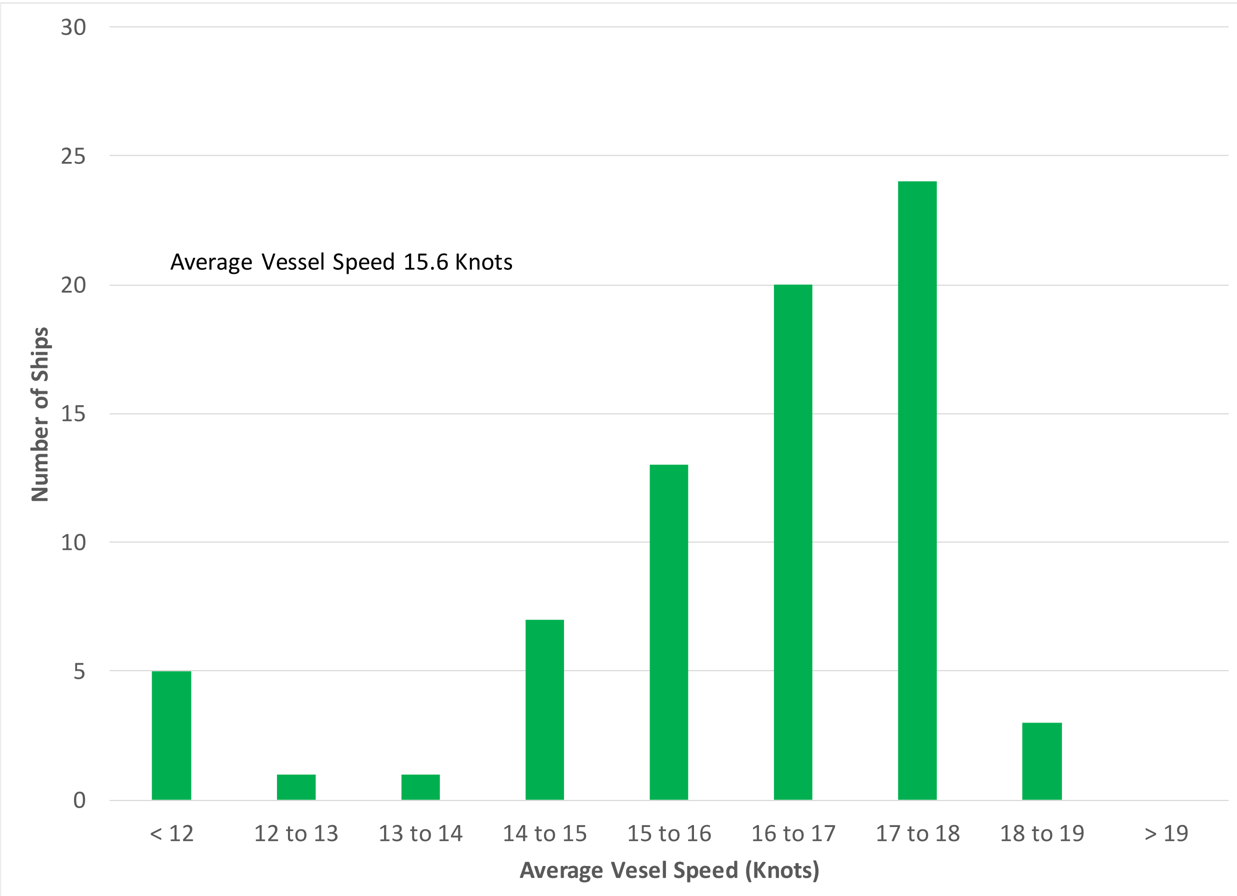
Regarding makeup fuel costs:

- The voyage distances between Vancouver and the Puget Sound ports range from about 155 NM from Deltaport to the Port of Seattle to 185 NM from Vanterm or Centerm to the Port of Tacoma. Only a portion of each voyage is available for faster steaming because of:
  - The slowdown in the approach to or from each port.
  - The slowdown for the First Narrows transit for Vanterm and Centerm.
  - The pickup and drop-off of Canadian and U.S. pilots around Victoria and Port Angeles and related slow steaming across the Strait of Juan de Fuca.

  The average voyage distance between the Vancouver and Puget Sound port areas available for faster steaming is about 135 NM. This includes the passage through Haro Strait.
- In the case of other voyages (Prince Rupert to Vancouver, Vancouver to Southern California, and between Busan and Vancouver) the voyages distances were sufficiently long that the minor local segments with lower speeds were ignored.
- The most important of these voyages are those between Vancouver and the Puget Sound ports because of the high volume (essentially every ship calling at the Port of Vancouver in 2015 called at one of the Puget Sound ports) and the relatively short distances.

Vessel speeds were estimated from AIS data for about 75 ships moving between Vanterm, Centerm and Deltaport in the Port of Vancouver and the container terminals in the ports of Seattle and Tacoma in February to April 2017. The average speed was 15.6 kn and Figure 3 depicts the distribution of speeds. Most vessels averaged 15 to 18 knots. A speed of 16.0 kn (15.6 kn rounded) was used for the evaluations.

Figure 3 – Container Ship Speeds between Port of Vancouver and Seattle and Tacoma



Source: Estimated from AIS data, 2017.

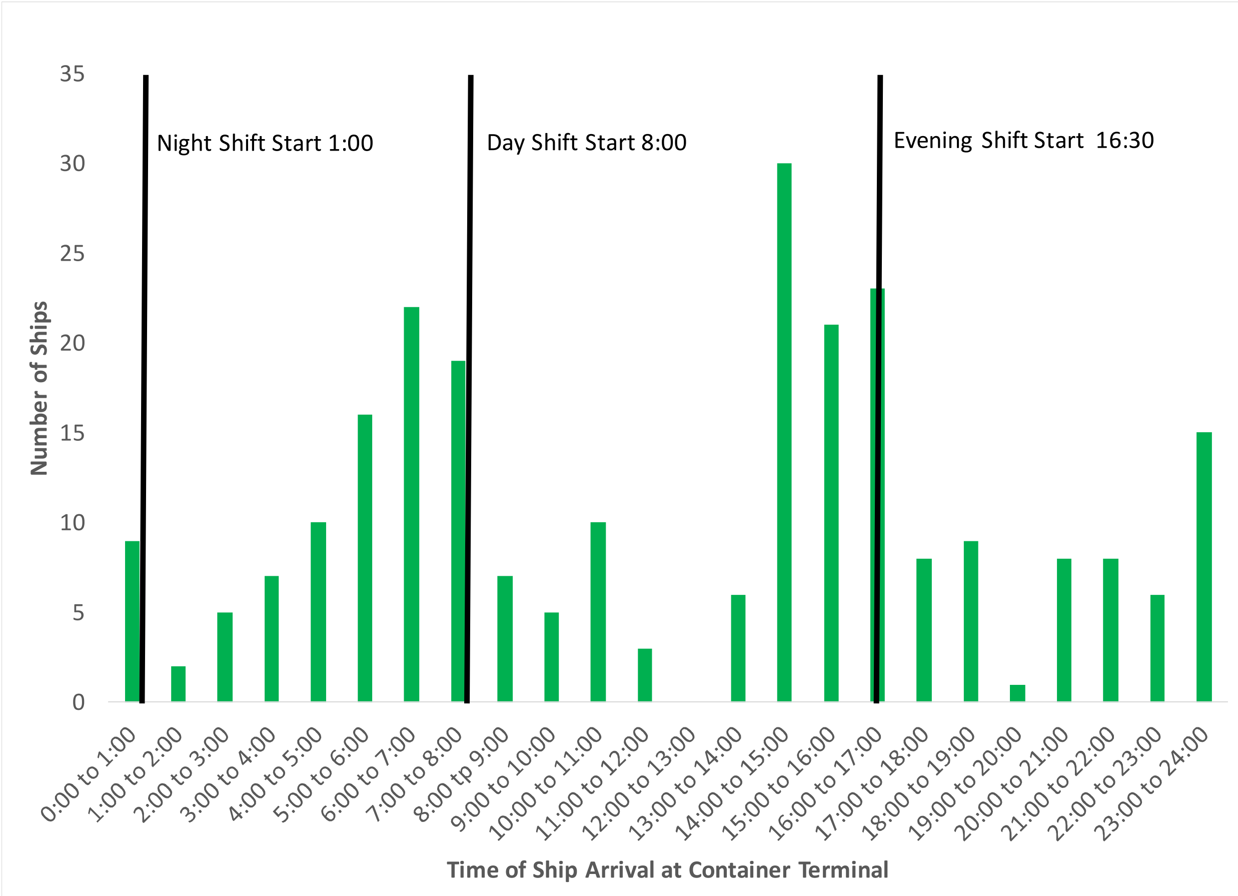
An issue is the degree to which the container carriers schedule arrivals at container terminals. If the arrivals were unscheduled, they would arrive somewhat evenly around the clock.

Figure 4 shows that the container ship arrivals are quite scheduled. The main patterns are:

- Many ships arriving between midnight and 8 AM with a concentration between 5 AM and 8 AM. This is to meet the 8 AM start of dayshift work, which is of relatively low cost and productive.
- Many ships also arriving between 14:00 and 17:00 to coincide with the 16:30 start of the evening shift.

This indicates that schedule consistency is important for container carriers.

Figure 4 – Container Ship Arrival Patterns at Port of Vancouver Container Terminals Q1 2017



Source: Estimated from VFPA data, 2017.

2.3.2 Evaluation for All Ships

2.3.2.1 Base Evaluation

This section provides the estimates of the ship-related differential costs with and without the vessel slowdown in Haro Strait. The cost estimates are for the two-month Trial period and utilize the 898 sample of ships in the 2015 dataset; the costs of the ships that participate in the 2017 trial may vary. These costs are only those of the vessel operators and exclude other potential cost impacts associated with supply chain or vessel scheduling disruptions or uncertainty which will be considered in the MAE of the next phase of the study.

Current time-charter rates were used for bulk carriers, general cargo ships and tankers. These reflect the costs of time gained or lost by such ships. As noted above, time-based costs do not reflect the cost structure of the container and cruise trades.

Many of the costs of container and cruise ships are fixed once the operator has established the service, such as a weekly container service with a fixed-day schedule at the ports of call and a string of ships, or a cruise line with a weekly (or other periodic) cruise service to Alaska. The fixed costs include the ownership costs of vessels, crew costs and most fuel costs. What varies most in the case of a container services are variable port charges such as wharfage and berthage, and container handling charges. A cruise line's variable costs include passenger handling fees and some port charges, and passenger-related costs such as food. Because both kinds of services must meet schedules, fuel used to make up lost time is a major variable cost and was treated as such.

Table 9 summarizes the results in total for the full period. The cost items are:

- Pilotage costs for all ship groups. They were estimated from the January 2017 PPA Tariff.
- The cost of ship time in Haro Strait for bulk carriers, car carriers, general cargo ships and tankers. These reflect current spot and short-term time-charter rates of such ships.
- Fuel costs (at 2017 prices) in Haro Strait, which reflect the lower consumption at 11 kn in Haro Strait versus the ships' regular service speeds in the Strait. These are appropriate for all ships except some passenger ships. Discussions with the Cruise Line International Association - North West & Canada (CLIA) confirmed that only cruise ships on repositioning voyages are affected by the slowdown. Other cruise ships are not affected because they have slack time in their movements between regional ports. The cost of ultra-low sulphur gasoil was used for all voyages.
- The cost of fuel (at 2017 prices) required for cruise ships to make up time lost in Haro Strait to maintain schedules. This affects cruise ships repositioning at the end of the Alaska season, typically to a California port en route to the Caribbean. One cruise line estimated 12 tonnes of fuel for a repositioning voyage in the fall of 2017; Seaport estimated about 6 tonnes for each of the 2015 ships. Another cruise line estimated the additional speed required to meet a scheduled arrival time in Hilo, Hawaii. The cost of ultra-low sulphur gasoil was used for all voyages.
- The cost of fuel required for container ships to make up time lost in Haro Strait to maintain scheduled arrivals and container terminals. The cost of ultra-low sulphur gasoil was used for voyages within the North American ECA and high-sulphur marine fuel for voyages to and from Busan.

Regarding makeup fuel for the container sector:

- Discussions with container carriers indicated that schedule maintenance is an important issue, especially in the relatively short voyages between the Vancouver and Puget Sound container terminals. If a vessel misses its berth window or arrives late when terminal labour has been ordered, costs are high, typically several tens of thousands of dollars.
- The estimate of about $574,000 reflects the industry-wide cost of the time lost in Haro Strait.
    - Not all container vessels are expected to consume makeup fuel because some will have sufficient flexibility within their voyages to avoid it.
    - But others will have more schedule issues and must either steam faster to make up time to avoid issues such as missed berth windows or extra expenses in container terminals due to late ship arrival.

Table 9 – Estimate of Additional Costs of 2015 Haro Strait Ship Transits for Trial Period (C$)

	Cost Component				
Ship Type	Pilotage	Ship Time	Haro Str. Fuel	Makeup Fuel	Total Cost
Bulk Carrier	$89,241	$76,842	-$97,714		$68,369
Car Carrier	12,108	47,758	-31,902		27,964
Container	46,134	0	-265,254	574,121	355,001
General Cargo	14,195	10,198	-9,973		14,420
Passenger	1,670	0	-19,137	56,123	38,656
Tanker	17,535	15,111	-14,336		18,310
Grand Total	$180,882	$149,909	-$438,315	$630,244	$522,720

Source: Consultant estimates.

The estimate of the cost to industry is about C$523,000 with the largest single item the makeup fuel for container ships.

Table 10 summarizes the cost per voyage by ship type and cost component and Table 11total cost range.

Table 10 – Estimate of Additional Costs per Ship Transit of 2015 Haro Strait Ships (C$ per Ship)

	Cost Component				
Ship Type	Pilotage	Ship Time	Haro Str. Fuel	Makeup Fuel	Total Cost
Bulk Carrier	$209	$180	-$229	$0	$160
Car Carrier	157	620	-414	0	363
Container	185	0	-1,061	2,296	1,420
General Cargo	233	167	-163	0	236
Passenger	62	0	-709	2,079	1,432
Tanker	313	270	-256	0	327

Source: Consultant estimates.

Table 11 – Range of Costs per Ship

	Cost per Ship (C$)		
Ship Type	Average	Minimum	Maximum
Bulk Carrier	$160	-$166	$2,683
Car Carrier	363	178	453
Container	1,420	210	4,371
General Cargo	236	-42	2,095
Passenger	1432	0	3,526
Tanker	327	-46	3,706

Source: Consultant estimates.

2.3.2.2 Further Investigations

This section examines some of the more important relationships behind the results.

The makeup fuel costs for container ships was examined in more detail because of its large magnitude. Table 12 breaks down the above cost by voyage to and from Vancouver.

- The largest amounts in total are for the voyages between Vancouver and the Puget Sound ports.
  - These constitute about half the calls and about 55% of the cost.
  - The costs per transit are also quite high for these ships.
- The costs for Prince Rupert are too high for the 2017 situation. In 2015, the service called at Seattle as well as Vancouver. In 2017, it does not call at Seattle and seems to steam quite slowly between Prince Rupert and Vancouver. It may have excess time its schedule because of the dropped port.
- A container carrier that links Busan with Vancouver stated that its fuel makeup cost would be about $2,000 for this voyage. The estimate in the table US$1,900.

Table 12 – Breakdown of Container Ship Makeup Fuel Cost by Voyage (C$)

Voyage	Makeup Fuel Cost	Number of Transits	Cost per Transit	Percent of Cost	Percent of Transits
In from Asia	$54,612	29	$1,883	10%	12%
Out to Asia	125,475	67	1,873	22%	27%
Out to California	41,584	15	2,772	7%	6%
In from Prince Rupert	36,847	11	3,350	6%	4%
In from Puget Sound Ports	200,596	85	2,360	35%	34%
Out to Puget Sound Ports	115,007	43	2,675	20%	17%
Total	$574,121	250	$2,296	100%	100%

Source: Consultant estimates.

The bridge watch period of 8 hours is when the pilotage cost starts to increase rapidly. Table 13 depicts this by ship type. The table adds unaffected passenger ships to bring the total to 898 ships. The upper part of the table summarizes costs by ship type and cost category for situations in which bridge watch time is less than 8 hours and the lower in which bridge watch time is greater than 8 hours. It shows, for example, that exempting ships that would exceed 8 hours of bridge time saves the shipping industry about $100,000 or about 20% of total costs; about half of the savings are in pilotage costs and about 75% of the savings are for bulk carriers and general cargo ships.

Table 13 – Additional Costs with Bridge Watch Time Greater Than / Less Than 8 Hours (C$)

Circumstance / Ship Type	Pilotage	Ship Time	Cost of Fuel Consumption: Haro Strait Reduction	Cost of Fuel Consumption: Schedule Makeup	Total Cost	Number of Ships
Bridge Watch < 8 Hours						
Bulk Carrier	$25,885	$67,913	-$86,522		$7,276	377
Car Carrier	12,108	47,758	-31,902		27,964	77
Container	40,080	0	-261,698	567,215	345,597	247
General Cargo	3,758	8,984	-8,708		4,034	54
Passenger	1,670	0	-19,137	56,123	38,656	17
Tanker	2,296	12,623	-11,916		3,003	47
Total < 8 Hours	$85,796	$137,279	-$419,882	$623,338	$426,531	819
Bridge Watch > 8 Hours						
Bulk Carrier	$63,356	$8,928	-$11,192		$61,092	50
Car Carrier	0	0	0	0	0	0
Container	6,054	0	-3,556	6,906	9,404	3
General Cargo	10,438	1,214	-1,265		10,386	7
Passenger	0	0	0	0	0	0
Tanker	15,239	2,488	-2,420		15,307	9
Total > 8 Hours	$95,086	$12,631	-$18,433	$6,906	$96,190	69
Passenger Not Applicable						10
Total Cost	$180,882	$149,909	-$438,315	$630,244	$522,720	898

Source: Consultant estimates.

Table 14 breaks down total ship costs by ship type and the pilotage situation for the Haro Strait Trial. The pilotage situations are:

- No increase in pilotage cost. Because bridge time is stated per hour or part thereof, a small increase in transit time may not change the billable hours of bridge time for a ship slowing down for the Haro Strait transit. In this case, there is no increase in pilotage cost.
- A one-hour increase in pilotage costs. In this case, the Haro Strait slowdown pushes the bridge time up by one hour but total bridge time remains below 8 hours. The 2017 PPA Tariff rate for bridge time is C$208.75.
- Additional time charges for pilotage. In this case, the Haro Strait slowdown pushes bridge time over 8 hours and results in additional time charges, which are considerable. The bridge time for some ships is already over 8 hours and additional bridge time increases bridge time charges by a large multiple.

The vessels with large relative dollar amounts in under “Additional Time” are bulk carriers, general cargo ships and tankers. These are all relatively slow ships and as shown above in Table 2 experience long-duration voyages when transiting Haro Strait.

Table 14 – Additional Costs by Pilotage Status and Ship Type (C$)

Ship Type / Pilotage Cost Situation	Pilotage	Ship Time	Cost of Fuel Consumption: Haro Strait Reduction	Cost of Fuel Consumption: Schedule Makeup	Total Cost	Number of Ships
Bulk Carrier						
No Increase	0	45,993	-58,069		-12,076	256
One Hour Increase	25,885	22,494	-29,224		19,156	124
Additional Time	63,356	8,355	-10,421		61,289	47
Bulk Carrier Total	89,241	76,842	-97,714		68,369	427
Car Carrier						
No Increase	0	11,601	-7,655		3,946	19
One Hour Increase	12,108	36,157	-24,247		24,018	58
Car Carrier Total	12,108	47,758	-31,902		27,964	77
Container						
No Increase	0	0	-55,683	118,422	62,739	55
One Hour Increase	40,080	0	-206,014	448,793	282,858	192
Additional Time	6,054	0	-3,556	6,906	9,404	3
Container Total	46,134	0	-265,254	574,121	355,001	250
General Cargo						
No Increase	0	5,865	-5,687		178	36
One Hour Increase	3,758	3,119	-3,021		3,856	18
Additional Time	10,438	1,214	-1,265		10,386	7
General Cargo Total	14,195	10,198	-9,973		14,420	61
Passenger						
No Increase	0	0	-10,468	30,819	20,351	19
One Hour Increase	1,670	0	-8,669	25,304	18,305	8
Passenger Total	1,670	0	-19,137	56,123	38,656	27
Tanker						
No Increase	0	9,682	-9,064		618	36
One Hour Increase	2,296	2,941	-2,852		2,385	11
Additional Time	15,239	2,488	-2,420		15,307	9
Tanker Total	17,535	15,111	-14,336		18,310	56
Total	$180,882	$149,909	-$438,315	$630,244	$522,720	898

Source: Consultant estimates.

Annex A – Time Costs of Container Ships

Table A1 summarizes built-up time costs of container ships estimated by Ocean Shipping Consultants (OSC) as part of a study for VFPA. While OSC estimated costs for nine ships from 2,000 TEU to 18,000 TEU, the table summarizes costs for three ships that fall in the size range most relevant to Haro Strait in 2015. The vessels have speeds that are comparable to those transiting Haro Strait: 18 kn and 19 kn.

The first cost line is that of the new building price, the capital cost of a ship at the time of the estimates, probably in 2015[14]. From these values, OSC derived the daily capital charges for each ship. The next section of the table deals with daily operating costs broken down into in four categories and adds capital charges and operating costs to generate an estimate of the time-charter equivalent cost.

The other major daily cost is ship fuel at sea and in port. The cost in port is that of the ship's auxiliary engines alone (these generate electricity for ship use), which burn marine diesel oil, while the cost at sea adds in the consumption of fuel by the ship's main engines, which are used for propulsion. The total daily cost is the sum of fuel and time-charter equivalent costs. The fuel costs used in this table are for the standard ship fuels used at sea: main engine intermediate fuel oil (IFO380) and marine diesel oil. These are not the low-sulphur fuels required in the North America emission control area (ECA) used where appropriate in this study.

[14] The report is dated 2016 but initial drafts were issued in late 2015.

Table A1 – Estimates of Deep-Sea Containership Ownership and Operating Costs

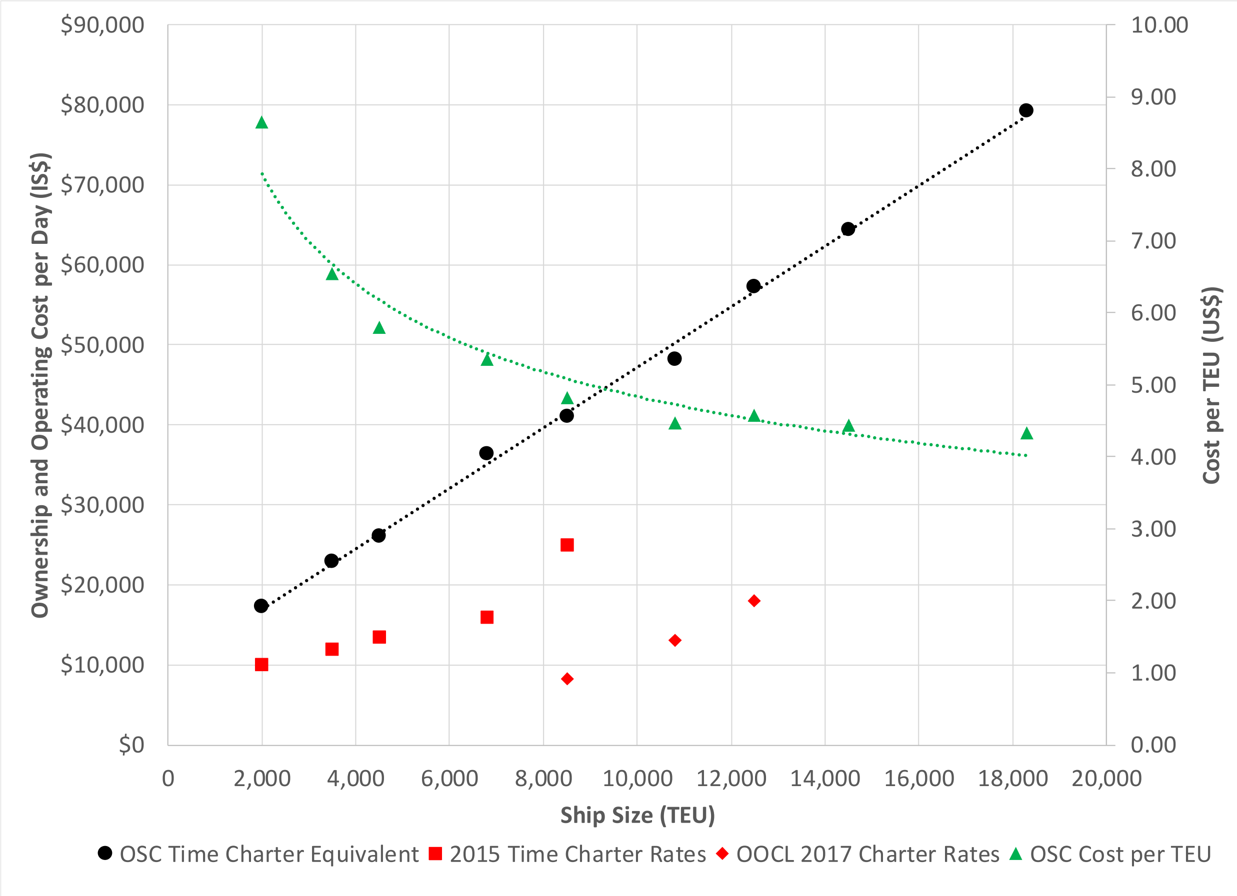
Capacity (TEU)	3,500	8,500	12,500
Speed (knots)	18	19	19
Newbuild Price (US$ m)	$38.0	$76.5	$114.0
Daily Ship Costs (US$/Day)			
Capital Charges	$15,666	$31,539	$46,999
Operating Costs			
Manning	$3,650	$3,650	$3,650
Repair & Maintenance	1,568	2,903	3,220
Insurance	936	1,733	2,133
Admin/Other Charges	1,100	1,200	1,300
Total	$7,254	$9,486	$10,303
Time-Charter Equivalent Costs	$22,920	$41,025	$57,302
Fuel Costs			
At Sea	$19,105	$36,190	$49,695
In Port	1,680	1,680	1,920
Total Costs			
At Sea	$42,025	$77,215	$106,997
In Port	24,600	42,705	59,222

Source: Ocean Shipping Consultants, "Container Traffic Forecast Study – Port of Vancouver, 2016," report prepared for Vancouver Fraser Port Authority, 2016.

Figure A1 presents the full range of the OSC cost estimates for ships ranging from 2,000 TEU to 18,000 TEU. It also includes some time charter rates for smaller ships in 2015 and 2017. These are considerably below the time-charter equivalent costs because they vary with market conditions and there has generally been an oversupply of container ships in recent years. The recent charters by Orient Overseas Container Line (OOCL) were at rates about 1/3 of the OSC estimates.

The chart also plots the time-charter equivalent costs per TEU which provides an indication the economies of scale in large container ships. These generally follow a declining power curve (shown). In this case, the curve flattens around 12,000 TEU which indicates larger ships have limited economies of scale.

Figure A1 – Time-Charter Equivalent Costs



Sources: time-charter equivalent costs, OSC, op cit.; time-charter rates, Alphaliner, 2015 and 2017.

Annex B – Estimation of Models of Ship Fuel Consumption at Design Speed

Bulk Carriers

Bulk carriers and general cargo ships (the Pilots' definitions)[15] were treated as one class for the evaluation and Fairplay register data was used for estimates of fuel consumption for bulk carriers. The Fairplay register had about 890 records of fuel consumption for bulk carriers. Regarding the Fairplay records and Haro Strait bulk carriers:

- The average service speeds were similar at about 14.5 kn. Minimum service speeds were 11.0 kn in the register and 13.0 kn for the Haro Strait ships, and maximum speeds were 16.3 kn (register) and 17.0 kn (Haro).

[15] The dataset from PPA included the PPA definition of ship type. Some of the vessels that the pilots classified as "general cargo" ships were called "bulk carriers" in registers. These were typically smaller ships that had cargo-handling gear, many of them OHBCs, but generically were bulk carriers. All ships PPA defined as bulk carriers or general cargo ships were treated as bulk carriers for the estimates of fuel consumption.

- The Haro Strait ships were relatively new with almost 60% built since 2010. Only 13% of the Fairplay register fleet was built since 2010.
- The ships in both cases were dominantly simple bulk carriers with small percentages of OHBCs and self-discharging bulk carriers, both of which have conventional bulk carrier hulls. About 5% of the Haro Strait vessels were general cargo ships.
- Several ships classified as “general cargo” by the pilots were classified as bulk carriers in the register. These were often OHBCs.
- The average bulk carrier size was about 65,000 DWT in both cases. The smallest ships were 7,000 DWT in the Fairplay records versus 11,000 DWT for the Haro Strait ships and in both cases the largest ship was about 210,000 DWT.

The model fitted to the Fairplay data of 890 records was:

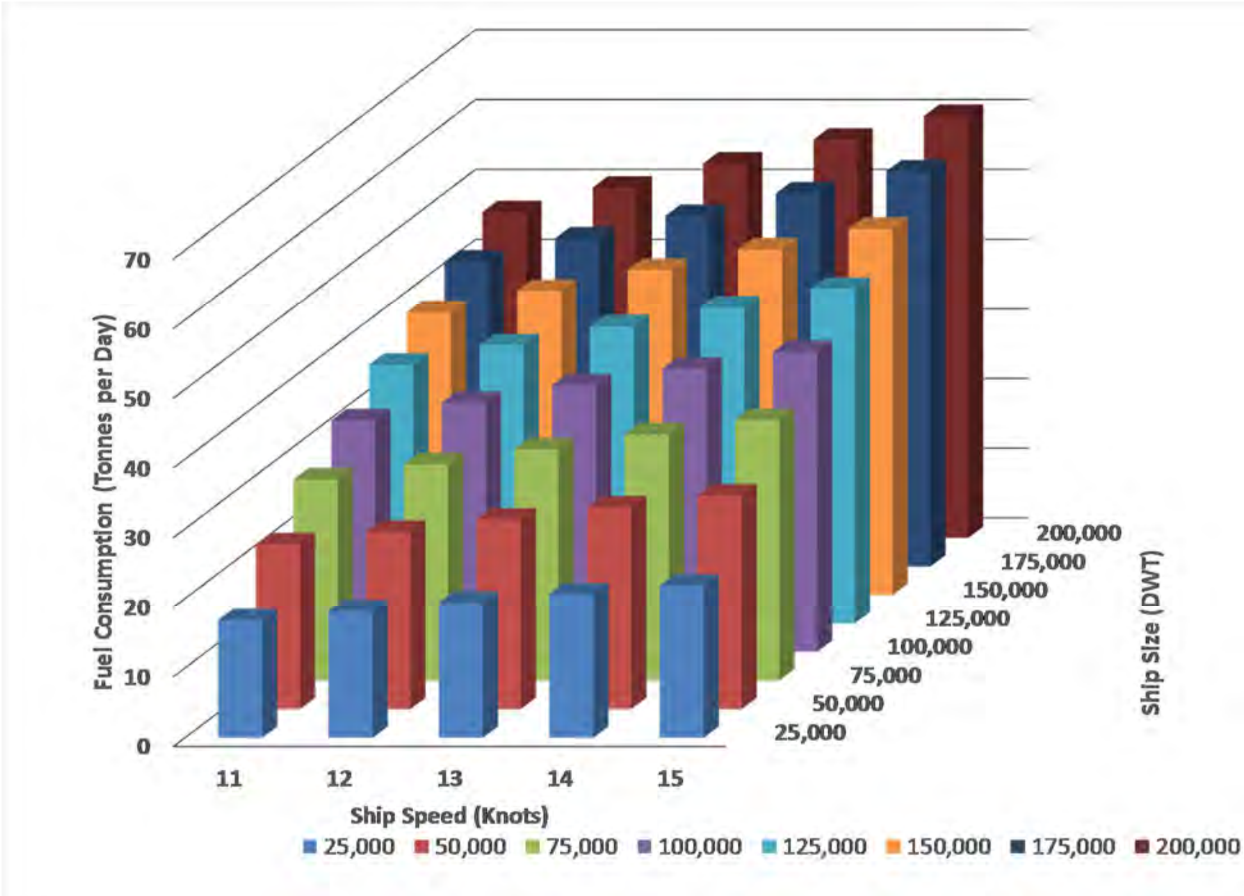
$$\text{Fuel consumption} = 0.0161(\text{ship size})^{0.4896}(\text{speed})^{0.8322}$$

Where ship size was in DWT and speed was in knots. Deadweight tonnage is the standard measure of size for bulk carriers and general cargo ships.

The model based on Fairplay records replicated the fuel consumption of the Fairplay ships quite well, with an average deviation of about 1%. Figure B1 depicts the relationship between fuel consumption and ship size and speed of the fitted model within the range of the register records.

This fuel consumption model was applied to bulk carriers and general cargo ships from the Aug-Oct 2015 pilot dataset.

Figure B1 – Fuel Consumption versus Ship Size and Speed for Bulk Carriers



Source: Estimated from data in Fairplay register, 2017.

Car Carriers

The Fairplay register had about 110 records of fuel consumption for car carriers.

Regarding the Fairplay records and Haro Strait car carriers:

- The average service speeds were 19.5 kn in both cases. Minimum service speeds were 12.5 kn in the register and 18.0 kn for the Haro ships, and maximum speeds were 24.0 kn (register) and 22.8 kn (Haro).
- The average built year was 2001 (register) and 2003 (Haro ships).
- The average car carrier size was about 17,000 DWT in both cases. The smallest ships were 2,400 DWT in the Fairplay records versus 12,000 DWT for the Haro Strait ships and the largest ships were about 50,000 DWT (register) and 26,000 DWT (Haro).

The model fitted to the Fairplay data of 110 records was:

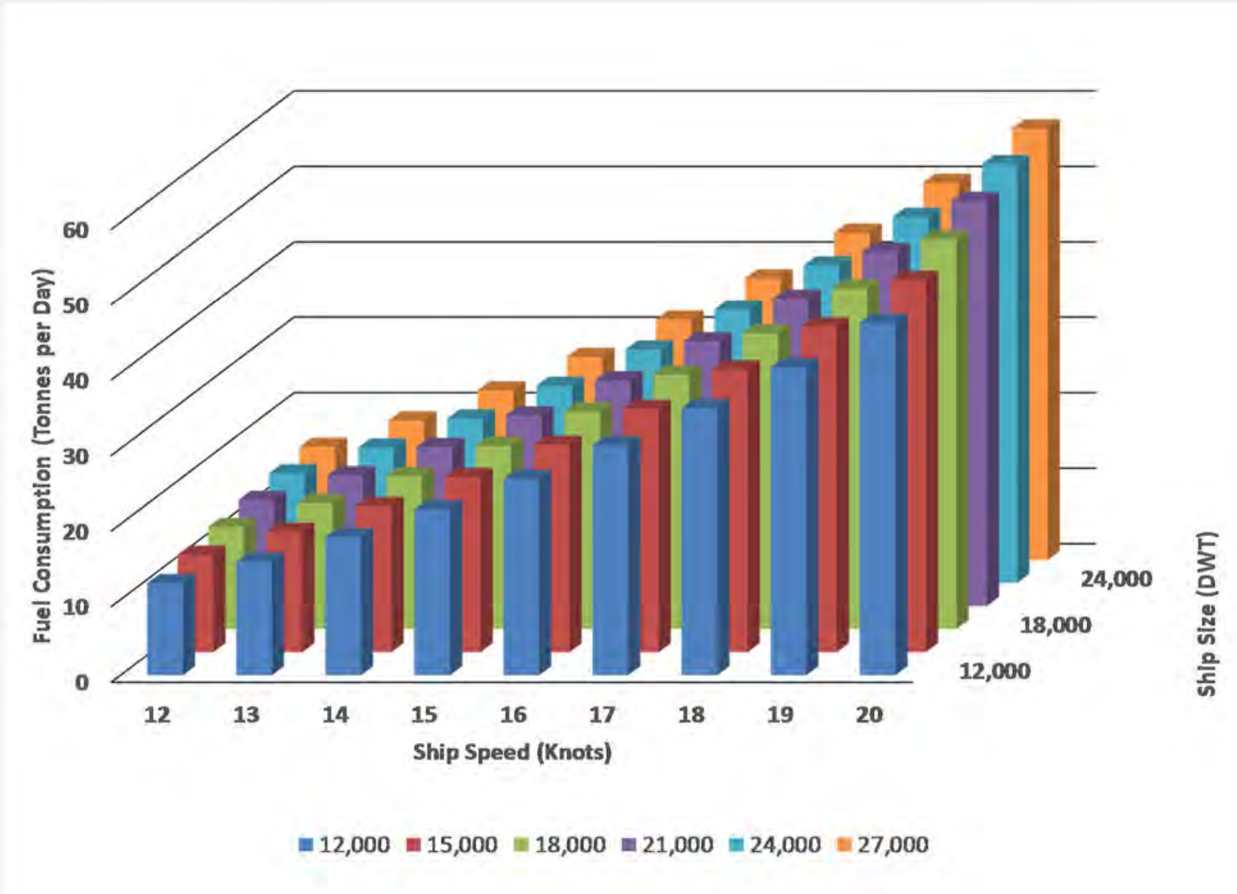
Fuel consumption = $0.00169(\text{ship size})^{0.251}(\text{speed})^{2.624}$

Where ship size was in DWT and speed was in knots. DWT as a measure of ship size was as good as or better than the available options (GRT, overall length, etc.) and only a few records of car capacity were available.

The model replicated the fuel consumption of the Fairplay ships moderately well, with an average deviation of about 2%. Figure 2B depicts the relationship between fuel consumption and ship size and speed within the range of the register records.

This fuel consumption model was applied to car carriers from the Aug-Oct 2015 pilot dataset.

Figure B2 – Fuel Consumption versus Ship Size and Speed for Car Carriers



Source: Estimated from data in Fairplay register, 2017.

Container Ships

Because of the limited fuel consumption data in the Fairplay register, Clarkson's 2011 container ship register was chosen. A build-year range of 2000 to 2010 (about 1,350 records), which covered about 85% of the container ships that transited Haro Strait in August – October 2015, was used for the model. The Clarkson data extended to a maximum ship size of 14,000 TEU, and 3,000 TEU was chosen as the lower limit although there were a few ship Haro Strait transits of about 2,000 TEU.

Regarding the Clarkson records and Haro Strait container ships:

- The average service speeds were 24.6 kn in both cases. Minimum service speeds were 12.5 kn in the register and 15.5 kn for the Haro ships, and maximum speeds were 29.3 kn (register) and 27.5 kn (Haro).
- The average build year was 2006 (register) and 2005 (Haro Strait ships).

- The average ship size was about 6,000 TEU in both cases. The smallest ships were 3,020 DWT in the Clarkson records versus 2,100 TEU for the Haro Strait ships and the largest ships were about 14,000 TEU (register) and 11,356 TEU (Haro).

The Clarkson register data ended before the first of the fuel-efficient ships were ordered, the 18,000 TEU Maersk Line "EEE" ships in early 2011. The 2010 limit of the Clarkson database means that it does not pick up the larger and more fuel efficient modern ships delivered after 2010 but few if any such ships were among the Haro Strait container ships. The largest Haro Strait container ships of 11,356 TEU (built in 2010 and 2011) were well within the upper limit of the Clarkson data and built before the move to greater fuel efficiency. In experiments with alternative evaluation periods, the 3,000 TEU / Year 2000 cut-off provided equivalent or better results than the others, such as a 2,000 TEU / Year 1996 cut-off.

The model fitted to the Clarkson data of 1,350 records was:

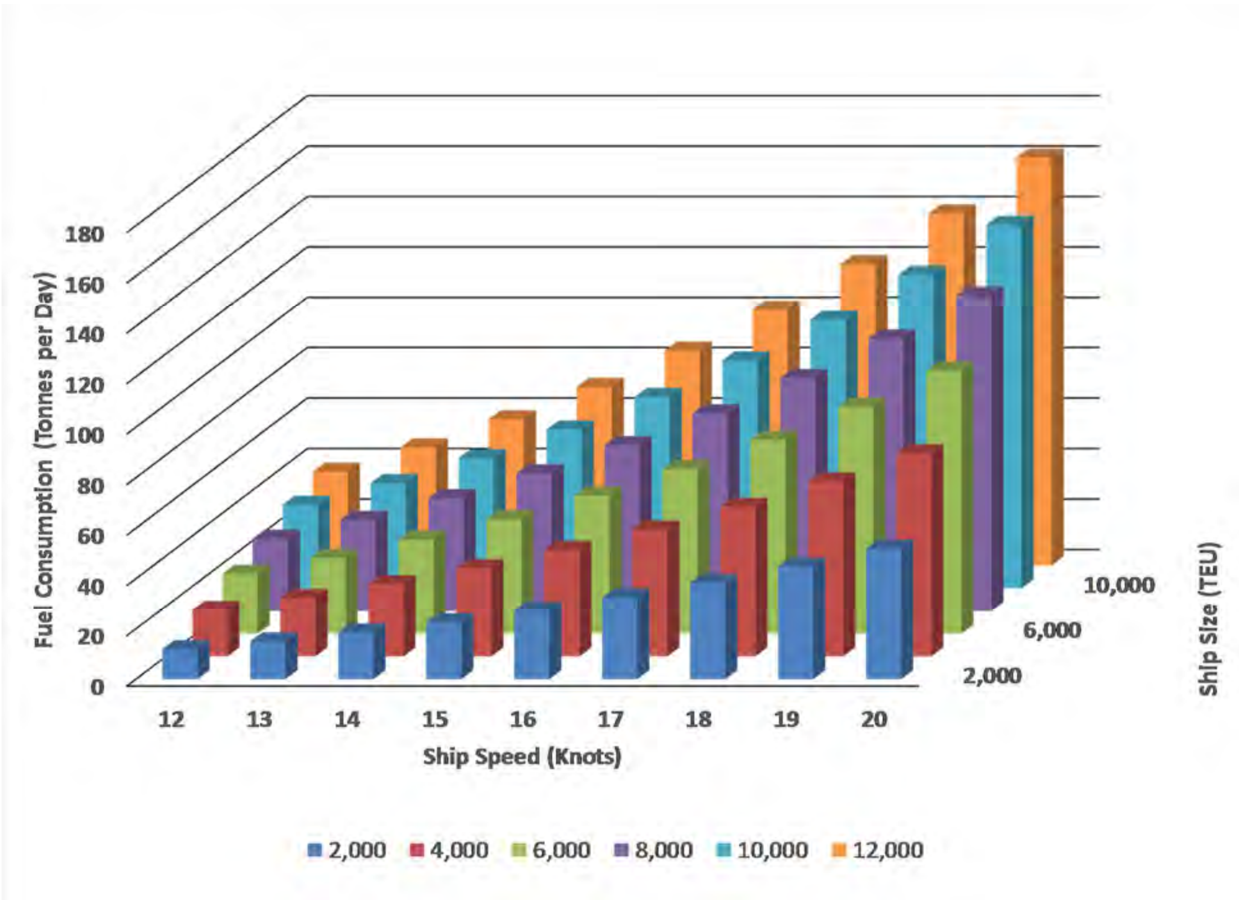
Fuel consumption = $0.000074(\text{ship size})^{0.6351}(\text{speed})^{2.883}$

The model replicated the fuel consumption of the Clarkson ships well, with an average deviation of about 0.5%.

Figure B3 shows the resulting relationship between ship size and speed with the 3,000 TEU / Year 2000 data within the range of the register records. The speed ranges from 12 kn to take in the lower speeds in the Clarkson register to a maximum of 20 knots, and from ship sizes of 2,000 TEU to 12,000 TEU.

This fuel consumption model was applied to container ships from the Aug-Oct 2015 pilot dataset.

Figure B3 – Fuel Consumption versus Ship Size and Speed for Container Ships



Source: Estimated from data in Clarkson Container Fleet CD, 2011.

Passenger (Cruise) Ships

After tailoring to represent the ranges of the Haro Straits passenger (cruise) ships, the Fairplay register provided only 23 records of fuel consumption for passenger ships. Regarding the Fairplay records and Haro Strait passenger ships:

- The average service speeds were similar at about 21 knots. Minimum service speeds were 17 kn in the register and 16 kn for the Haro ships, and maximum speeds were 25 kn in both cases.
- The Haro Strait ships were newer with about 80% built since 2000 versus only 30% in the Fairplay register. The average built year was 1998 (register) and 2004 (Haro ships).
- The average passenger ship size was about 70,000 GRT (2,200 passengers) in the Fairplay records and about 80,000 GRT (2,400 passengers) for the Haro Strait ships.

The model fitted to the Fairplay data of 23 records was:

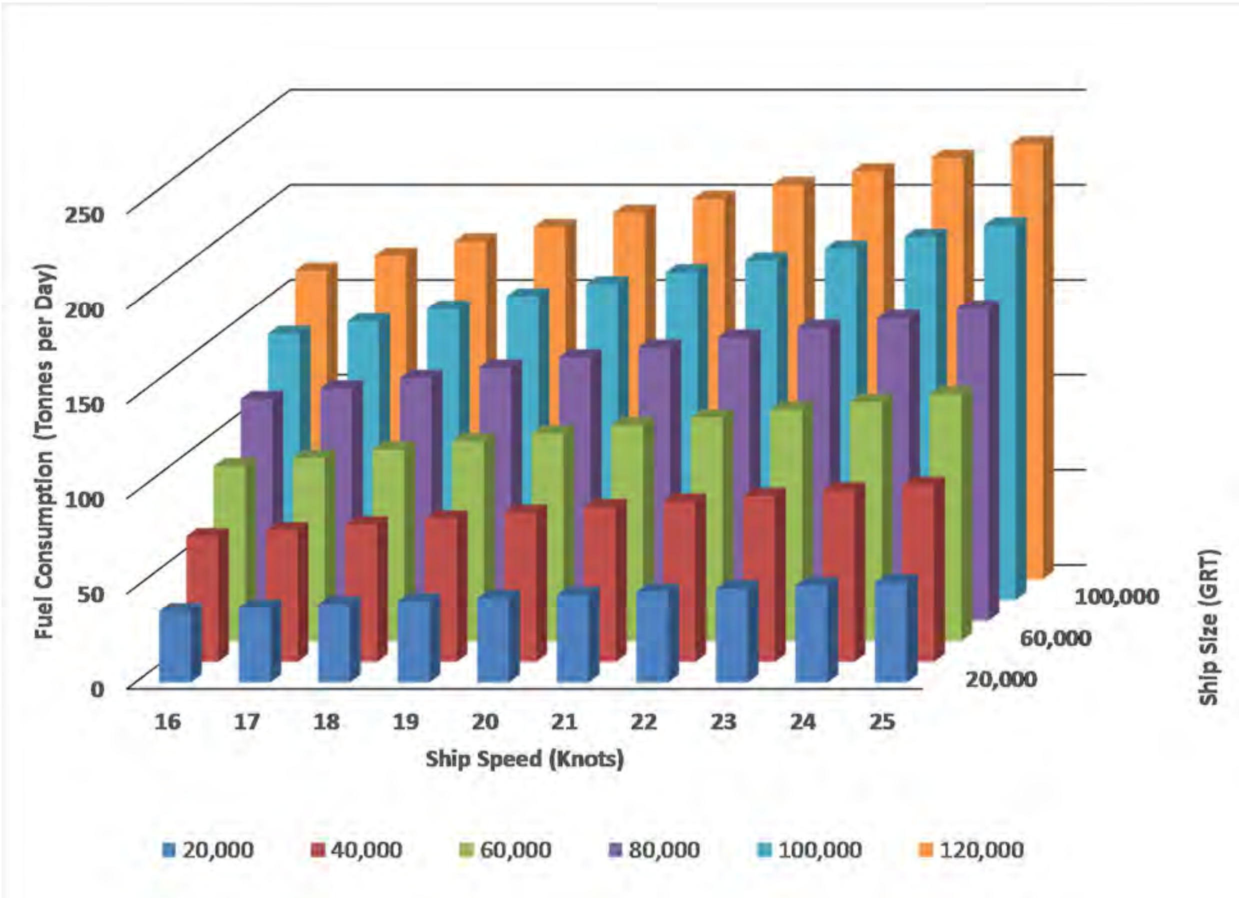
Fuel consumption = 0.001319 (ship size) $^{0.820}$ (speed) $^{0.76864}$

Where ship size was in GRT and speed was in knots.

The model replicated the fuel consumption of the Fairplay ships only moderately well, with an average deviation of about 3%. Figure B4 depicts the relationship between fuel consumption and ship size and speed within the range of the register records.

This fuel consumption model was applied to cruise ships from the Aug-Oct 2015 pilot dataset.

Figure B4 – Fuel Consumption versus Ship Size and Speed for Passenger Ships



Source: Estimated from data in Fairplay register, 2017.

Tankers

After cutting down to represent the ranges of the Haro Straits tankers, the Fairplay register had about 470 records of fuel consumption. The ship size range was up to 80,000 DWT to take in the few Panamax tankers (old definition, primarily 32.3 m beam) in the Haro Strait dataset.

Regarding the Fairplay records and Haro Strait tankers:

- The average service speeds were similar at about 14.5 knots. Minimum service speeds were 10.6 kn in the register and 13.5 kn for the Haro Strait ships, and maximum speeds were 16.2 kn (register) and 15.5 kn (Haro).
- The Haro Strait ships were newer with almost 25% built since 2010 versus only 2% in the Fairplay register. The average build year was 2003 (register) and 2008 (Haro ships).

- The average tanker size was about 40,000 DWT in the Fairplay records and about 35,000 DWT for the Haro Strait ships.

The model fitted to the Fairplay data of 470 records was:

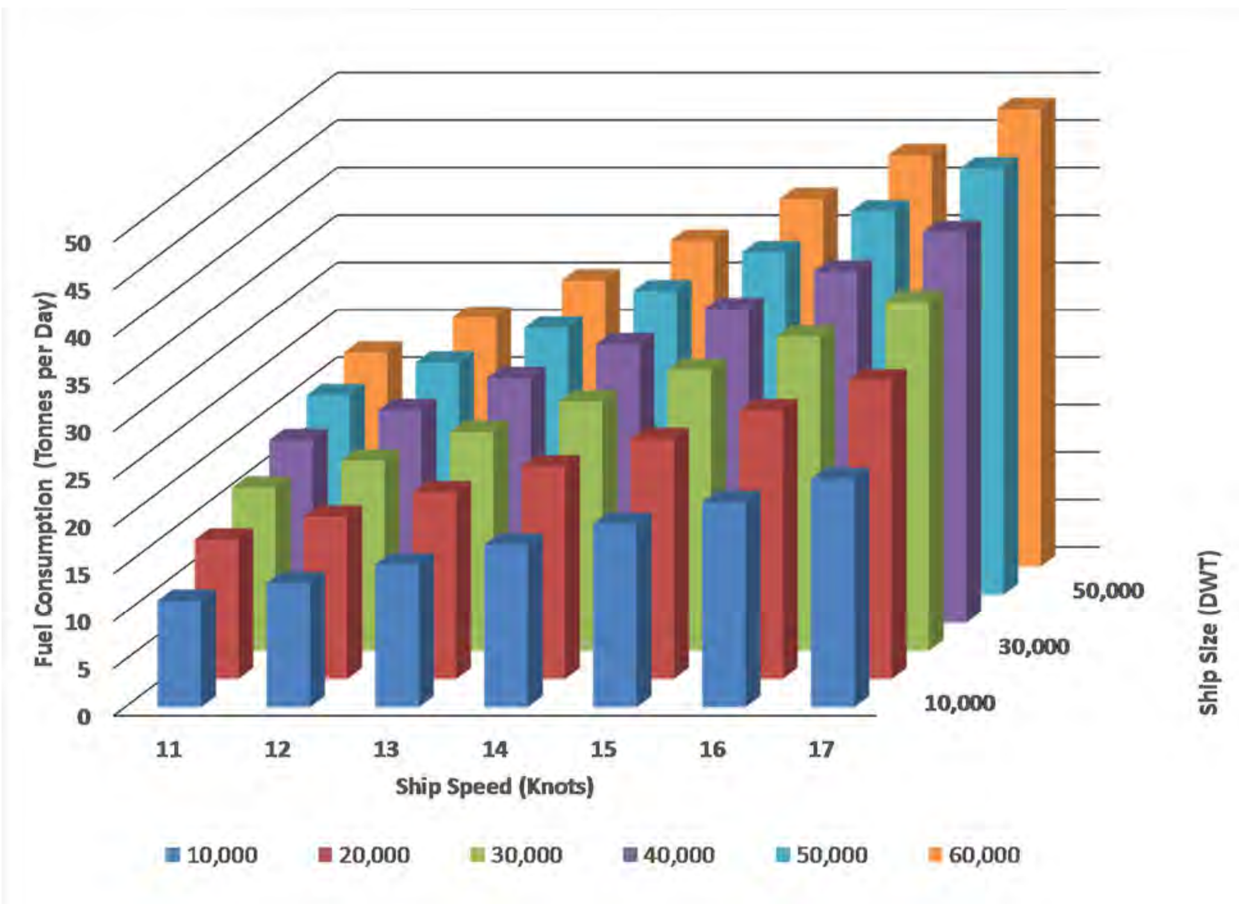
Fuel consumption = 0.004812(ship size) $^{0.3878}$ (speed) $^{1.7455}$

Where ship size was in DWT and speed was in knots. DWT is one standard measure of ship size for tankers.

The model replicated the fuel consumption of the Fairplay ships quite well, with an average deviation of about 1%. Figure B5 depicts the relationship between fuel consumption and ship size and speed within the range of the register records.

This fuel consumption model was applied to tankers from the Aug-Oct 2015 pilot dataset.

Figure B5 – Fuel Consumption versus Ship Size and Speed for Tankers



Source: Estimated from data in Fairplay register, 2017.

Annex C – Ship Fuel Consumption versus Speed

A general fuel consumption model was needed to extend the estimates of fuel consumptions at design speeds down to those of typical service speeds today, to 11 knots in Haro Strait and for cruise and container ship voyages involving schedule maintenance.

The norm in the shipping industry is to apply a cubic power relationship for fuel consumption as a function of ship speed: if the speed of a ship doubles, fuel consumption increases eightfold[16]. A review of the evidence for the variability of fuel consumption with ship speed was performed. First, information from the study of marine fuel supply and demand cited above was extracted, from which estimates of the power exponents for these ships were developed. [17]

Table C1 lists the design speeds for several types and sizes of ships and estimates of their average speeds in 2007, 2012 and 2016 (the years of relevance to the study authors) and the fuel consumptions at these speeds. Both fuel prices and the shipping market conditions prevailing in the year influenced speeds. Although 2007 was the year in which signs of the global financial crisis first appeared, fuel prices were high and shipping markets were strong. By 2012, fuel prices were again high but the crisis was lingering and shipping markets were weak. In 2016 fuel prices were relatively low although shipping markets were not robust.

To use the example of 8,000 – 12,000 TEU container ships in the table:

- The design speed of these ships was 25.5 knots.

  Fuel consumption at this speed was not stated in the report; the average consumption from the 2011 Clarkson register for ships in this size range was about 250 tonnes per day at an average design speed of 25.0 kn.

Main engine fuel consumption was estimated at:

- 200 t/d at 21.3 kn in 2007
- 95.6 t/d at 16.3 kn in 2012, and
- 124.8 t/d at 18.5 kn in 2016.

Estimates of the power exponents (X) for these ships used the following equations:

$\text{Fuel 2} = (\text{Fuel 1}) * (\text{Speed 2} / \text{Speed 1})^{X}$

$\text{Ln}(\text{Fuel 2}) = \text{Ln}(\text{Fuel 1}) + X * \text{Ln}(\text{Speed 2} / \text{Speed 1})$

$X = (\text{Ln}[\text{Fuel 2}] - \text{Ln}[\text{Fuel 1}]) / \text{Ln}(\text{Speed 2} / \text{Speed 1})$

The results are in Table C2. The resulting exponents (X) are typically between 3.25 and 3.50. The exception is bulk carriers over 200,000 DWT; in this case, the power exponent was 1.6. This supports the information in the literature that fuel consumption generally varies with the third power of speed.

[16] Citations include: Martin Stopford, *Maritime Economics*, 2009, which quotes and applies the cube power rule; The INTERTANKO, Optimum speed calculator, 29 June 2012 states that "The bunker consumption is varying as a function of the speed with an exponent of power of 3…".
[17] EnSys Energy with Navigistics Consulting, op. cit.

Table C1 – Average Vessel Speeds and Fuel Consumptions at Sea: Design and Actual 2007, 2012 and 2016 (Knots)

	Ship Size Range			*Design*	Average Sea Speed (Knots)			Fuel Consumption in Year (t/d)		
Ship Type	Lower	Upper	Size Units	Speed	2007	2012	2016	2007	2012	2016
Bulk Carrier	60,000	99,999	dwt	15.3	13.0	11.9	11.7	37.7	28.8	27.2
Bulk Carrier	100,000	199,999	dwt	15.3	12.8	11.7	11.6	55.5	42.3	41.1
Bulk Carrier	200,000		dwt	15.7	11.5	12.2	11.9	51.2	56.3	54.1
Container	3,000	4,999	TEU	24.1	18.6	16.1	16.4	90.4	58.7	62.5
Container	5,000	7,999	TEU	25.1	20.6	16.3	17.5	151.7	79.3	99.5
Container	8,000	11,999	TEU	25.5	21.3	16.3	17.7	200.0	95.6	124.8
Container	12,000	14,499	TEU	28.9	20.6	16.1	18.5	231.7	107.8	173.9
Container	14,500		TEU	25		14.8	19.7		100.0	183.2
Oil Tanker	80,000	119,999	dwt	15.3	13.3	11.6	12.7	49.2	31.5	43.0
Oil Tanker	120,000	199,999	dwt	16	13.7	11.7	12.9	65.4	39.4	55.0
Oil Tanker	200,000		dwt	16	14.6	12.5	12.8	103.2	65.2	70.6

Source: EnSys Energy with Navigistics Consulting, “Supplemental Marine Fuel Availability Study,” MARPOL Annex VI Global Sulphur Cap 2020 Supply-Demand Assessment, July 15, 2016, Figures 3.6 and 3.9.

Table C2 – Estimate of Exponents for Vessel Speed versus Fuel Consumption

	Ship Size Range			*2012 v 2007*				*2016 v 2012*			
Ship Type	Lower	Upper	Size Units	Ln Fuel 2	Ln Fuel 1	Ln(S2/S1)	X	Ln Fuel 2	Ln Fuel 1	Ln(S2/S1)	X
Bulk Carrier	60,000	99,999	dwt	3.36	3.63	-0.09	3.05	3.30	3.36	-0.02	3.37
Bulk Carrier	100,000	199,999	dwt	3.74	4.02	-0.09	3.02	3.72	3.74	-0.01	3.35
Bulk Carrier	200,000		dwt	4.03	3.94	0.06	1.61	3.99	4.03	-0.02	1.60
Container	3,000	4,999	TEU	4.07	4.50	-0.14	2.99	4.14	4.07	0.02	3.40
Container	5,000	7,999	TEU	4.37	5.02	-0.23	2.77	4.60	4.37	0.07	3.19
Container	8,000	11,999	TEU	4.56	5.30	-0.27	2.76	4.83	4.56	0.08	3.23
Container	12,000	14,499	TEU	4.68	5.45	-0.25	3.10	5.16	4.68	0.14	3.44
Container	14,500		TEU					5.21	4.61	0.29	2.12
Oil Tanker	80,000	119,999	dwt	3.45	3.90	-0.14	3.26	3.76	3.45	0.09	3.44
Oil Tanker	120,000	199,999	dwt	3.67	4.18	-0.16	3.21	4.01	3.67	0.10	3.42
Oil Tanker	200,000		dwt	4.18	4.64	-0.16	2.96	4.26	4.18	0.02	3.36

Source: Calculated from data in Table C1.

A somewhat more complicated and complete approach was chosen to calculate differences in ship fuel consumption with speed by incorporating the hydrodynamic properties of a ship into the estimates. This still does not address factors such as engine design and efficiency, hull form and condition, and propeller type and design. These are some of the factors to be considered when retrofitting a ship for permanently-lower speeds and fuel consumptions[18].

The approach selected to estimate variation in ship fuel consumption with speed uses the Froude number (Fn) as a hydrodynamic measure, calculated as: (vessel speed in m/s) / ([vessel length in m]) * $9.81^{)\,0.5}$

Where 9.81 is a gravitational coefficient and vessel length is LOA.

Fuel Indexes are then calculated for speeds under study from the Froude number with the following formula:

Fuel Index = - 0.0664 + 2.4325 * Fn – 24.4453 * Fn^2 + 145.1438 * Fn^3

And finally fuel consumptions are calculated in proportion to the ratios of the Fuel Index applied to the original fuel consumption.

The article cited above and in the footnote below includes an example of reduction in the speed of at 332.6 m LOA VLCC from 15.6 knots design speed to 10 knots and fuel consumption from a design 97.1 t/d to 30.2 t/d. The resulting power exponent for this ship was about 2.6.

This approach was adopted for the study:

- Calculate the Froude number for each vessel and speed.
- Calculate the Fuel Index for each vessel and speed.
- Estimate the variation in fuel consumption for a ship operating at two speeds as the ratio of the Fuel Indexes.

[18] This was adapted from St. D. Amand., “Optimal Economic Speed and the Impact on Marine GHG Emissions,” *Society of Naval Architects and Marine Engineers (SNAME) Transactions,* 2012.

Appendix D

Vessel noise modelling report - JASCO Applied Sciences

Modelling of Cumulative Vessel Noise for Haro Strait Slowdown Trial

Final Report

Submitted to:

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Vancouver Fraser Port Authority
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Contract: 17-0070

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Disclaimer:

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

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1. Introduction

The Vancouver Fraser Port Authority's Enhancing Cetacean Habitat and Observation (ECHO) Program carried out a voluntary vessel slowdown trial in Haro Strait to investigate whether reducing vessel speeds is a viable method for decreasing noise in sensitive Southern Resident Killer Whale (SRKW) habitat. The slowdown trial introduced a voluntary speed limit of 11 knots (speed through water) in Haro Strait from 7 Aug. to 6 Oct., 2017. The aim of the slowdown trial, which was focused primarily at commercial vessels but encouraged for all types of water craft, was to reduce noise exposures in this area where SRKW density is highest during summer. Noise emitted from vessels is usually lower at reduced transit speeds, due to decreases in propeller cavitation and machinery vibration. Thus, implementing a speed limit for commercial vessels in Haro Strait may be an effective means to improve acoustic habitat conditions for SRKW in the region.

ECHO has engaged JASCO Applied Sciences (JASCO) to carry out cumulative vessel noise simulations for Haro Strait as part of a project to model potential changes in SRKW behavioural responses resulting from the implementation of voluntary slowdowns. The acoustic modelling uses an approach similar to the ones applied previously for the Roberts Bank Terminal 2 (RBT2) Environmental Impact Statement (EIS) (MacGillivray et al. 2014a) and ECHO Regional Ocean Noise Contributors Analysis (MacGillivray et al. 2016a). Time-snapshots of underwater noise levels are simulated, based on historical ship movement data, using JASCO's cumulative vessel noise model. The outputs of the noise simulation are then input to SMRU's behavioural response model for estimating behavioural effects on SRKW in critical habitat areas. Simulated noise exposures are used to compare potential behavioural disturbances and lost foraging opportunities for SRKW under baseline and slowdown conditions. The area covered by the acoustic model includes the slowdown area in Haro Strait plus a buffer region to capture noise from vessel traffic outside the slowdown zone (Figure 1).

During the 2017 slowdown trial, JASCO had collected source level measurements with three underwater listening stations situated next to the traffic lanes in Haro Strait and Georgia Strait. The trial measurements had shown that slowdowns were indeed an effective means of reducing underwater noise emissions from cargo vessels (MacGillivray and Li 2018). By comparing measurements of participating vessels during the trial with measurements of vessels before and after the trial as controls, statistically-significant scaling laws of source levels versus speed had been calculated for various vessel categories. Results from the source level measurement study were used in this modelling study to simulate the effect of slowdowns on noise emissions of vessel traffic in Haro Strait.

Two phases of acoustic modelling are presented in this report:

- Phase 1: Six pre-trial scenarios were modeled before the slowdown trial, using best-available estimates of voluntary slowdown participation rates and the effectiveness of speed reductions at reducing underwater radiated noise from the vessels.
- Phase 2: Eight post-trail scenarios were modeled after the slowdown trial, using actual participation-rate and noise-reduction data collected during the trial. These included two scenarios that modelled future projected traffic conditions for the study area.

This noise modelling study differs from past studies carried out for the RBT2 EIS and the ECHO program in the following ways:

- This study incorporates 1.5 years of vessel source level data collected with the Strait of Georgia Underwater Listening Station (ULS), whereas the source levels from previous studies carried out for RBT2 and ECHO were based primarily on data collected at Lime Kiln by The Whale Museum and Beam Reach (TWMBR) (Hemmera Envirochem Inc. et al. 2014).
- The noise simulations for this study, and the previous ECHO work, are based on Automated Information System (AIS) vessel tracking data from MarineTraffic (MT) collected in July 2015, whereas the noise modelling for T2 used vessel tracking data from the Vessel Traffic Operational Support System (VTOSS).

Both the ULS and MT datasets offer improved coverage and data quality compared to the older TWMBR and VTOSS datasets.

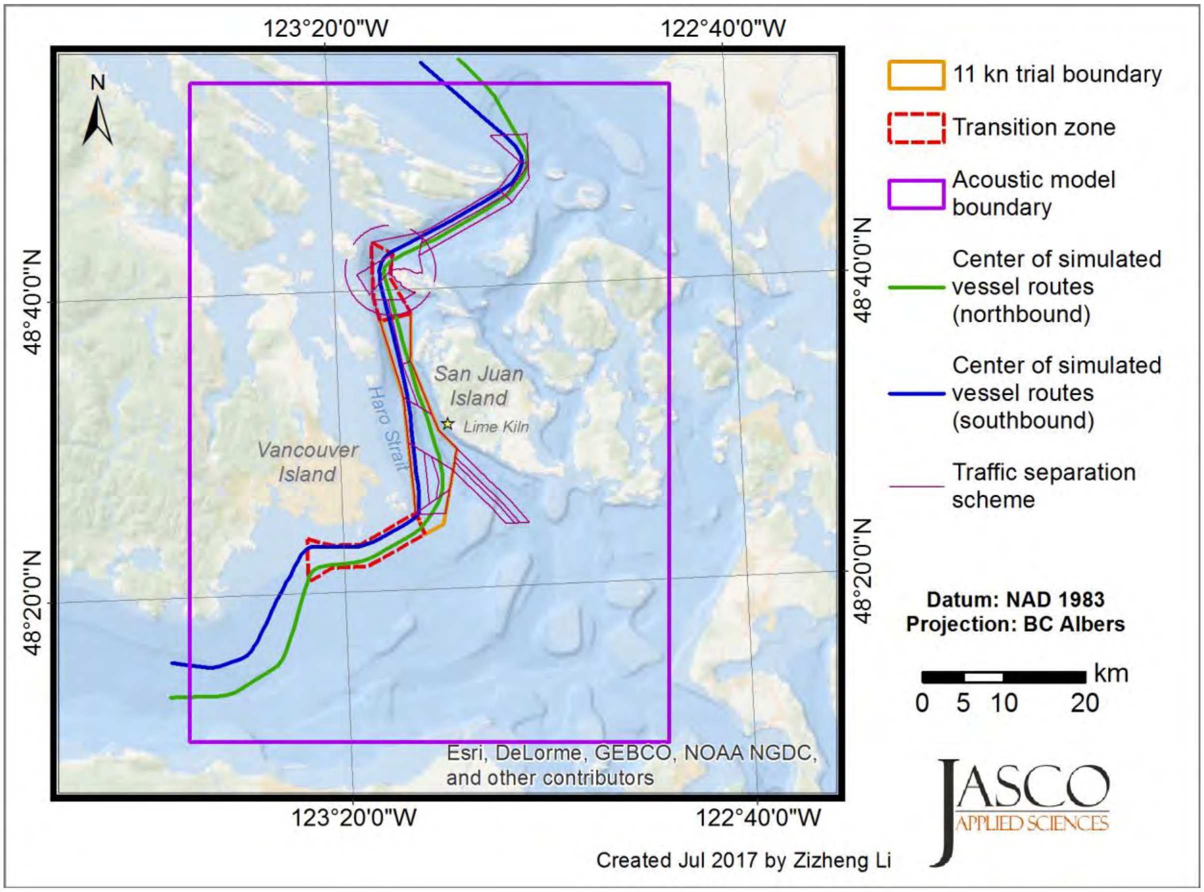

Figure 1. Map of modelling study boundary (purple) including slowdown zone. Vessels are assumed to reduce their speed to 11 knots inside the trial boundary (orange). The centers of the inbound and outbound routes, used for modelling piloted vessel routes in Haro Strait, were extracted from 2015 AIS merchant vessel density data. Historical vessel tracks were found to be approximately normally distributed along the inbound and outbound routes.

2. Modelling Methods

2.1. Model Description

JASCO's cumulative vessel noise model can simulate underwater sound levels generated by large ensembles of vessels on a regional scale. The model combines information from several sources—including vessel tracking data, noise emission data, and environmental data—to predict marine environmental noise from ship traffic (Figure 2). Vessel sound emissions are determined by referencing a database of source levels (according to vessel type and speed). The transmission of sound from each vessel is determined according to a database of pre-computed transmission loss curves for the study area. When run in time-lapse mode, the model generates sequences of 2-dimensional maps, or "snapshots", of the dynamic sound field, yielding sound pressure level (SPL) as function of easting, northing, frequency, and time.

The model represents the region of interest on a computational grid (easting and northing) where each grid cell is 200 m × 200 m. The steps in the model calculation are as follows:

1. For each 1-minute time step, the model computes the location of each vessel and assigns it to the appropriate grid cell.
2. The noise emitted by each vessel is calculated according to its category-specific source level and speed (Section 3.2).
3. The propagation of vessel noise to surrounding grid cells is calculated from sound transmission curves, which are based on water depth, water column properties, and the seabed composition (Section 3.3).
4. The noise contributions from all vessels are summed together to calculate the cumulative noise in each grid cell.
5. The contribution of wind-driven ambient noise, derived from the time-dependent wind speed (Section 3.4), is added to the computational grid.
6. A map of 1/3-octave-band cumulative SPL is generated for the current time step; the model then advances to the next time step (calculation step 1) until finished.

All model calculations are frequency-dependent. For this study, the modelled frequency range covered the hearing range of most marine mammals present in the study area (9 Hz to 78,000 Hz). More details about the development of the cumulative vessel noise model are provided in Section 2.1 of MacGillivray et al. (2014b).

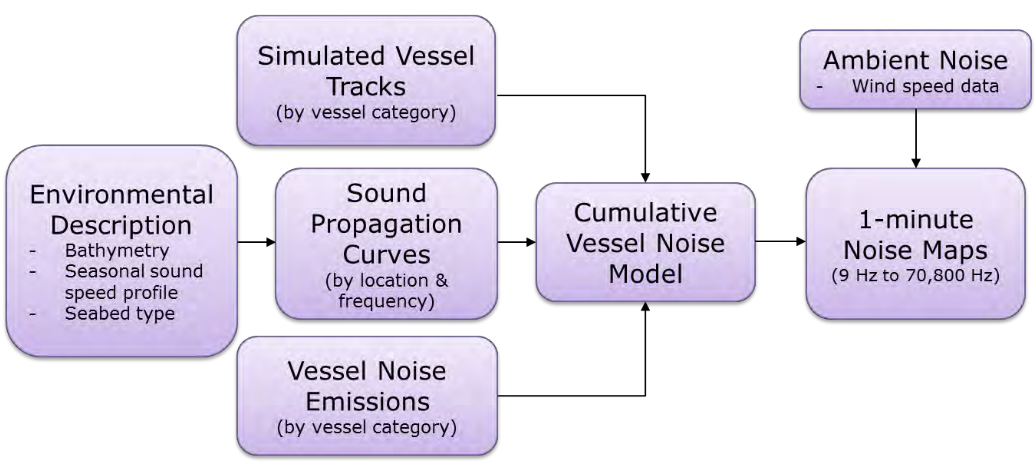

Figure 2. High-level flow chart showing inputs and outputs of the cumulative vessel noise model (time-lapse mode).

2.2. Model Scenarios

This study simulated vessel noise in Haro Strait during a single day (24 hours) in July. Baseline vessel traffic was based on historical AIS data for the study area. Fourteen model scenarios were used to simulate different vessel traffic and slowdown conditions, including six pre-trial scenarios for Phase 1 (scenarios S1-S6) and eight post-trail scenarios for Phase 2 (scenarios S7-S14) (Table 1). For scenarios S1-S8 and S13-S14, which were intended to represent present-day traffic conditions (as of 2017), the number of piloted vessel transits through Haro Strait was based on daily vessel counts provided by the Pacific Pilotage Authority (PPA) (Dominic Tollit, SMRU pers. comm., 3 Apr 2017). For scenarios S9 and S10, which were intended to represent trial conditions, the same number of ship transits was used as for scenarios S1-S8 and S13-S14 because the number of piloted vessel transits recorded during the two-month trial period was consistent with the PPA data (Krista Trounce, VFPA, pers. comm., 1 Feb 2018). For scenarios S11 and S12, which were intended to represent future conditions, the number of piloted vessel transits was based on a regional traffic forecast to 2026 from the Port of Vancouver (VFPA, pers. comm., 10 Oct 2017).

Table 2 summarizes the number of simulated vessel movements during 24 hours for the baseline and future model scenarios. Additional tug movements in the future scenarios correspond to required tanker escorts, as detailed in the PPA notices to industry (Obermeyer 2015). The pre-trial model scenarios considered partial and total slowdown participation rates of 50% and 100%, respectively. For two of the post-trial model scenarios (S11 and S12), the participation rate was adjusted to be the actual participation rate observed during the trial (Table 3). In this study, slowdowns were only applied to piloted vessels transiting through Haro Strait and to Washington State Ferries (WSF) trips between Sidney and Anacortes. All vessels assumed to be unaffected by the slowdown zone, which included non-piloted vessels and cargo vessel traffic bound to and from the USA, were identical between the 14 model scenarios.

Table 1. Summary of Phase 1 (pre-trial) and Phase 2 (post-trial) model scenarios. S7 and S8 correspond to post-trial updates of S3 and S4. Likewise, S13 and S14 correspond to post-trial updates of S1 and S2.

Scenario		Traffic conditions	Piloted ship speeds	Slowdown participation rate (%)	Number of ship transits	Speed scaling coefficients (C_v)
Phase 1 Pre-trial	S1	Baseline	Baseline	n/a	Average	Ross model
	S2				High	
	S3		11 knots	100	Average	
	S4				High	
	S5		11 knot/baseline	50	Average	
	S6				High	
Phase 2 Post-trial	S7	Baseline	11 knots	100	Average	Trial result
	S8				High	
	S9		Trial mean/baseline	Actual trial rate	Average	
	S10				High	
	S11	Future	Baseline	n/a	Average	
	S12		11 knots	100		
	S13	Baseline	Baseline	n/a	Average	
	S14				High	

Table 2. Numbers of daily piloted vessel transits in Haro Strait representing the three traffic conditions in the model. Baseline piloted vessel counts through Haro Strait were based on PPA daily vessel counts (Dominic Tollit, SMRU, pers. comm., 3 Apr 2017). Average and high traffic conditions represent median and 95th percentile vessel counts, respectively. Future traffic conditions are based on the Port of Vancouver's regional traffic forecast (to 2026).

Vessel category	Baseline		Future
	Average traffic (ships per 24 h)	High traffic (ships per 24 h)	Average traffic (ships per 24 h)
Bulker*	8	10	9
Containership	4	6	5
Tanker	1	2	2**
Vehicle Carrier	1	2	1
Cruise	0	1	0
Total	**14**	**21**	**19**

* Includes both bulk carriers and general cargo vessels.
** Future traffic scenario includes two additional escort tugs accompanying piloted tankers.

Table 3. Mean slowdown speed and overall participation rate recorded during the slowdown trial, by category.

Vessel category	Slowdown speed (kts)	Participation rate (%)
Bulker	11.30	55
Containership	11.40	68
Tanker	10.95	55
Vehicle Carrier	11.48	66
Cruise	10.64	90

2.3. Speed Scaling of Source Levels

Underwater noise emissions (i.e., source levels) of marine vessels generally increase with speed due to associated increases in machinery vibration and propeller-induced cavitation. Several past studies have used measurements to attempt to derive scaling laws of source levels with speed (Ross 1976, Arveson and Vendittis 2000, Wales and Heitmeyer 2002, McKenna et al. 2013). The most widely applied scaling law is Ross's classical power-law model (Ross 1976), which relates changes in source level (SL) to relative changes in speed according to the following formula:

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

In this equation, SL is the source level at speed through water, v, $\mathrm{SL}_{\mathrm{ref}}$ is the source level at some reference speed v_{ref}, and C_v is a coefficient corresponding to the slope of the curve. A higher coefficient indicates a larger difference in noise emissions per percentage change in speed. For example, according to Eqn 1, a 50% reduction in speed corresponds to a decibel SL reduction of $3 \times C_v$. The original model, developed by Ross, recommended a scaling coefficient of $C_v = 6$ based on historical vessel noise measurements and cavitation experiments. Nonetheless, different trends of source level versus speed (including negative trends) may be accommodated by adjusting the value of the scaling coefficient, C_v.

This form of power law (with adjustable C_v) is used by JASCO's cumulative vessel noise model to simulate speed-dependent changes in source level for individual ships.

For the pre-trial model scenarios, we used Ross's value of the scaling coefficient of $C_v = 6$. For the post-trial scenarios we used category-dependent scaling coefficients that were derived from results of the slowdown trial (see Section 3.2). Furthermore, the scaling coefficients for the post-trial scenarios were taken to be frequency dependent. Different scaling coefficients were used to model the effect of speed on source levels for three frequency ranges. These frequency ranges were based on the three frequency bands that were recently identified by an expert working group convened by the Coastal Ocean Research Initiative (CORI) (Heise et al. 2017) as being particularly relevant to the acoustic quality of SRKW habitat:

- Broadband (10–100,000 Hz), for evaluating behavioural or physiological impacts.
- Communication masking (500–15,000 Hz), for evaluating effects of noise on communication space.
- Echolocation masking (15,000–100,000 Hz).

We could not use the broadband CORI band directly, because it overlaps the communication and echolocation CORI bands and frequency bands in the noise model must be non-overlapping. To address this issue, we derived a new set of scaling coefficients for frequencies below 500 Hz based on the trial results. The scaling coefficients below 500 Hz were very close to the broadband values, however, since broadband source levels of vessels are generally dominated by low-frequency noise.

3. Data Sources and Model Inputs

3.1. Vessel Traffic

Movements of piloted vessels through Haro Strait were simulated differently for each model scenario, based on the assumed slowdown participation rate and the number of ship transits. Both the time of departure and the choice of inbound or outbound route were randomly selected for each simulated vessel movement. Baseline speeds for each category were based on average historical vessel speeds along the inbound and outbound routes, as determined from 2015 AIS data (Figure 3). For scenarios S3-S8 and S12-S14, speeds of participating vessels inside the slowdown zone were taken to be 11 knots for all categories. For scenarios S9 and S10, speeds of participating vessels inside the slowdown zone were taken to be the trial-mean values for each category (Figure 4). Acceleration and deceleration times in the transition zones were assigned on a category-specific basis, in consultation with pilots from the Pacific Pilotage Authority (PPA). Each simulated trip was displaced slightly from the center of the route, in a randomized fashion, to more-realistically represent the observed distribution of traffic along the traffic routes. Details of the vessel traffic simulations are provided in Appendix A.

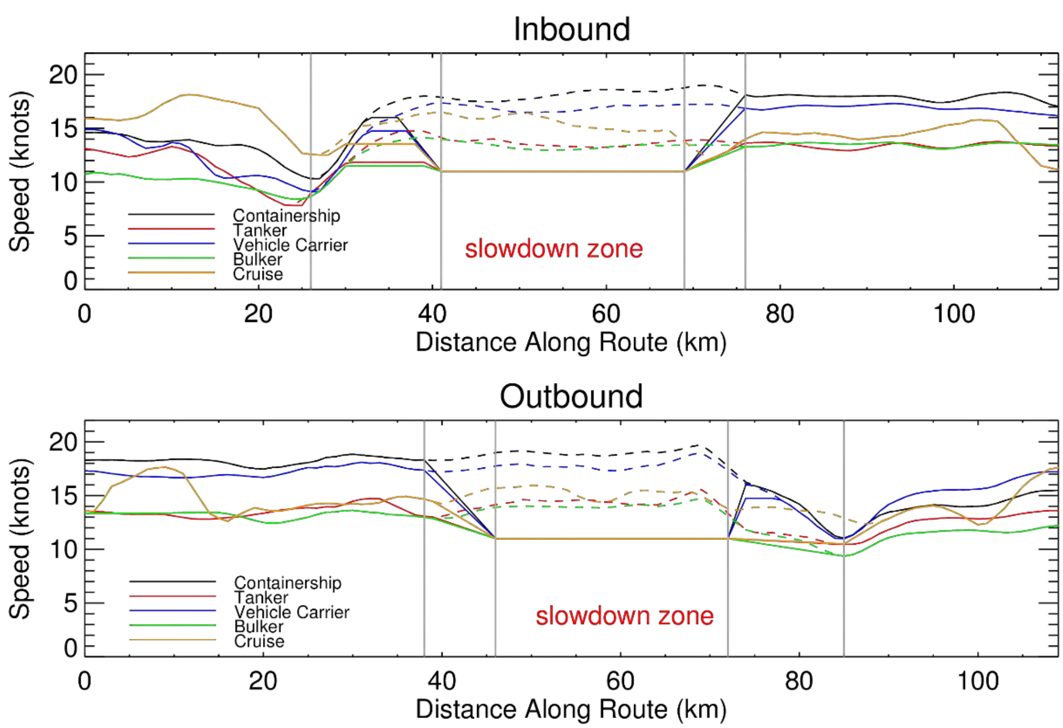

Figure 3. Speeds of piloted vessels along route based on historical data and an 11 knot speed limit inside the slowdown zone (all scenarios except S9 and S10): Dashed = baseline speed, solid = slowdown speed. Vertical gray lines indicate the boundaries of the transition zones. Baseline speeds are based on 2015 mean historical AIS data for each vessel category. The distance along each route is relative to a start point just outside the model boundary (see simulated vessels routes in Figure 1).

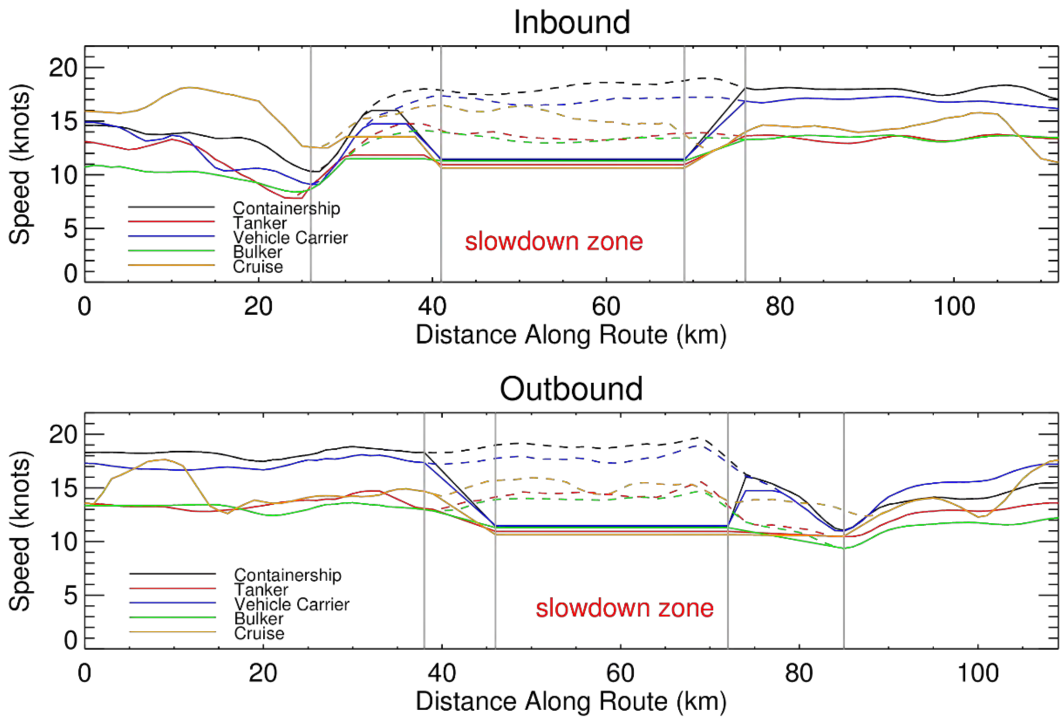

Figure 4. Speeds of piloted vessels along route based on slowdown speeds measured during the trial (scenarios S9 and S10 only): Dashed = baseline speed, solid = slowdown speed. Vertical gray lines indicate the boundaries of the transition zones. Baseline speeds outside the slowdown zone are based on 2015 mean historical AIS data for each vessel category. Speeds inside the slowdown zone are based on average speeds, by category, recorded during the trial. The distance along each route is relative to a start point just outside the model boundary (see simulated vessels routes in Figure 1).

Baseline vessel traffic, which included non-piloted vessels and piloted vessels bound to and from the USA, were simulated based on actual AIS vessel tracks for a single day in July (Figure 5)[1]. We selected this day (30 Jul 2015) because the total number of hours of non-piloted vessel traffic over the 24-hour period was close to the median daily value for the month (i.e., it represented an average day). Vessel tracks were assigned to an appropriate source level category based on their type classification. These AIS data were previously used to generate shipping density maps for a study of noise contributors in the Salish Sea; additional details regarding these data and the vessel categories in the model may be found in the final report for that study (MacGillivray et al. 2016b). Baseline traffic was held constant between scenarios, except for the WSF sailing between Sidney and San Juan, which was assumed to reduce speed to 11 knots where it intersected the slowdown zone.

[1] The AIS dataset included only vessels carrying AIS transceivers. Only moving vessels were included in the model. In Canada, federal regulations require every vessel of 500 deadweight tons or more to carry AIS, except fishing vessels. In practice, many smaller craft and fishing vessels also carry AIS for safety.

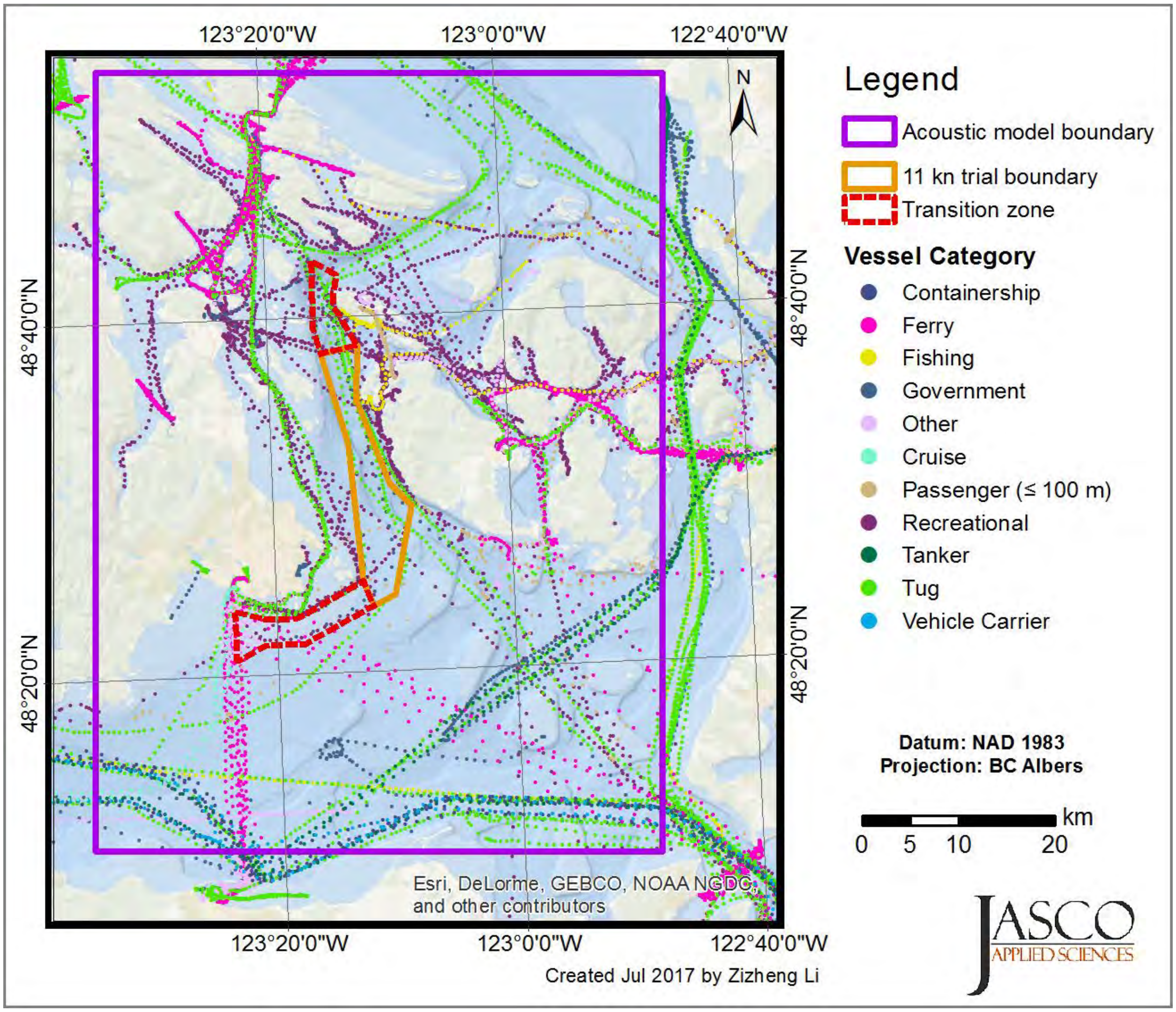

Figure 5. Baseline vessel traffic included in the model, based on AIS vessel tracks for 30 Jul 2015. Each point on the map represents a time-stamped vessel position report. The total amount of vessel hours on this day was approximately equal to the median 24-hour value for July 2015. A total of 216 vessels were included in the baseline.

3.2. Vessel Noise Emissions

Since September 2015, measurements of vessel noise emissions (i.e., source levels) have been collected on the Underwater Listening Station (ULS) in the Strait of Georgia. Situated in the inbound shipping lane on the VENUS East Node, the ULS records noise emissions of merchant vessels bound for the Port of Vancouver, as well as ferry traffic along several passenger and cargo routes (Figure 6). Automated processing of vessel source levels is performed by JASCO's ShipSound software, which uses AIS vessel tracking data to detect when vessels transit through the measurement funnel of the ULS. Valid vessel tracks, as selected by automated system, are used for the vessel source level analysis, which conforms approximately to the ANSI standard for ship sound measurements (ANSI/ASA S12.64/Part 1 2009).

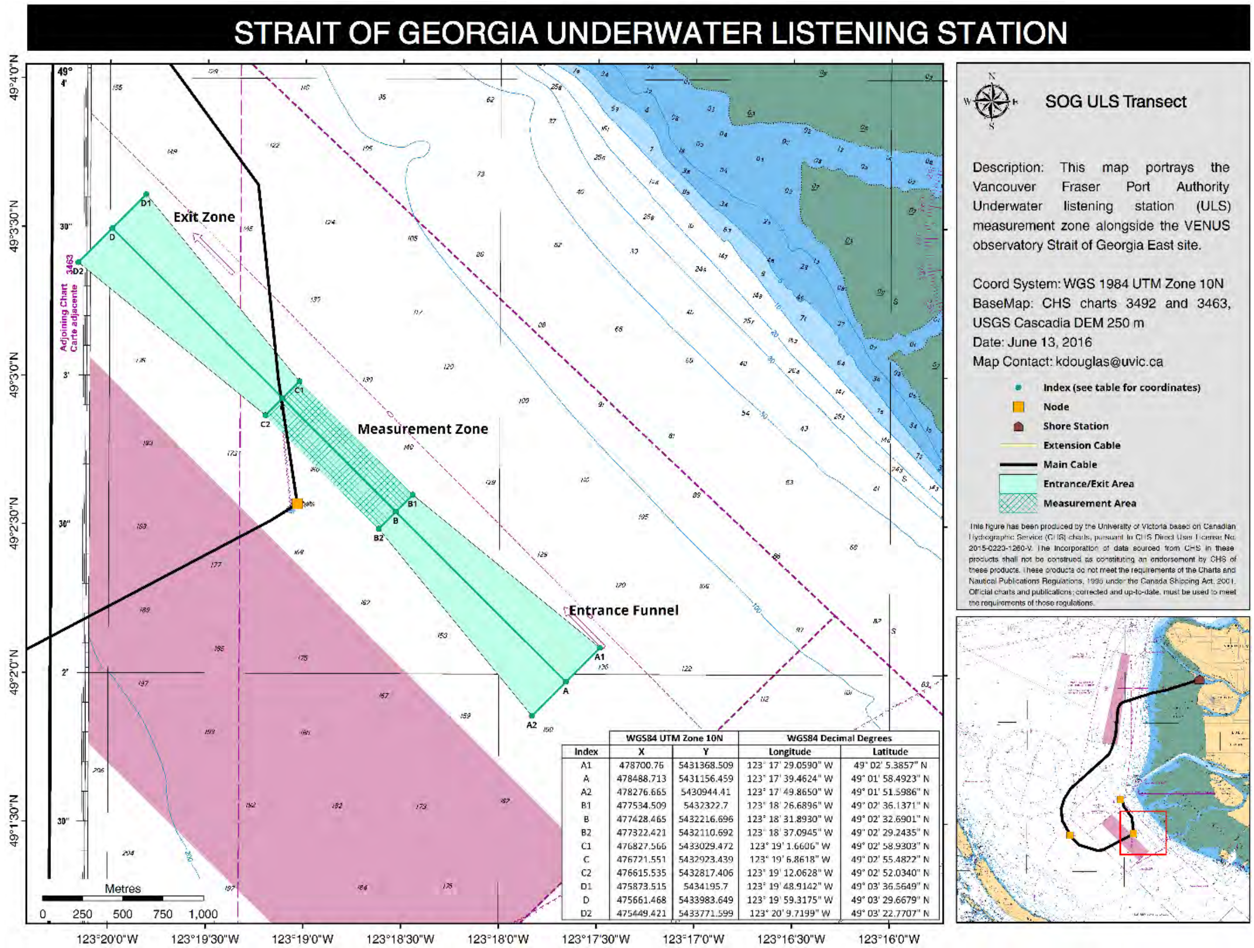

Figure 6. ULS location (yellow square) at the VENUS East Node in Georgia Strait. The measurement funnel (cyan) is used by pilots to ensure accurate vessel source level measurements.

For this study, source level measurements from the ULS were assigned to ten different categories, according to vessel class information embedded in the AIS logs (Table 4). Average frequency-dependent source levels were calculated for each vessel category and used to represent noise emissions of corresponding vessels in the cumulative noise model. Source levels for four additional vessel categories not covered by the ULS data were obtained from other sources: Passenger (< 100 m)[2]; Clipper Ferry[3]; Recreational[4]; and Other[4]. For each vessel category, average monopole source levels (MSL) were compiled in 1/3-octave frequency bands (centre frequencies from 10 Hz to 63 kHz), covering the frequency range where noise emissions from vessels overlap the hearing sensitivity of marine mammals and fish inside the study area (Figure 7).

[2] Passenger (< 100 m) source levels were based on whale watching boast source level measurements (Erbe 2002) because a manual review of the AIS data determined that the majority of small passenger vessels tracked in Haro Strait were indeed whale watching boats.
[3] Clipper Ferry jet catamarans were based on a vessel source level measurement from Veirs et al. (2016).
[4] Recreational and Other source levels were based on a prior review of published vessel measurements carried out for the Roberts Bank Terminal 2 cumulative modelling assessment (MacGillivray et al. 2014b).

Table 4. Number of measurements used to calculate mean (power average) source levels for each vessel category represented in the ULS data. The Government category includes Navy and Research vessels. Ferries measurements were grouped before averaging to properly account for repeat vessel passes.

Category	Measurements	Unique vessels
Bulker	464	445
Containership	233	118
Tug	206	67
Tanker	86	50
Vehicle Carrier	31	28
Fishing	23	20
Cruise	17	11
Ferry (Ro-ro Passenger)	1505	8
Ferry (Ro-ro Cargo)	134	3
Government	6	5
Total	**2705**	**755**

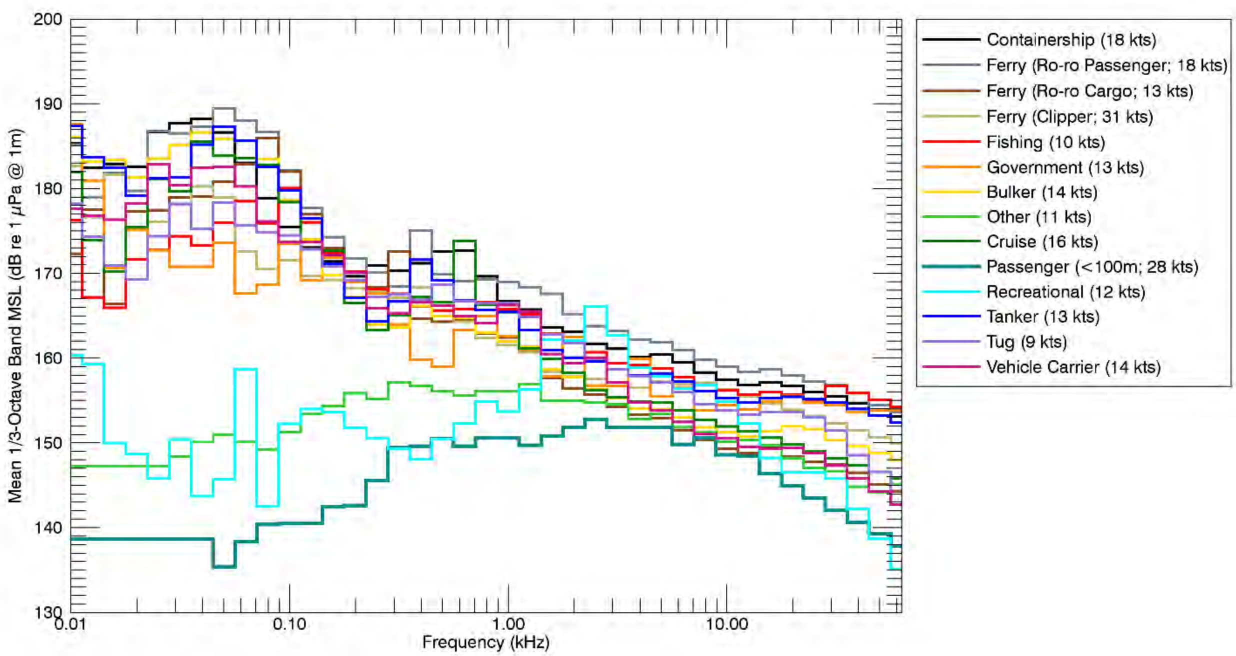

Figure 7. Frequency-dependent source levels by vessel category, in 1/3-octave-bands. The reference speed (average transit speed, in knots) for each category is indicated in the legend. ULS source levels were extrapolated above 31 kHz based on the terminal slope of the 1/3-octave-band level curves.

For the pre-trail model scenarios (S1-S6), a default speed coefficient (C_v = 6), based on historical data, was applied for all categories (Figure 8). For the post-trial model scenarios (S7-S14), unique speed scaling coefficients, based on the trial measurements, were applied to each vessel category (Table 5). These speed scaling coefficients were calculated based on measured differences in speeds and source levels between vessels that participated in the trial and non-participating vessels measured before and after the trial. The trial measurements also showed that noise reductions associated with the slowdowns were frequency-dependent, with the largest reductions measured at the low and high end of the frequency range. Source levels from the trial were analyzed in terms of three different frequency bands, corresponding to the CORI bands for assessing noise impacts on SRKW, with each band assigned a unique scaling coefficient. The frequency divisions between the CORI bands do not line up exactly with the divisions between the 1/3-octave bands used by the model, however, so scaling coefficients from the trial were assigned to the closest matching frequency bands in the model. Furthermore, an additional set of scaling coefficients was calculated from the trial data for the 1/3-octave frequency bands 10-400 Hz since the frequency bands in the model must be non-overlapping (these corresponded very closely to the broadband values, however, since broadband vessel source levels are dominated by noise below 500 Hz).

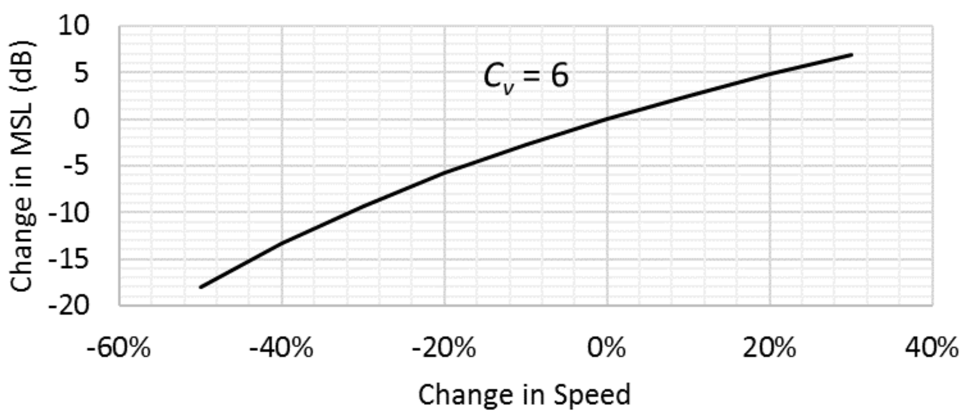

Figure 8. Trend of MSL vs. change in speed, based on the Ross power-law model, for a scaling parameter value of C_v = 6.

Table 5. MSL versus speed power-law scaling coefficients (C_V) as determined from the slowdown trial measurements. Scaling coefficients for the Containership, Bulker, Cruise, Tanker, and Vehicle Carrier categories were based on differences in source levels between participating vessels and a control group (MacGillivray and Li 2018, Tab. 8). Scaling coefficients for Passenger (< 100 m) vessels were based on a dedicated study of whale watch vessel noise emissions carried out concurrently with the slowdown trial (Wladichuk and Hannay 2018). Scaling coefficients for other vessel categories were based on trends of source levels versus speed through water measured during the trial (MacGillivray and Li 2018, §3.6).

Vessel type	1/3-Octave frequency bands (Hz)		
	10–400	500–12500	16000–63000
Containership	5.1	4.1	7.9
Ferry	6.0	6.0	6.0
Fishing	1.5	0.4	6.0
Naval	4.7	5.9	8.0
Government	4.4	0.7	6.0
Bulker	8.2	4.2	7.0
Cruise	4.9	5.4	8.2
Recreational	2.3	2.2	2.8
Tanker	7.7	4.5	9.9
Tug	1.8	1.8	2.0
Vehicle Carrier	5.2	4.1	7.7
Passenger (< 100 m)	1.3	2.0	2.9
Other	5.7	3.2	3.4
Clipper	6.0	6.0	6.0

3.3. Sound Propagation

JASCO's Marine Operations Noise Model (MONM) was used to simulate frequency-dependent sound transmission curves (i.e., transmission loss) for the study area. This model was previously validated via field tests using a controlled sound source at several different locations within the study area (Warner et al. 2014). MONM accounts for the different environmental factors that influence underwater sound propagation, including the sound speed profile of the water, the water depth, and the seabed sediment layering. A set of 100 sound-transmission-versus-range curves was used to represent noise propagation in different parts of the study area. Different curves were used to represent different combinations of frequency, water depth, and source depth (Figure 9). More details regarding the methods used to generate the sound transmission curves for the study area are described in Section 3.3 of MacGillivray et al. (2016b).

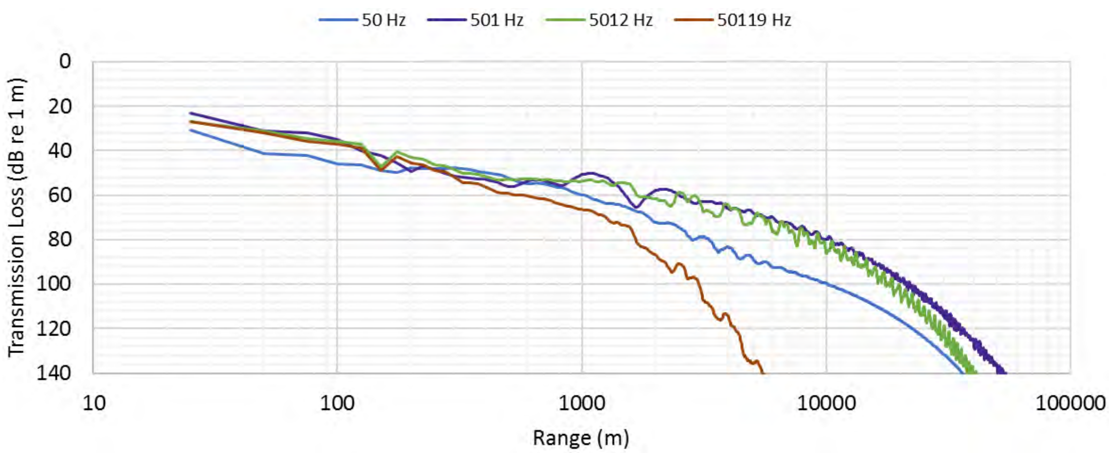

Figure 9. Examples of frequency-dependent sound transmission versus range curves, for Haro Strait in July, as calculated by JASCO's Marine Operations Noise Model (MONM). The modelled receiver depth is 10 m, which is near the sea surface, since marine mammals spend most of their time in this zone.

3.4. Ambient Noise

Wind-driven ambient noise was included in the model, based on historical wind speed data for Haro Strait for a 24-hour period in July (Figure 10). Time-dependent wind noise was calculated in 1/3-octave frequency bands, based on published curves of ambient noise versus frequency and wind speed (Figure 11). Aggregate sound levels in all grid cells (see Section 2.1) were computed from the sum of the vessel noise plus the wind-driven ambient noise, for each time step in the model.

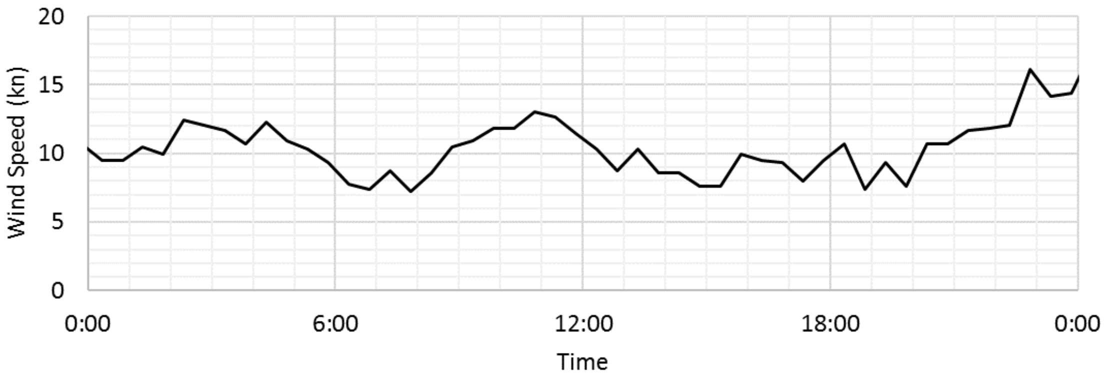

Figure 10. Simulated wind speed in Haro Strait during a 24-hour period in July. Wind speeds are based on historical data from the NOAA National Buoy Data Center[5] for 26 Jul 2015. Mean wind speeds on this day (10.5 knots) were closest to the average value for the month.

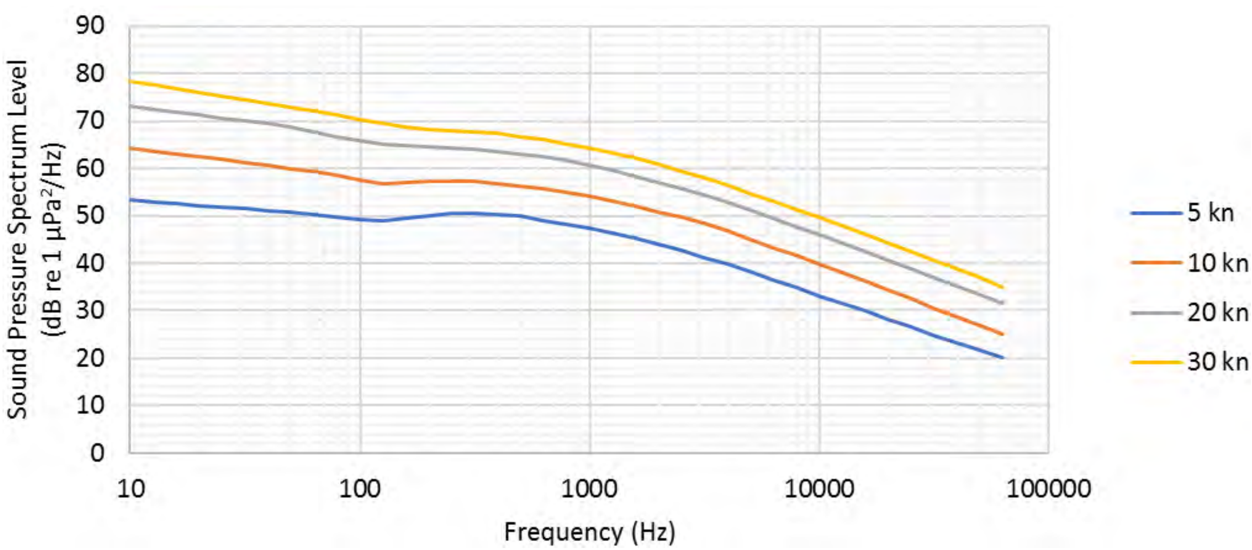

Figure 11. Wind-driven ambient noise level as a function of frequency, for wind speeds ranging from 5 to 30 knots (Cato 2008).

[5] Station 46088 New Dungeness Met Buoy: http://www.ndbc.noaa.gov/station_history.php?station=46088

4. Model Results

For each model scenario, a set of time-dependent sound pressure level (SPL) grids were generated that represented 1-minute snapshots of vessel traffic noise over a 24-hour period. The SPL snapshots from the model simulations (examples shown in Figures 12–14) were rendered as animations to show the time evolution of the vessel traffic noise in the study area. Digital files of SPL from the vessel noise model were used as input to a model of potential behavioural effects of noise on SRKW. Results from the behavioural response and masking study are described in (Joy et al. 2018).

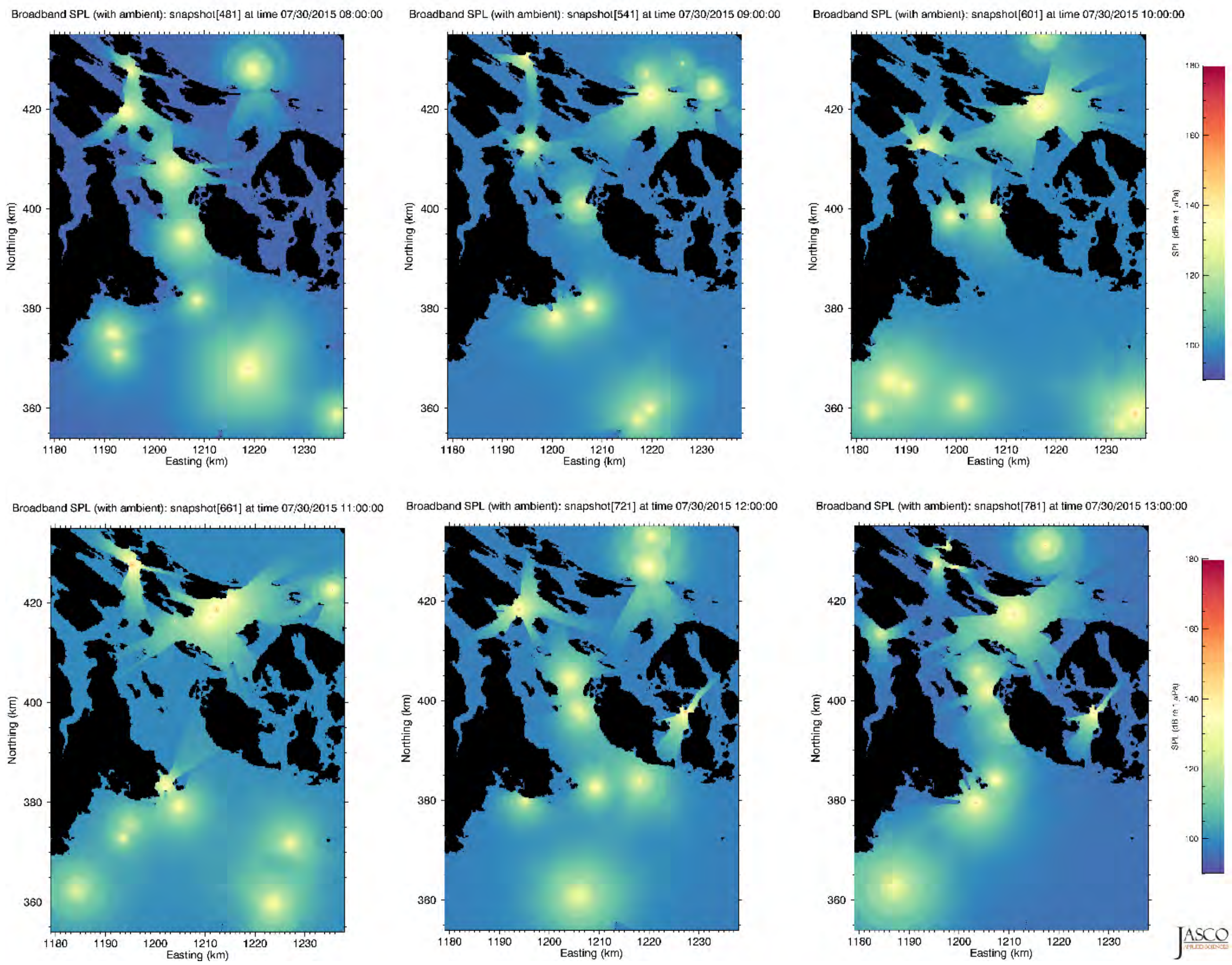

Figure 12. Example time snapshots of SPL (broadband, 9 to 70,800 Hz) for the study area for scenario S4 (pre-trial: high traffic, 100% participation) from 08:00 to 13:00 in 1-hour increments. Easting and northing are BC Albers projected coordinates.

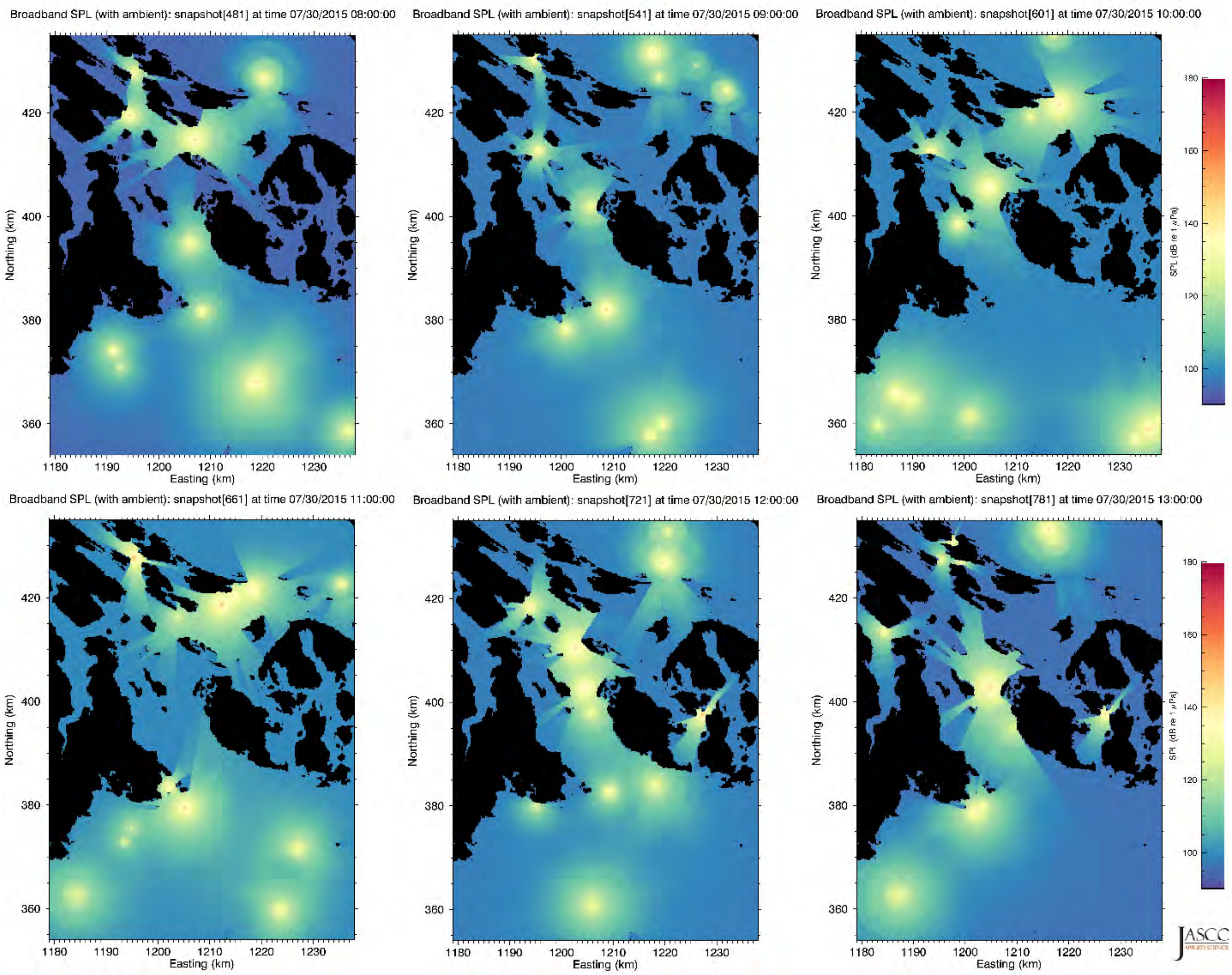

Figure 13. Example time snapshots of SPL (broadband, 9 to 70,800 Hz) for the study area for scenario S10 (post-trial, high traffic, slowdown trial actual participation) from 08:00 to 13:00 in 1-hour increments. Easting and northing are BC Albers projected coordinates.

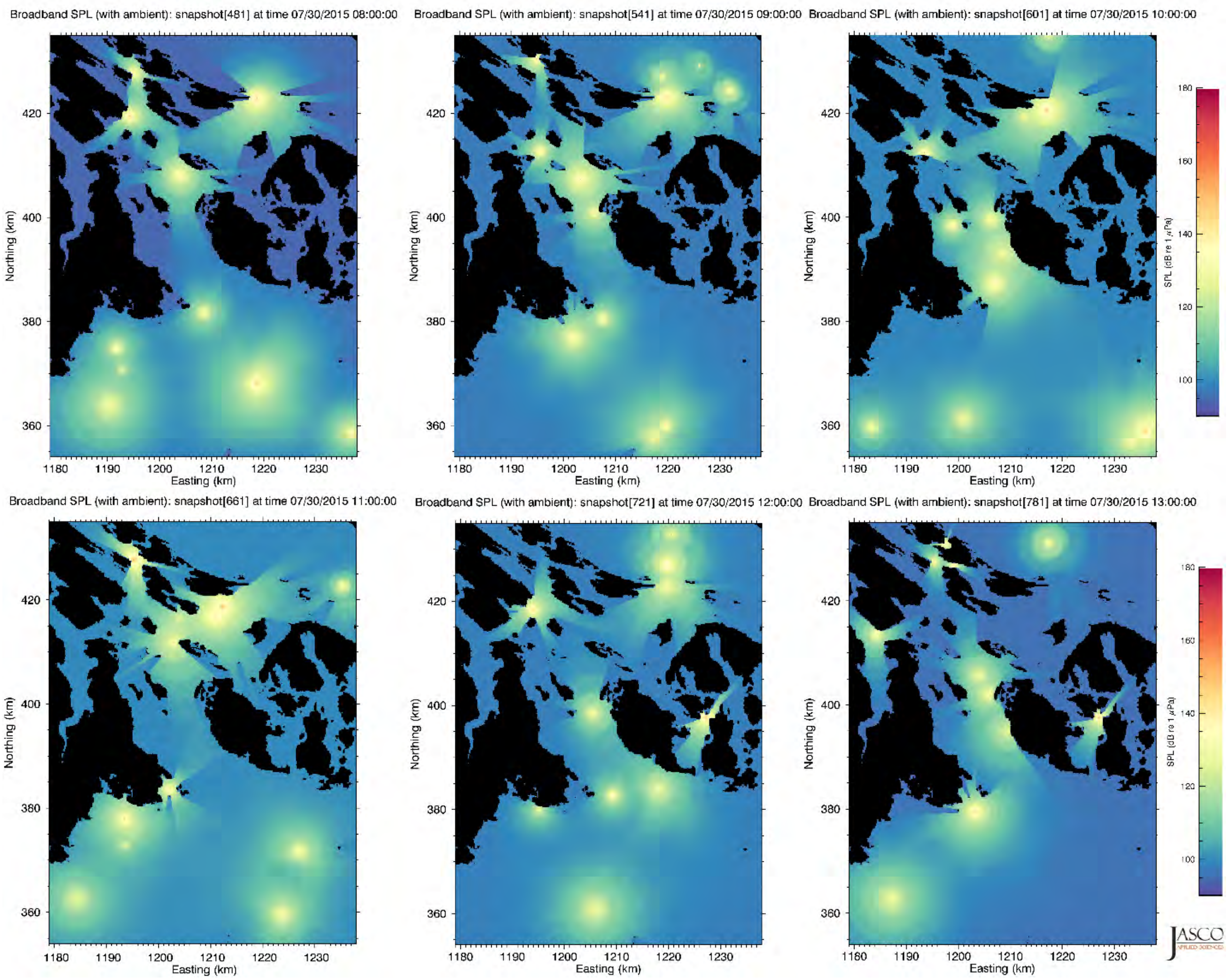

Figure 14. Example time snapshots of SPL (broadband, 9 to 70,800 Hz) for the study area for scenario S12 (post-trial; future traffic projections, average traffic, 100% participation) from 08:00 to 13:00 in 1-hour increments. Easting and northing are BC Albers projected coordinates.

Eight receiver locations were selected to sample the modelled SPL in key SRKW feeding habitat areas within the study area (Figure 15). Time-dependent sound levels were extracted from the model output at these locations for all model scenarios. The extracted sound levels were plotted versus time, both for broadband noise and for the 50 kHz frequency band, to show how noise levels varied over the 24-hour period of simulation (Figure 16). Additional plots of sound levels versus time at the eight receiver locations are provided in Appendix B. Peaks in the SPL versus time plots correspond to passes of individual vessels by the receiver location. Away from the shipping lanes (i.e., at locations 1-5), levels in the 50 kHz frequency band were seldom above wind-driven ambient because of the strong high-frequency sound attenuation in seawater (the attenuation coefficient in seawater at 50 kHz at this location is estimated to be 13 dB/km in summer based on the formulae of François and Garrison (1982)).

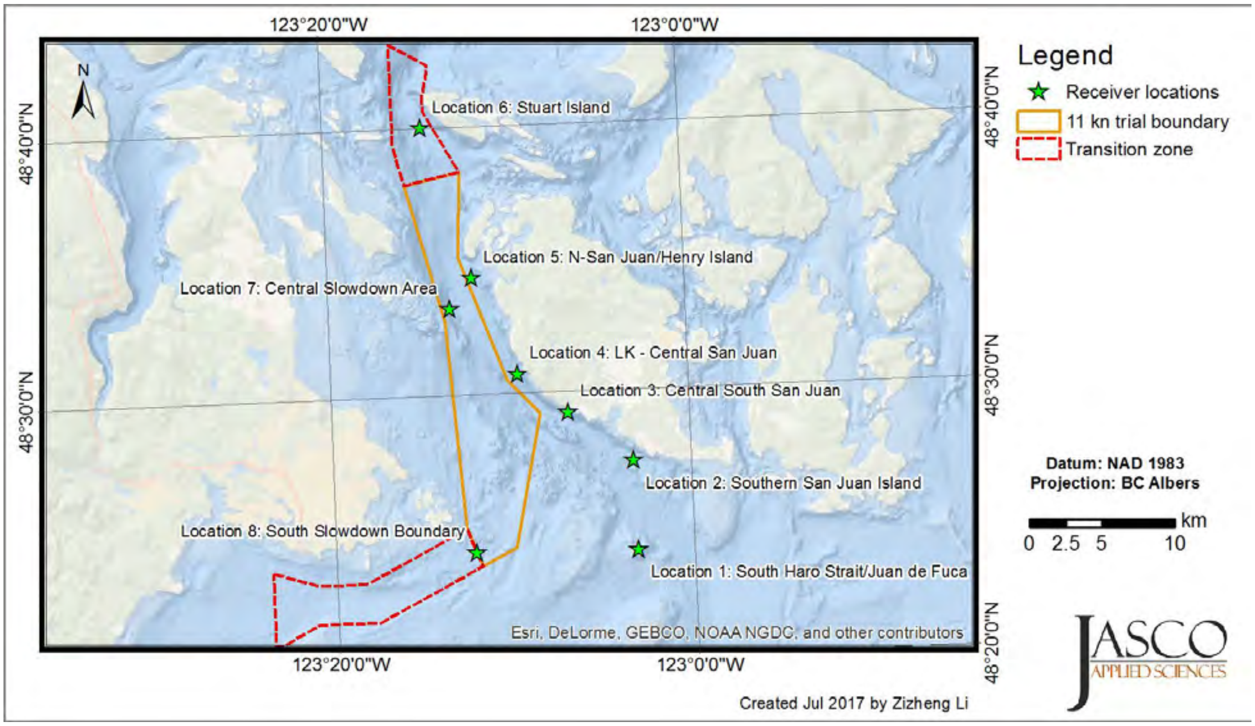

Figure 15. Eight selected sampling locations for analyzing time-dependent SPL from the model. Location 1 is an important area where SRKW travel and forage before entering Haro Strait. Locations 2–5, along the shore of San Juan and Henry Islands, are important feeding areas with high SRKW density (Hauser et al. 2007). Location 6 is in the northernmost study area where SRKW are likely present in summer and winter, and is also part of J-pod core region, which extends to Swanson Channel and Rosarios Strait (Hauser et al. 2007). Locations 7 and 8 are on the traffic routes, to sample sound levels directly in the slowdown zone.

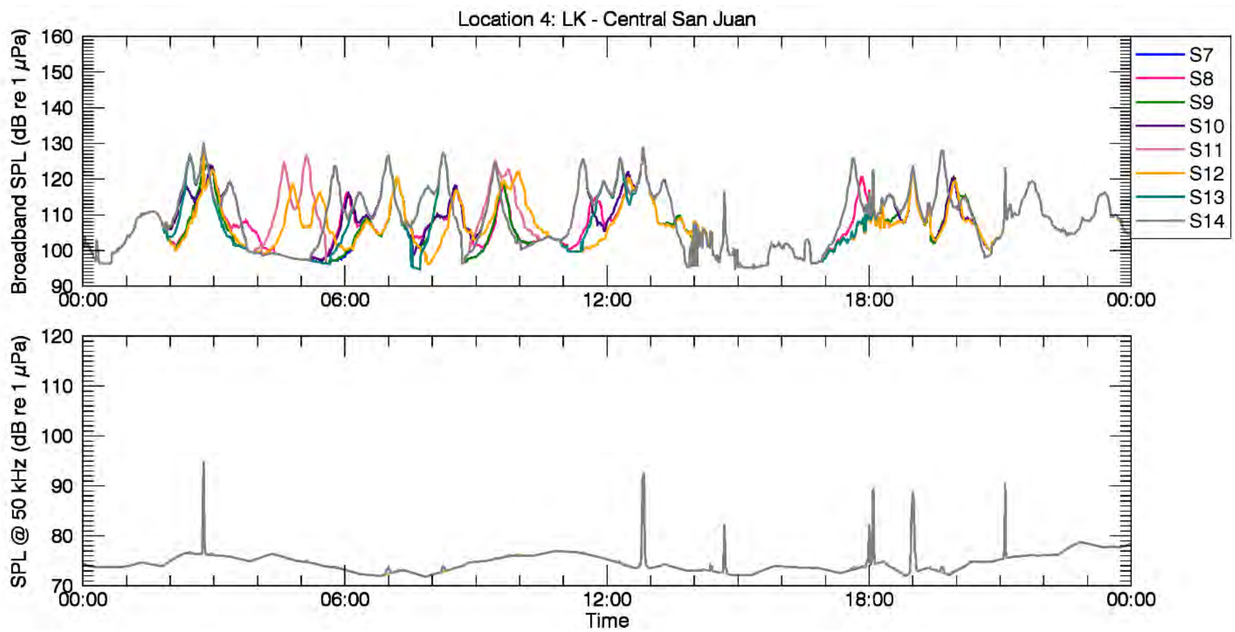

Figure 16. Modelled SPL versus time at receiver location 4 (Lime Kiln - Central San Juan). The plot shows both broadband (top) and 50 kHz 1/3-octave band (bottom) sound levels for the eight post-trial model scenarios (S7-S14). Baseline traffic was the same between scenarios S7-S14, so differences are due only to changes in slowdown conditions or number of simulated cargo vessels. The 50 kHz band was nearly the same for all scenarios at this receiver location because noise at 50 kHz is primarily driven by nearby vessels and wind rather than by distant vessels (i.e., due to the strong sound attenuation at 50 kHz). As a result, only noise from non-piloted vessels transiting close to the west side of San Juan Island (which is the same between all scenarios) exceeds wind-driven ambient at 50 kHz.

To interpret the time-varying model outputs, a statistical analysis was applied to the modelled noise levels. Sampled sound levels were used to generate cumulative distribution functions (CDFs) at each location, showing the percent of time that modelled sound levels were below a specified threshold level. The following example illustrates how to interpret the CDF curves. At location 4 (near Lime Kiln), the SPL was 105.2 dB at the 50th percentile level for scenario S1; this means that, 50% of the time, baseline sound levels were at or below 105.2 dB near Lime Kiln, under average traffic conditions. Figures 17–21 compare CDF curves for the pre-trial and post-trial model scenarios for different slowdown participation rates and traffic conditions.

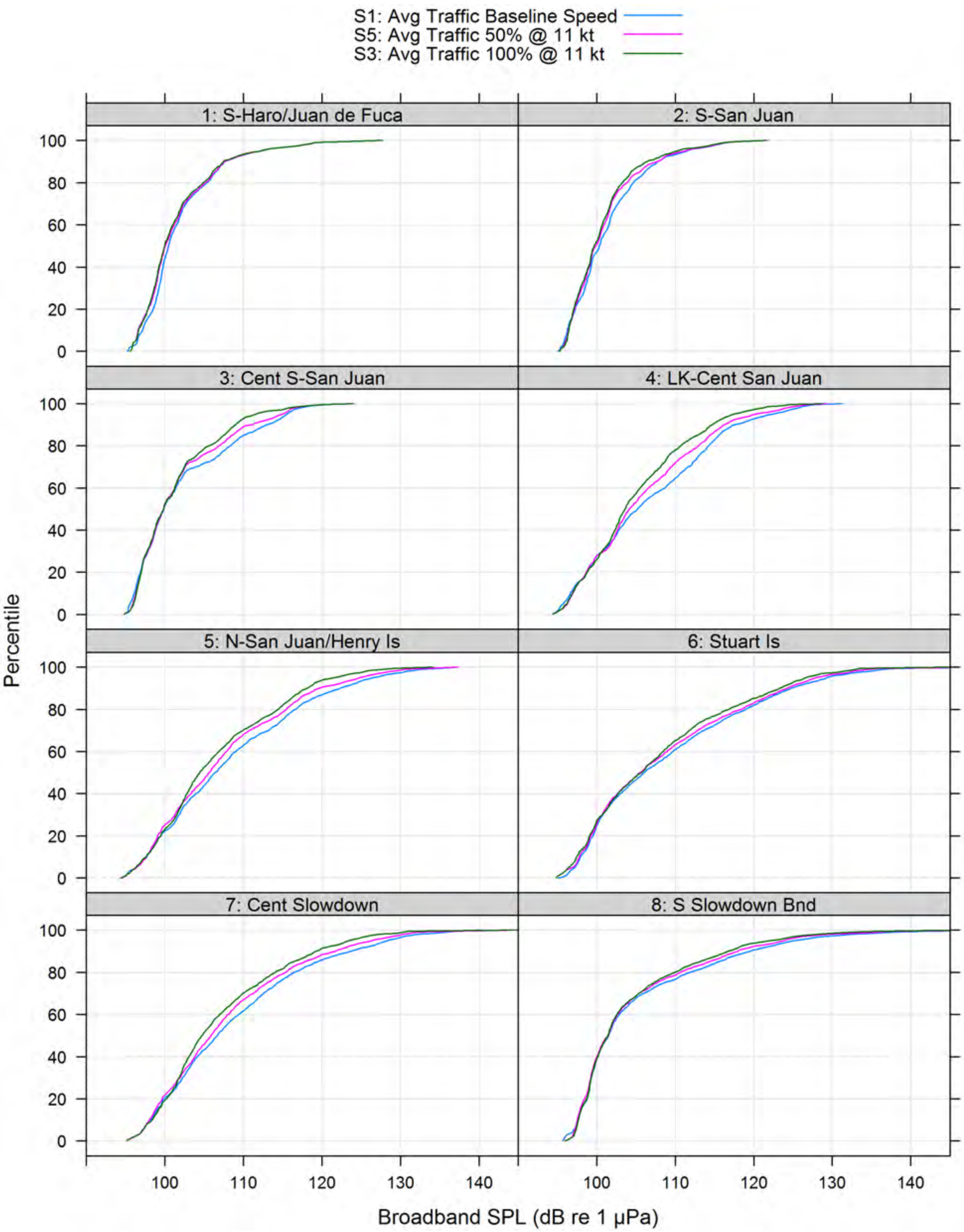

Figure 17. CDF curves of time-dependent SPL for pre-trial scenarios S1, S3, and S5 (average traffic conditions with 0%, 50%, and 100% slowdown participation) at the eight receiver locations shown in Figure 15. These charts show the percent of time that SPL falls below a specified decibel level for a particular receiver location and model scenario.

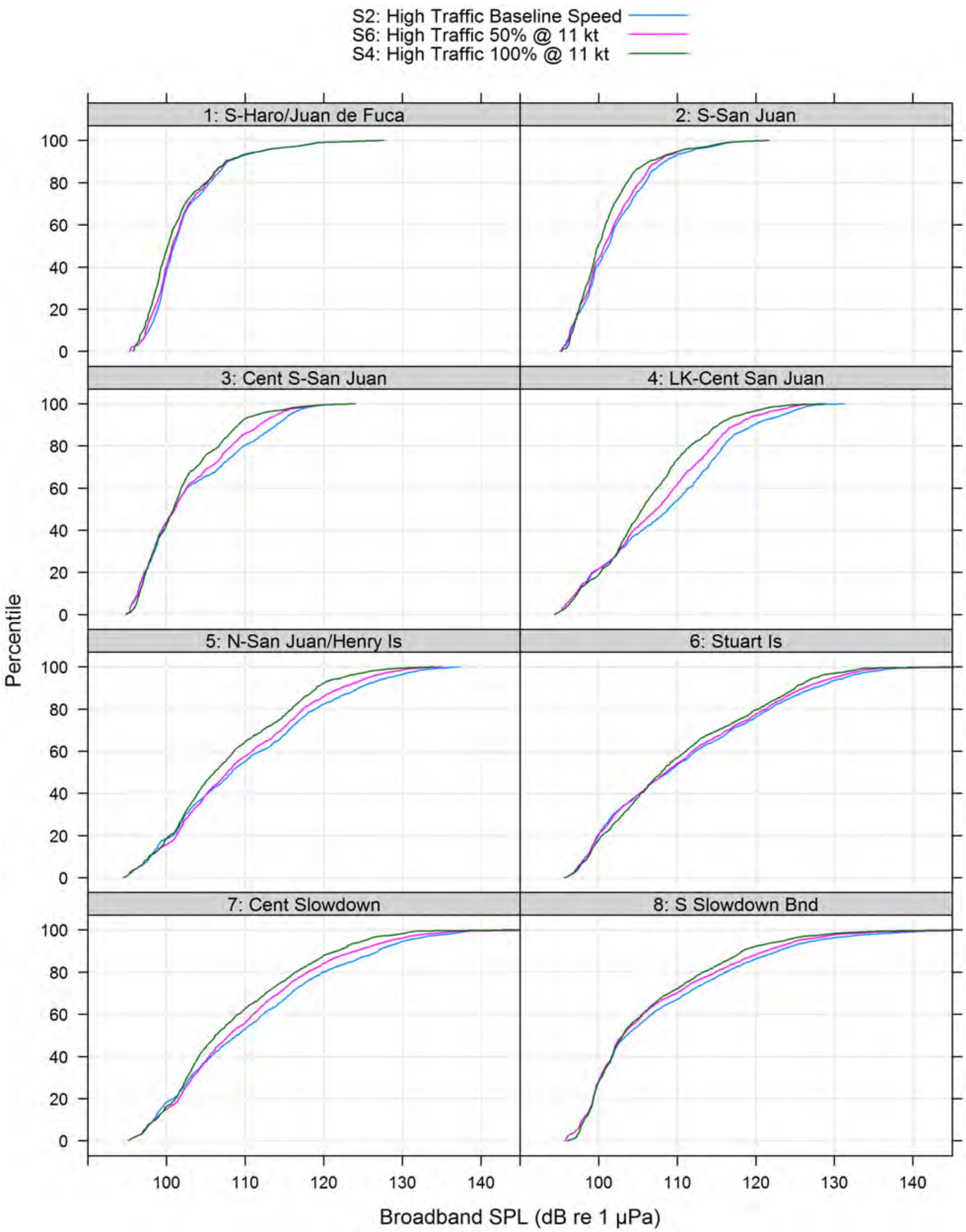

Figure 18. CDF curves of time-dependent SPL for pre-trial scenarios S2, S4, and S6 (high traffic conditions with 0%, 50%, and 100% slowdown participation) at the eight receiver locations shown in Figure 15. These charts show the percent of time that SPL falls below a specified decibel level for a particular receiver location and model scenario.

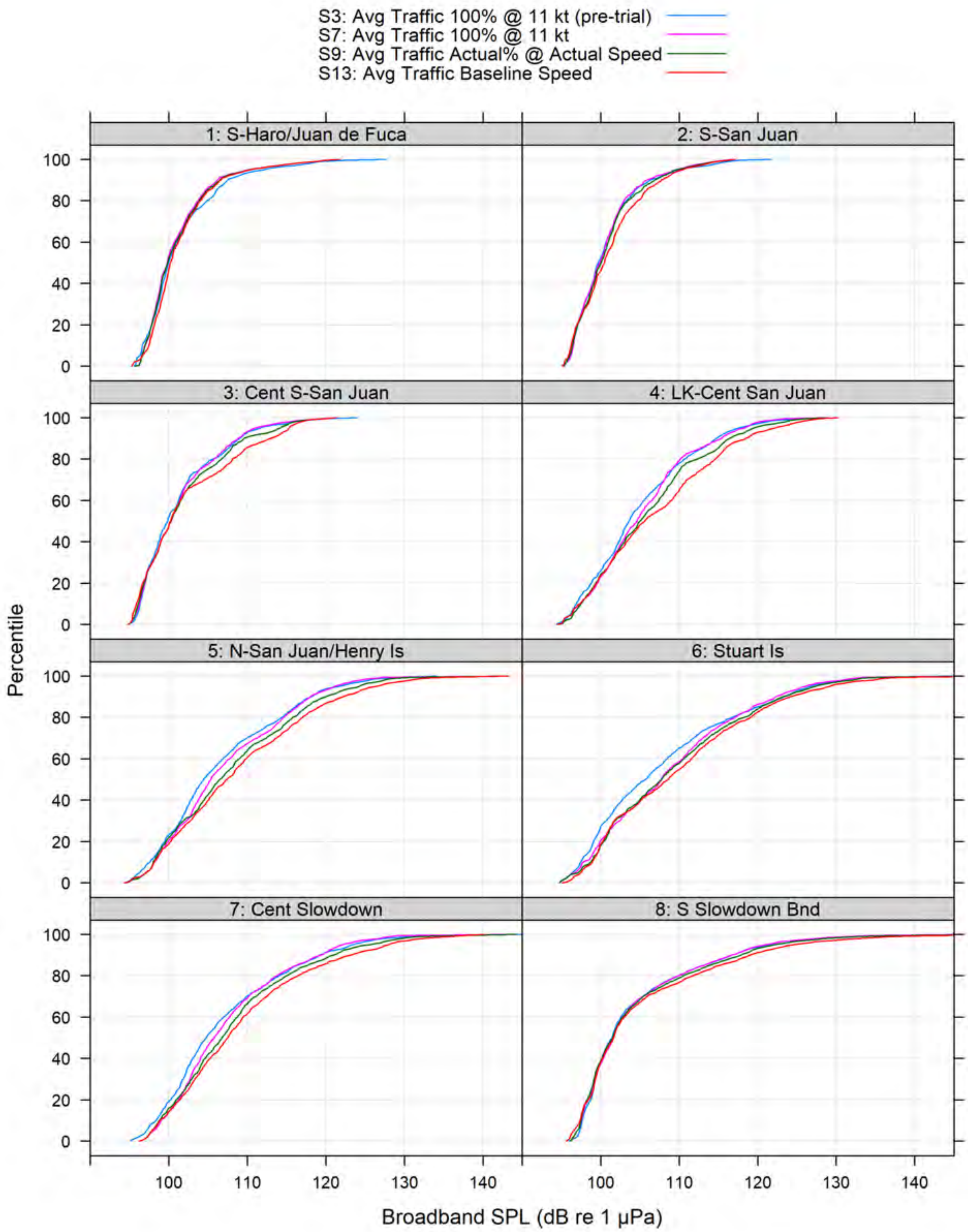

Figure 19. CDF curves of time-dependent SPL for post-trial scenarios S7, S9, and S13 (average traffic conditions with 100%, actual and 0% slowdown participation, respectively, using new C_v values) at the eight receiver locations shown in Figure 15. Pre-trial scenario S3 (average traffic, 100% participation using C_v = 6) is shown for reference. These charts show the percent of time that SPL falls below a specified decibel level for a particular receiver location and model scenario.

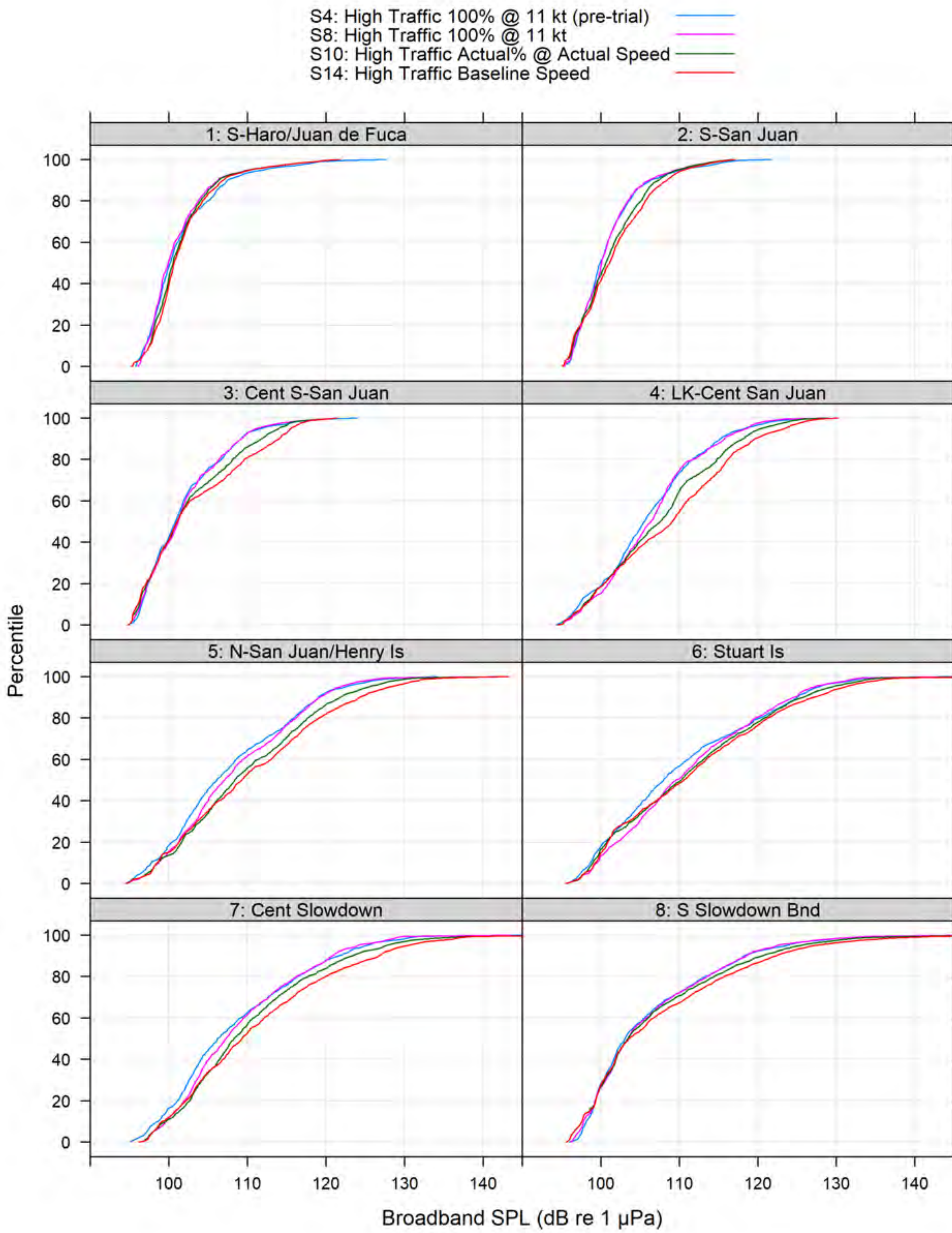

Figure 20. CDF curves of time-dependent SPL for post-trial scenarios S8, S10 and S14 (high traffic conditions with 100%, actual, and 0% slowdown participation, respectively, using new C_v values) at the eight receiver locations shown in Figure 15. Pre-trial scenario S4 (high traffic with 100% participation using C_v = 6) is shown for reference. These charts show the percent of time that SPL falls below a specified decibel level for a particular receiver location and model scenario.

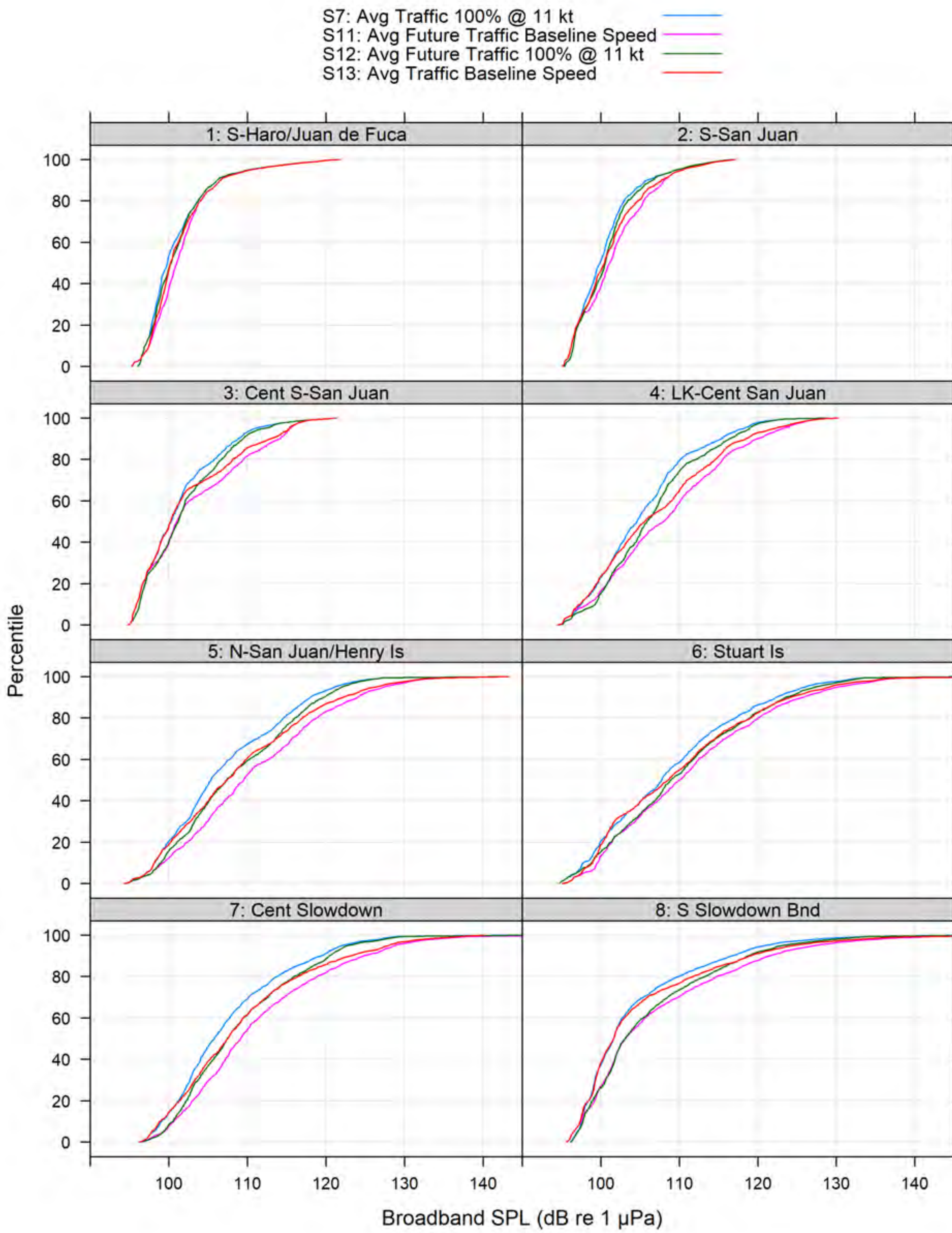

Figure 21. CDF curves of time-dependent SPL for post-trial scenarios S7, S11, S12, and S13 (average traffic conditions, present and future, with 0% and 100% slowdown participation, using new C_v values) at the eight receiver locations shown in Figure 15. These charts show the percent of time that SPL falls below a specified decibel level for a particular receiver location and model scenario.

5. Discussion

5.1. Pre-trial Scenarios

For the pre-trial model scenarios (S1-S6), differences between the CDFs were used to calculate how changes in slowdown participation affected noise levels in the study area (Figure 22). All pre-trial scenarios were based on the same baseline vessel data, so the differences were attributable to changes associated with vessel slowdowns in Haro Strait. For example, the differences in CDFs between scenarios S1 and S3 at location 4 (near Lime Kiln) was -1.6 dB at the 50th percentile level, meaning the modelled effect of 100% slowdown participation during average traffic conditions was to reduce the median (i.e., 50th percentile) noise level by 1.6 dB near Lime Kiln, based on the pre-trial model assumptions. Similarly, for the 50% participation scenarios (S5 and S6) the modelled change in median noise levels at location 4 was -1.1 dB and -1.4 dB, respectively, under average-traffic and high-traffic conditions. The participation rate for these latter two scenarios most closely matched the actual slowdown participation rates that were observed during the trial. While these calculated reductions are based on the pre-trail scenarios, the range of speed scaling coefficients for cargo vessels that were measured during the trial (C_v = 4.1–8.2) bracketed the pre-trial estimated value of C_v = 6. Thus, we expect that the pre-trial modelled reductions are still broadly representative of the actual reductions in noise levels that would result from slowing traffic in Haro Strait under current conditions.

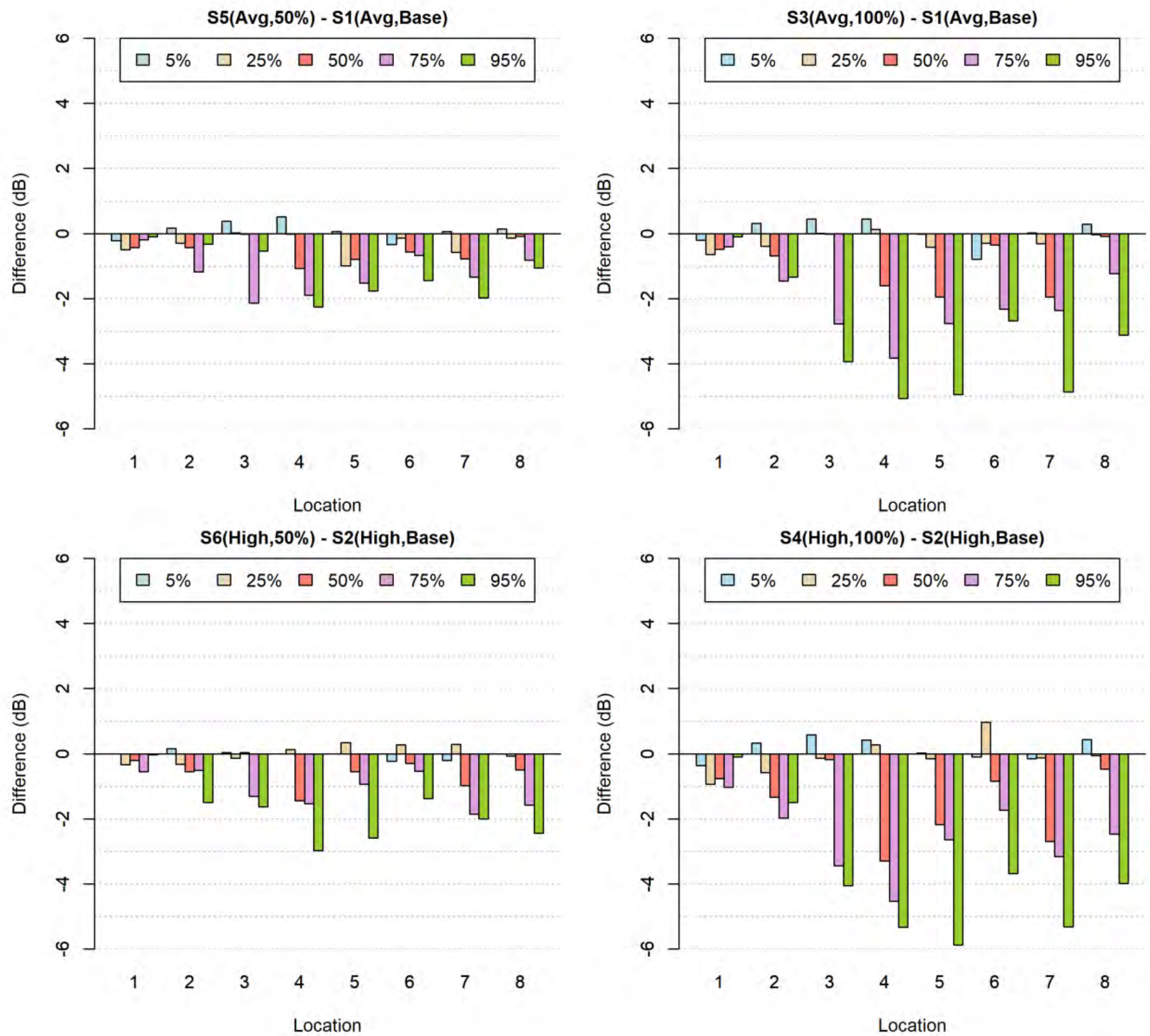

Figure 22. Pre-trial predictions of changes in sound levels due to implementing an 11 knot slowdown zone in Haro Strait at the eight receiver locations shown in Figure 15. The reductions were calculated by subtracting the modelled CDF curves for the different model scenarios at the 5th, 25th, 50th (median), 75th, and 95th percentile levels. The *n*th percentile level is the sound level that is exceeded (100 – *n*) percent of the time (e.g., the 95% level is exceeded 5% of the time). A negative change corresponds to a reduction in SPL due to vessel slowdowns. Tabulated differences are provided in Appendix C.1.

5.3. Post-trial Scenarios

Differences between CDFs were also analyzed for the post-trial scenarios to determine how changes in slowdown participation affected noise levels in the study area (Figure 23). This included a comparison of actual slowdown trial conditions (S9, S10) to updated baseline models, based on post-trial data (S13, S14). For example, the predicted change in the median (i.e., 50th percentile) noise levels at location 4 (near Lime Kiln) during the slowdown trail was -0.6 dB under average-traffic conditions and -1.5 dB under high-traffic conditions. The predicted changes in the 75th percentile noise levels were even greater at this location: -2.7 dB under average-traffic conditions and -2.0 dB under high-traffic conditions. The greatest changes were predicted to be on the west side of San Juan Island (locations 4 and 5) and on the traffic lanes inside the slowdown zone (location 7). The smallest changes were predicted to be to the south of the slowdown zone, in Juan de Fuca Strait (locations 1 and 2). At all locations, the predicted changes were generally greatest for the higher percentiles noise levels (75%, 95%) and smallest for the lower percentiles noise levels (5%, 25%). This reflects the fact that changes in noise levels were most strongly affected by the slowdowns during those times when piloted vessels were present near the receivers.

One potential downside of the slowdown mitigation is that, while the intensity of vessel noise emissions is reduced, the duration of noise exposure is increased because of longer transit times. This is evidenced in the CDF differences (see Figure 23) whereby noise levels at the lowest exposure levels (i.e., low percentiles) were predicted to either decrease by a small amount or, in some instances, increase relative to the current baseline. For example, for the 100% slowdown participation scenarios, the lowest 5th percentile of noise levels at Lime Kiln (location 4), were predicted to increase by 0.1 dB under average traffic conditions and 0.4 dB under high traffic conditions. However, such increases were generally limited to times when modelled SPL was below ~105 dB re 1 μPa.

Differences between the CDFs for the pre-trail and post-trail scenarios were used to determine how adjusting the speed scaling coefficients affected the predicted noise levels in the model (Figure 24). Comparisons for the 100% participation scenarios indicated that SPL from the post-trial model scenarios was generally higher than SPL from the pre-trial scenarios at the eight receiver locations (e.g., median SPL was 0.8–1.0 dB higher at location 4). Thus, assimilating the trial results into the cumulative vessel noise model resulted in slightly higher noise level predictions. These differences cannot be entirely attributed to the slowdowns, however, because adjusting the speed scaling coefficients for the post-trial models also affected the baseline vessel traffic (i.e., noise from all vessels was adjusted in the post-trial scenarios).

For the future traffic scenarios (S11 and S12), differences between CDFs were used to determine how noise levels would increase relative to current conditions and how future noise levels would be reduced by slowdown participation (Figure 25). Comparing scenarios S11 and S13 showed that median SPL would increase in future (e.g., by 2.3 dB at receiver location 4) due to increases in vessel traffic (under average traffic conditions). Comparing scenarios S11 and S12, however, showed that 100% slowdown participation would reduce noise from future traffic by a comparable amount (e.g., by 2.0 dB at receiver location 4). Thus, slowing piloted vessels may offset additional noise from future traffic increases in Haro Strait.

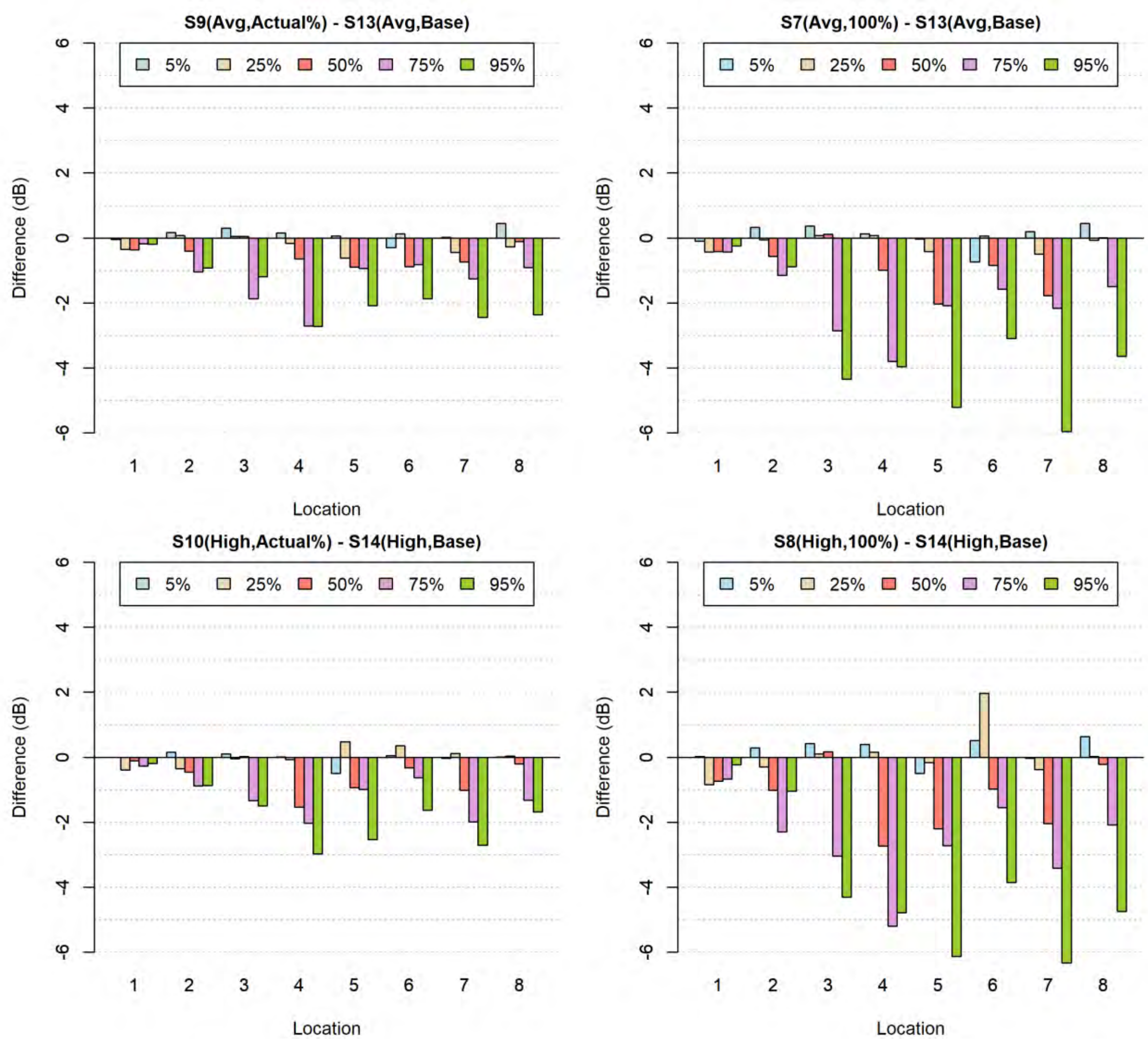

Figure 23. Post-trial predictions of changes in sound levels due to implementing an 11 knot slowdown zone in Haro Strait at the eight receiver locations shown in Figure 15. The reductions were calculated by subtracting the modelled CDF curves for the different model scenarios at the 5th, 25th, 50th (median), 75th, and 95th percentile levels. The *n*th percentile level is the sound level that is exceeded (100 – *n*) percent of the time (e.g., the 95% level is exceeded 5% of the time). A negative change corresponds to a reduction in SPL due to vessel slowdowns. Panels on the left side represent actual trial conditions. Tabulated differences are provided in Appendix C.2.

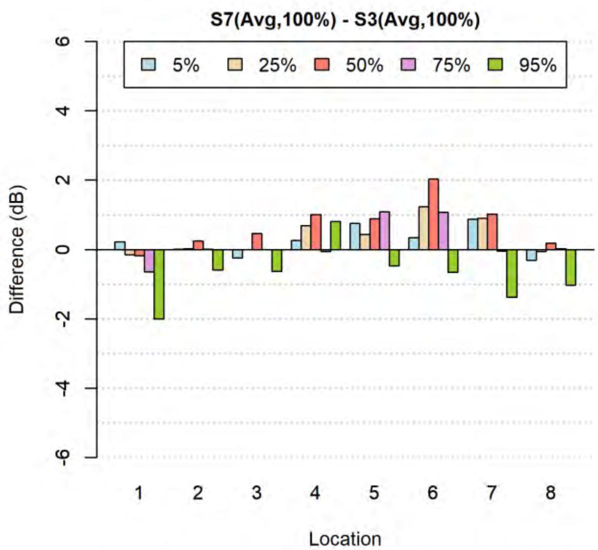

Figure 24. Changes in modelled sound levels that resulted from adjusting speed-scaling coefficients (C_v), according to the slowdown trial results, at the eight receiver locations shown in Figure 15. The differences were calculated by subtracting the modelled CDF curves for the different model scenarios at the 5th, 25th, 50th (median), 75th, and 95th percentile levels. The *n*th percentile level is the sound level that is exceeded (100 – *n*) percent of the time (e.g., the 95% level is exceeded 5% of the time). Positive differences indicate SPL was higher for the post-trial model scenarios. Tabulated differences are provided in Appendix C.2.

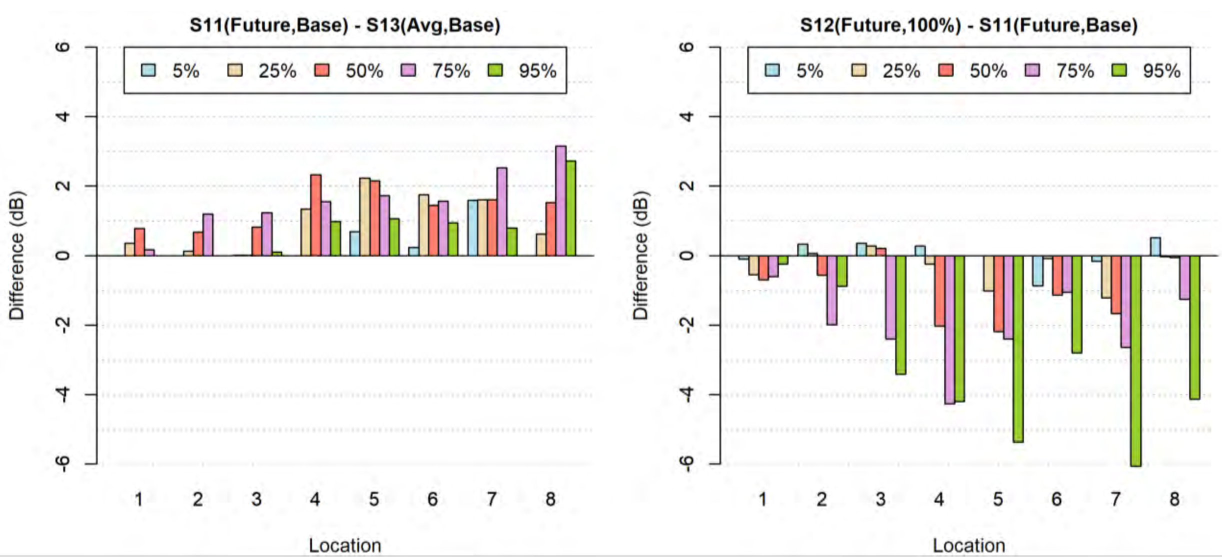

Figure 25. Differences in modelled sound levels between future conditions and present conditions for baseline traffic (left) and between baseline and 100% slowdown participation under future conditions (right). The differences were calculated by subtracting the modelled CDF curves for the different model scenarios, at the 5th, 25th, 50th (median), 75th, and 95th percentile levels. The *n*th percentile level is the sound level that is exceeded (100 – *n*) percent of the time (e.g., the 95% level is exceeded 5% of the time). On the left panel, positive differences indicate SPL is higher under future traffic conditions. On the right panel, negative difference indicate SPL is lower due to traffic slowdowns. Tabulated differences are provided in Appendix C.2.

6. Conclusions

Results from both the pre-trail and post-trial vessel noise modelling showed that implementing an 11 knot slowdown zone in Haro Strait would reduce noise levels in key SRKW habitat. Post-trial models, based on actual participation rates from the 2017 slowdown trial, predicted median noise levels near Lime Kiln (receiver location 4) decreased by 0.6 dB during average traffic conditions and by 1.5 dB during high-traffic conditions. Scenarios based on 100% slowdown participation predicted even greater reductions (e.g., 1.0 dB for average traffic and 2.7 dB for high traffic, near Lime Kiln). For all scenarios, the greatest reductions in noise levels were achieved near the west side of San Juan Island (locations 4 and 5), while the least reductions were observed toward the south, in Juan de Fuca Strait (location 1 and 2). This is because the large volume of USA-bound merchant traffic that travels through Juan de Fuca Strait was unaffected by the Haro Strait slowdown zone. At some locations, the slowdowns also increased minimum noise levels by a small amount, due to overall increases in vessel transit time. These increases, however, were limited to periods when modelled noise levels were below ~105 dB re 1 μPa. Thus, the modelling predicted that implementing a slowdown zone would reduce noise levels in Haro Strait for the majority of the time.

While the post-trial scenarios used updated speed-scaling coefficients derived from source level measurements from the 2017 trial, the pre-trial scenarios assumed that source levels varied with speed according to a scaling coefficient of $C_v = 6$, for all vessels, based on historical data (Ross 1976). This pre-trial value was within the range of C_v values measured for piloted vessels during the actual slowdown trial (4.1–8.2). For example, for a containership slowing from 18 to 11 knots, a scaling coefficient of $C_v = 6$ predicts an MSL reduction of 12.8 dB, whereas the actual MSL reduction measured during the trial for containerships was 11.5 dB. The pre-trial scenarios did not, however, capture the frequency dependence in the vessel noise reductions that were observed during the trial. Comparing equivalent pre-trial and post-trail model results showed that adjusting the speed scaling coefficients increased modelled noise levels in Haro Strait by a small amount (e.g., median SPL was 0.8-1.0 dB higher at location 4 for the post-trial 100% slowdown scenarios). Nonetheless, differences between baseline and slowdown conditions were similar for the pre-trial and post-trial scenarios, which indicates that Ross's original speed scaling coefficient of $C_v = 6$ was a reasonable assumption for modelling the effect of slowdowns on large vessels before the trial data became available.

Model scenarios representing future conditions (S11 and S12) predicted that, without slowdowns, future changes in vessel traffic would increase noise levels throughout Haro Strait, but that much of this increase would be offset by an 11 knot slowdown. For example, without slowdowns, median noise levels were predicted to increase by 2.3 dB near Lime Kiln (location 4), compared to average present-day conditions. With slowdowns, however, median future noise levels at this location would be reduced by 2.0 dB (a net increase of 0.3 dB, relative to present-day), assuming 100% of piloted vessels transit at 11 knots through the slowdown zone. Thus, the post-trial models suggest that average increases in vessel noise in Haro Strait, due to projected increases in future vessel traffic, could be offset by implementing an 11 knot speed limit.

7. Acknowledgments

We would like to thank Dominic Tollit (SMRU), whose discussions with the pilots provided valuable information regarding navigation practices along traffic routes within the study area. We also thank Karen Hiltz and Nicole Chorney (JASCO), who performed editorial review of this document. Finally, we would like to thank Krista Trounce and Orla Robinson (VFPA) who provided helpful technical feedback on draft versions of this report.

Glossary

1/3-octave-band
Standard, non-overlapping frequency bands approximately one-third of an octave wide (see octave). Standard 1/3-octave-band centre frequencies (f_c) are given by the formula $f_c = 10^{n/10}$ where n is an integer. Measured in the unit Hz.

automated identification system (AIS)
A radio-based tracking system whereby vessels regularly broadcast their identity, location, speed, heading, dimensions, class, and other information to nearby receivers.

broadband sound level
The total sound pressure level over the entire modelled or measured frequency range.

BC Albers
A standard map projection that is used by the province of British Columbia for representing spatial information with minimal distortion.

cumulative distribution function (CDF)
For a time-varying quantity (such as SPL), a curve that shows the percent of time that the quantity falls below a specified value.

decibel (dB)
One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI S1.1-1994 R2004).

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

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

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

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

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

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

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

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

Unless otherwise stated, SPL refers to the root-mean-square sound pressure level (rms SPL).

sound speed profile
The speed of sound in the water column as a function of depth below the water surface.

source level (SL)
The sound pressure level at 1 meter distance from a theoretical point source that radiates the same total sound power as the actual source. Unit: dB re 1 µPa @ 1 m.

transmission loss (TL)
The decibel reduction in sound level between a source and a receiver that results from sound spreading away from an acoustic source subject to the influence of the surrounding environment. Also called propagation loss. Measured in unit dB re 1 m.

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Appendix A. Simulated Vessel Movements

The table below lists the simulated movements for piloted vessels through Haro Strait for each of the 14 model scenarios. The time of departure and the route (inbound/outbound) was randomly selected for each vessel movement. The speed of the vessel along the route was based on either the baseline speeds or slowdown speed, as appropriate (Section 3.1). Historical vessel tracking data showed that individual ship tracks were approximately normally distributed inside each traffic lane. To simulate this distribution, a random deviation parameter (a standard normal random variable) was assigned to each track, where a value of 1 corresponds to the root-mean-square (rms) distance of vessel traffic from the center of the route (equal to half the rms width). The rms width of the vessel traffic was calculated at several points along both routes, using the MarineTraffic AIS vessel density data, and was found to vary from 440 m at the north end of the study area to 600 m at the south end. The deviation parameter therefore corresponds to the lateral distance of a vessel from the center of the route, as a fraction of the rms traffic width.

Vessel	Category	Date	Departure time	Route	Deviation from center of route (× 1/2 rms width)	Speed in slowdown zone
Scenarios S1 and S13 (Average Traffic, Baseline)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	Baseline
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	Baseline
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	Baseline
4	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	Baseline
5	Tanker	7/30/2015	4:32:10	Inbound	0.067	Baseline
6	Containership	7/30/2015	6:14:24	Inbound	−0.045	Baseline
7	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	Baseline
8	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	Baseline
9	Containership	7/30/2015	10:09:07	Outbound	−0.244	Baseline
10	Containership	7/30/2015	11:31:12	Outbound	−0.705	Baseline
11	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	Baseline
12	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	Baseline
13	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	Baseline
14	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	Baseline
Scenarios S2 and S14 (High Traffic, Baseline)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	Baseline
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	Baseline
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	Baseline
4	Vehicle Carrier	7/30/2015	0:28:48	Outbound	−0.033	Baseline
5	Containership	7/30/2015	1:35:02	Outbound	−0.058	Baseline
6	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	Baseline
7	Cruise	7/30/2015	3:56:10	Inbound	−0.593	Baseline
8	Tanker	7/30/2015	4:32:10	Inbound	0.067	Baseline
9	Tanker	7/30/2015	5:31:12	Outbound	−0.137	Baseline
10	Containership	7/30/2015	6:14:24	Inbound	−0.045	Baseline

Vessel	Category	Date	Departure time	Route	Deviation from center of route (× 1/2 rms width)	Speed in slowdown zone
11	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	Baseline
12	Containership	7/30/2015	9:27:22	Inbound	−2.011	Baseline
13	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	Baseline
14	Bulk Carrier/Gen. Cargo	7/30/2015	9:57:36	Outbound	0.101	Baseline
15	Containership	7/30/2015	10:09:07	Outbound	−0.244	Baseline
16	Containership	7/30/2015	11:31:12	Outbound	−0.705	Baseline
17	Bulk Carrier/Gen. Cargo	7/30/2015	15:00:00	Inbound	0.732	Baseline
18	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	Baseline
19	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	Baseline
20	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	Baseline
21	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	Baseline
Scenarios S3 and S7 (Average Traffic, 11 kn @ 100% participation)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	11 kn
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	11 kn
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	11 kn
4	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	11 kn
5	Tanker	7/30/2015	4:32:10	Inbound	0.067	11 kn
6	Containership	7/30/2015	6:14:24	Inbound	−0.045	11 kn
7	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	11 kn
8	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	11 kn
9	Containership	7/30/2015	10:09:07	Outbound	−0.244	11 kn
10	Containership	7/30/2015	11:31:12	Outbound	−0.705	11 kn
11	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	11 kn
12	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	11 kn
13	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	11 kn
14	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	11 kn
Scenarios S4 and S8 (High Traffic, 11 kn @ 100% participation)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	11 kn
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	11 kn
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	11 kn
4	Vehicle Carrier	7/30/2015	0:28:48	Outbound	−0.033	11 kn
5	Containership	7/30/2015	1:35:02	Outbound	−0.058	11 kn
6	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	11 kn
7	Cruise	7/30/2015	3:56:10	Inbound	−0.593	11 kn
8	Tanker	7/30/2015	4:32:10	Inbound	0.067	11 kn
9	Tanker	7/30/2015	5:31:12	Outbound	−0.137	11 kn

Vessel	Category	Date	Departure time	Route	Deviation from center of route (× 1/2 rms width)	Speed in slowdown zone
10	Containership	7/30/2015	6:14:24	Inbound	−0.045	11 kn
11	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	11 kn
12	Containership	7/30/2015	9:27:22	Inbound	−2.011	11 kn
13	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	11 kn
14	Bulk Carrier/Gen. Cargo	7/30/2015	9:57:36	Outbound	0.101	11 kn
15	Containership	7/30/2015	10:09:07	Outbound	−0.244	11 kn
16	Containership	7/30/2015	11:31:12	Outbound	−0.705	11 kn
17	Bulk Carrier/Gen. Cargo	7/30/2015	15:00:00	Inbound	0.732	11 kn
18	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	11 kn
19	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	11 kn
20	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	11 kn
21	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	11 kn
Scenario S5 (Average Traffic, 11 kn @ 50% participation)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	11 kn
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	Baseline
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	11 kn
4	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	11 kn
5	Tanker	7/30/2015	4:32:10	Inbound	0.067	11 kn
6	Containership	7/30/2015	6:14:24	Inbound	−0.045	Baseline
7	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	11 kn
8	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	Baseline
9	Containership	7/30/2015	10:09:07	Outbound	−0.244	Baseline
10	Containership	7/30/2015	11:31:12	Outbound	−0.705	11 kn
11	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	11 kn
12	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	Baseline
13	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	Baseline
14	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	Baseline
Scenario S6 (High Traffic, 11 kn @ 50% participation)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	11 kn
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	11 kn
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	11 kn
4	Vehicle Carrier	7/30/2015	0:28:48	Outbound	−0.033	Baseline
5	Containership	7/30/2015	1:35:02	Outbound	−0.058	Baseline
6	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	Baseline
7	Cruise	7/30/2015	3:56:10	Inbound	−0.593	11 kn
8	Tanker	7/30/2015	4:32:10	Inbound	0.067	Baseline

Vessel	Category	Date	Departure time	Route	Deviation from center of route (× 1/2 rms width)	Speed in slowdown zone
9	Tanker	7/30/2015	5:31:12	Outbound	−0.137	11 kn
10	Containership	7/30/2015	6:14:24	Inbound	−0.045	11 kn
11	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	Baseline
12	Containership	7/30/2015	9:27:22	Inbound	−2.011	Baseline
13	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	11 kn
14	Bulk Carrier/Gen. Cargo	7/30/2015	9:57:36	Outbound	0.101	Baseline
15	Containership	7/30/2015	10:09:07	Outbound	−0.244	11 kn
16	Containership	7/30/2015	11:31:12	Outbound	−0.705	Baseline
17	Bulk Carrier/Gen. Cargo	7/30/2015	15:00:00	Inbound	0.732	Baseline
18	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	Baseline
19	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	11 kn
20	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	11 kn
21	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	11 kn
Scenario S9 (Average Traffic, Actual slowdown speed @ actual slowdown participation rate)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	11.30 kn
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	Baseline
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	11.40 kn
4	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	11.30 kn
5	Tanker	7/30/2015	4:32:10	Inbound	0.067	10.95 kn
6	Containership	7/30/2015	6:14:24	Inbound	−0.045	Baseline
7	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	11.30 kn
8	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	Baseline
9	Containership	7/30/2015	10:09:07	Outbound	−0.244	Baseline
10	Containership	7/30/2015	11:31:12	Outbound	−0.705	11.40 kn
11	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	11.30 kn
12	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	Baseline
13	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	11.48 kn
14	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	Baseline
Scenario S10 (High Traffic, Actual slowdown speed @ actual slowdown participation rate)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	11.30 kn
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	11.30 kn
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	11.40 kn
4	Vehicle Carrier	7/30/2015	0:28:48	Outbound	−0.033	Baseline
5	Containership	7/30/2015	1:35:02	Outbound	−0.058	Baseline
6	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	11.30 kn
7	Cruise	7/30/2015	3:56:10	Inbound	−0.593	10.64 kn

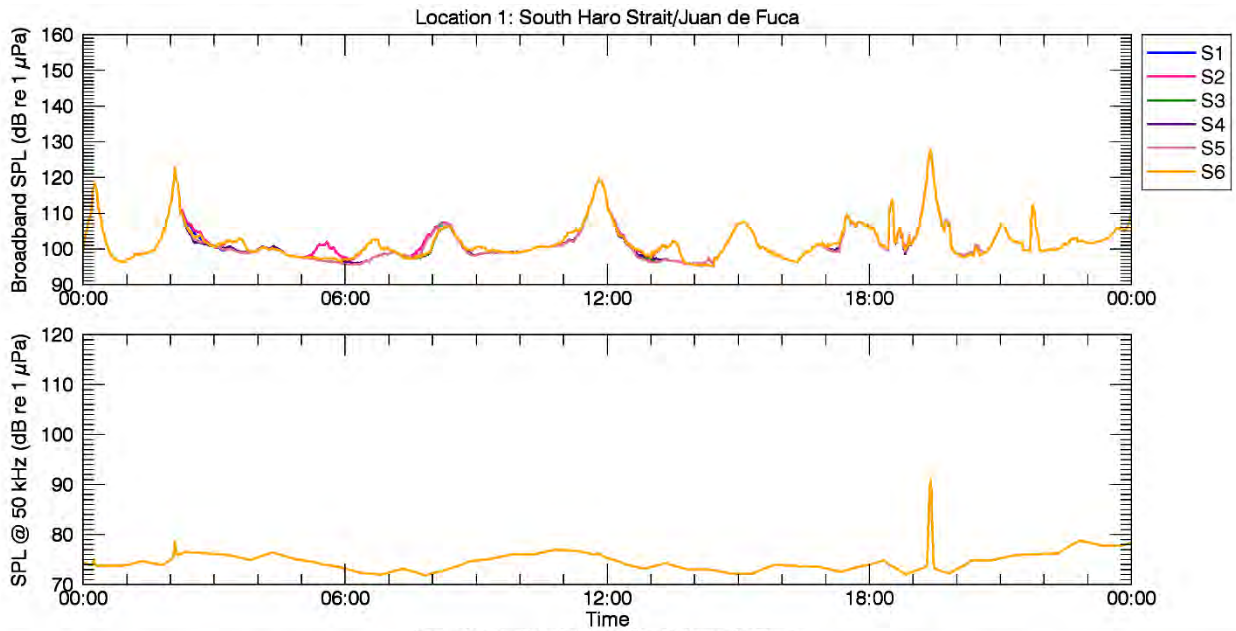
Vessel	Category	Date	Departure time	Route	Deviation from center of route (× 1/2 rms width)	Speed in slowdown zone
8	Tanker	7/30/2015	4:32:10	Inbound	0.067	Baseline
9	Tanker	7/30/2015	5:31:12	Outbound	−0.137	10.95 kn
10	Containership	7/30/2015	6:14:24	Inbound	−0.045	11.40 kn
11	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	Baseline
12	Containership	7/30/2015	9:27:22	Inbound	−2.011	Baseline
13	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	11.30 kn
14	Bulk Carrier/Gen. Cargo	7/30/2015	9:57:36	Outbound	0.101	Baseline
15	Containership	7/30/2015	10:09:07	Outbound	−0.244	11.40 kn
16	Containership	7/30/2015	11:31:12	Outbound	−0.705	Baseline
17	Bulk Carrier/Gen. Cargo	7/30/2015	15:00:00	Inbound	0.732	Baseline
18	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	Baseline
19	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	11.30 kn
20	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	11.48 kn
21	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	11.30 kn
Scenario S11 (Future Traffic Condition, Average Traffic, Baseline)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	Baseline
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	Baseline
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	Baseline
4	Bulk Carrier/Gen. Cargo	7/30/2015	1:59:31	Inbound	-0.150	Baseline
5	Containership	7/30/2015	3:07:12	Inbound	−1.010	Baseline
6	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	Baseline
7	Tanker	7/30/2015	4:32:10	Inbound	0.067	Baseline
8	Containership	7/30/2015	6:14:24	Inbound	−0.045	Baseline
9	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	Baseline
10	Tanker	7/30/2015	7:09:08	Outbound	0.035	Baseline
11	Tug	7/30/2015	7:09:13	Outbound	0.035	Baseline
12	Tug	7/30/2015	7:16:19	Inbound	0.076	Baseline
13	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	Baseline
14	Containership	7/30/2015	10:09:07	Outbound	−0.244	Baseline
15	Containership	7/30/2015	11:31:12	Outbound	−0.705	Baseline
16	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	Baseline
17	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	Baseline
18	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	Baseline
19	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	Baseline
Scenario S12 (Future Traffic Condition, Average Traffic, 11 kn @ 100% participation)						
1	Bulk Carrier/Gen. Cargo	7/30/2015	0:05:46	Inbound	1.889	11 kn

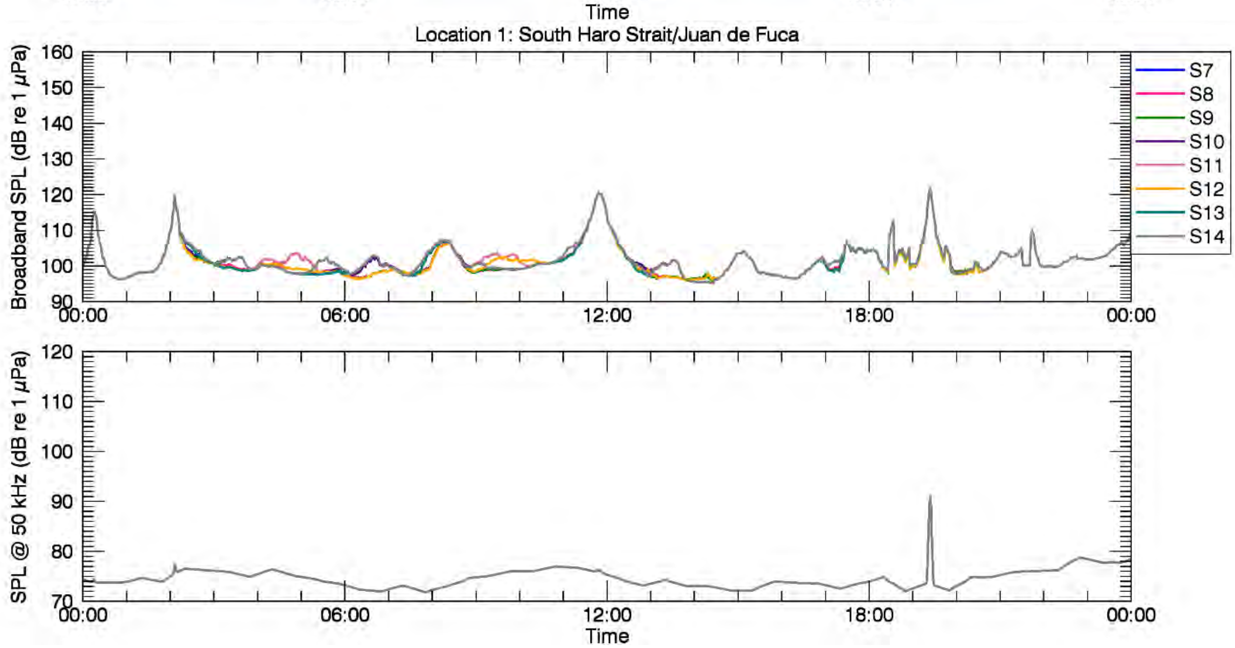
Vessel	Category	Date	Departure time	Route	Deviation from center of route (× 1/2 rms width)	Speed in slowdown zone
2	Bulk Carrier/Gen. Cargo	7/30/2015	0:12:58	Inbound	−0.967	11 kn
3	Containership	7/30/2015	0:27:22	Inbound	−1.299	11 kn
4	Bulk Carrier/Gen. Cargo	7/30/2015	1:59:31	Inbound	-0.150	11 kn
5	Containership	7/30/2015	3:07:12	Inbound	−1.010	11 kn
6	Bulk Carrier/Gen. Cargo	7/30/2015	3:53:17	Outbound	−0.247	11 kn
7	Tanker	7/30/2015	4:32:10	Inbound	0.067	11 kn
8	Containership	7/30/2015	6:14:24	Inbound	−0.045	11 kn
9	Bulk Carrier/Gen. Cargo	7/30/2015	6:48:58	Inbound	−0.25	11 kn
10	Tanker	7/30/2015	7:09:08	Outbound	0.035	11 kn
11	Tug	7/30/2015	7:09:13	Outbound	0.035	11 kn
12	Tug	7/30/2015	7:16:19	Inbound	0.076	11 kn
13	Bulk Carrier/Gen. Cargo	7/30/2015	9:40:19	Inbound	0.421	11 kn
14	Containership	7/30/2015	10:09:07	Outbound	−0.244	11 kn
15	Containership	7/30/2015	11:31:12	Outbound	−0.705	11 kn
16	Bulk Carrier/Gen. Cargo	7/30/2015	16:01:55	Outbound	0.73	11 kn
17	Bulk Carrier/Gen. Cargo	7/30/2015	16:32:10	Outbound	0.378	11 kn
18	Vehicle Carrier	7/30/2015	17:26:53	Inbound	1.438	11 kn
19	Bulk Carrier/Gen. Cargo	7/30/2015	17:44:10	Outbound	1.702	11 kn

Appendix B. Modelled Sound Levels

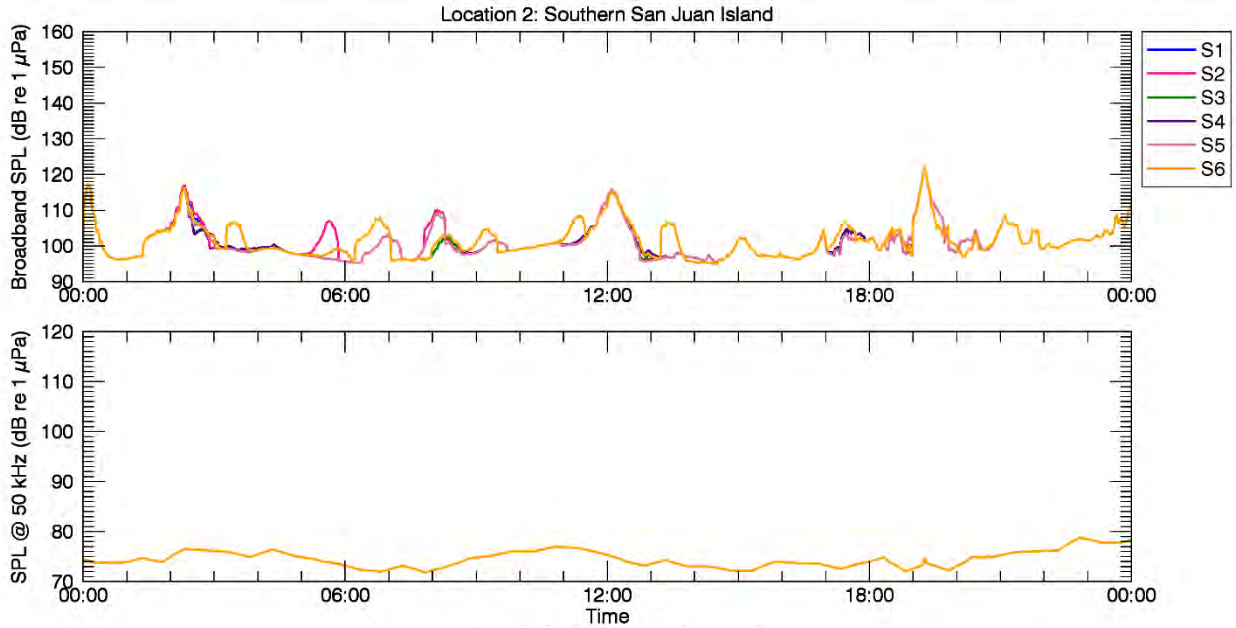
The plots below show modelled SPL (top = broadband, bottom = 1/3-octave-band @ 50 kHz) vs. time for scenarios S1 to S6 and S7 to S14 at each of the eight receiver locations in the study area (see Figure 15 for a map of the receiver locations).

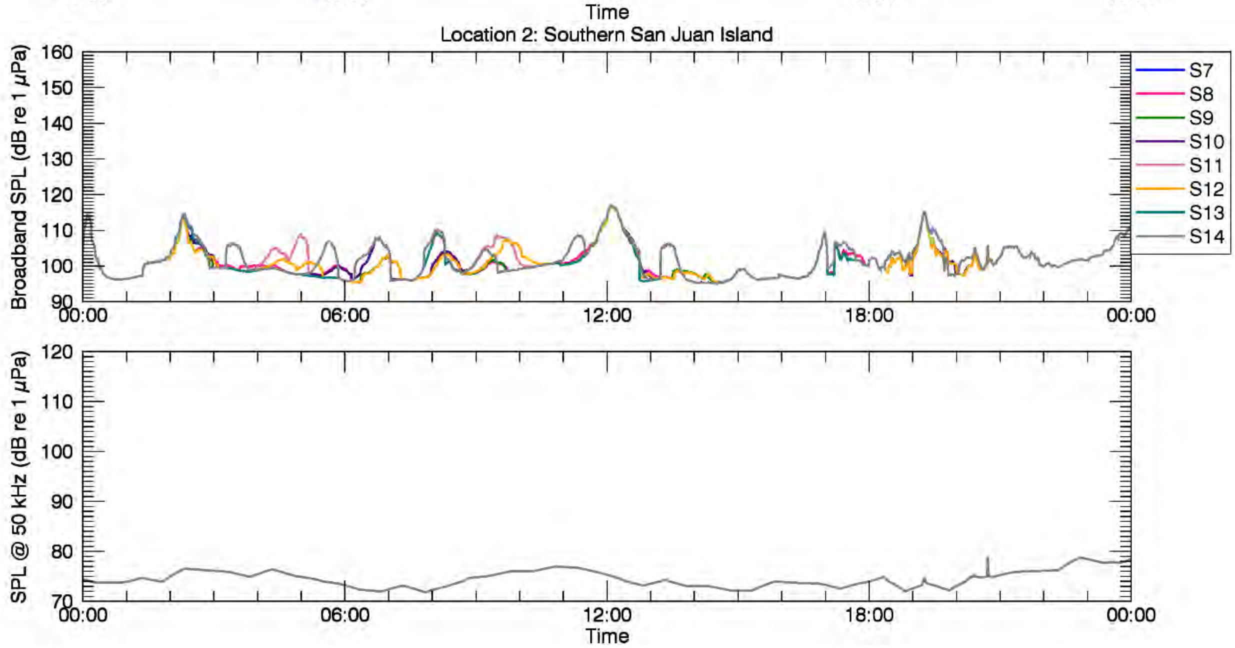
B.1. Location 1



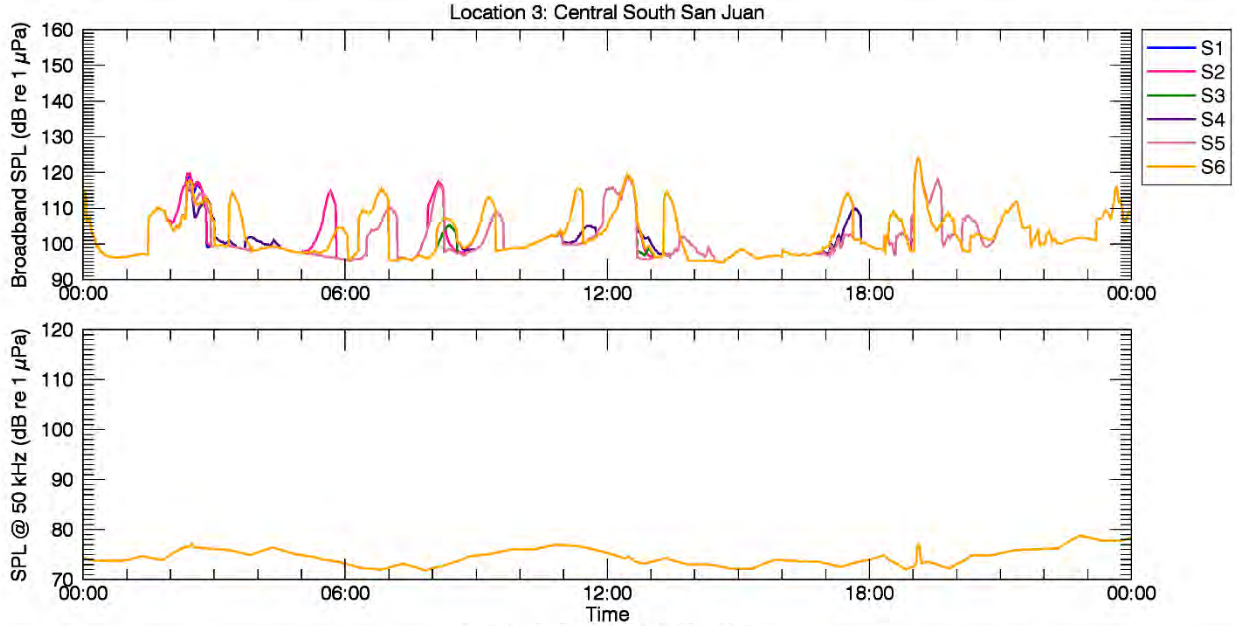


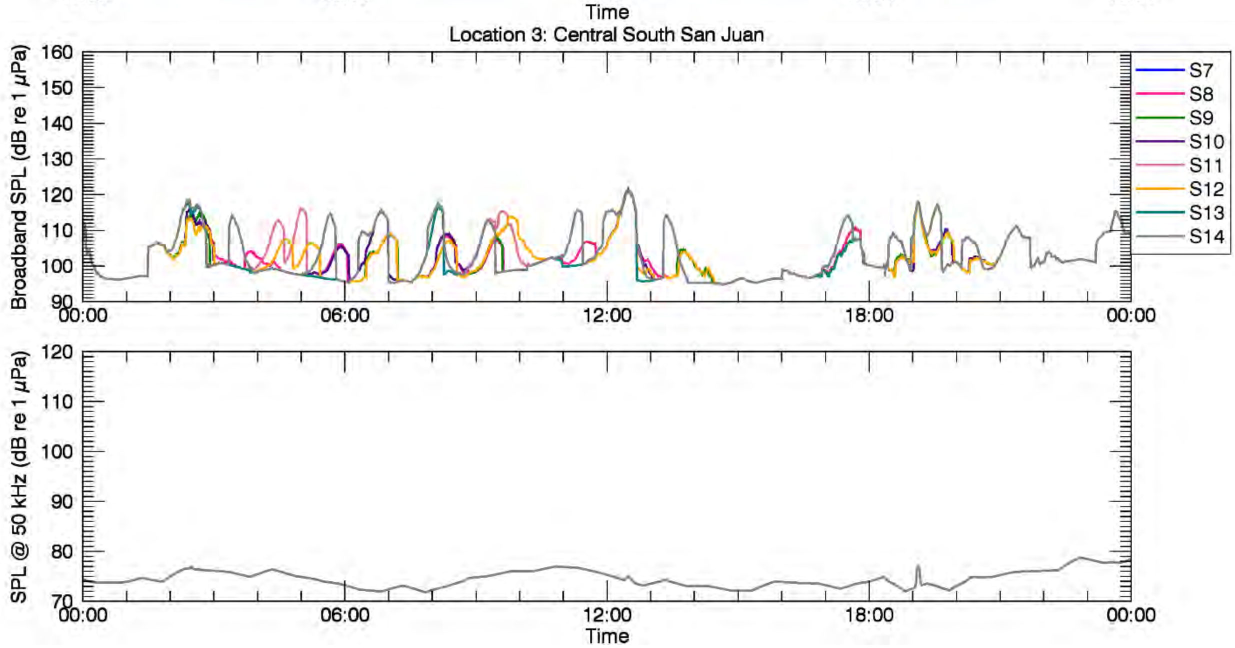
B.2. Location 2





B.3. Location 3





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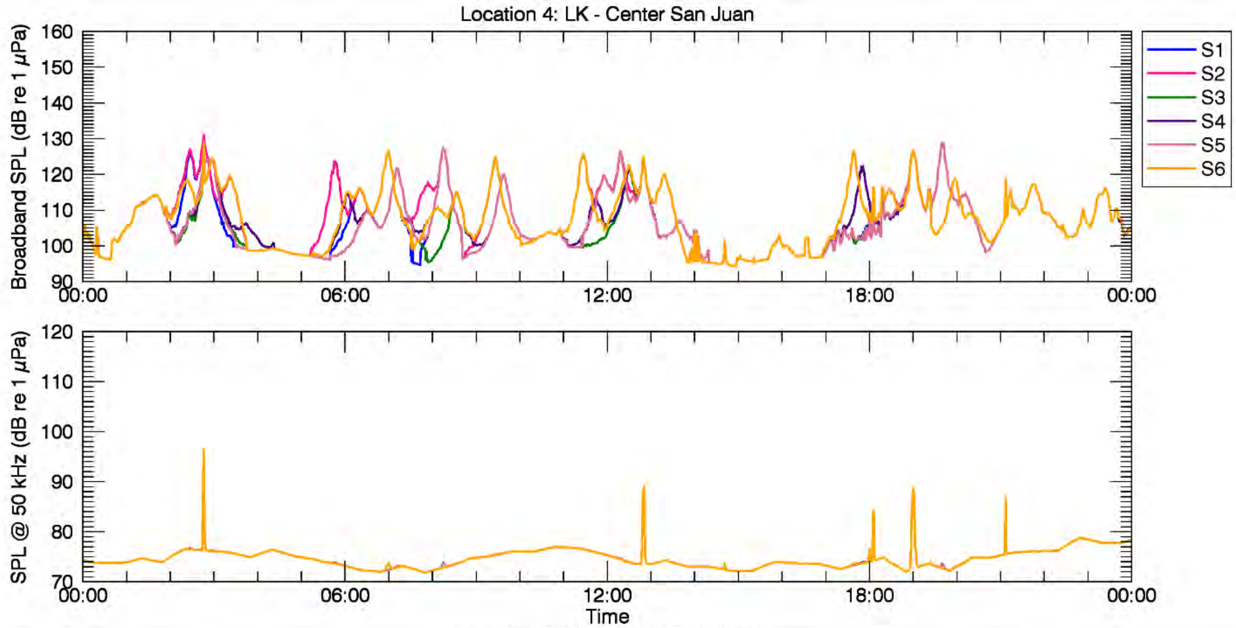

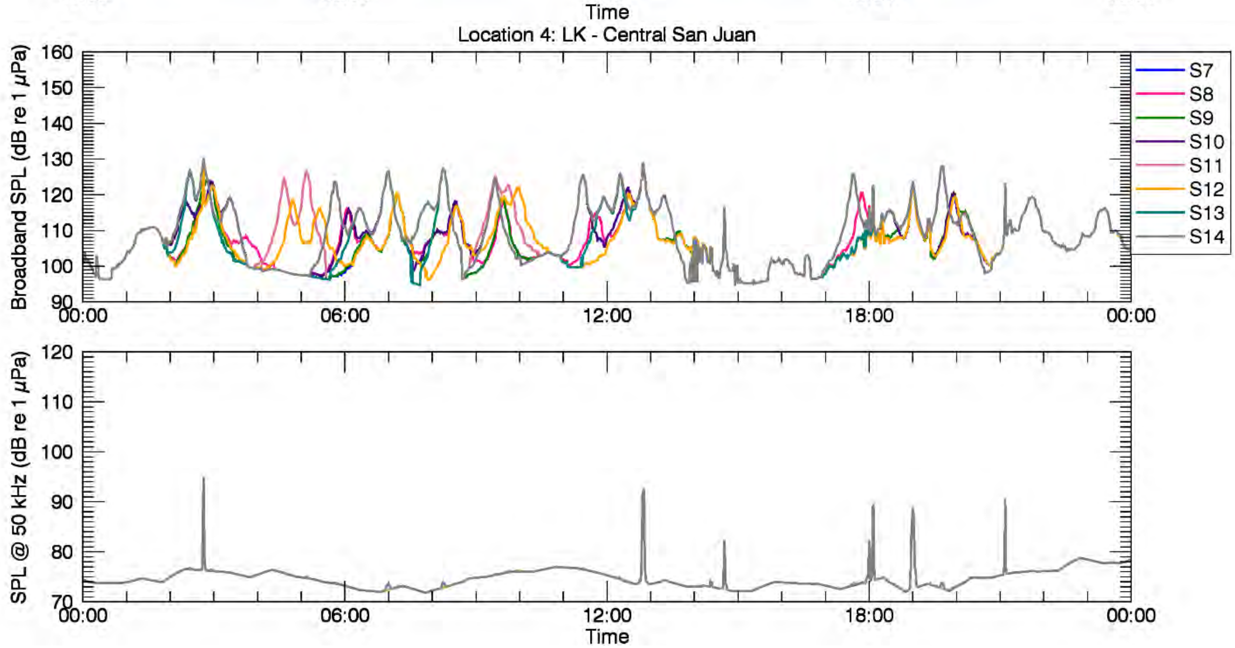

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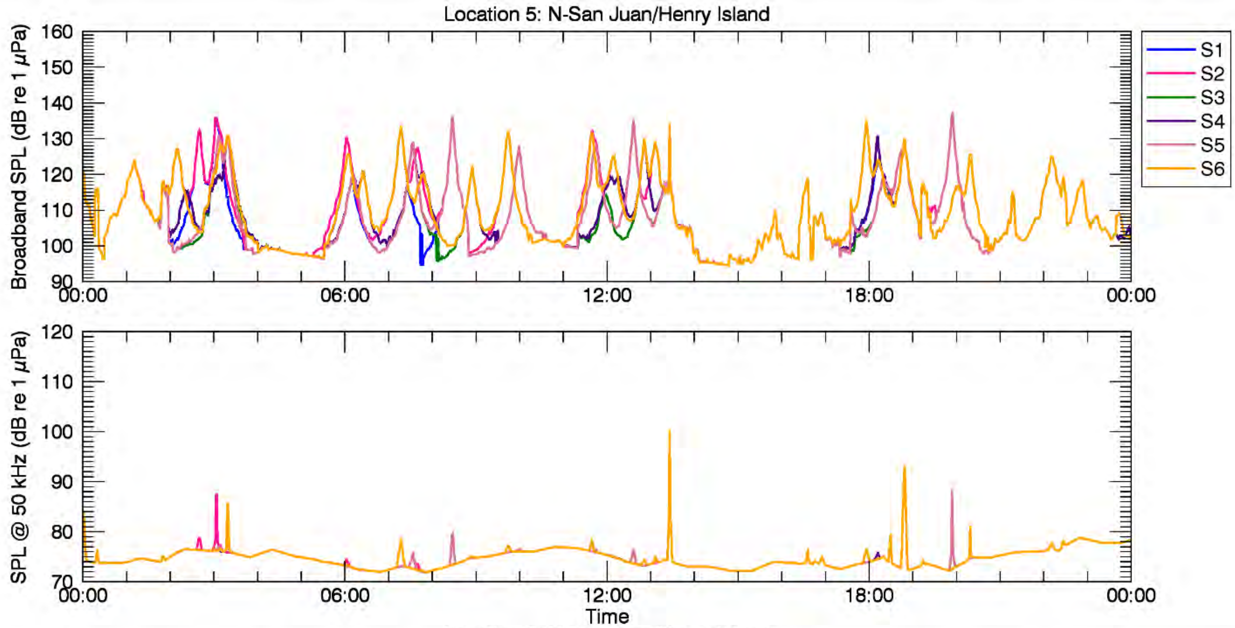

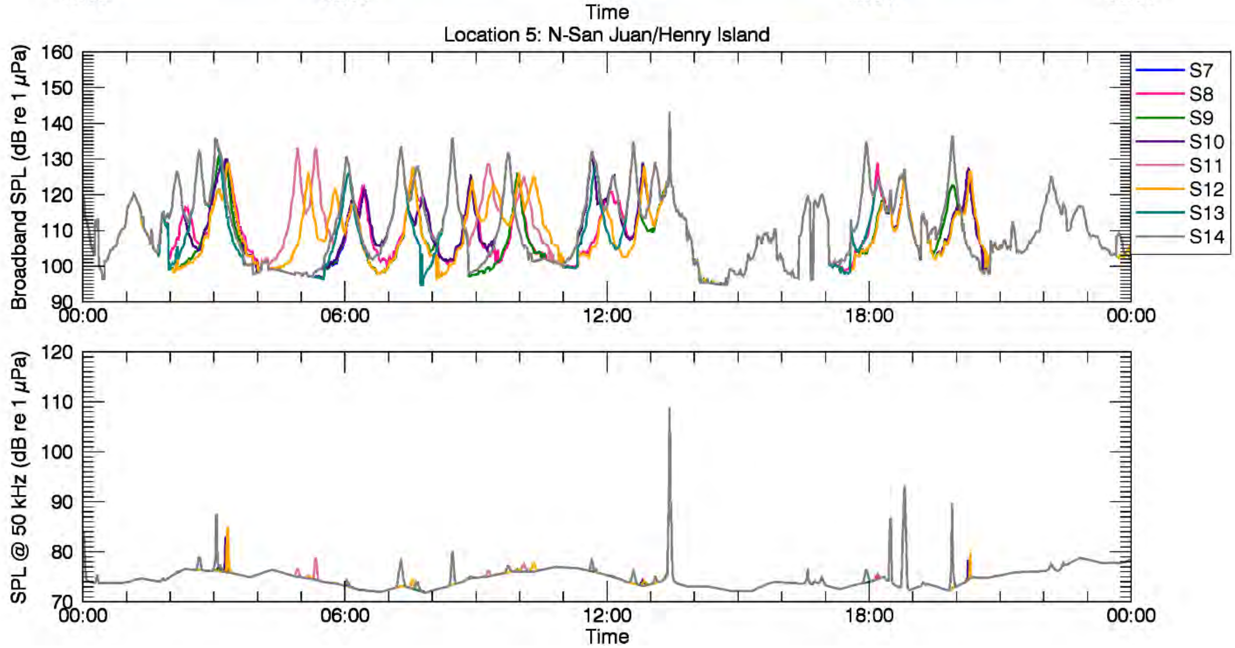

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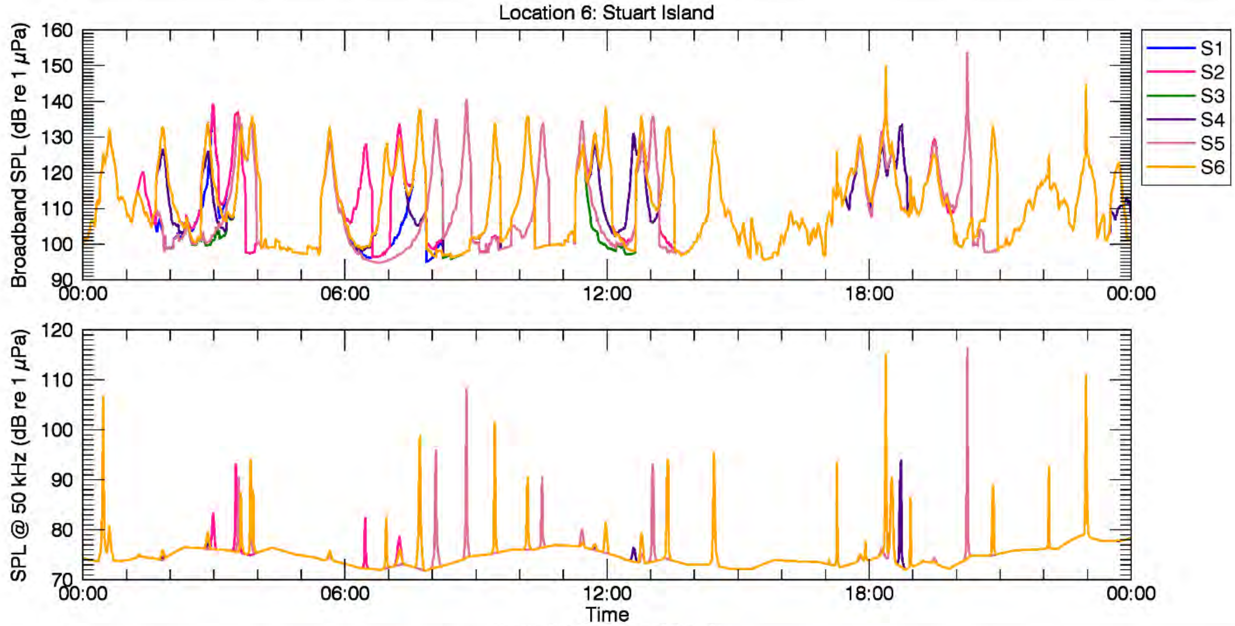

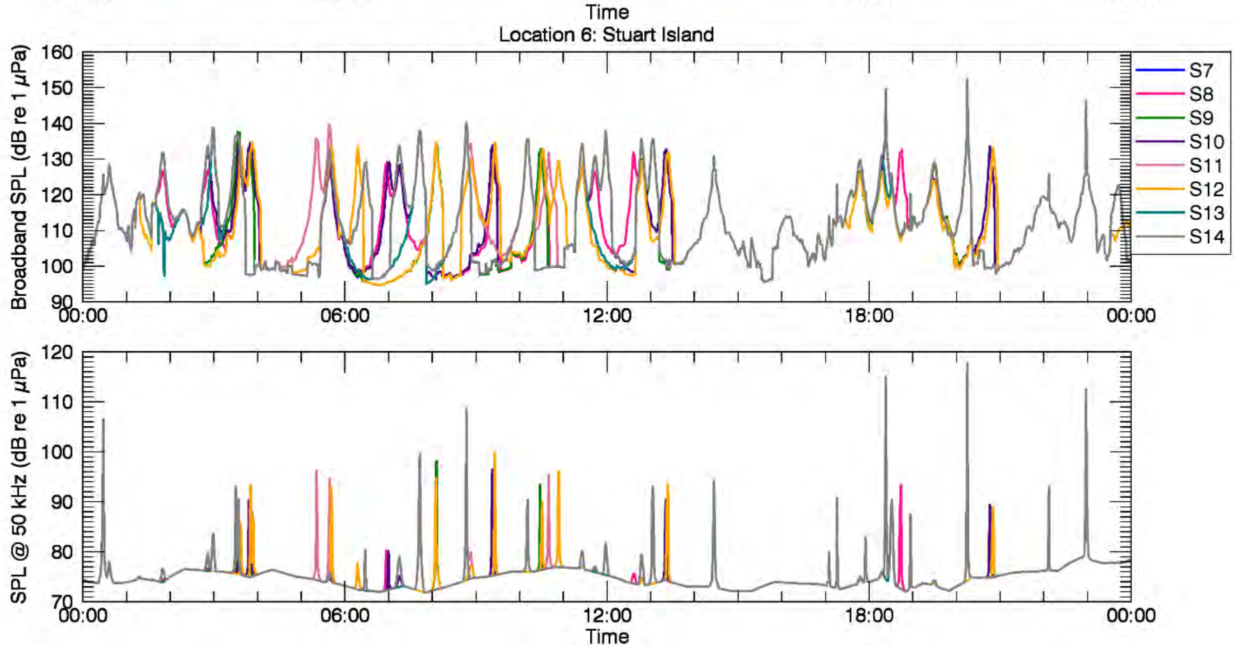

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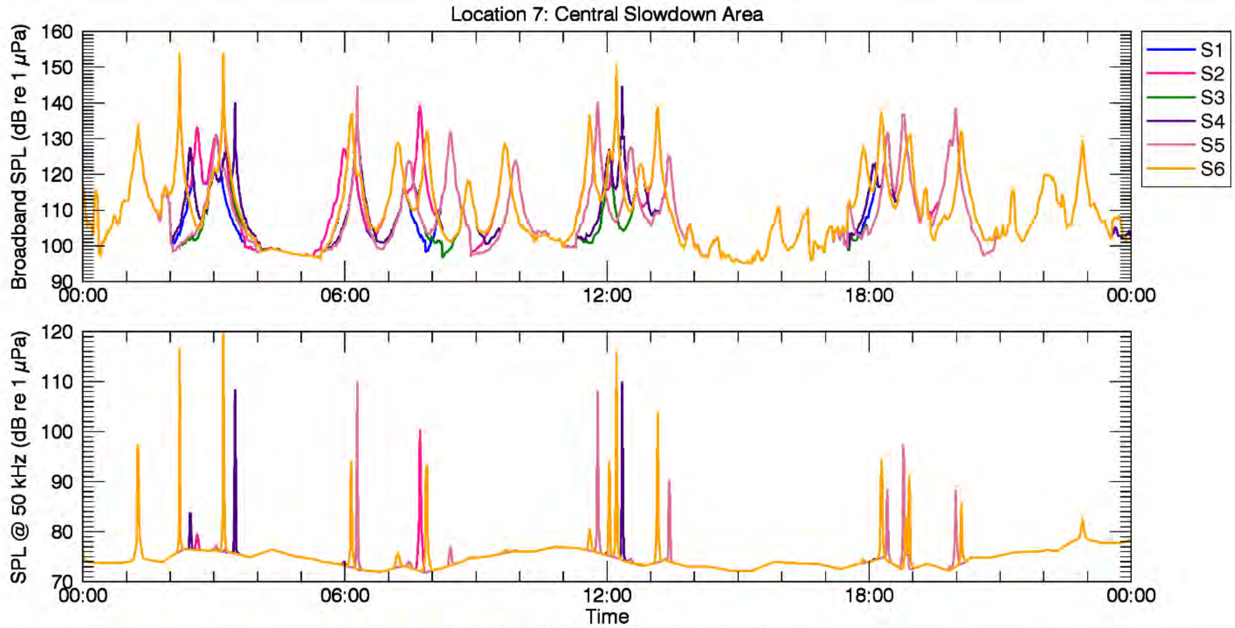

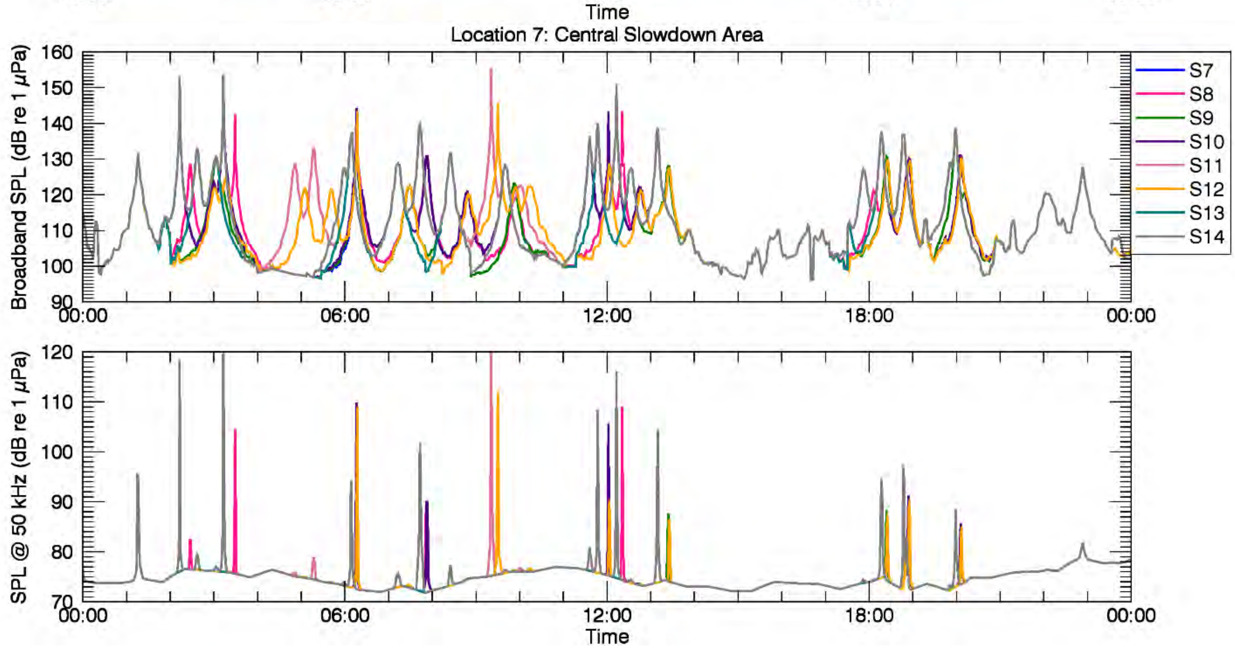

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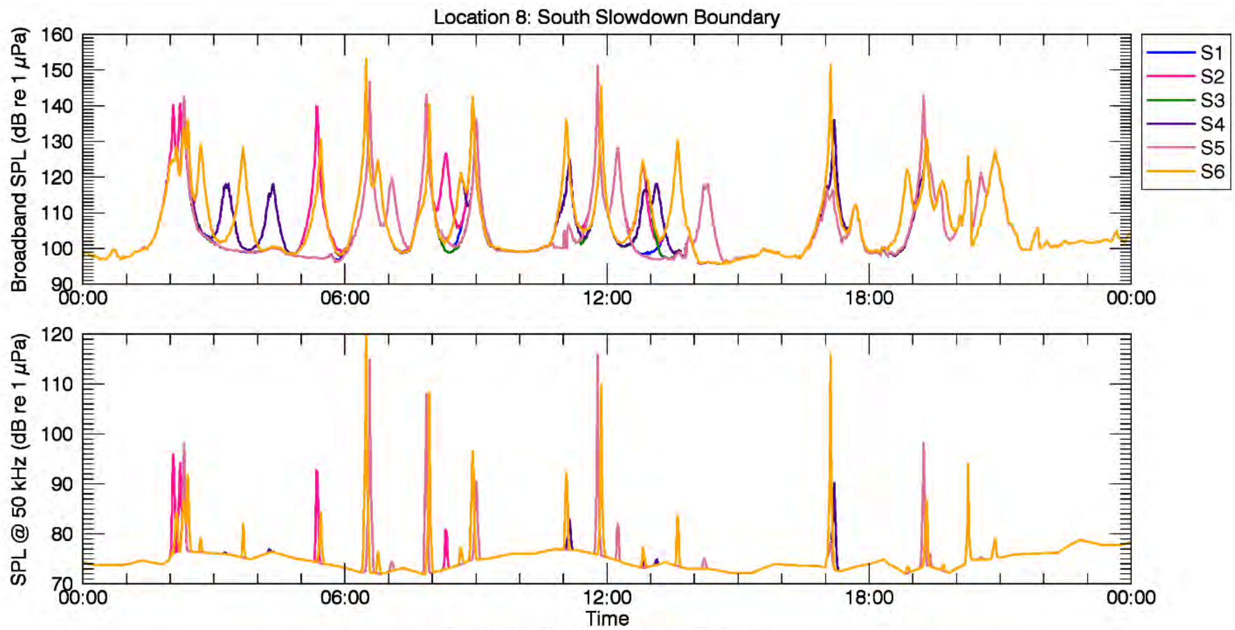

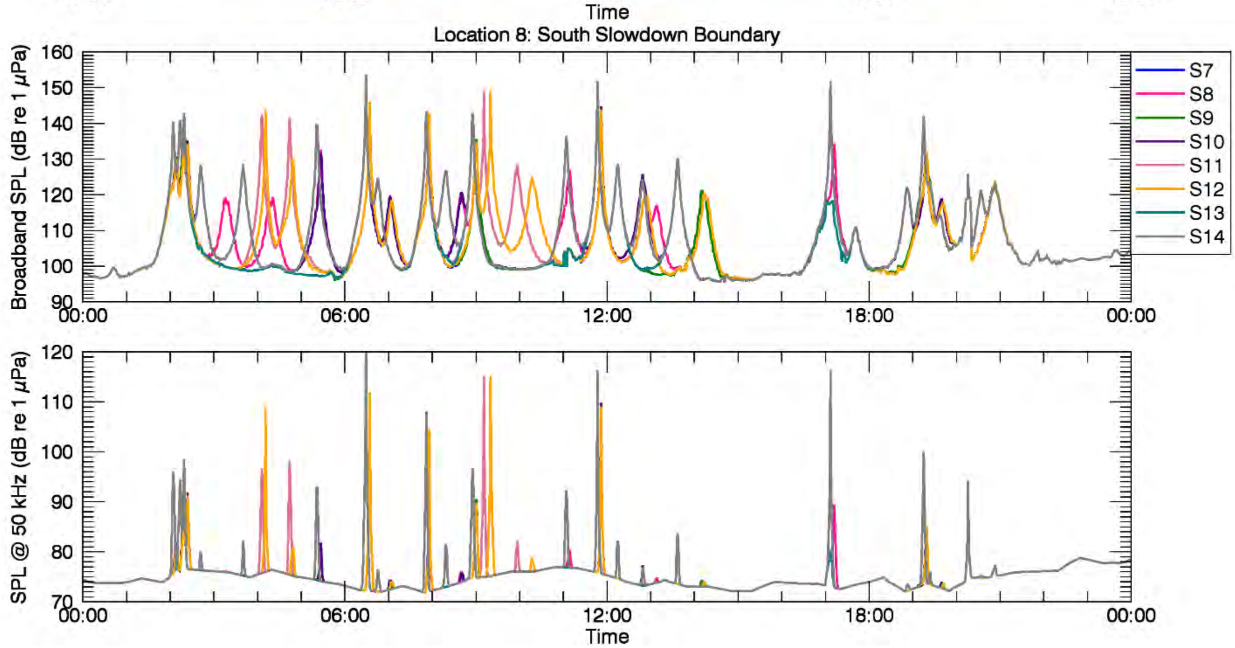

Appendix C. Tabulated Slowdown Differences

The table below lists the differences in modelled SPL at each receiver location in the study area (see Figure 15) for selected pairs of pre-trial and post-trial scenarios under different traffic conditions and rates of slowdown participation. The differences are calculated from the decibel difference of the CDF curves at the 5th, 25th, 50th, 75th, and 95th percentile levels, where the *n*th percentile level is the sound level that is exceeded (100 – n) percent of the time (e.g., the 95th percentile SPL is exceeded 5% of the time).

C.1. Pre-trial Scenarios

Location	SPL difference at *n*th percentile level (dB)				
	5th	25th	50th	75th	95th
Slowdown Differences: Average Traffic 50% Participation @ 11 knots (S5 – S1)					
1	-0.222	-0.493	-0.430	-0.185	-0.095
2	0.163	-0.293	-0.431	-1.176	-0.319
3	0.382	0.023	-0.017	-2.138	-0.538
4	0.513	-0.014	-1.068	-1.900	-2.250
5	0.060	-0.993	-0.788	-1.528	-1.768
6	-0.331	-0.136	-0.561	-0.664	-1.440
7	0.061	-0.582	-0.779	-1.338	-1.980
8	0.145	-0.131	-0.089	-0.818	-1.057
Slowdown Differences: Average Traffic 100% Participation @ 11 knots (S3 – S1)					
1	-0.207	-0.646	-0.490	-0.410	-0.098
2	0.314	-0.394	-0.681	-1.456	-1.331
3	0.449	0.015	-0.016	-2.778	-3.937
4	0.443	0.126	-1.598	-3.831	-5.058
5	-0.012	-0.421	-1.949	-2.764	-4.947
6	-0.794	-0.295	-0.346	-2.325	-2.686
7	0.029	-0.312	-1.942	-2.360	-4.868
8	0.295	-0.024	-0.086	-1.229	-3.126
Slowdown Differences: High Traffic 50% Participation @ 11 knots (S6 – S2)					
1	0.001	-0.334	-0.200	-0.548	-0.031
2	0.158	-0.326	-0.546	-0.513	-1.495
3	0.031	-0.135	0.035	-1.304	-1.634
4	0.000	0.131	-1.448	-1.536	-2.970

Location	SPL difference at *n*th percentile level (dB)				
	5th	25th	50th	75th	95th
5	0.000	0.339	-0.552	-0.932	-2.587
6	-0.229	0.271	-0.296	-0.530	-1.379
7	-0.207	0.289	-0.979	-1.852	-2.001
8	0.000	-0.073	-0.494	-1.581	-2.436
Slowdown Differences: High Traffic 100% Participation @ 11 knots (S4 – S2)					
1	-0.360	-0.930	-0.757	-1.023	-0.098
2	0.329	-0.583	-1.338	-1.976	-1.495
3	0.582	-0.141	-0.177	-3.434	-4.048
4	0.418	0.279	-3.289	-4.532	-5.326
5	0.018	-0.145	-2.175	-2.635	-5.874
6	-0.093	0.967	-0.848	-1.731	-3.678
7	-0.146	-0.128	-2.697	-3.166	-5.320
8	0.434	-0.056	-0.464	-2.467	-3.980

C.2. Post-Trial Scenarios

Location	SPL difference at *n*th percentile level (dB)				
	5th	25th	50th	75th	95th
Slowdown Differences: Average Traffic Actual% Participation @ Actual Speeds (S9 – S13)					
1	-0.047	-0.352	-0.369	-0.171	-0.191
2	0.171	0.071	-0.403	-1.042	-0.922
3	0.304	0.053	0.054	-1.865	-1.185
4	0.159	-0.164	-0.639	-2.705	-2.722
5	0.060	-0.611	-0.891	-0.934	-2.085
6	-0.295	0.133	-0.877	-0.821	-1.863
7	0.022	-0.446	-0.734	-1.254	-2.439
8	0.455	-0.267	-0.116	-0.906	-2.358
Slowdown Differences: Average Traffic 100% Participation @ 11 knots (S7 – S13)					
1	-0.093	-0.428	-0.412	-0.436	-0.246

Location	SPL difference at *n*th percentile level (dB)				
	5th	25th	50th	75th	95th
2	0.323	-0.054	-0.558	-1.143	-0.879
3	0.363	0.070	0.113	-2.859	-4.351
4	0.133	0.072	-0.996	-3.799	-3.957
5	-0.028	-0.414	-2.031	-2.076	-5.206
6	-0.733	0.066	-0.847	-1.577	-3.094
7	0.195	-0.493	-1.771	-2.167	-5.960
8	0.455	-0.075	0.003	-1.492	-3.644
Slowdown Differences: High Traffic Actual% Participation @ Actual Speeds (S10 – S14)					
1	0.000	-0.395	-0.117	-0.274	-0.187
2	0.155	-0.347	-0.456	-0.886	-0.865
3	0.097	-0.042	0.018	-1.330	-1.497
4	0.005	-0.076	-1.536	-2.024	-2.967
5	-0.499	0.474	-0.932	-0.989	-2.539
6	0.046	0.358	-0.324	-0.627	-1.626
7	-0.026	0.121	-1.014	-1.994	-2.708
8	0.006	0.032	-0.206	-1.323	-1.684
Slowdown Differences: High Traffic 100% Participation @ 11 knots (S8 – S14)					
1	0.019	-0.844	-0.737	-0.669	-0.226
2	0.294	-0.297	-1.013	-2.288	-1.045
3	0.416	0.097	0.167	-3.034	-4.306
4	0.399	0.159	-2.736	-5.197	-4.780
5	-0.495	-0.169	-2.198	-2.727	-6.125
6	0.509	1.962	-0.974	-1.542	-3.846
7	-0.026	-0.371	-2.035	-3.417	-6.327
8	0.632	0.028	-0.214	-2.079	-4.746
Pre-vs-post-trial Differences: Average Traffic 100% Participation (S7 – S3)					
1	0.229	-0.147	-0.173	-0.637	-2.002
2	0.003	0.017	0.243	0.014	-0.595
3	-0.245	0.002	0.467	-0.004	-0.631
4	0.257	0.691	1.006	-0.060	0.808

Location	SPL difference at *n*th percentile level (dB)				
	5th	25th	50th	75th	95th
5	0.753	0.442	0.890	1.091	-0.467
6	0.340	1.241	2.027	1.075	-0.660
7	0.871	0.897	1.025	-0.048	-1.373
8	-0.310	-0.053	0.189	0.019	-1.029
Pre-vs-post-trial Differences: High Traffic 100% Participation (S8 – S4)					
1	0.190	-0.081	-0.224	-0.601	-1.982
2	-0.021	-0.028	0.168	-0.152	-0.595
3	-0.325	0.191	0.360	0.249	-0.552
4	0.585	0.287	0.826	-0.344	0.227
5	0.822	0.513	1.010	0.185	-0.586
6	0.983	1.741	1.606	0.167	-0.492
7	0.839	0.919	1.068	-0.344	-1.059
8	-0.372	0.111	0.357	0.141	-1.366
Future Traffic Differences: Avg Traffic Future (S11 – S13)					
1	0.000	0.351	0.783	0.169	0.000
2	0.000	0.126	0.670	1.195	0.000
3	0.005	0.007	0.816	1.237	0.102
4	0.000	1.343	2.322	1.555	0.984
5	0.693	2.228	2.150	1.732	1.065
6	0.234	1.754	1.441	1.569	0.947
7	1.595	1.602	1.604	2.527	0.799
8	0.000	0.626	1.527	3.148	2.724
Future Slowdown Differences: Avg Traffic 100% Participation (S12 – S11)					
1	-0.093	-0.556	-0.692	-0.605	-0.246
2	0.323	0.056	-0.569	-1.986	-0.879
3	0.358	0.278	0.208	-2.397	-3.409
4	0.269	-0.238	-2.030	-4.260	-4.205
5	0.000	-1.014	-2.184	-2.406	-5.369
6	-0.866	-0.090	-1.139	-1.054	-2.805
7	-0.161	-1.215	-1.670	-2.643	-6.062

Location	SPL difference at *n*th percentile level (dB)				
	5th	25th	50th	75th	95th
8	0.509	-0.026	-0.057	-1.260	-4.127

Appendix E

SRKW behavioural response modelling report - SMRU Consulting North America

Modelling of SRKW Behavioural Responses and Masking from Vessel Noise Exposure during the Haro Strait Slowdown Trial

Prepared for the ECHO Program of Vancouver Fraser Port Authority

[May 2018]

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Modelling of SRKW Behavioural Responses and Masking from Vessel Noise Exposure during the Haro Strait Slowdown Trial

May 2018

Prepared by SMRU Consulting NA

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Executive Summary

Underwater noise may be impacting the population recovery of endangered Southern Resident Killer Whales (SRKW). One of the potential mitigation measures to reduce the impact of vessel noise on SRKW is a vessel slowdown, but the exact benefits to SRKW are not well understood, given vessel source level intensity will drop but vessels will also take longer to travel through the area. To study this, the Vancouver Fraser Port Authority's ECHO Program initiated a voluntary piloted vessel slowdown trial, which took place August 7 through October 6, 2017 in Haro Strait, an SRKW hot-spot off the west coast of San Juan Island in the core of their summer critical habitat.

In order to better understand the potential benefits of a slowdown trial to SRKW a two-step process was initiated which included noise modelling, followed by SRKW behavioural response modelling. Prior to the slowdown trial, fine-scale vessel noise was modelled for a 24-hour period by Jasco Applied Sciences Ltd., for six scenarios that included using baseline (normal) speeds and then varying compliance to 11 knot slowdown speeds for current average and high-level traffic volumes. After completion of the slowdown trial, eight additional post-trial scenarios were modelled using newly developed vessel speed-noise level relationships based on slowdown trial results. Four scenarios were comparable with pre-trial modelling, two scenarios modelled the average vessel speeds and compliance rates estimated from the slowdown trial itself, while the final two post-trial scenarios modelled average future traffic volume.

This study uses an SRKW-noise exposure model (SMRU 2014a) to predict how slowdown related reductions in noise levels in Haro Strait may affect the number of SRKW behavioural responses (BRs) and degree of residual echolocation click masking. The model uses a ten-year SRKW effort-corrected habitat use synthesis coupled with low and moderate severity dose-response relationships and a high frequency (50 kHz) click masking model to determine, for each scenario, a relative effect metric termed 'potential lost foraging time'. This spatially-explicit probabilistic model aims to accumulate how many minutes each whale is inhibited or disrupted from its ability to forage due to received noise levels; either from an associated change in behavioural state (i.e., from foraging to traveling, e.g., Lusseau et al. 2009), or via masking of communication calls/whistles and echolocation clicks.

When vessels are moving slower during 'speed compliance', or when there are fewer vessels (average traffic volume vs high traffic volume), there is clear reduction in the number of BRs and consequently a reduction in the time foraging is potentially affected by vessel noise The pre-trial scenarios modelled with 100%, 11 knot speed compliance during the slowdown period resulted in a reduction of 'potential lost foraging time' per whale of 20.6% and 21.4% (average and high traffic volume respectively) compared to baseline (normal) vessel speeds. For 50% 11 knot speed compliance, the pre-trial modelling showed reductions at 8.1% and 10.4% respectively.

The application of new vessel speed-noise relationships (speed scaling coefficients) increased the baseline 'potential lost foraging time' by 4.9% and 1.2% (average and high traffic volume respectively). The comparable post-trial scenarios modelled with 100%, 11 knot speed compliance, predicted the 'potential lost foraging time' per whale was reduced by 22.7% and 24.3% (average and high traffic volume respectively) compared to baseline (normal) vessel speeds.

Using the observed trial compliance rate of 57 percent of vessels slowing down, the mean actual slowdown speeds (instead of 11 knots), and the post-trial vessel speed-noise relationship, the reduction in 'potential lost foraging time' per whale from baseline conditions was 11.5% and 10.3% for average and high traffic volumes respectively. Overall, these reductions reflect decreased numbers of moderate severity BRs and to a lesser extent low severity BRs. Changes in lost foraging time due to residual click masking were very small across scenarios, typically showing a minor (1%) increase from baseline. Masking increases are a consequence of fewer lost foraging minutes from higher severity behavioural responses allowing for more minutes that whales were potentially susceptible to modelled click masking.

Overall, the post-trial modelling results highlight a number of important conclusions:

- The use of new vessel speed-noise relationships (speed scaling coefficients) developed by Jasco during the slowdown trail resulted in a ~3% higher prediction of current baseline effects compared to published uniform speed coefficients, but their use also resulted in a greater benefit in effect reduction when comparing vessel slowdowns with the baseline conditions.
- Vessel noise effects on foraging SRKW during the 2017 Haro Strait slowdown trial were predicted by a computer simulation model to be on an average traffic day, 11.5% lower than current baseline conditions.
- This study highlights that despite the longer duration of exposure during a speed slowdown, the resulting concurrent decrease in received noise levels at whales, reduces the overall number of predicted behavioural response caused by vessel noise. Predicted levels of residual echolocation click masking remain similar during a slowdown. Overall, vessel speed slowdowns are shown to be an effective noise mitigation method for increased future traffic volumes.
- The number of predicted behavioural responses caused by vessel noise varied by pod, with the highest predicted for J-pod due to their higher occurrence in the study area. Overall, the highest responses were predicted in the summer months (June through September).
- Absolute values of 'potential lost foraging time' should be treated with caution but do provide additional perspective. The slowdown trial resulted in a predicted reduction in impact to SRKW foraging of 1.6 hours per whale, or 126 hours for the population of 78 animals (the whale population at the time of model development). Compared to current baseline, a 100% compliance to an 11 knot speed slowdown would result on average, in a reduction of 3.18 hours in potential noise effects on foraging <u>per whale</u> across the 61-day slowdown period. This can be extrapolated to total reduction of 248 hours for the population.
- Based on the modelling results, when 50 to 100 percent of vessels comply with a vessel slowdown, these concurrent lower vessel source levels result in a clear positive benefit in the amount of time SRKW are potentially disturbed by vessel traffic noise, despite the longer exposure times due to slower vessel speeds through Haro Strait.

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List of Acronyms

AIS: Automated Identification System
BR: Behavioural Response
dB: Decibel
DTAG: Digital Acoustic Recording Tag
ECHO: Enhancing Cetacean Habitat and Observation
HF: High Frequency
Hz: Hertz
kHz: kilohertz
PSD: Power Spectral Density
SRKW: Southern Resident killer whale

1. Introduction

1.1 Purpose of the Study

Underwater noise has the potential to affect marine mammals through behavioural changes, range displacement, communication masking, decreased foraging efficiency, hearing damage, and physiological stress. Underwater noise may be impacting the population recovery of endangered Southern Resident Killer Whales (SRKW). The environmental assessment conducted for a proposed terminal near Roberts Bank, Vancouver, BC, considered the potential effects of underwater noise from large commercial vessels (e.g., merchant ships, ferries, tugs, large passenger vessels) on SRKW using a spatially explicit SRKW-noise exposure model (SMRU 2014a). This simulation model used data from a ten-year SRKW habitat use synthesis and a commercial vessel noise model to predict both the number of noise-related behavioural responses or BRs (using an SRKW-specific dose-response relationship) and the extent of any residual high frequency echolocation click masking (Erbe 2002).

One of the various mitigation measures under consideration to reduce the impact of commercial vessel noise on SRKW is a vessel slowdown (Veirs et al. 2018), but the exact benefits of such a measure are not well understood. Therefore, Vancouver Fraser Port Authority's ECHO Program initiated a voluntary commercial vessel slowdown trial, which took place August 7 through October 6, 2017 in Haro Strait, a well-documented Southern Resident killer whale (SRKW) hot-spot off the west coast of San Juan Island in the core of summer critical habitat (Figure 1). All vessels transiting Haro Strait were asked to reduce their speed to 11 knots from averages of 18+ knots for container ships and 13+ knots for bulk carriers. This level of speed reductions may, at least in theory, reduce instantaneous sound intensity levels by as much as 75% for container ships and 40% for bulk carriers, but vessels will also take longer to travel through the area. SMRU Consulting North America monitored underwater ambient noise levels and killer whale presence before and during the slowdown trial. These analyses have been presented to ECHO in previous reports.

Before the trial started, in order to better understand the potential benefits of a slowdown trial to SRKW, a variety of baseline speed and vessel slowdown traffic scenarios estimating fine-scale commercial vessel noise were modelled by Jasco Applied Science (JASCO 2017). Six pre-trial scenarios were modelled in total, varying the number of commercial vessels transiting Haro Strait and the proportion of vessels that might comply with the voluntary vessel slowdown trial. The resulting noise layers for each scenario were used to re-run the SRKW-noise exposure model (SMRU 2014a) to estimate the number of SRKW behavioural responses and residual click masking that result from slowdown-related reductions in noise levels in Haro Strait, i.e., by running the model with data from the slowdown trial we will be able to simulate the benefits of slower ships to killer whales. In addition, the trial helped collect data to better understand the relationship between reduced vessel speed and underwater noise both at the individual vessel level as well as in terms of ambient noise. Empirical vessel source level data collected during this trial and via the Underwater Listening Station was used to derive new vessel speed-noise level relationships in the form of frequency specific speed scaling coefficients. These new data were incorporated into eight additional post-trial scenarios, which were also run through the SRKW-noise exposure model to provide not only better precision on estimates of the benefits of a vessel slowdown to SRKW, but also to investigate potential effects of increased traffic volume in the future.

1.2 Project Description

Noise was modelled for six pre-trial model scenarios (Table 1) and eight post-trial model scenarios that used newly collected information on vessel speed-noise relationships by vessel category (Table 2) for the Haro Strait study area (Figure 1) plus a 20 km buffer region (JASCO 2017).

For the pre-trial scenarios, two scenarios modelled current vessel traffic at baseline speeds, firstly using an "average" (50^{th} %ile) per summer day number (scenario S1) of large commercial piloted vessels (n=14) and secondly using a "high" (95^{th} %ile; scenario S2) daily traffic volume (n=21) of piloted vessels (details of assumptions in Appendix 1). As well as piloted vessels, a number of non-piloted AIS-enabled vessels transit the study area. The speed and number of these vessels were kept consistent from baseline scenarios when modeling the slowdown scenarios, i.e., all scenarios assumed baseline traffic conditions for non-piloted vessels. Scenarios 3 and 4 (average and high traffic volume) reduced the speed of all piloted vessels to the proposed slowdown speed of 11 knots (i.e., 100% compliance), while scenarios 5 and 6 modelled only 50% compliance to slowdown speeds (with remaining vessels at normal speeds).

For the post-trial scenarios, two scenarios (S7 and S8) repeated pre-trial scenarios 3 and 4 (100% compliance at 11 knots), but used, as per all post-trial scenarios, new information on vessel speed-noise relationships by vessel category. Scenarios 9 and 10 used data that aimed to best match the mean vessel speeds and used compliance rates by vessel category actually recorded during the slowdown trial. The overall compliance rate was set at 57% for both scenarios. Scenarios 11 and 12 modelled a future traffic condition by adding 1 containership, 1 bulker and 1 tanker with an escort tug to the average (50^{th} %ile) number of piloted ship transits. Scenario 11 assumed baseline (normal) speeds, while scenario 12 assumed 100% compliance of piloted vessels to the proposed slowdown trial speed of 11 knots. Scenarios 13 and 14 repeated pre-trial baseline scenarios 1 and 2, with the new vessel speed-noise relationships, to ensure valid matched comparisons. All scenarios assumed baseline traffic conditions for non-piloted vessels, as only piloted vessels were considered to slowdown in this study. For each model scenario, Jasco Applied Science provided broadband noise levels (9 Hz to 70.8 kHz), as well as noise levels in the 1/3 octave band centred on 50 kHz (JASCO 2017).

Table 1 Summary table of six pre-trial baseline and slowdown model scenarios. All scenarios assume baseline (normal or current) traffic conditions.

Scenario Number	Traffic Conditions	Piloted Ship Speeds	Slowdown Compliance Rate	Number of Piloted Ship Transits
S1	Baseline	Baseline	n/a	Average (50th %ile)
S2	Baseline	Baseline	n/a	High (95th %ile)
S3	Baseline	11 knot	100%	Average (50th %ile)
S4	Baseline	11 knot	100%	High (95th %ile)
S5	Baseline	11 knot / baseline	50%	Average (50th %ile)
S6	Baseline	11 knot / baseline	50%	High (95th %ile)

Table 2 Summary table of eight post-trial model scenarios, that include new vessel speed-noise level relationships by vessel category. Six scenarios assume slowdown speed with baseline (normal or current) traffic conditions and two scenarios that assume increased future traffic conditions (three commercial vessels and one support tug).

Scenario Number	Traffic Conditions	Piloted Ship Speeds	Slowdown Compliance Rate	Number of Piloted Ship Transits
S7	Baseline	11 knot	100%	Average (50th %ile)
S8	Baseline	11 knot	100%	High (95th %ile)
S9	Baseline	57% "Per trial" mean 43% baseline	57% "Per trial"	Average (50th %ile)
S10	Baseline	57% "Per trial" mean 43% baseline	57% "Per trial"	High (95th %ile)
S11	Future	Baseline	n/a	Average (50th %ile)
S12	Future	11 knot	100%	Average (50th %ile)
S13	Baseline	Baseline	n/a	Average (50th %ile)
S14	Baseline	Baseline	n/a	High (95th %ile)

2. Methods

2.1 Study Area

The Haro Strait study area for modelling is depicted in Figure 1. The model area includes all of Haro Strait and surrounding waters, including the 11 knot slowdown trial boundary as well as associated speed transition areas to the north and south, including the area around the Victoria pilot station at Brotchie. The slowdown boundary represents a distance of 16.6 nm for inbound vessels and 14.9 nm for outbound vessels. The underlying SRKW-noise exposure model uses SRKW effort-corrected habitat use and monthly pod presence (Hemmera and SMRU 2014) within a wider regional study area for which ten years of reliable SRKW sightings data was available (Figure 2).

2.2. SRKW-noise exposure model

The SRKW-noise exposure model was first developed to capture the large variability in noise levels received by whales as large commercial vessel are transiting through the Salish Sea (SMRU 2014a). This requires fine-scale information on SRKW habitat use and monthly presence as well as received noise levels. Data used for the piloted vessel noise layer were provided in one-minute time increments across 200m sized grid cells for 14 scenarios (Tables 1 and 2), covering a 24-hour summer period (i.e., 1440 one-minute files for each of the 12 scenarios). Relative SRKW summer density predictions (Figure 2) and pod monthly occurrences were compiled from a 10-year synthesis (2001-2011) of effort-corrected sightings (Hemmera and SMRU 2014) within the Salish Sea.

Figure 1 Map of modelled study area with slowdown zone superimposed. SMRU Consulting NA have collected and analysed two years of ambient noise measurements at Lime Kiln hydrophone.

The SRKW-noise exposure model is a spatially-explicit probabilistic model that accumulates across five-minute time increments how many times each whale receives noise at levels that may temporarily inhibit or disrupt its ability to forage, either from an associated change in behavioural state (i.e., from foraging to traveling, e.g., Lusseau et al. 2009), or via masking of communication calls/whistles and echolocation clicks (Erbe 2002). The method used in this study followed advice from an SRKW Technical Advisory Group, convened by Port Metro Vancouver in 2013 (see http://www.robertsbankterminal2.com/wp-content/uploads/RBT2-TAG-Summary-Report-SRKW-November-2013.pdf).

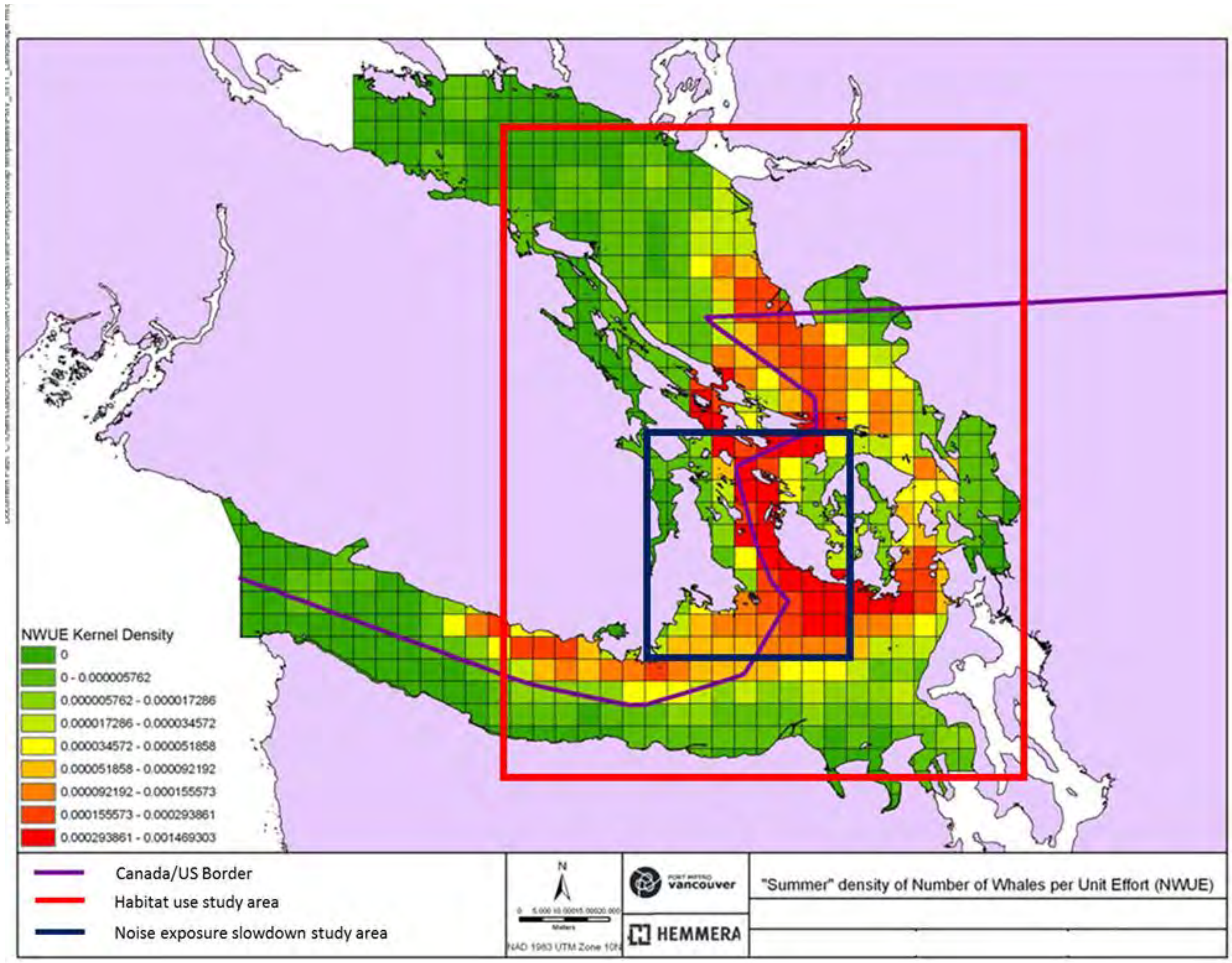

Figure 2 SRKW density per unit effort based on effort corrected sightings 2001-2011 in the broader regional area (Hemmera and SMRU 2014), where red denotes higher and green lower density probabilities. The red box depicts the extent of the summer SRKW habitat use study area used in SRKW-noise exposure model (SMRU 2014a). The study area for the slowdown trial is shown as a blue box and denotes a well documented hot-spot within summer critical habitat of SRKW.

Two dose-response relationships were developed using resident killer whale data from a theodolite whale-vessel tracking study (Williams et al. 2014), a DFO digital acoustic recording tag (DTAG) study and a passive acoustic monitoring study (see SMRU 2014b, and Figure 3). Underlying the dual dose-response relationship is the concept that at higher received noise levels, there is a higher probability of a disruption and that this disruption has the potential to last longer than the time period of the dose (e.g., through a switch in behaviour). In other words, the nearer a SRKW is located to a noise source, the higher the likelihood a behavioural response occurs. A "moderate severity" behavioural response is defined as moderate to extensive changes in locomotion speed, direction and/or dive profile, moderate or prolonged cessation of vocal activity, potential avoidance of area (Southall et al. 2007). Analysis of DTAG data indicated that these effects have an average duration of ~25 minutes (SMRU 2014c). At lower received levels (decreased vessel-whale proximity) the probability of a behavioural response declines to zero. If no moderate severity behavioral response is predicted to occur, the model assesses if noise levels are sufficient to trigger a “low severity” behavioural response (defined in the literature as minor changes in respiration rates, locomotion speed, direction or deviation by Southall et al. (2007), but can encompass lost foraging opportunities within this model). The duration of these low severity behavioural responses (BRs) are considered short-term (5 minutes).

The SRKW-specific dose-response relationships had broadband received noise level median threshold values of 129 and 137 dB re 1 µPa for low severity and moderate severity BRs respectively (SMRU 2014b). Moderate and low severity BRs had a 1% probability at received noise levels of 120 and 111 dB re 1 µPa respectively, resulting in response zones of up to 1.4 km and 3.8 km from a 320 m container ship travelling at 20 knots. Uncertainty around these dual dose-response relationships was derived from the combined results of the three field studies (SMRU 2014b; Figure 3).

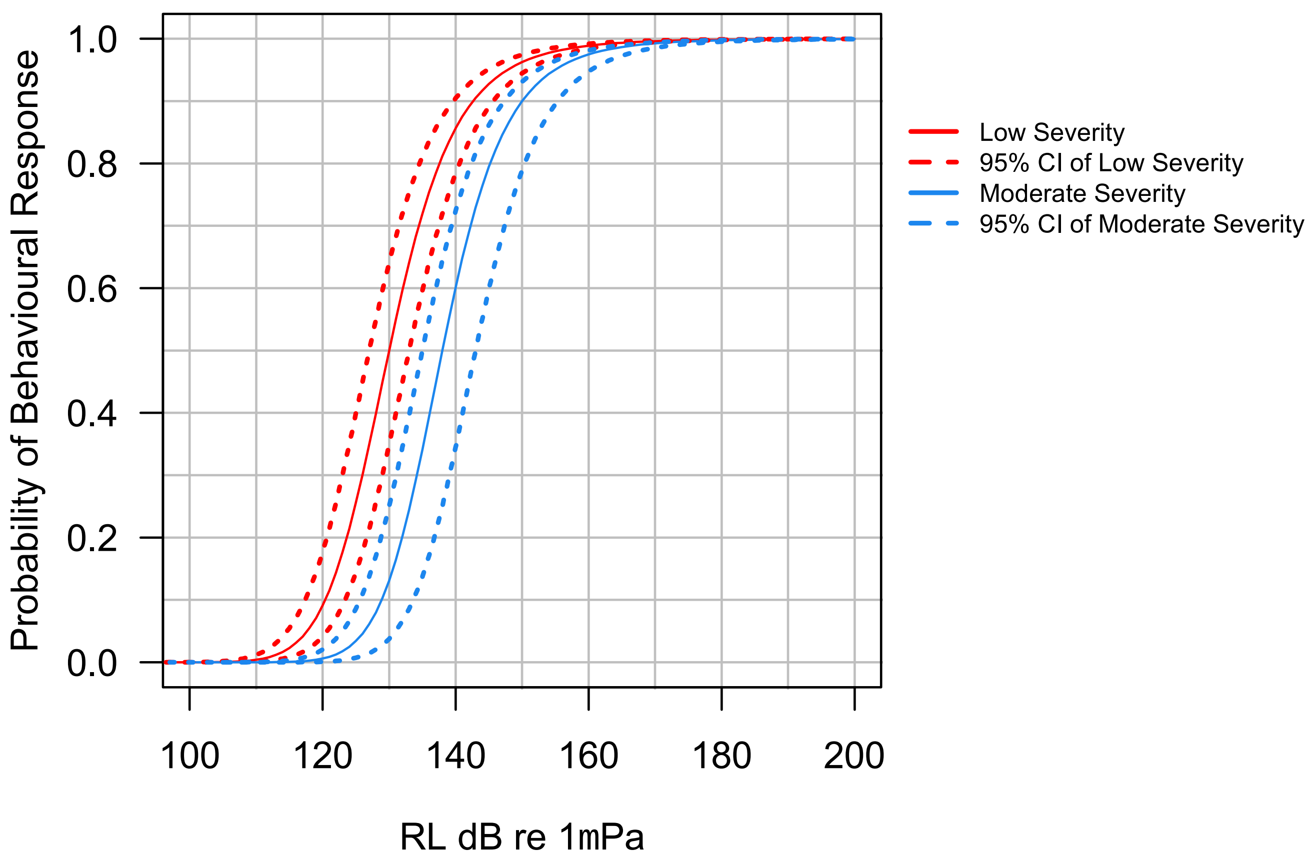

Figure 3 Low severity and moderate severity behavioural dose-response curves developed for SRKW with corresponding 95% confidence intervals (dotted lines) from SMRU (2014b). RL=Received level of broadband unfiltered noise.

Masking of echolocation clicks can occur even at low broadband noise levels if noise levels in high frequency critical bands are exceeded. The SRKW-noise exposure model aimed to capture this possibility by calculating the degree of additional or residual high frequency masking when no BR was predicted. Foraging related echolocation clicks have a peak intensity centered at 50 kHz (Au et al. 2004) and this frequency band was selected to assess the degree of click detection range reduction.

The SRKW-noise exposure model methodology and key assumptions are summarised in the following nine steps;

1. **Estimate presence and distribution of SRKW pods in the study area**. Each of the three pods (J, K and L) was determined present or absent in the regional study area and the 78 individuals from the population (based on January 1, 2017 population estimates from the Center for Whale Research) were distributed as per relative density predictions by pod and monthly (May through October) probability of occurrence using Hemmera and SMRU (2014).
2. **Determine distribution of individual SRKW at predicted pod locations.** Individual whales in each pod were distributed over multiple 200 m grid cells using a kernel smoothing approach. The following steps were only undertaken for pods distributed within the Haro Strait slowdown trial study area.
3. **Determination of received broadband Sound Pressure Level and Power Spectral Density at 50 kHz.** This step uses fine-scale data from the Haro Strait commercial vessel (slowdown) predictive noise model developed by Jasco Applied Sciences to estimate noise maxima within sequential 5-minute increments for a) the broadband (20 Hz – 96 kHz) received Sound Pressure Levels (SPLs) and b) the Power Spectrum Density (PSDs) at 50 kHz.
4. **Model dual behavioural responses based on SPL dose.** The number of low and moderate severity behavioural responses (BRs) were predicted based on SRKW-specific dose-response relationships described above and in detail in SMRU 2014b. Moderate severity BRs lasted 5 times as long with a duration of 25 minutes during which no low severity BRs were estimated. Moderate severity BRs had a lower chance of occurring, however, their net effect on ‘potential lost foraging time’ is greater than low severity BRs. The potential effects from vessel proximity (i.e., physical disturbance rather than BR to noise) were not explicitly included in the SRKW-noise exposure model.
5. **Model residual high frequency click masking based on 50 kHz PSD.** At lower broadband noise levels, when no behavioural response was predicted, the model estimated the degree of additional or residual high frequency masking using a precautionary maximum click detection range (threshold) of 250 m and calculating a proportional detection distance range reduction due to 50 kHz noise levels. A 1-dimensional loss function was used to simply translate this proportional loss into proportion of minutes within each 5-minute increment that residual click masking occurred.
6. **Accumulate BRs and click masking over a twenty-four hour period**. The above process was repeated for each 5-minute increment of the day, and the number of low and moderate behavioural responses and degree of masking were accumulated for each individual whale across the 288 5-minute periods per day. ‘Potential lost foraging time’ was accumulated by summing all 25-minute moderate severity BRs, all 5-minute low severity BRs and all residual click masking minutes.

7. **Accumulate BRs and click masking over summer six-month period or the vessel slowdown trial period.** The twenty-four hour period totals were accumulated for the 184 days of summer (May-October) as well as the slowdown trial period (August 7th to October 6th), by integrating monthly variability in pod occurrence (Hemmera and SMRU 2014).
8. **Calculate 95% confidence intervals.** The entire model simulation was run 500 times to generate the 95% quantiles or confidence intervals (CIs).
9. **Re-run the model for each of the twelve model scenarios.** See Tables 1 and 2 for details of each scenario.

In summary, the dose-response function is what probabilistically determines whether a low or moderate BR occurs when the whale is exposed to noise from a passing commercial vessel (e.g., Lusseau et al. 2009). The severity of a single BR (i.e., low vs moderate) determines the length of time the individual whale is disrupted from foraging. The intensity of the high-frequency (50 kHz PSD) sound levels determines the degree of residual high frequency masking implied by a proportional reduction in the distance that echo-location is fully inhibited, i.e., complete masking of communication calls/whistles and echolocation clicks (Erbe 2002). These BRs and residual masking minutes are subsequently converted into a relative effect metric termed 'potential lost foraging time', summarized over time. As this 'lost time' is a negative effect metric, then a reduction in that effect is considered beneficial. The simulation model acts on individual whales at 5-minute resolution, but can be integrated over time, over space or across whales into pod or all SRKW summaries.

3. Results

The simulation tool accumulated, through a dose-response relation, the number of behavioural responses to all AIS-enabled vessel transits through Haro Strait for each individual whale located in the study area (SMRU 2014b). An example of a model run, assuming a whale were located at Lime Kiln, is shown in Figure 4. Panel A shows how SPL changes over the day as ships pass and how different compliance rates affect SPL levels, and the relative timing of each vessel's acoustic footprint. Panels B and C show how the probability of low and moderate BRs increase with passing ships and how slowdowns decrease these probabilities of disturbance responses. All model output metrics are on a "per whale" basis.

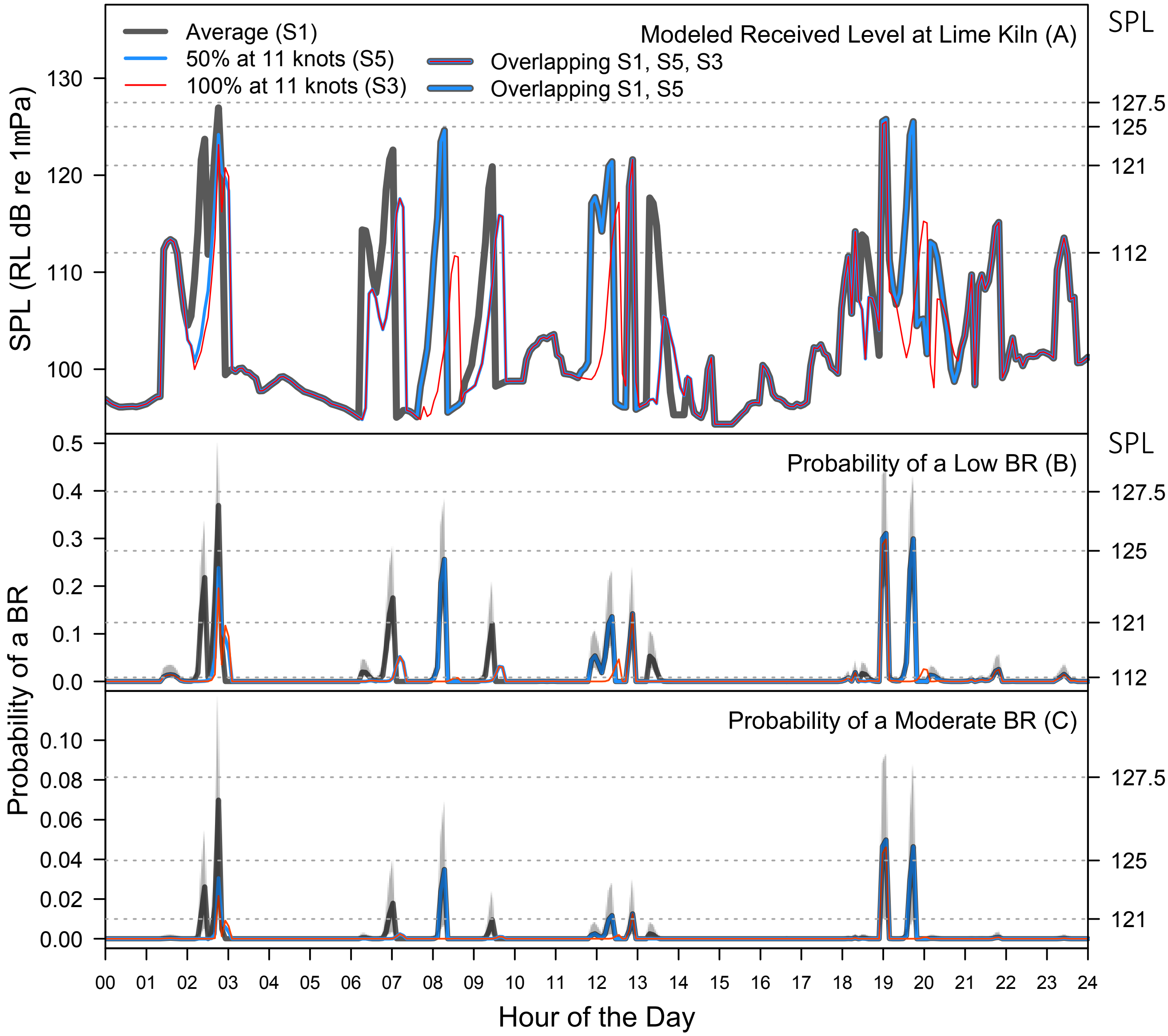

Figure 4. Panel (A) are the sequential 5-minute increments of received broadband (9 Hz to 70.8 kHz) sound pressure level (SPL, dB re 1µPa) or dose from the "average" traffic volume (S1, S5, S3) developed by Jasco Applied Sciences (Appendix 1) in the grid square that contains the Lime Kiln hydrophone. On the bottom x-axis, 00 and 24 both correspond to midnight. Panels (B) and (C) depict related probabilities of expected low and moderate behavioural responses (BRs) using broadband received SPLs and the killer whale specific dose-behavioural response relationship (see Figure 3; SMRU 2014b). 95% CI are shown as grey-shaded areas that largely appear as narrow grey points at the peak BRs in Panels (B) and (C). On the right y-axis of all three panels, selected received SPL levels are provided as cross-referenced examples (112 and 121 dB re 1µPa are the 1% probability of response for low and moderate BRs, respectively; 127.5 dB re 1µPa is the maximum SPL for this day and location; 125 dB re 1µPa is an example selected between 121 and 127.5).

The results section is broken into the sub-sections listed below. These include the results for a six-month time window (representing May-October when SRKW are more likely to be in the region) as well as the two-month trial duration are presented:

Section 3.1	Individual histories collected into pod-specific information of the total number of low and moderate severity BRs per whale to derive per whale statistics (median with 95% confidence intervals) for each pod for a six-month period for the pre-trial scenarios (Table 3) and the post-trial scenarios (Table 4).
Section 3.2	Median daily rates of low and moderate severity BRs per whale per month (May-October; pre-trial Figure 5, post-trial Figure 6.
Section 3.3	Median daily rates of low and moderate severity BRs, and residual click masking minutes per whale across a six-month period (184-days) for the pre-trial scenarios (Table 5) and post-trial scenarios (Table 6).
Section 3.4	Median daily rates of low and moderate severity BRs, and residual click masking minutes per whale across a 61-day vessel slowdown trial period for the pre-trial scenarios (Table 7) and the post-trial scenarios (Table 8).
Section 3.5	For the vessel slowdown trial period, low and moderate severity BRs were converted to 'potential lost foraging time' and accumulated with residual click masking minutes for a combined effect on SRKW for the pre-trial scenarios (Table 9, Figure 7) and the post-trial scenarios (Table 10, Figures 8 and 9).

3.1 Six-month period – by pod summary

Estimated numbers of BRs are presented in the tables and figures as 'per whale' estimates. The simulation was run on the 78 whales alive at the time of pre-trial modelling. Subsequent to this modelling work, the SRKW population has decreased to 76 whales. This reduction in number of living whales is unlikely to have any appreciative effect on these 'per whale' estimates but will affect any results that are summed 'across all whales'. An approach centred on the ecological effects viewpoint will reflect how often each pod was considered to be present in Haro Strait (Table 3). Across the 61-day slowdown trial, J-pod was estimated to be in Haro Strait on 19.01 'whale days', with K-pod present 13.41 and L-pod present 14.04 'whale days', resulting in a population average of 15.44 'whale days' (a whale day is thus a term used for number of days pods were predicted to be present in the study area). These days of whale presence are based on historical sightings from 2001 to 2011 recorded in the BC Cetacean Sightings Network and Orca Master datasets for the region, not the actual recorded presence of SRKW during the 2017 trial period (Hemmera and SMRU 2014).

Across the modelled six-month study period, pre-trial baseline per whale number of BRs were higher for J-pod compared to K-pod (~41% higher) and L-pod (~33% higher), reflecting differences in pod occurrence in the study area (Table 3).

For pre-trial average vessel volume and 100% 11 knot speed compliance, the reduction from baseline speeds (i.e., S3 v S1) in numbers of low and moderate severity BRs per whale was 30 (21.1%) and 19

(28.1%) respectively for J-pod, 18 (17.8%) and 11 (23.9%) for K-pod and 17 (15.9%) and 9 (18.4%) for L-pod.

For pre-trial high vessel volume and 100% slowdown speed, the reduction from baseline speeds (i.e., S4 v S2) in numbers of low and moderate severity BRs per whale was 41 (24%) and 25 (31.6%) respectively for J-pod, 26 (21.3%) and 16 (28.6%) for K-pod and 22 (17.1%) and 14 (23.7%) for L-pod.

The application of the new vessel speed-noise level relationships can be assessed by comparing the pre-trial and post-trial baselines (S1 v S13 and S2 v S14) and also 100% 11 knot speed compliance scenarios S3 vs S7 and S4 vs S8 (Tables 3 and 4). The effect was small, resulting in small (0-3) increases in low severity BRs per whale and a very small (0-1) changes in moderate severity BRs per whale. The scenario results for actual slowdown trial compliance rate with trial mean speeds (S9 and S10) were very similar to those for 50% slowdown speed compliance to 11 knots (S5 and S6) (Tables 3 and 4). Future traffic at normal speeds (S11) resulted in a 10-12% increase by pod from baseline (S13) in low severity BRs and 9-12% increase in moderate severity BRs, while future traffic at 100% 11 knot speed compliance (S12) compared to baseline resulted in decreases of 6-12% and 12-23% in low and moderate severity BRs respectively.

Table 3. Median number of low and moderate severity BRs in Haro Strait per whale by pod for a six-month period for each pre-trial scenario (plus 95% confidence intervals (95% CI)).

Scenario Number	Summary Traffic Conditions	Behavioural Response severity	J-pod median (95% CI)	K-pod median (95% CI)	L-pod median (95% CI)
S1	Baseline – average vessel speed and average vessel numbers	Low BRs	142 (64, 244)	101 (35, 195)	107 (38, 202)
		Mod. BRs	66 (22, 392)	46 (10, 356)	49 (11, 360)
S2	Baseline – average vessel speed and high vessel numbers	Low BRs	171 (75, 297)	122 (42, 233)	129 (44, 242)
		Mod. BRs	79 (26, 409)	56 (11, 372)	59 (14, 372)
S3	11 knot Slowdown (100% compliance) – average vessel numbers	Low BRs	112 (49, 199)	83 (28, 162)	90 (31, 176)
		Mod. BRs	47 (14, 367)	35 (7, 344)	40 (8, 351)
S4	11 knot Slowdown (100% compliance) – high vessel numbers	Low BRs	130 (56, 231)	96 (30, 188)	107 (36, 205)
		Mod. BRs	54 (16, 379)	40 (8, 350)	45 (9, 357)
S5	11 knot Slowdown (50% compliance) – average vessel numbers	Low BRs	129 (58, 223)	93 (32, 180)	100 (35, 187)
		Mod. BRs	57 (18, 381)	41 (9, 350)	44 (10, 353)
S6	11 knot Slowdown (50% compliance) – high vessel numbers	Low BRs	152 (67, 265)	109 (36, 211)	119 (41, 226)
		Mod. BRs	67 (22, 394)	48 (10, 361)	53 (12, 365)

Table 4 Median number of low and moderate severity BRs in Haro Strait per whale by pod for a six-month period for each post-trial scenario (plus 95% confidence intervals (95% CI)).

Scenario Number	Summary Traffic Conditions	Behavioural Response severity	J-pod median (95% CI)	K-pod median (95% CI)	L-pod median (95% CI)
S7	11 knot Slowdown (100% compliance) – average vessel numbers	Low BRs	114 (52, 202)	84 (28, 162)	91 (31, 176)
		Mod. BRs	47 (14, 369	35 (7, 343)	39 (8, 348)
S8	11 knot Slowdown (100% compliance) – high vessel numbers	Low BRs	131 (59, 232)	96 (32, 186)	107 (36, 204)
		Mod. BRs	53 (16, 377)	39 (8, 349)	45 (9, 355)
S9	Per trial mean/baseline (57% compliance) – average vessel numbers	Low BRs	129 (59, 224)	93 (32, 178)	99 (35, 187)
		Mod. BRs	56 (19, 379)	40 (9, 350)	44 (10, 353)
S10	Per trial mean/baseline (57% compliance) – high vessel numbers	Low BRs	153 (69, 266)	109 (38, 209)	119 (41, 224)
		Mod. BRs	66 (22, 393)	47 (10, 359)	51 (12, 364)
S11	Future scenario Baseline speeds – average vessel numbers	Low BRs	162 (74, 280)	114 (40, 218)	121 (42, 226)
		Mod. BRs	74 (25, 403)	51 (11, 365)	54 (13, 367)
S12	Future scenario 11 knot Slowdown (100% compliance) – average vessel numbers	Low BRs	128 (57, 225)	93 (31, 180)	102 (35, 195)
		Mod. BRs	51 (15, 374)	38 (7, 348)	43 (9, 353)
S13	Baseline – average vessel speed and average vessel numbers	Low BRs	145 (67-251)	104 (38, 199)	109 (38, 202)
		Mod. BRs	66 (23, 391)	47 (11, 358)	49 (11, 358)
S14	Baseline – average vessel speed and high vessel numbers	Low BRs	173 (78, 299)	123 (43, 234)	129 (44, 242)
		Mod. BRs	79 (27, 413)	55 (13, 370)	58 (12, 371)

3.2 Six-month and slowdown periods – monthly summary

Numbers of pre-trial BRs varied across the six-month study period, reflecting differences in SRKW presence through the summer, with values highest June through September (Average traffic volume: median low severity BRs = 0.76 per day per whale, median moderate severity BRs = 0.4 per day per whale; Figure 5) and lower in May (Average traffic volume: median low severity BRs = 0.13 per day per whale, median moderate severity BRs = 0.06 per day per whale) and October (Average traffic volume: median low severity BRs = 0.35 per day per whale, median moderate severity BRs = 0.17 per day per whale; Figure 5). The peak value was observed in July for high traffic volume at normal speeds (S2), where low severity BRs = 1.02 per day per whale and moderate severity BRs = 0.53.

A similar monthly trend was observed for post-trial scenarios (Figure 6). The peak value was observed in July for average traffic volume at normal speeds in the future traffic scenario (S11), where low severity BRs = 0.97 per day per whale and moderate severity BRs = 0.51.

In Figure 5 and 6, the 95% confidence limits are included for all estimated numbers. These confidence limits represent the uncertainty around the estimated 'true' number of behavioural responses and reflect the variability in SRKW presence in this region, and the probability of the individual responding the vessel noise level given its present. The upper 95% confidence limits are longer in the upper direction especially for moderate severity BRs across all scenarios and months, reflecting the skew in the behavioural response distribution.

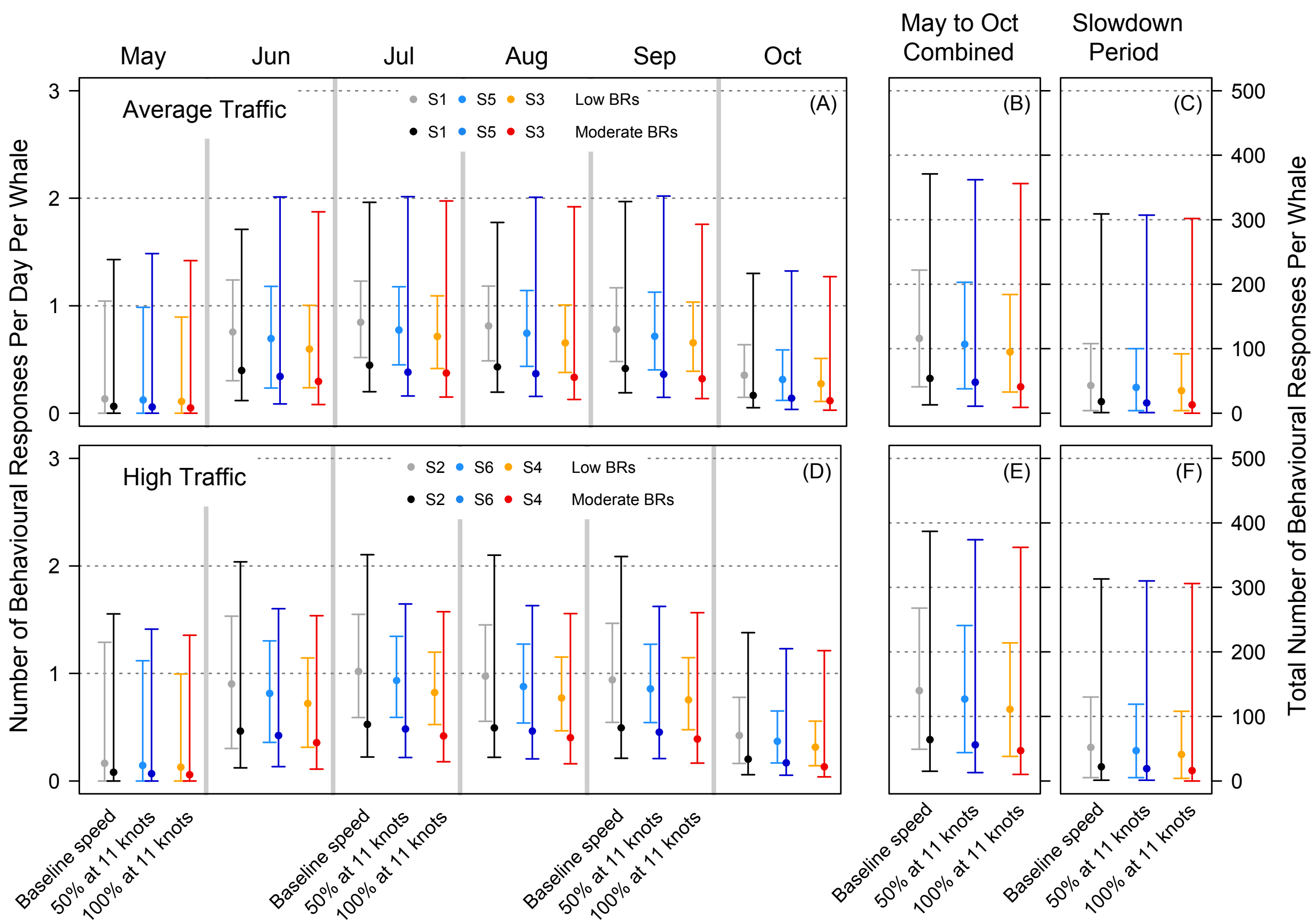

Figure 5. Median pre-trial number of low and moderate severity BRs in Haro Strait per day per whale for each month (A, D), plus total numbers across six months combined (B, E), and 2-month (Aug-Sept) slowdown period (C, F), for average traffic (upper panels) and high traffic (lower panels) volume pre-trial scenarios. 95% confidence limits are included for all estimated numbers, with the upper 95% confidence limits longer in the upper direction especially for moderate severity BRs across all scenarios and months, reflecting the skew in the behavioural response distribution.

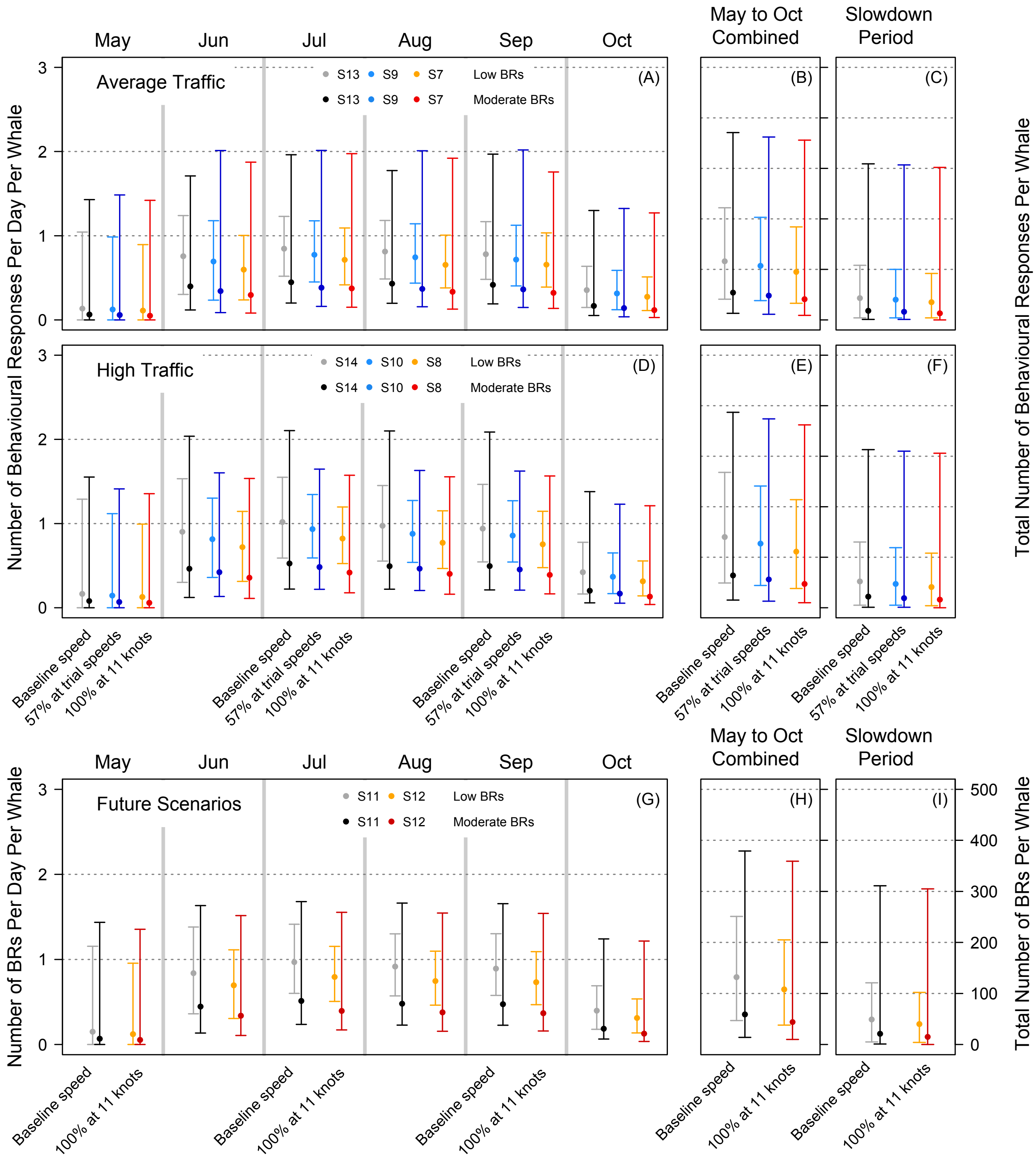

Figure 6. Median post-trial number of low and moderate severity BRs in Haro Strait per day per whale for each month (A, D, G). The total numbers across six months combined (B, E, H), and across the 61-day slowdown period (Aug-Sept) (C, F, I), are shown for current average traffic (upper panels), high traffic (middle panels), and future average traffic (lower panels) volume post-trial scenarios. 95% confidence limits are included for all estimated numbers, with the upper 95% confidence limits longer in the upper direction especially for moderate severity BRs across all scenarios and months, reflecting the skew in the behavioural response distribution.

3.3 Six-month period – Overall per day summary

When evaluated over the six-month period, for all pre-trial scenarios, the overall median number of low severity BRs per day per whale was ~2.26 times as frequent as the number of moderate severity BRs (Table 5). For the post-trial scenarios, the ratio was 2.31 (Table 6). For baseline speeds at average traffic volume (S1), the number of low and moderate severity BRs per day per whale are 0.63 (3.15 minutes) and 0.29 (7.25 minutes), with a residual 1.94 minutes of residual click masking, per day per whale. For baseline speeds at high traffic volume (S2) the number of low and moderate severity BRs are 0.76 and 0.35 per day per whale, with a residual 1.97 minutes of residual click masking, per day per whale. Baseline BRs are ~20.7% higher when comparing high traffic to average traffic volume. Residual click masking minutes are only 1.5% higher when comparing high traffic to average traffic volume (Table 5). Estimated 95% confidence intervals are wide, especially for moderate BRs (Figures 5 and 6), reflecting the skew in the distribution that incorporates variability in where each of the pods were placed within the study area for each simulation, as well as uncertainty incorporated into the dose-response function and monthly probability of occurrence. The noise layer had no incorporated uncertainty. After the application of the new vessel speed-noise level relationships, median number of BRs per day are very similar but residual click masking increases by 5-6% from comparable pre-trial results. For baseline speeds at predicted future average traffic volumes (S11) the number of low and moderate severity BRs per day per whale are 0.72 and 0.32, with a residual 2.07 minutes of residual click masking, per day per whale (Table 6).

Table 5. Median number of low and moderate severity BRs and masking minutes in Haro Strait per day per whale for a six-month period for each pre-trial scenario (plus 95% confidence intervals).

Scenario Number	Summary Traffic Conditions	# of Low BR per day per whale (95% CI)	# of Mod BR per day per whale (95% CI)	# of click masking minutes per day per whale (95% CI)
S1	Baseline – average vessel speed and average vessel numbers	0.63 (0.22, 1.21)	0.29 (0.07, 2.02)	1.94 (0.89, 3.47)
S2	Baseline – average vessel speed and high vessel numbers	0.76 (0.27, 1.46)	0.35 (0.08, 2.1)	1.97 (0.91, 3.51)
S3	11 knot Slowdown (100% compliance) – average vessel numbers	0.52 (0.18, 1)	0.22 (0.05, 1.93)	1.96 (0.89, 3.51)
S4	11 knot Slowdown (100% compliance) – high vessel numbers	0.6 (0.21, 1.16)	0.26 (0.05, 1.97)	2.0 (0.91, 3.58)
S5	11 knot Slowdown (50% compliance) – average vessel numbers	0.58 (0.21, 1.1)	0.26 (0.06, 1.97)	1.96 (0.9, 3.48)
S6	11 knot Slowdown (50% compliance) – high vessel numbers	0.69 (0.24, 1.31)	0.3 (0.07, 2.03)	1.99 (0.91, 3.54)

Pre-trial, the number of low and moderate severity BRs per day per whale at baseline speeds for average traffic volume decreased by 7.9% and 10.3% for 50% compliance to 11 knot speeds, and by 17.5% and 24.1% at 100% compliance to 11 knot speeds (Table 5), noting all decreases are calculated as absolute percent reductions from 100%.

Pre-trail, the number of low and moderate severity BRs per day per whale at baseline speeds for high traffic volume decreased by 10.5% and 14.3% for 50% compliance to 11 knot speeds, and by 21.1% and 25.7% at 100% compliance to 11 knot speeds (Table 5).

Pre-trail, the number of residual click masking minutes per day per whale at baseline speeds for average and high traffic volume increased by 1% and 1% for 50% compliance to 11 knot speeds and by 1% and 1.5% at 100% compliance to 11 knot speeds (Table 5).

Table 6 Median number of low and moderate severity BRs and masking minutes in Haro Strait per day per whale for a six-month period for each post-trial scenario (plus 95% confidence intervals).

Scenario Number	Summary Traffic Conditions	# of Low BR per day per whale (95% CI)	# of Mod BR per day per whale (95% CI)	# of click masking minutes per day per whale (95% CI)
S7	11 knot Slowdown (100% compliance) – average vessel numbers	0.52 (0.18, 1.01)	0.22 (0.05, 1.92)	2.06 (0.93, 3.71)
S8	11 knot Slowdown (100% compliance) – high vessel numbers	0.61 (0.21, 1.16)	0.25 (0.05, 1.96)	2.09 (0.95, 3.76)
S9	Per trial mean/baseline (57% compliance) – average vessel numbers	0.58 (0.21, 1.09)	0.26 (0.06, 1.96)	2.05 (0.93, 3.69)
S10	Per trial mean/baseline (57% compliance) – high vessel numbers	0.69 (0.24, 1.3)	0.3 (0.07, 2.03)	2.08 (0.94, 3.73)
S11	Future scenario Baseline speeds – average vessel numbers	0.72 (0.26, 1.36)	0.32 (0.08, 2.06)	2.07 (0.94, 3.71)
S12	Future scenario 11 knot Slowdown (100% compliance) – average vessel numbers	0.59 (0.21, 1.11)	0.24 (0.05, 1.95)	2.09 (0.95, 3.76)
S13	Baseline – average vessel speed and average vessel numbers	0.64 (0.23, 1.22)	0.29 (0.07, 2.02)	2.06 (0.93, 3.67)
S14	Baseline – average vessel speed and high vessel numbers	0.77 (0.27, 1.46)	0.35 (0.08, 2.09)	2.06 (0.95, 3.70)

Post-trial (using the new vessel speed-noise level relationships), the number of low and moderate severity BRs per day per whale compared to baseline speeds (S13) for average traffic volume decreased by 9.4% and 10.3% for actual trial (57%) compliance with trial mean speeds (i.e., S13 with S9) and by 18.8% and 24.1% for 100% compliance to 11 knot speeds (i.e., S13 with S7) (Tables 5 and 6). In other words, the new vessel speed-noise level relationship made little difference to the effect of a 100% speed compliance for average traffic volume. The 57% mean trial speed compliance decrease (S9) was similar to decreases observed for the 50% at 11 knot speed compliance scenarios.

Post-trial (using the new vessel speed-noise level relationships), the number of low and moderate severity BRs per day per whale compared to baseline speeds (S14) for high traffic volume decreased by 10.4% and 14.3% for actual trial (57%) compliance with trial mean speeds (i.e., S14 with S10) and by 20.8% and 28.6% for 100% compliance to 11 knot speeds (i.e., S14 with S8) (Table 6).

Post-trial (using the new vessel speed-noise level relationships), the number of residual click masking minutes per day per whale compared to baseline speeds for average and high traffic volume decreased by 1.1% and increased by 1% for actual trial (57%) compliance with trial mean speeds and was identical and increased by 1.5% for 100% compliance to 11 knot speeds (Table 6). Residual click masking minutes thus changed a small amount post-trail after the application of new vessel speed-noise level relationships.

Post-trial (using the new vessel speed-noise level relationships), the number of low and moderate severity BRs per day per whale compared to baseline speeds (S13) for average traffic volume increased by 12.5% and 10.3% for the future traffic scenario (S11) at baseline speeds and decreased by 7.8% and 17.2% at 100% compliance to 11 knot speeds of future traffic (i.e., S13 with S12) (Table 6). Residual click masking increased for both comparisons by 0.5% and 1.5%.

3.4 Slowdown trial months - Number of BRs and masking minutes

When evaluated over the 61-day trial slowdown period, for all pre-trial scenarios, the overall number of low severity BRs per day per whale was ~2.5 times as frequent as the number of moderate severity BRs (Table 7). For the post-trial scenarios, the ratio averaged 2.54 (Table 8). For pre-trial baseline speeds at average traffic volume the number of low and moderate severity BRs are 0.7 and 0.3 per day per whale, with a residual 2.21 minutes of residual click masking, per day per whale. For baseline speeds at high traffic volume the number of low and moderate severity BRs are 0.85 and 0.36 per day per whale, with a residual 2.24 minutes of residual click masking, per day per whale. Baseline BRs are 20.7% higher when comparing high traffic to average traffic volume. Residual click masking minutes are only 1.4% higher when comparing high traffic to average traffic volume (Table 7).

For post-trial baseline speeds at average traffic volume the number of low and moderate severity BRs are 0.72 and 0.31 per day per whale, with a residual 2.35 minutes of residual click masking, per day per whale. For baseline speeds at high traffic volume the number of low and moderate severity BRs are 0.87 and 0.36 per day per whale, with a residual 2.34 minutes of residual click masking, per day per whale. Baseline BRs are 18.5% higher when comparing high traffic to average traffic volume.

Residual click masking minutes are almost identical when comparing high traffic to average traffic volume (Table 8).

Post-trial (using the new vessel speed-noise level relationships), for baseline speeds at average traffic volume in the future (S11) the number of low and moderate severity BRs per day per whale were 0.8 and 0.34, with a residual 2.35 minutes of residual click masking, per day per whale (Table 8).

Table 7. Median number of low and moderate severity BRs and masking minutes in Haro Strait per day per whale for the 61-day slowdown trail period for each pre-trial scenario (plus 95% confidence intervals).

Scenario Number	Summary Traffic Conditions	# of Low BR per day per whale (95% CI)	# of Mod BR per day per whale (95% CI)	# of click masking minutes per day per whale (95% CI)
S1	Baseline – average vessel speed and average vessel numbers	0.7 (0.07, 1.77)	0.3 (0.02, 5.07)	2.21 (0.58, 4.9)
S2	Baseline – average vessel speed and high vessel numbers	0.85 (0.08, 2.13)	0.36 (0.02, 5.13)	2.24 (0.58, 4.95)
S3	11 knot Slowdown (100% compliance) – average vessel numbers	0.57 (0.07, 1.51)	0.21 (0, 4.95)	2.22 (0.58, 4.94)
S4	11 knot Slowdown (100% compliance) – high vessel numbers	0.67 (0.07, 1.77)	0.26 (0, 5.02)	2.28 (0.59, 5.03)
S5	11 knot Slowdown (50% compliance) – average vessel numbers	0.66 (0.07, 1.64)	0.26 (0.02, 5.03)	2.23 (0.58, 4.95)
S6	11 knot Slowdown (50% compliance) – high vessel numbers	0.77 (0.08, 1.95)	0.31 (0.02, 5.08)	2.26 (0.59, 5)

Pre-trail the number of low and moderate severity BRs per day per whale at baseline speeds for average traffic volume decreased by 5.7% and 13.3% for 50% compliance to 11 knot speeds, and by 18.6% and 30% at 100% compliance to 11 knot speeds (Table 7).

Pre-trial the number of low and moderate severity BRs per day per whale at baseline speeds for high traffic volume decreased by 9.4% and 13.9% for 50% compliance to 11 knot speeds, and by 21.2% and 27.8% at 100% compliance to 11 knot speeds (Table 7).

Pre-trail the number of residual click masking minutes per day per whale at baseline speeds for average and high traffic volume increased by 0.9% and 0.9% for 50% compliance to 11 knot speeds and by 0.5% and 1.8% at 100% compliance to 11 knot speeds (Table 7).

Post-trial (using the new vessel speed-noise level relationships), the number of low and moderate severity BRs per day per whale compared to baseline speeds (S13) for average traffic volume decreased by 8.3% and 16.1% for actual trial (57%) compliance with trial mean speeds (i.e., S13 with S9) and by 18.1% and 32.3% at 100% compliance to 11 knot speeds (i.e., S13 with S7) (Table 8). In other words, the new vessel speed-noise level relationship made little difference to the effect of a 100% speed compliance for average traffic volume. The 57% mean trial speed compliance decrease (S9) was similar to decrease observed for the 50% at 11 knot speed compliance scenario (S6).

Post-trial (using the new vessel speed-noise level relationships), the number of low and moderate severity BRs per day per whale compared to baseline speeds (S14) for high traffic volume decreased by 9.2% and 13.9% for actual trial (57%) compliance with trial mean speeds (i.e., S14 with S10) and by 23.0% and 30.6% at 100% compliance to 11 knot speeds (i.e., S14 with S8) (Table 8).

Post-trial (using the new vessel speed-noise level relationships), the number of residual click masking minutes per day per whale compared to baseline speeds for average and high traffic volume decreased by 0.9% and increased by 0.9% for actual trial (57%) compliance with trial mean speeds and were identical and increased by 1.3% at 100% compliance to 11 knot speeds (Table 8). Residual click masking minutes thus changed a small amount after the use of new vessel speed-noise level relationships, noting that click masking is only calculated if there are no behavioural responses.

Post-trial (using the new vessel speed-noise level relationships), the number of low and moderate severity BRs per day per whale compared to baseline speeds (S13) for average traffic volume increased by 11.1% and 9.7% for the predicted future traffic scenario (S11) at baseline speeds and decreased by 8.3% and 19.4% at 100% compliance to 11 knot speeds for future traffic (i.e., S13 with S12) (Table 8). Residual click masking remained identical and increased by 1.3% respectively.

Table 8 Median number of low and moderate severity BRs and masking minutes in Haro Strait per day per whale for the 61-day slowdown trail period for each post-trial scenario (plus 95% confidence intervals).

Scenario number	Summary Traffic Conditions	# of Low BR per day per whale (95% CI)	# of Mod BR per day per whale (95% CI)	# of click masking minutes per day per whale (95% CI)
S7	11 knot Slowdown (100% compliance) – average vessel numbers	0.59 (0.07, 1.51)	0.21 (0, 4.97)	2.35 (0.59, 5.20)
S8	11 knot Slowdown (100% compliance) – high vessel numbers	0.67 (0.07, 1.75)	0.25 (0, 5.02)	2.38 (0.6, 5.26)
S9	Per trial mean/baseline (57% compliance) – average vessel numbers	0.66 (0.08, 1.62)	0.26 (0, 5.02)	2.33 (0.59, 5.18)
S10	Per trial mean/baseline (57% compliance) – high vessel numbers	0.79 (0.08, 1.93)	0.31 (0.02, 5.08)	2.36 (0.6, 5.23)
S11	Future scenario Baseline speeds – average vessel numbers	0.8 (0.08, 1.98)	0.34 (0.02, 5.10)	2.35 (0.6, 5.20)
S12	Future scenario 11 knot Slowdown (100% compliance) – Average vessel numbers	0.66 (0.07, 1.67)	0.25 (0, 5.00)	2.38 (0.6, 5.25)
S13	Baseline – average vessel speed and average vessel numbers	0.72 (0.08, 1.77)	0.31 (0.02, 5.07)	2.35 (0.59, 5.22)
S14	Baseline – average vessel speed and high vessel numbers	0.87 (0.08, 2.13)	0.36 (0.02, 5.13)	2.34 (0.59, 5.21)

3.5 Slowdown trial months - Total 'potential lost foraging time'

The SRKW-noise exposure model defines low severity BRs to have an effect duration of 5 minutes, while moderate severity BRs have an effect duration of 25 minutes. Thus, when calculating the total 'potential lost foraging time' metric, the influence of one moderate severity BR is therefore increased by a factor of five over one low severity BR. Residual click masking minutes are summed as calculated.

Evaluating the 61-day duration of the slowdown trial, the total (sum of) 'potential lost foraging time' per whale is highest (i.e., effect is worst) using post-trial results at baseline speeds, totalling 13.98 hours for current average traffic volume, 15.97 hours for current high traffic volume and 15.22 for future average traffic volume (Table 10). Overall, moderate severity responses dominate (53-55%) the total 'potential lost foraging time', followed by low severity responses (27-28%), with masking contributing 18-19%.

At pre-trial 50% compliance at 11 knot speeds, the total ‘potential lost foraging time’ per whale was reduced by 8% (average traffic volume) and 10.4% (high traffic volume), from 13.33 to 12.27 hours and 14.13 total hours. At pre-trial 100% compliance at 11 knot speeds, the total ‘potential lost foraging time’ per whale was reduced by 20.6% (average traffic volume) and 21.4% (high traffic volume) to 10.59 hours and 12.40 total hours (Table 9, Figure 7). Differences from baseline speeds to 100% compliance are consequently 2.74 hours and 3.37 hours respectively. Reductions reflect decreased numbers of moderate severity BRs and to a lesser extent low severity BRs. Click masking minutes were very similar across scenarios, increasing by a very small fraction during slowdown scenarios.

Average vessel traffic had fewer BRs when compared to high vessel traffic. The ‘potential lost foraging time’ per whale day was 0.86 and 1.02 hours per whale for baseline S1 and S2 scenarios (3.6% and 4.3% of a whale day), dropping respectively to 0.69 and 0.80 hours with 100% compliance at 11 knot speeds (Table 9), or a reduction of 10.2-13.2 minutes per whale day per whale. The equivalent absolute percent reduction in percent of whale day is 0.7% and 1% for average and high traffic scenarios with 100% compliance. In comparison, the future average traffic scenario at baseline speeds (S11) was 0.99 hours or 4.1% of a whale day (Table 10).

Overall the post-trial model results highlight a number of important conclusions. Firstly, the new vessel speed-noise relationships result in a small (~3%) increase in baseline noise effects. However, this results in a small but beneficial positive change in the percentage reduction from baseline in the time foraging is potentially affected by vessel noise during a slowdown where compliance to 11 knots is 100% (from -20.6% pre-trial to -22.7% post-trial for average vessel volume and -21.4% pre-trial to -24.3% post-trial for high vessel volume). Secondly, the actual slowdown trial was estimated on an average traffic day to reduce the potential effects of vessel noise by 11.5%. Thirdly, the additional three commercial vessels and a tug that were added to the baseline scenario (normal speed and traffic volume) to account for potential future traffic volume result in an 8.9% increase in ‘potential lost foraging time’, if transiting at normal speeds (S13: 13.98 hours, S11: 15.22 hours), the equivalent of 1.24 hours per whale for the slowdown period or 0.3% of a whale day. Lastly, if instead, 100% of piloted vessels transit comply to an 11 knot slowdown for the future traffic scenario, then the ‘potential lost foraging time’ is estimated to be reduced by 14.1%, from the baseline scenario (S13: 13.98 hours, S12: 12.00 hours), the equivalent of 2 hours per whale for the slowdown period or 0.5% of a whale day. In other words, a fully compliant slowdown to 11 knots is shown to more than compensate for the predicted increase in future traffic volume (Table 10).

By comparing the potential lost foraging time for the post-trial high traffic volume scenario with 100% of commercial vessels complying to 11 knots (S8) to that with average traffic volume with no vessel slowdowns (S13), there remains a 13.6% decrease in potential lost foraging time (S13 to S8). This also implies that if vessel traffic volumes increase, then slowing those vessels down may (at least through the area covered in this simulation study) partially offset the potential impacts of higher vessel traffic volumes.

As with the summary statistics of all months, the estimated 95% confidence intervals are wide, especially for moderate BRs. As stated previously, this reflects the shape of the BR distribution that incorporates variability in where each of the pods was placed within the study area for each simulation, as well as uncertainty incorporated into the dose-response function and monthly probability of occurrence. The influence of unusually high numbers of BRs was more pronounced when calculated using a 61-day sampling day compared to entire six-month (184-day) period (i.e., the upper 95% confidence limit is substantially higher for the 61-day trial). JASCO's noise layer had no incorporated uncertainty.

Table 9. Potential lost foraging time (minutes) in Haro Strait for Low BRs, Moderate BRs and click masking (plus 95% confidence intervals) per whale with respective sum total estimates per whale for the 61-day slowdown trial period, and respective hours per study day (lost time averaged over the 61-day study period) and hours (and as a %) per whale day (lost time per day a whale is present over the 61-day study period) across each pre-trial scenario. All lost foraging time is the sum of lost foraging minutes from low and moderate BRs and residual click masking.

Scen -ario	Summary Traffic Conditions	Lost foraging time due to Low BR (95% CI)	Lost foraging time due to Mod BR (95% CI)	Sum of lost foraging time due to Low and Mod BR	Lost foraging time due to click masking (95% CI)	Sum of all lost foraging time	Lost foraging time (hrs) per study day	Lost foraging time (hrs) per whale day	Lost foraging time as a % of whale day
S1	Baseline – average vessel speed and average vessel numbers	215 (20, 540)	450 (25, 7725)	665	134.74 (35.1, 299.3)	799.74	0.219	0.86	3.6
S2	Baseline – average vessel speed and high vessel numbers	260 (25, 650)	550 (25, 7825)	810	136.4 (35.5, 302.2)	946.4	0.259	1.02	4.3
S3	11 knot Slowdown (100% compliance) – average vessel numbers	175 (20, 460)	325 (0, 7550)	500	135.38 (35.4, 301.1)	635.38	0.174	0.69	2.9
S4	11 knot Slowdown (100% compliance) – high vessel numbers	205 (20, 540)	400 (0, 7650)	605	139.1 (36.1, 307.0)	744.1	0.203	0.80	3.3
S5	11 knot Slowdown (50% compliance) – average vessel numbers	200 (20, 500)	400 (25, 7675)	600	135.92 (35.7, 301.9)	735.92	0.201	0.79	3.3
S6	11 knot Slowdown (50% compliance) – high vessel numbers	235 (25, 595)	475 (25, 7750)	710	137.92 (35.8, 305.0)	847.92	0.232	0.92	3.8

Table 10. Potential lost foraging time (minutes) in Haro Strait for Low BRs, Moderate BRs and click masking (plus 95% confidence intervals) per whale with respective sum total estimates per whale for the 61-day slowdown trial period, and respective hours per study day (lost time averaged over the 61-day study period) and hours (and as a %) per whale day (lost time per day a whale is present over the 61-day study period) across each post trial-trial scenario. All lost foraging time is the sum of lost foraging minutes from low and moderate BRs and residual click masking.

Scen -ario	Summary Traffic Conditions	Lost foraging time due to Low BR (95% CI)	Lost foraging time due to Mod BR (95% CI)	Sum of lost foraging time due to Low and Mod BR	Lost foraging time due to click masking (95% CI)	Sum of all lost foraging time	Lost foraging time (hrs) per study day	Lost foraging time (hrs) per whale day	Lost foraging time as a % of whale day
S7	11 knot Slowdown (100% compliance) – average vessel numbers	180 (20, 460)	325 (0, 7575)	505	143.08 (36.2, 317.2)	648.08	0.177	0.70	2.9
S8	11 knot Slowdown (100% compliance) – high vessel numbers	205 (20, 535)	375 (0, 7650)	580	144.91 (36.6, 321.1)	724.91	0.198	0.78	3.3
S9	Per trial mean/baseline (57% compliance) – average vessel numbers	200 (25, 495)	400 (0, 7650)	600	142.18 (36.1, 316.1)	742.18	0.203	0.80	3.3
S10	Per trial mean/baseline (57% compliance) – high vessel numbers	240 (25, 590)	475 (25, 7750)	715	144.0 (36.7, 319.1)	859.04	0.235	0.93	3.9
S11	Future scenario Baseline speeds – average vessel numbers	245 (25, 605)	525 (25, 7775)	770	143.46 (36.4, 317.4)	913.46	0.250	0.99	4.1
S12	Future scenario 11 knot Slowdown (100% compliance) – average vessel numbers	200 (20, 510)	375 (0, 7625)	575	145.04 (36.7, 320.5)	720.04	0.197	0.78	3.3

Scen-ario	Summary Traffic Conditions	Lost foraging time due to Low BR (95% CI)	Lost foraging time due to Mod BR (95% CI)	Sum of lost foraging time due to Low and Mod BR	Lost foraging time due to click masking (95% CI)	Sum of all lost foraging time	Lost foraging time (hrs) per study day	Lost foraging time (hrs) per whale day	Lost foraging time as a % of whale day
S13	Baseline – average vessel speed and average vessel numbers	220 (25, 540)	475 (25, 7725)	695	143.65 (36.2, 318.1)	838.65	0.229	0.91	3.8
S14	Baseline – average vessel speed and high vessel numbers	265 (25, 650)	550 (25, 7825)	815	143.03 (36.2, 318.1)	958.03	0.262	1.03	4.3

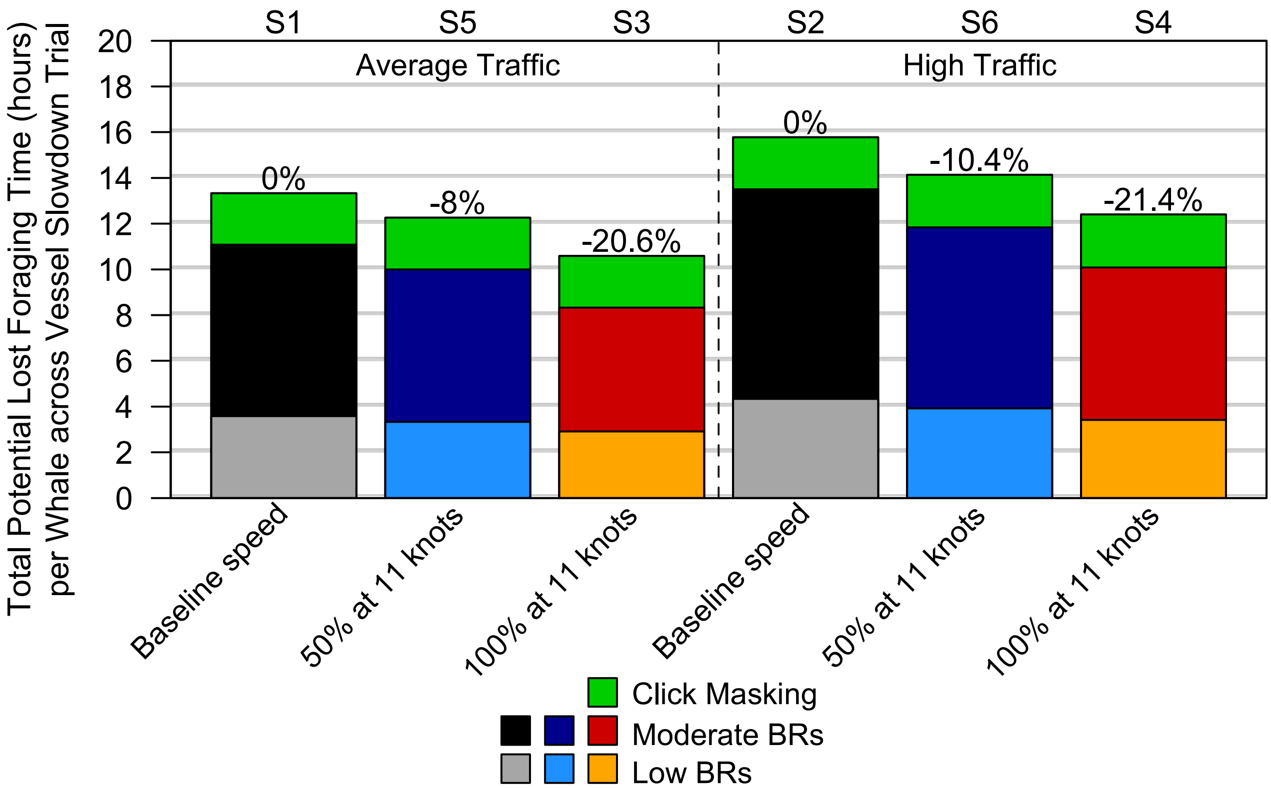

Figure 7. Potential lost foraging time (hours) per whale for sum total estimates of Low BRs, Moderate BRs and click masking for the 61-day slowdown trial period across average traffic (left panel) and high traffic (right panel) pre-trial scenarios. The percentage reduction in 'potential lost foraging time' from current average and high traffic baseline speed scenarios (S1 and S2) to 50% (S5 and S6) and 100% (S3 and S4) compliance to 11 knot speed scenarios has been provided above each bar. Colours of scenarios are consistent with those in Figure 5.

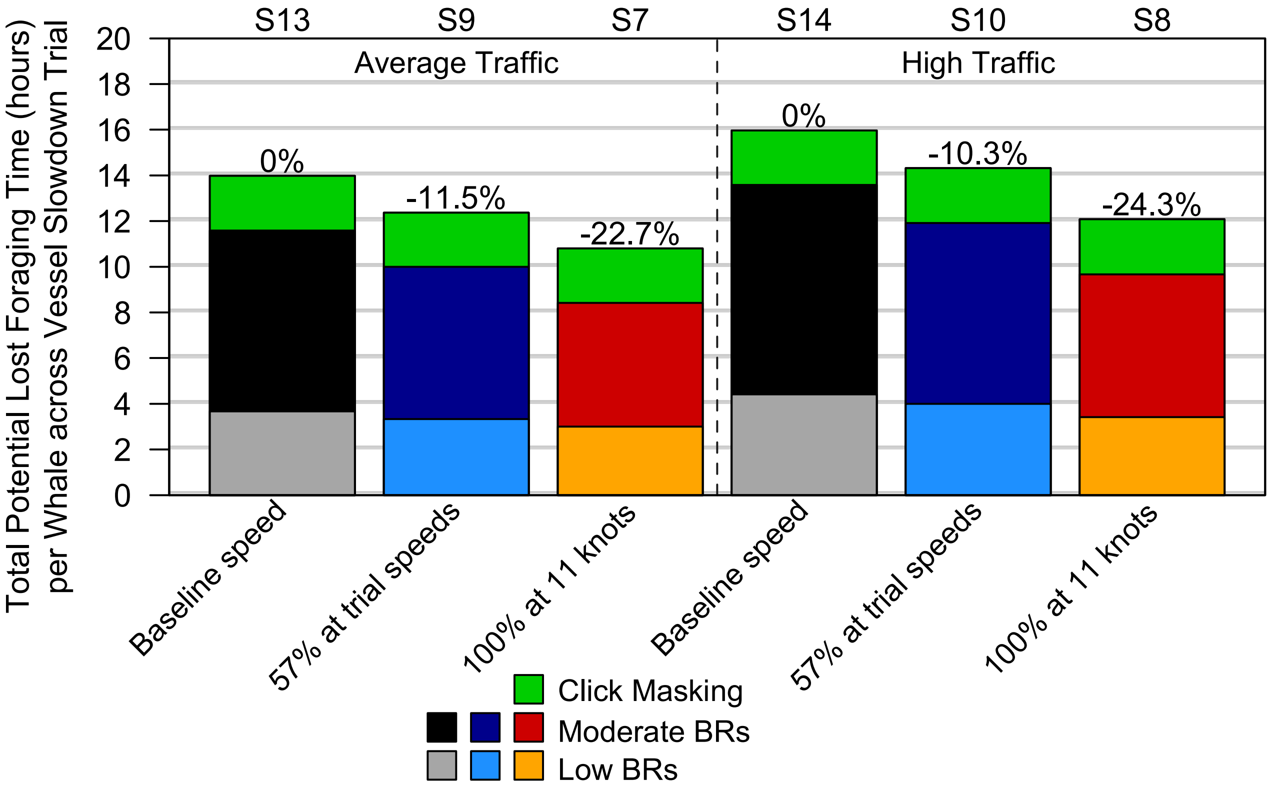

Figure 8. Potential lost foraging time (hours) per whale for sum total estimates of Low BRs, Moderate BRs and click masking for the 61-day slowdown trial period across average traffic (left panel) and high traffic (right panel) post-trial current traffic scenarios. The percentage reduction in 'potential lost foraging time' from current average and high traffic baseline speed scenarios (S13 and S14) to 57% compliance at trial speeds (S9 and S10) and 100% (S7 and S8) compliance to 11 knot speed scenarios has been provided above each bar. Colours of scenarios are consistent with those in Figure 5.

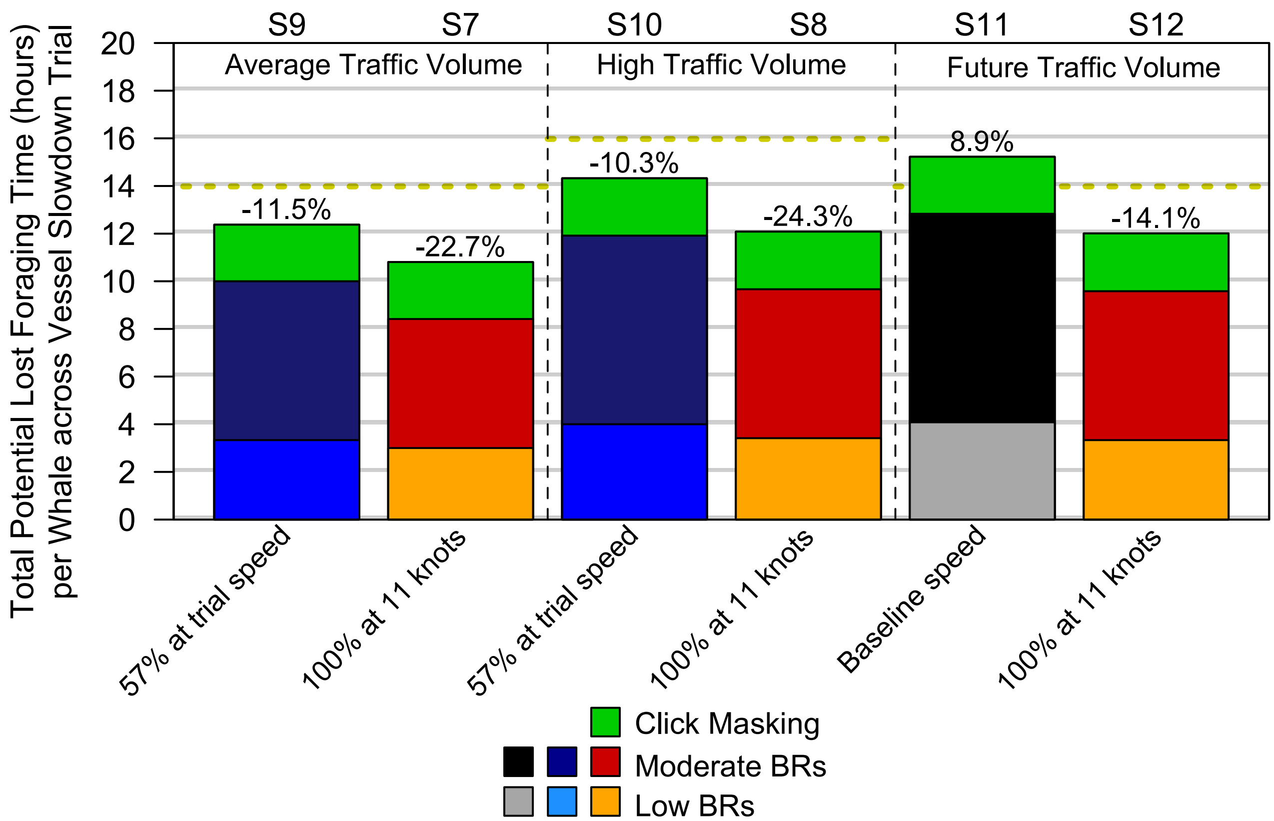

Figure 9. Potential lost foraging time (hours) per whale for sum total estimates of Low BRs, Moderate BRs and click masking for the 61-day slowdown trial period across current average and high traffic, as well as future average traffic post-trial scenarios. The percentage reduction in 'potential lost foraging time' from the appropriate average traffic (S13) baseline scenario, or the high traffic (S14) baseline speed scenario has been provided above each bar. The dashed yellow bars in each panel reflect the comparison against which change in 'potential lost foraging time' is compared, i.e., S13 using baseline speeds for an average traffic day in left and right panels of figure, and S14 using baseline speeds for a high traffic day for centre panel. Colours of scenarios are consistent with those in Figure 6.

4. Discussion

This noise effect modelling report describes the results of a computer simulation that aims to assess the benefits to SRKW of a vessel slowdown in Haro Strait under a variety of operational conditions or scenarios. These modeled noise conditions included pre-trial baseline conditions with both average and high traffic volume, and two compliance levels (100% and 50%) to the 11 knot speed limit proposed for the slowdown period. Post-trial, the noise model used the new vessel speed-noise level relationships developed during the trial, and remodelled both baseline and 100% compliance to 11 knots, as well as the 57% observed compliance level and actual speeds observed during the slowdown trial (details in Appendix 1). A future traffic volume scenario included both average traffic volume at baseline speeds and 100% compliance to an 11 knot speed.

The simulation utilizes an SRKW-noise exposure model (SMRU 2014a) developed to assess the impact of shipping noise by quantifying the number of SRKW behavioural responses (BRs) and the number of residual echolocation click masking minutes lost by comparing different potential noise scenarios over a two month (61-day) slowdown trial from August 7 to October 6, 2017. This report provides numbers of BRs by pod and by month across a six-month summer period, and then focuses on the two month slowdown trial period for six pre-trial scenarios (termed S1 to S6) and eight post-trial scenarios (termed S7 to S14). Due to the challenges involved in estimating BRs and masking and converting to a 'potential lost foraging time', it is important to focus more on the percent delta change in calculated values, rather than the absolute values of hours or minutes provided. As more lost foraging time due to vessel noise is a negative effect, then a reduction in time lost foraging is a positive effect. As such reductions in 'potential lost foraging time' from baseline are positive in benefit to SRKW.

In evaluating net benefits to SRKW, it is important to acknowledge that commercial vessels complying with the 11 knot slowdown speed will pass through the study area more slowly than normal. Thus, despite instantaneous probabilities of BRs being lower, the exposure duration could be longer. As a commercial vessel moves through an area, there is a moving acoustic footprint around the vessel. Low and moderate severity behavioural responses can occur within these acoustic footprints, however, as the vessels decrease speed, this footprint decreases in size and therefore, at locations more distant from the shipping lane the exposure duration for a given exposure level decreases. For example, in Figure 4, a whale located within the Lime Kiln grid square for a 24-hour period during average traffic conditions (normal speed, average number of vessels), would be exposed to noise levels of at least 121 dB re 1µPa for 14, 5-minute time windows (of 288 possible daily windows). If 100% of the same number of vessels complied with an 11 knot slowdown, there would be only 4, 5-minute time windows at 121 dB re 1µPa despite the longer passage times. Therefore, despite the slower moving vessels being present in the area for longer, they do not result in more time periods of potential BR, as their lower source levels are less likely to lead to modelled disturbance of SRKW through the dose-response relation. Therefore, there is a net decrease in lost foraging time (a positive outcome for the whales) when vessels decrease their speeds, based on the BR thresholds used in this model.

The SRKW pod comparisons are a result of compiling the behavioural responses of 78 whales belonging to pods J, K, and L across a six-month period, as well as the actual two-month (61-day) slowdown period. The median daily rates of low and moderate severity BRs varied by pod, with J-pod experiencing the most BRs. This is largely reflective of variation in SRKW pod occurrence in the study area due to preferential habitat selection of the Haro Strait region (J pod has the highest occupancy of the three pods, estimated to be 19 days across the 61-day slowdown trial period compared to 13.4 and 14.0 for K-pod and L-pod). Likewise, monthly comparisons of BRs (June through September highest) are a measure of seasonal variability in occupancy of this region, reflecting estimated pod-specific variation in occurrence. Sightings data from 2001-2011 indicates all pods are present for fewer days in May and October, compared to the months of June through September (Figures 5 and 6). These model estimates of SRKW presence are based on historical data, and do not represent the actual attendance of SRKW in the Haro Strait slowdown region in 2017.

Differences between an average and a high traffic volume day (for example S1 and S2 respectively) showed increased impacts on SRKW across all response measures. There were 21.6% more low BRs, 20.7% more moderate BRs and 1.5% more minutes of residual click masking with high traffic volume compared to average volumes in the Haro Straight study area for the six-month assessment period (there are only slightly higher percentage gains when restricting comparison to the 61-day slowdown trial period). This supports the logical conclusion that more ships moving at average (unmitigated) speeds translates to more 'potential lost foraging time' for SRKWs.

The positive benefit to SRKW of compliance to 11 knot speeds was clearly illustrated in both pre-trial and post-trial results (Figures 7, 8 and 9), noting that the application of the new vessel speed-noise level relationships had a small but positive effect compared to original pre-trial model predictions. On an average traffic volume day for the slowdown period, 100% compliance to 11 knot speeds resulted in 20.6-22.7% reduction in 'potential lost foraging time', with the percent reduction slightly larger at 21.4-24.3% on a high traffic volume day. At 50% compliance to 11 knot speeds 'potential lost foraging time' reduced by 8 and 10.4% for average and high traffic volumes, respectively, while reductions for the actual trial compliance (57%) and speeds were 11.5 and 10.3% for average and high traffic volumes respectively. Reductions reflect decreased numbers of moderate severity BRs and to a lesser extent low severity BRs. Percent reductions in both low and moderate BRs are higher than those estimated for total 'potential lost foraging time' (Tables 5 through 8). Click masking minutes were less variable across scenarios and increased from baseline by ~1% in pre-trial scenarios and were similar (average traffic volume) or increased by 1% (high traffic volume) in post-trial 100% slowdown compliance scenarios (Figures 7 and 8). Estimated 95% confidence intervals are wide, especially for moderate BRs, reflecting a right skew in the probability distribution of SRKW response to vessel noise (noting that no uncertainty was included in the noise layer provided).

We observe the same trends when we summarize these same results as the estimated time lost from foraging per 'slowdown trial period' and per whale day. Due to the challenges involved in estimating BRs and masking and converting to a 'potential lost foraging time', as stated earlier it is better to focus on the percent change, rather than the absolute values quoted. Pre-trial, at 100% compliance to 11 knots during the slowdown trial period, the total 'potential lost foraging time' per whale was reduced for average traffic volume from 13.33 to 10.59 total hours (i.e., a reduction of 2.74 hours), or 51.6 to 41.4 minutes (i.e., a reduction of 10.2 minutes) per whale day. Using the post-trial vessel speed-noise level relationships the reduction totalled 3.18 hours, or 12.6 minutes per whale day for each whale (equivalent of an absolute change of 0.9%, from 3.8% to 2.9% of a whale day). These reductions equate to 214 and 248 hours total across all 78 individual whales combined over the 61-day trial period. Reductions per whale for high traffic volume were 3.37 and 3.89 hours for pre and post trials respectively or 13.2 and 15 minutes per whale day for each whale (equivalent of an absolute change of 1.0%, from 4.3% to 3.3% of a whale day). (Tables 9 and 10).

The additional three commercial vessels and a tug that were added to the baseline scenario (normal speed and traffic volume) to account for potential future traffic volume, result in an 8.9% increase in 'potential lost foraging time', the equivalent of 1.2 hours per whale for the slowdown period or 0.3% of a whale day if transiting at normal speeds. Lastly, if instead, 100% of piloted vessels transit comply to a 11 knot slowdown for the future traffic scenario, then the 'potential lost foraging time' is estimated to be reduced by 14.1%, from the baseline scenario, the equivalent reduction of 2.0 hours per whale for the slowdown period or 0.5% of a whale day. In other words, a fully compliant slowdown to 11 knots is shown to more than compensate for the predicted increase in future traffic volume (Tables 9 and 10).

The results of this simulation study have suggested clear benefits of piloted-vessel slowdowns to SRKWs in this hot-spot region of critical habitat. Despite SRKW enduring longer noise-exposure times due to slower vessel speeds through Haro Strait, the concurrent lower source levels or acoustic intensity of these vessels resulted in a 22.7-24.3% positive benefit (compared to baseline) in the predicted amount of time SRKW are potentially disturbed by vessel traffic noise when all piloted vessels are travelling at 11 knot speeds and post-trail speed coefficients are used. The predictions based on the actual slowdown trial compliance levels and speeds indicated a lower reduction in the time foraging is affected by vessel noise, but still resulted in an 10.3-11.5% positive benefit compared to baseline scenarios.

5. References

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Appendix 1.

Table A1 (Copy of Table 2 in Jasco Report[1])

Numbers of piloted vessel transits in Haro Strait representing the three traffic conditions in the model. Baseline daily piloted vessel counts through Haro Strait were based on PPA daily vessel counts (Dominic Tollit, SMRU Consulting, pers. comm., 3 Apr 2017). Average and high traffic conditions represent median and 95th percentile vessel counts, respectively. Future traffic conditions are based on the Port of Vancouver's regional traffic forecast (to 2026).

Vessel category	Baseline		Future
	Average traffic (ships per 24 h)	High traffic (ships per 24 h)	Average traffic (ships per 24 h)
Bulker*	8	10	9
Containership	4	6	5
Tanker	1	2	2
Tug	0	0	2
Vehicle Carrier	1	2	1
Cruise	0	1	0
Total	**14**	**21**	**19**

* Includes both bulk carriers and general cargo vessels.

Table A2 (Table 3 in Jasco Report)

Mean slowdown speed and overall participation rate recorded during the slowdown trial, by category.

Vessel category	Slowdown speed (kts)	Participation rate (%)
Bulker	11.30	55
Containership	11.40	68
Tanker	10.95	55
Vehicle Carrier	11.48	66
Cruise	10.64	90

[1] MacGillivray, A., Z. Li, and H. Yurk. 2018. Modelling of Cumulative Vessel Noise for Haro Strait Slowdown Trial: Final Report. Document 01577. Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority ECHO Program. (Accessed 29 March 2018).

Appendix F

Noise model validation memo - SMRU Consulting North America

Validation of JASCO Noise Model Using Empirical Data.

Technical Memo Prepared for the ECHO Program

[May 2018]

SMRU Consulting North America

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Validation of JASCO Noise Model Using Empirical Data.

2 May 2018

Prepared by SMRU Consulting NA

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Table of Contents

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1 Introduction

The aim of this technical memo is to compare fine-scale noise level predictions (developed by JASCO Applied Sciences to assess the benefits of a vessel slowdown in Haro Strait, see MacGillivray et al 2018) to two lunar months of empirical data collected at the Lime Kiln hydrophone. JASCO provided broadband (9 Hz – 78 kHz) sound pressure levels (SPL, dB re 1µPa) estimates and 1/3 octave band estimates (dB re 1µPa) centered on 50 kHz for two current traffic baseline speed conditions for the Haro Strait study area (Figure 1) in July. The first traffic scenario modeled an average (50th percentile) traffic volume day (Scenario S1) and the second scenario, a high (95th percentile) traffic volume day (Scenario S2). The JASCO predictions used average sound speed profiles for July based on data collected by DFO. These water conditions should be broadly similar from August to September. The resolution of the data were 1-minute increments and 200m grids. Broadband SPLs were used in an SRKW-noise exposure model (SMRU 2014) for assessing the number of low and moderate severity behavioral responses, while 50 kHz power spectral density (PSD, dB re 1µPa^2/Hz) data were used to assess residual amounts of click masking (SMRU 2014). The PSD levels were estimated from the 1/3 octave SPL provided by JASCO by subtracting 40.36 dB in order to account for the bandwidth of the 1/3 octave band at 50 kHz.

2 Methods

For the last two years, SMRU Consulting North America have been collecting ambient noise data using a calibrated hydrophone located in waters 23m deep in front of Lime Kiln State Park. The JASCO noise predictions were made at 10 m depth. This difference in depth should not result in large differences and should only affect noise levels below ~35 Hz. A JASCO noise file was converted to an ArcGIS raster coverage, and the location of the Lime Kiln hydrophone overlaid to select the appropriate single 200m grid cell for noise level comparisons (Figure 1).

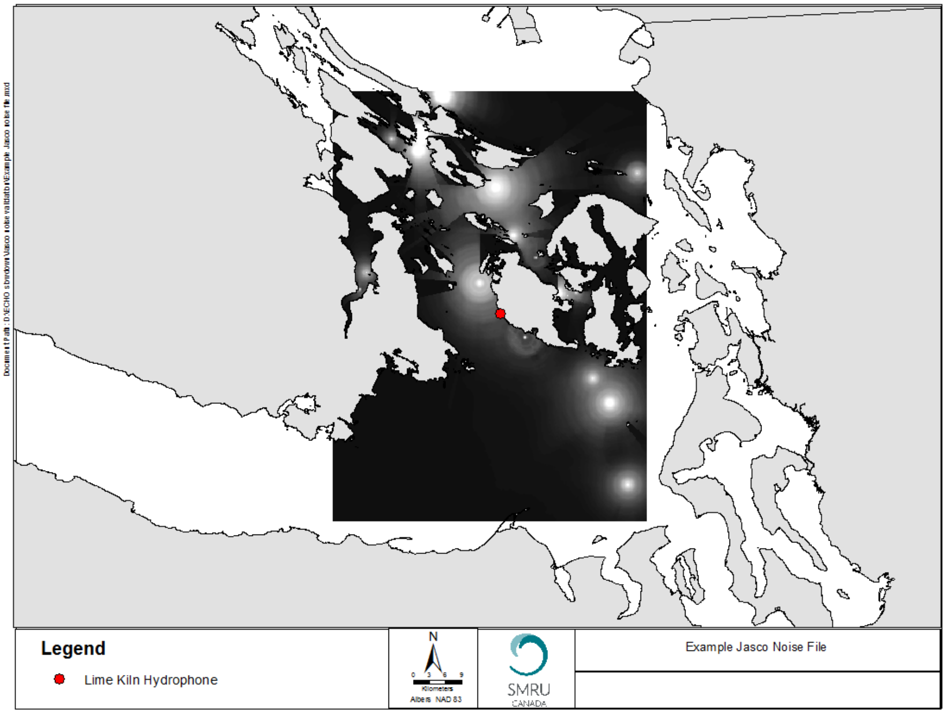
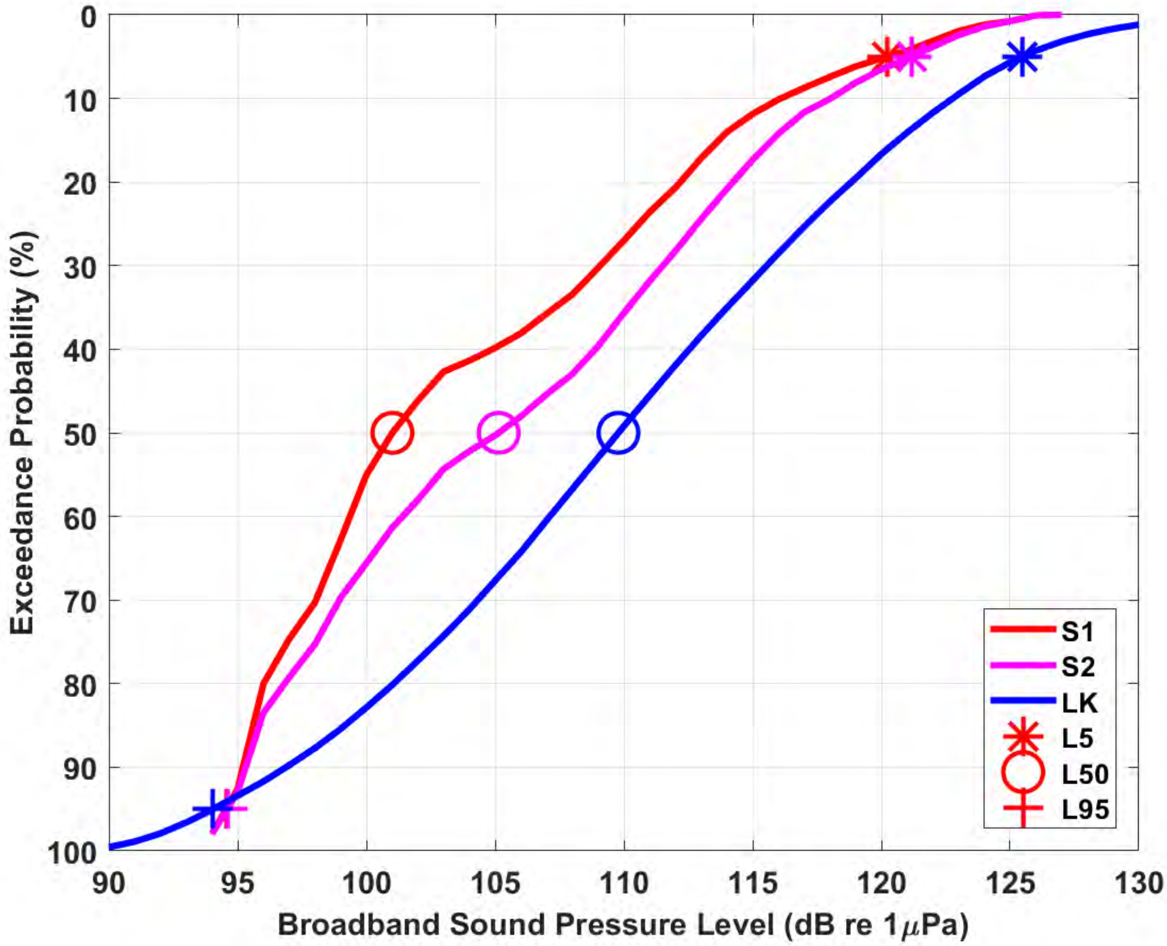


Figure 1 Location of the Lime Kiln hydrophone and JASCO Haro Strait noise prediction study area.

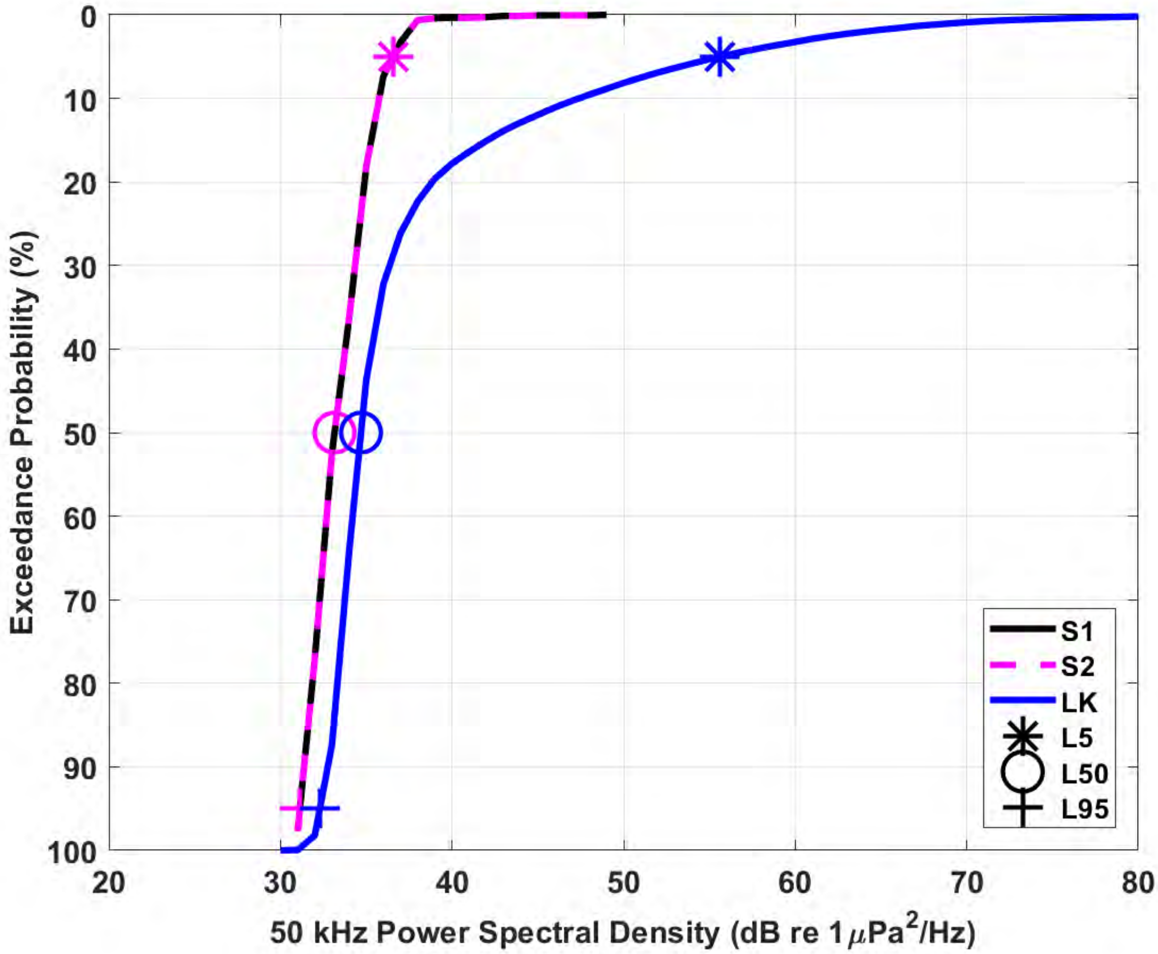
Comparative ambient noise data from the Lime Kiln Hydrophone were pooled across the lunar months of August and September 2016 (n=76,608 minutes). These months were chosen because data at Lime Kiln were not available for July 2016 (due to a cable failure) and August/September should be representative of conditions in July based on traffic patterns, weather conditions and sound speed profiles. Datasets were compared using cumulative distribution functions, where L50 represents the median value and Leq represents the mean value. Differences between JASCO predictions for each scenario were compared with the empirical data from Lime Kiln for both broadband noise SPL (dB re 1µPa, Figure 2) and the 50 kHz PSD (dB re 1µPa^2/Hz, Figure 3).

In recognition that JASCO noise predictions can not easily replicate the number and frequecy of small boats that transit past Lime Kiln in the day, as the JASCO model accounts only for AIS-enabled vessel traffic, we repeated the comparison using Lime Kiln data between 21:00 and 06:00 (i.e., night time). This restricted the data to 25,439 minutes. The resulting cumulative distribution functions are provided for both broadband noise SPL (dB re 1µPa, Figure 4) and the 50 kHz PSD (dB re 1µPa^2/Hz, Figure 5).



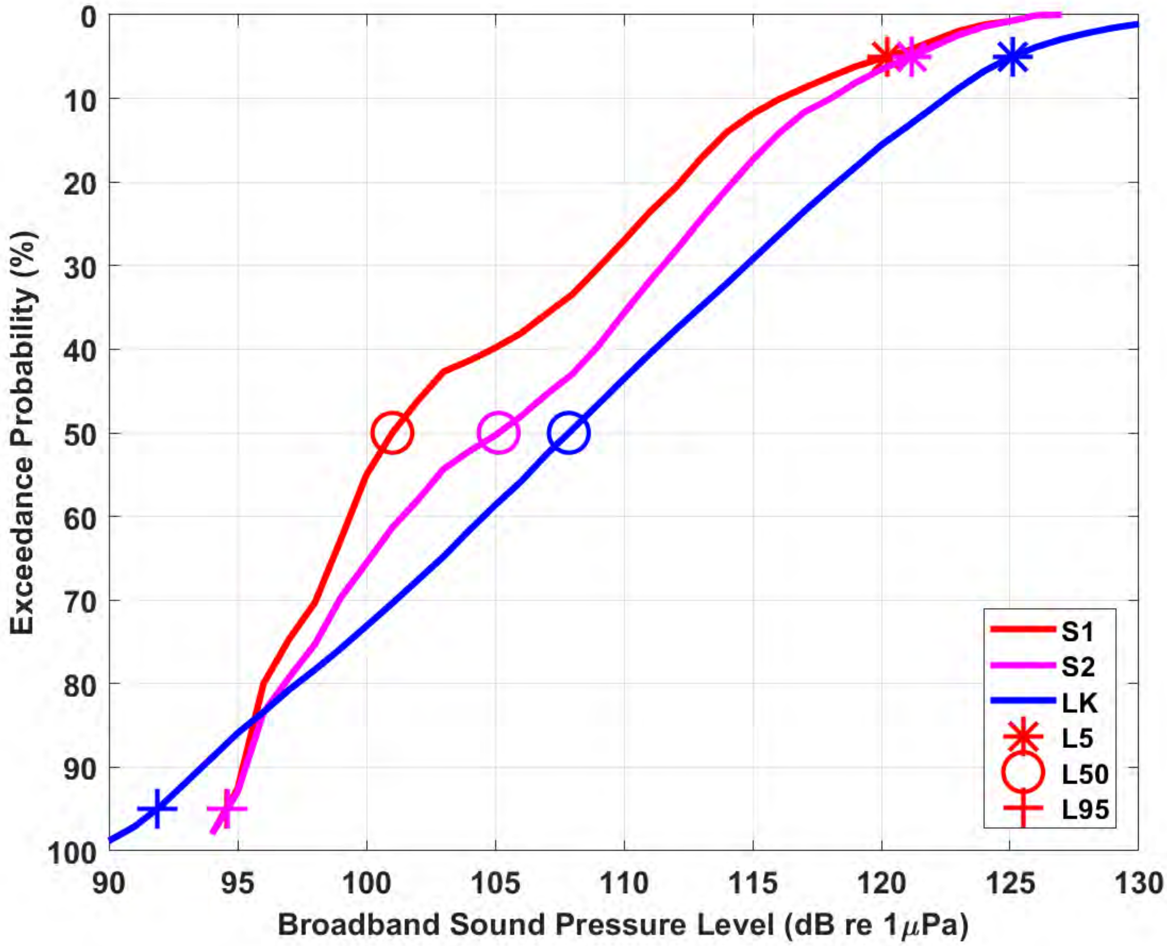
	Metric	S1 SPL (dB)	S2 SPL (dB)	LK SPL (dB)	S1-LK (dB)	S2-LK (dB)
1	L5	120.2	121.2	125.5	-5.3	-4.3
2	L50	101.0	105.1	109.8	-8.8	-4.7
3	L95	94.6	94.6	94.0	0.5	0.5
4	Leq	104.6	106.4	110.4	-5.9	-4.0

Figure 2 Comparison of JASCO average traffic (S1) and high traffic (S2) broadband model SPL predictions for the Lime Kiln hydrophone location compared with two months of data recorded at Lime Kiln (LK).



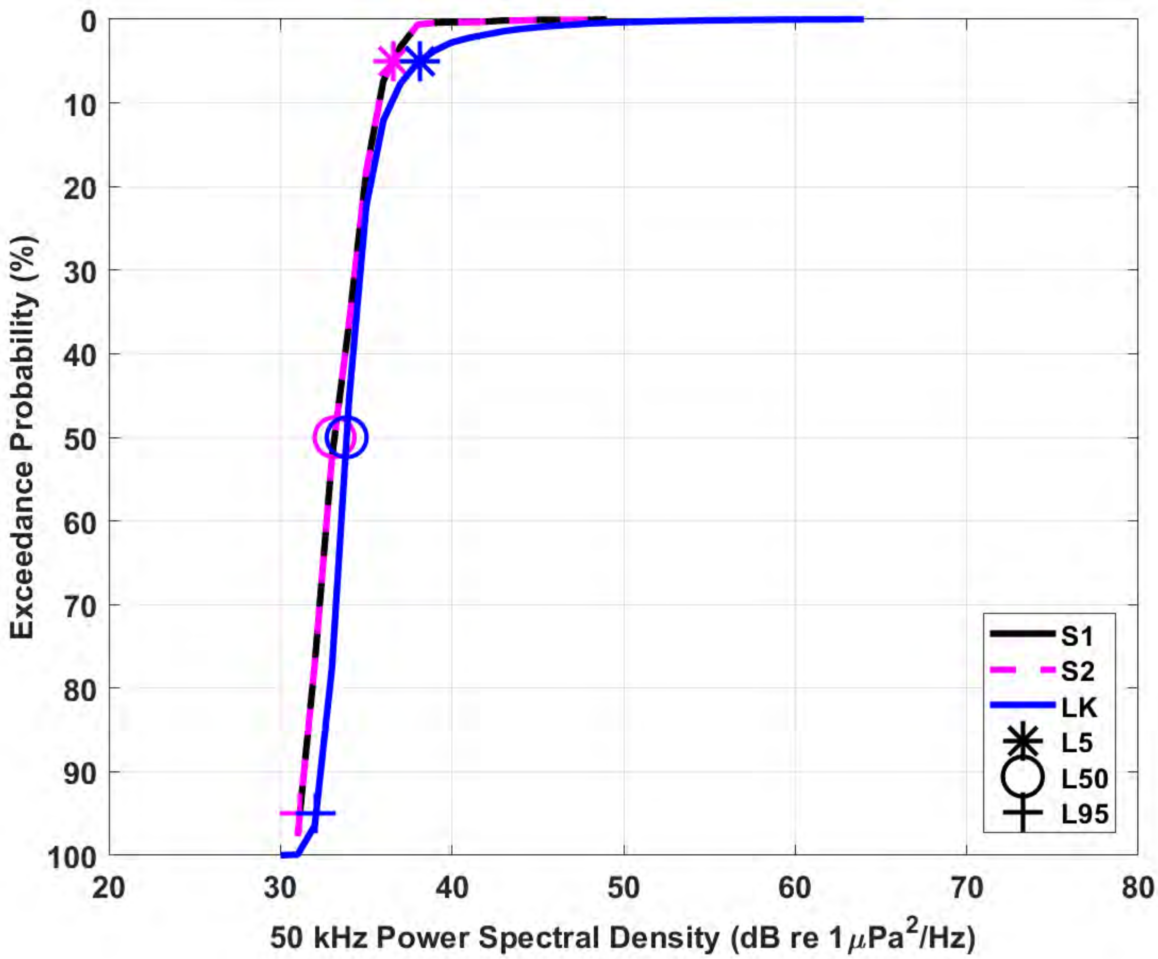
	Metric	S1 SPL (dB)	S2 SPL (dB)	LK SPL (dB)	S1-LK (dB)	S2-LK (dB)
1	L5	36.6	36.6	55.6	-19.1	-19.1
2	L50	33.2	33.2	34.7	-1.5	-1.5
3	L95	31.1	31.1	32.3	-1.2	-1.2
4	Leq	34.0	34.0	38.0	-4.1	-4.1

Figure 3 Comparison of JASCO average traffic (S1) and high traffic (S2) 50 kHz model PSD predictions for the Lime Kiln hydrophone location compared with two months of data recorded at Lime Kiln (LK).



	Metric	S1 SPL (dB)	S2 SPL (dB)	LK SPL (dB)	S1-LK (dB)	S2-LK (dB)
1	L5	120.2	121.2	125.1	-4.9	-3.9
2	L50	101.0	105.1	107.9	-6.9	-2.7
3	L95	94.6	94.6	91.9	2.7	2.7
4	Leq	104.6	106.4	108.6	-4.0	-2.2

Figure 4 Comparison of JASCO average traffic (S1) and high traffic (S2) broadband model SPL predictions for the Lime Kiln hydrophone location compared with two months of data recorded at Lime Kiln (LK) during night time hours.



	Metric	S1 SPL (dB)	S2 SPL (dB)	LK SPL (dB)	S1-LK (dB)	S2-LK (dB)
1	L5	36.6	36.6	38.1	-1.5	-1.5
2	L50	33.2	33.2	33.9	-0.7	-0.7
3	L95	31.1	31.1	32.1	-0.9	-0.9
4	Leq	34.0	34.0	34.9	-0.9	-0.9

Figure 5 Comparison of JASCO average traffic (S1) and high traffic (S2) 50 kHz model PSD predictions for the Lime Kiln hydrophone location compared with two months of data recorded at Lime Kiln (LK) during night time hours.

3 Results

The broadband L50 SPL recorded overall at the calibrated Lime Kiln hydrophone using August and September, 2016 data, was 109.8 dB re 1µPa. The JASCO noise model L50 SPL predictions for average (S1) and high (S2) traffic volumes were 101 and 105.1 dB re 1µPa respectively, mismatches of 8.8 and 4.7 dB. The Leq was mismatched by 5.9 and 4.0 dB respectively (Figure 2). When only using night time data, model mismatches at the Lime Kiln hydrophone were smaller, at 6.9 and 2.7 dB for L50 and 4.0 and 2.2 dB for Leq (Figure 4). Model predictions at L5 were underestimates, while predictions at L95 were overestimates (Figure 2 and Figure 4).

The median (L50) 50 kHz PSD recorded at Lime Kiln during these two months was 34.7 dB re 1µPa^2/Hz. The JASCO noise model L50 PSD predictions for average (S1) and high (S2) traffic volumes were both 33.2 dB re 1µPa^2/Hz, resulting in very small mismatches of 1.5 dB. The Leq was underestimated by 4.1 dB (Figure 3). When only using night time data, model prediction underestimates were negligible for both L50 at 0.7 dB and Leq at 0.9 dB (Figure 5). A notable difference is exhibited at L95 (an underestimate of 19.1 dB) for the two months of data (Figure 3), which is not seen when using the night time data, where the underestimate is only 1.5 dB (Figure 5).

4 Discussion

This noise model validation is for one single location with Haro Strait. Despite the use of a flow shield on the hydrophone, ambient noise recordings at Lime Kiln will be impacted to some extent by flow noise (i.e. recorded noise levels will be higher than those experienced by an animal at that location). Coupled with the effects of small boat noise (and their use of echo-sounders), which were not included in the predictive noise models, we consider the broadband SPL predictions as a good representation of noise conditions at Lime Kiln, especially when comparing the night time period (Figure 4), in which the effects of small boat noise is reduced considerably, but flow noise still remains.

Comparison of 50 kHz PSD values shows very good agreement between JASCO noise model predictions and empirical measurements (Figure 3 and Figure 5). The large underestimate of 19.1 dB at L5 using the full two months of data can be attributed to depth sounders and fish finders that are used extensively by small boats that frequent the Lime Kiln area and which use a 50 kHz signal to detect the bottom or fish (Figure 3). This underestimate at L5 is reduced to just 1.5 dB when only night time data are used. The similarity in 50 kHz PSD at average and high traffic volumes reflects the high transmission loss within the 50 kHz band (~160 dB at ~1.5 km range), resulting in little impact on the level of ambient noise at this frequency at Lime Kiln. As a result, any additional vessel modelled to transit within the southbound lane have very little impact on received levels at Lime kiln within this band.

This validation shows good agreement between JASCO noise modeling and empirical acoustic data at a single site and demonstrates the value of comparing models with data collected in situ.

5 Acknowledgements

We wish to thank Alex MacGillivray and Zizheng Li of JASCO for comments on this report.

6 References

MacGillivray, A., Z. Li, and H. Yurk. 2018. Modelling of Cumulative Vessel Noise for Haro Strait Slowdown Trial: Final Report. Document 01577, Version 1.0. Technical report by JASCO Applied Sciences for Vancouver Fraser Port Authority ECHO Program.

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