ECHO Program

Slowdown co-benefits study summary

Executive summary

To better understand the potential benefits of the ECHO Program's voluntary ship slowdowns, the ECHO Program commissioned Starcrest Consulting Group (Starcrest) and Point Blue Conservation Science (Point Blue) to evaluate how the program's slowdowns may affect air emissions and whale strike risk. The results of this study suggest that the program's slowdowns can both reduce air emissions and reduce the risk of whale strikes in the slowdown areas. This framing document summarizes the study's key findings and methodology. To read the full technical analysis related to air emissions and whale strike risk, see Attachments A and B, respectively.

Partners

- Transport Canada – Funding partner
- Starcrest Consulting Group – Air emissions analysis
- Point Blue Conservation Science – Whale strike risk analysis

Key findings

The results of this study show that the ECHO Program's slowdowns offer benefits in terms of reducing emissions and decreasing the risk of whale strikes within the slowdown regions. Specifically:

1. Slowdowns can reduce air emissions

- The study showed that the program's slowdowns could reduce greenhouse gas and air pollutant emissions (such as carbon dioxide, sulfur and nitrogen oxides, and particulate matter) by between **11% and 25%**, depending on location and emission type. In aggregate, across all slowdown areas and ship types, the reduction in air emissions attributable to the slowdowns was 14%.

2. Slowdowns can reduce risk of whale strikes

- The study showed that the program's slowdowns could reduce the proportional risk of whale strikes to humpbacks and fin whales by between **18% to 27%,** depending on the slowdown location and the type of whale species being considered.

- The study results highlighted that strike risk reduction was corelated not only to the reduction in speed, but also to the actual speed of the vessel. The slower a vessel travelled, the lower the risk of strike. For example, vehicle carriers showed the greatest change in speed (2.2 knot reduction) and the greatest associated reduction in strike risk (21.8%) when speeds during the slowdown were compared to a baseline period immediately prior to the slowdowns. However, tankers had a relatively small change in speed (1.0 knot reduction) but the slowest absolute speed (11.0 knots) which showed the second greatest reduction in strike risk (20.7%).

Methodology

Assessing air-emission co-benefits

During the ECHO Program's voluntary slowdowns, data on ship traffic and ship characteristics were collected in order to calculate air emissions for each ship transit. This analysis was then re-evaluated with substituted speed data taken from comparable vessels during a baseline period when the slowdowns were not in effect. These data were collected using the Automatic Identification System (AIS) and included information about vessel type, draft, length, breadth, and speed through water averages throughout the slowdowns.

Air emissions for each transit were calculated by Starcrest using their catalogue of recorded air emissions by vessel characteristics such as engine type, fuel types, and operational variables from the AIS data. This catalogue was used to estimate air emissions for the actual vessels and speeds recorded during the slowdowns. The emissions were then re-calculated substituting the speed of a comparable vessel collected during the baseline period. Estimated emission reductions resulting from the slowdown were then determined based on the difference between these values. Air emissions were calculated for carbon dioxide, oxides of nitrogen, oxides of sulfur, particulate matter and diesel particulate matter.

As air emissions are not spatially limited to their emission location, an assessment was also undertaken to evaluate how sensitive total air emissions are to vessel speed between the slowdown regions on a representative transit within the Georgia Basin air shed (see details in Attachment A).

Assessing whale strike risk co-benefits

Whale strike collision models are based on avoidance behavioural models coupled with the breadth, draft and speed of the vessel. As the avoidance behavioural models for SRKW (Southern Resident Killer Whales) have not been rigorously developed, the whale strike risk model focuses on humpback and fin whales. Whale strike risk was calculated for both humpback and fin whales, for the following main commercial vessel types: container vessels, bulkers and general cargo, cruise ships, car carriers and tankers.

Since actual whale densities are not known within the slowdown areas, the co-benefits are developed based on proportional changes in strike risk. The speed through water is a non-linear indicator of strike risk, meaning that as vessel speed increases linearly, the risk of strike increases non-linearly with further reductions in speed providing outsized benefit. Given this relationship, it is impossible to average the speed through water within a slowdown area and expect an accurate strike risk evaluation.

To address this, the AIS data were broken into vectors for each AIS data point, and modelled sea currents were used to calculate the speed through water and time of transits for each point segment within the slowdown regions. As a result, each individual transit within a slowdown region generates several hundred vector segments each of which were summed to evaluate a single vessel transit.

Whale strike risk analysis was conducted using actual, measured vessel transits throughout the slowdowns. This analysis was then recalculated with substituted speed data taken from comparable vessels during a baseline period prior to the slowdowns, in order to represent expected strike risk for the same period when slowdowns were not in place. The relative difference between these strike risk values provides the proportional strike risk reductions due to the slowdowns. Further details are provided in Attachment B.

Air Emissions Benefit of Vessel Speed Reduction During Enhancing Cetacean Habitat and Observation (ECHO) Program

Prepared for

Vancouver Fraser Port Authority

March 2023

STARCREST CONSULTING GROUP, LLC
ENVIRONMENTAL MANAGEMENT • AIR QUALITY • CLIMATE • SUSTAINABILITY

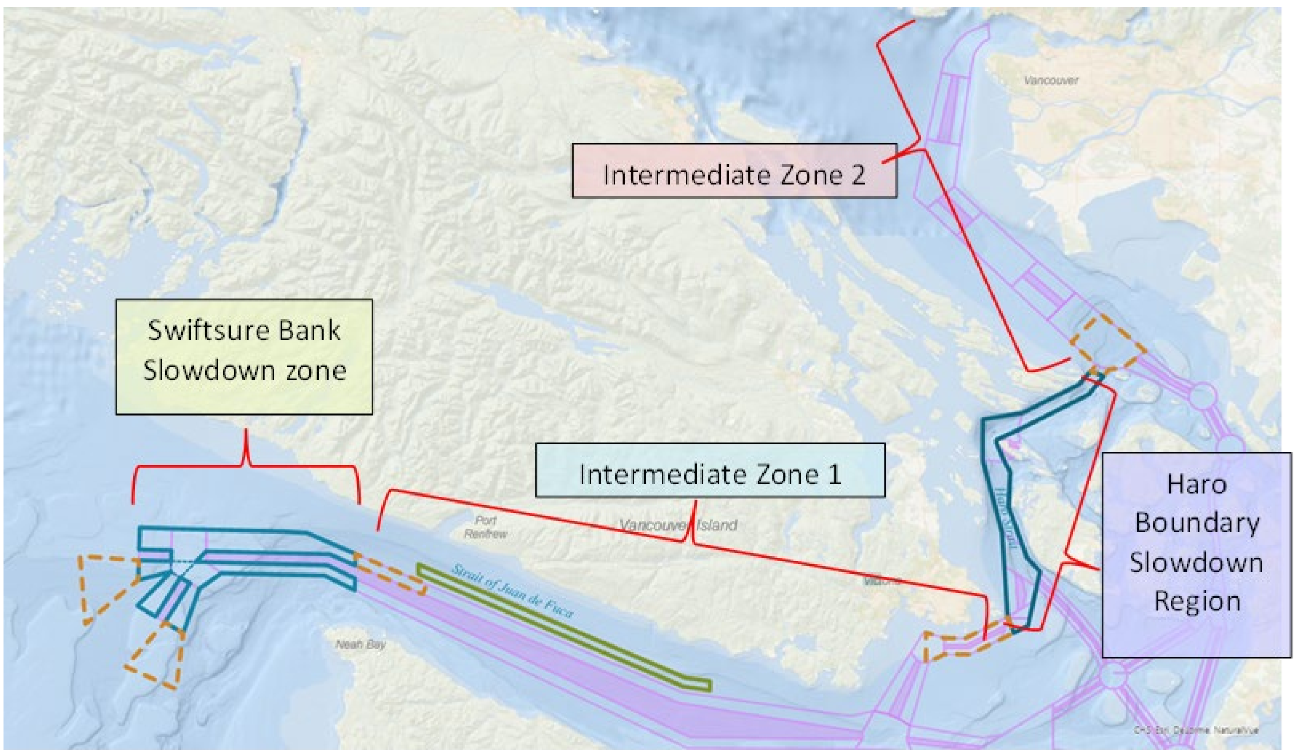
Established 1997

Table of Contents

EXECUTIVE SUMMARY

The purpose of this study is to quantify the emissions benefits of seasonal slowdowns, organized by the Vancouver Fraser Port Authority's ECHO Program (ECHO), which have as their primary objective, to reduce the impacts of underwater noise on endangered Southern Resident killer whales. The Program's slowdown regions are shown in the Figure E.1 below, with the two slowdown regions and the intermediate zones bracketing the two slowdown regions. Note that there are three slowdown regions Swiftsure Bank, Haro Strait, and Boundary Pass. Due to their proximity, Haro Straight and Boundary Pass are grouped together as Haro Boundary in the Figure and in the remainder of the report.

Figure E.1: The ECHO Program Slowdown Regions



Vessel identification and operational information was provided to Starcrest Consulting Group (Starcrest) by the ECHO team for all transits through the Swiftsure Bank, Haro Strait, and Boundary Pass slowdown areas for both the non-slowdown season (March through May 2022) and slowdown season (June through October 2022). The information was used to determine the emissions of particulate material (PM), diesel particulate material (DPM), nitric oxide and nitrogen dioxide (NOx), sulfur oxides (SOx), and carbon dioxide (CO2) from all vessels transiting the slowdown areas during the slowdown season. The emissions are grouped by the five ECHO vessel types and summed for the total slowdown season emissions by area and vessel type.

Calculation of the emission benefits of the slowdown speeds requires estimating the baseline emissions (emissions that would have occurred without the slowdown program) for the same vessel transits that occurred during the slowdown season. Baseline speeds are calculated from speed correlation factors (SCFs) generated from the non-slowdown period (March through May 2022) vessel speed data. The SCFs are used to change each vessels slowdown season speed to its corresponding baseline speed. The baseline speeds are then used to recalculate each vessel transit's emission. The emission reductions for each vessel transit are calculated by subtracting the slowdown emissions from the baseline emissions.

The emissions benefits for all vessel transits are grouped and summed by ECHO vessel type and area. The Haro Strait and Boundary Pass reductions are then combined and reported as the Haro Boundary emissions. The baseline emissions, slowdown reductions, and percent reduction from baseline results are shown in Table E.1 and represent the total emission benefits in the slowdown regions for the 2022 slowdown season.

Table E.1: 2022 Slowdown Season Baseline Emissions and Emission Reductions by Vessel Type and Slowdown Region

	PM (tons)	DPM (tons)	NOx (tons)	SOx (tons)	CO2 (tons)
Baseline					
Haro Boundary	**5.06**	**5.04**	**439.53**	**11.41**	**18,708**
Bulk	2.17	2.17	177.74	4.58	7,513
Car Carrier	0.29	0.29	25.50	0.60	982
Container	1.79	1.77	183.65	4.38	7,177
Passenger	0.60	0.60	36.12	1.40	2,295
Tanker	0.20	0.20	16.53	0.45	740
Swiftsure Bank	**9.83**	**9.74**	**817.63**	**22.95**	**37,623**
Car Carrier	0.84	0.84	65.18	1.84	3,010
Bulk	1.86	1.86	171.18	4.46	7,312
Container	2.42	2.36	271.22	6.20	10,167
Passenger	3.78	3.75	230.35	8.34	13,668
Tanker	0.93	0.93	79.70	2.11	3,466
Grand Total Baseline Emissions	**14.89**	**14.78**	**1,257.16**	**34.36**	**56,331**
Emission Reductions					
Haro Boundary	**1.27**	**1.28**	**75.39**	**2**	**3589**
Bulk	0.52	0.52	25.38	0.69	1,126
Car Carrier	0.06	0.06	4.71	0.11	183
Container	0.58	0.58	38.54	1.11	1,829
Passenger	0.08	0.08	5.09	0.23	370
Tanker	0.03	0.03	1.67	0.05	82
Swiftsure Bank	**1.26**	**1.28**	**90.06**	**2.73**	**4,478**
Bulk	0.30	0.30	16.23	0.54	894
Car Carrier	0.25	0.25	17.30	0.53	868
Container	0.18	0.19	23.65	0.60	978
Passenger	0.32	0.32	19.83	0.69	1,133
Tanker	0.21	0.21	13.05	0.37	605
Grand Total Emission Reductions	**2.53**	**2.55**	**165.45**	**4.92**	**8,067**
Percent Reduction From Baseline					
Haro Boundary	**25%**	**25%**	**17%**	**19%**	**19%**
Bulk	24%	24%	14%	15%	15%
Car Carrier	22%	22%	18%	19%	19%
Container	32%	33%	21%	25%	25%
Passenger	13%	13%	14%	16%	16%
Tanker	16%	16%	10%	11%	11%
Swiftsure Bank	**13%**	**13%**	**11%**	**12%**	**12%**
Bulk	16%	16%	9%	12%	12%
Auto Carrier	30%	30%	27%	29%	29%
Container	8%	8%	9%	10%	10%
Passenger	8%	9%	9%	8%	8%
Tanker	22%	22%	16%	17%	17%
Grand Total	**17%**	**17%**	**13%**	**14%**	**14%**

Overall, the seasonal slowdown resulted in a 13% to 17% reduction in emissions in the slowdown regions depending on the pollutant, and close to equal amounts of reductions are generated in each of Swiftsure Bank and Haro-Boundary zones. Of note is that the effectiveness of the slowdown showed an almost two-fold difference in the air quality benefits between the regions with the Haro Boundary region vessels achieving close to the same total emission reductions with half of the number of transits (i.e., averaging almost twice the emissions reductions per vessel transit). This difference is explained by the different operational behavior of the vessels with most of the vessels transiting the Haro Boundary zone reducing their speeds approximately 50% more than in the Swiftsure Bank area.

Additionally, an analysis was performed to determine how sensitive the total air emissions in the Georgia air basin are to the vessel speed behavior in the two regions of the air basin not subject to speed reductions (the intermediate zones in the Figure E.1). Three scenarios were modeled where the slowdown zone speeds were kept at the slowdown season speeds and the intermediate zones speeds were varied. In Scenario 1, the intermediate zone vessel speeds were assumed to be the baseline intermediate zone speeds. In Scenario 2 the speeds assumed were 2% to 5% less and in Scenario 3, 2% to 5% more than the baseline speeds. The results of the analysis are shown in Table E.2.

Table E.2: Total Georgia Airshed Emissions changes relative to the baseline period for the three scenarios

	Georgia Airshed				
	PM (ton)	DPM (ton)	NOx (ton)	SOx (ton)	CO2 (ton)
Scenario 1	-2.3	-2.3	-240.0	-5.6	-10,106
Scenario 2	-3.6	-3.6	-375.1	-8.8	-15,984
Scenario 3	-0.9	-0.9	-99.9	-2.2	-3,990
Percent Change from Scenario 1					
Scenario 2	59%	59%	56%	58%	58%
Scenario 3	-62%	-62%	-58%	-61%	-61%

The results show that a modest 2% to 5% change in vessel speeds outside the slowdown zones increased or decreased the benefits achieved in the slowdown areas by approximately 60% within the entirety of the air shed. The sensitivity study demonstrates that the overall airshed emissions are sensitive to the vessel speed behavior outside the slowdown zones. However, the true emission benefits of the ECHO program for the Georgia air basin are unknown and can only be determined with information about the actual behavior of the vessels in the non-slowdown regions.

1. Introduction

The ECHO voluntary vessel slowdown program in the Swiftsure Bank, Haro Strait, and Boundary Pass seasonal slowdown areas is aimed at reducing the effect of underwater noise associated with commercial shipping on the welfare of the endangered Southern Resident killer whales. Slow down trials were begun in 2017 in Haro Strait and were expanded to Boundary Pass in 2018. Seasonal slowdowns were expanded to Swiftsure Bank with the addition of the outbound shipping lane slowdowns in 2020 and both the inbound and outbound shipping lanes added to the seasonal slowdowns in 2022. Acoustic evaluations of these seasonal slowdown effects have repeatedly demonstrated that vessel slowing successfully reduced the noise associated with ship traffic. Behavioral modelling, based on these acoustic results, has shown a benefit to killer whales' ability to use sound to navigate, communicate, and hunt, demonstrating the utility of the program.

Vessel slowdown programs have been used by many to reduce shipping emissions. However, the purpose of the slowdown regions considered here focuses on the reduction of underwater noise. The focus of this study is to evaluate the co-benefit of the vessel slowdown in reducing air emissions. While vessel speed is only monitored within the slowdown region, air emissions were also considered throughout the relevant air shed. This evaluation not only considers the air emission reductions associated with the slowdown areas but also considers how behavior of vessel traffic in the intermediate zones, not considered by the seasonal slowdown but still within the Georgia Basin air shed, may affect total air emissions through a separate sensitivity study. Starcrest Consulting Group was retained by the ECHO Program to estimate the emission reduction benefits of the slowdown in the three seasonal slowdown regions: Swiftsure Bank, Haro Strait and Boundary Pass. Emission reductions for particulate matter (PM), diesel particulate matter (DPM), oxides of nitrogen (NOx), oxides of sulfur (SOx), and carbon dioxide (CO2) were calculated.

The ECHO Program staff provided Starcrest with vessel speed through water, transit duration, and direction of travel as well as the vessel's name, IMO number, and ECHO classification type (passenger, container, auto carrier, bulk carrier, and tanker) for vessels operating within the three slowdown regions from March 2022 through to the end of October 2022. Information provided during the months where the slowdown was implemented (June through October) were used to determine the emissions for each vessel transit in each slowdown area. The emissions for each transit were summed to generate the slowdown season emissions for each region. The remaining months (March through May) speed information was used to determine baseline speeds for each vessel type. This resulted in speed correlation factors (SCFs) which would be used to convert the slowdown speeds to baseline speeds for each of the vessel transits used to generate the slowdown season emissions. The emissions were then recalculated using the new baseline speeds to determine the baseline emissions for each vessel transit and then summed for each area's baseline emissions. The emission reductions for each area were then calculated by subtracting the slowdown season emissions from the baseline emissions for each vessel transit and then grouped and summed for the slowdown seasons total emission reductions by ECHO vessel type.

The ECHO Program also requested that Starcrest perform a sensitivity analysis to determine the relative effect of ship behavior in the intermediate regions between the slowdown regions on the calculated emissions co-benefits in the entire Georgia Air Basin. Three scenarios were requested where emissions from the entire transit from the Swiftsure Bank to English Bay were calculated. Vessel speeds used to determine Scenario 1 emissions were the non-slowdown speeds recorded in March through May 2022 in the Swiftsure Bank and Haro Boundary zones, and since the program did not collect information on ship operations in the Intermediate zones, the baseline speeds in the Swiftsure Bank and Haro Boundary zone are assumed for Intermediate zone 1 and 2 respectively. Scenario 1 emissions were calculated using the baseline speeds in the intermediate zones. The Intermediate zones' speeds were decreased (Scenario 2) or increased (Scenario 3) as described in section 3 to represent scenarios where vessel behaviors in the intermediate zones reflected an overall modest (2% to 5%) decrease or increase in speed within the intermediate zones relative to the baseline speeds used in Scenario 1. For all scenarios, the speeds in the slowdown zones (Swiftsure Bank and Haro Boundary) were assumed constant at the slowdown season values.

2. EMISSIONS CALCULATION METHODOLOGY

This section provides a brief overview of the emissions calculation methodology used to determine the emission reductions associated with the vessel speed slowdown.

Vessel activity data and the methods of estimating emissions are discussed below for propulsion engines, auxiliary engines and boilers. In general, emissions are estimated as a function of vessel power demand with energy expressed in kW-hr multiplied by an emission factor, where the emission factor is expressed in terms of grams per kilowatt-hour (g/kW-hr). Emission factor adjustments (for low propulsion engine load, different fuel usage, or emission controls) are then applied to the various activity and operational data. Equations 2.1 and 2.2 report the basic equations used in estimating emissions.

Equation 2.1

E = Energy x EF x FCF

Where:
E = Emissions
Energy = Energy demand, calculated using Equation 2.2 below as the energy output of the engine(s) or boiler(s) over the period of time, kW-hr
EF = Emission factor, expressed in terms of g/kWh, depends on engine type, IMO level of NOx control (tier) and fuel used
FCF = Fuel correction factors are used to adjust from a base fuel associated with the EF and the fuel being used, dimensionless

The 'Energy' term of the equation is where most of the location-specific information is used. Energy is calculated using Equation 2.2:

Equation 2.2

$$\text{Energy} = \text{Load x Activity}$$

Where:
Energy = Energy demand by mode, kW-hr
Load = maximum continuous rated (MCR) propulsion engine power multiplied by the load factor (LF), kW; reported auxiliary engine(s) operational load, kW; or auxiliary boiler operational load, kW
Activity = time of activity, hours

Vessel IMO numbers from MarEx data for the vessels that operated in the seasonal slowdown period are matched with IHS Markit data to determine the type of vessel (Bulk, Car Carrier, Container etc.) keel laid date (that determines age, IMO tier level, and emission factor for the vessel) and type of engine (slow speed, medium speed, or high speed).

2.1. Propulsion Engine Maximum Continuous Rated Power (MCR)

MCR power is defined as the manufacturer's tested maximum engine power and is used to determine propulsion engine load by mode. The international convention is to document MCR in kilowatts, and it is the highest power available from a ship engine during average cargo and sea conditions. It is assumed that the 'Power' value in the IHS data is the best proxy for MCR power. For diesel-electric configured ships, MCR is the combined electric propulsion engine(s) rating, in kW.

2.2. Propulsion Engine Load Factor

The propulsion engine load factor is used to estimate how much of the propulsion engine(s') MCR is being used. The propulsion engine load factor is estimated using the Propeller Law, which states that propulsion engine load varies with the cube of the ratio of actual speed to the ship's maximum rated speed, as illustrated by the following equation.

Equation 2.3

$$LF = (Speed_{Actual} / Speed_{Maximum})^3$$

Where:
LF = load factor, dimensionless
$Speed_{Actual}$ = speed through water, knots
$Speed_{Maximum}$ = maximum speed, knots

For the purpose of estimating emissions, the load factor has been capped at 1.0 so that there are no calculated propulsion engine load factors greater than 100% (i.e., calculated load factors above 1.0 are assigned a load factor of 1.0). This may occur when, for example, a ship is moving with a tide and with the wind and the tide and wind action moves the ship faster than the rated speed even though the propulsion engine is set for less than the rated speed. In such a case the calculated load would not accurately reflect the actual operating load on the engine.

2.3. Propulsion Engine Activity

Activity is measured in hours of operation and determined from the time difference from the vessel entering and exiting the slowdown region.

2.4. Propulsion Engine Emission Factors

Diesel cycle engines are the most prevalent type of propulsion engines on vessels that transited the region. The two predominant diesel propulsion engine types installed on vessels are:

- Slow speed diesel engines, having maximum engine speeds less than 130 rpm

- Medium speed diesel engines, having maximum engine speeds over 130 rpm (typically greater than 400 rpm) and less than 2,000 rpm.

In addition to diesel propulsion engines, a few visiting ships are equipped with a gas turbine propulsion system. The gas turbine uses fuel oil/marine distillate fueled combustion to drive a gas turbine for propulsion.

Emission factors for all engine types used in this study were obtained from equations or values included in USEPA's document entitled "Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions," dated September 2020 (USEPA's EI Guidance Document)[1]. The PM10 and DPM emission factors are based on the following equation for all engines the exception of steam propelled propulsion engines:

Equation 2.4

$$\mathbf{PM/DPM\ EF = PM_{base}\ or\ DPM_{base} + (S_{act} \times BSFC \times 0.2247 \times 7)}$$

Where:

PM or DPM EF = PM10 or DPM emission factors adjusted for the fuel type and sulfur content of the fuel (g/kW-hr)
PMbase or DPMbase= Base emission factor assuming zero fuel sulfur (g/kWhr)
= 0.1545 g/kW-hr for distillate fuel (MGO and MDO)
= 0.5761 g/kW-hr for residual fuel (HFO)
Sact = actual fuel sulfur level (weight ratio)
BSFC = brake specific fuel consumption in g/kW-hr
0.02247 is fraction of sulfur in fuel that is converted to direct sulfate
7 is molecular weight ratio of sulfate PM to sulfur = 224/32 = 7

The SOx emission factor is based on the following equation:

Equation 2.5

$$\mathbf{SO_2\ EF = S_{act} \times BSFC \times 2 \times 0.97753}$$

Where:

SO2 EF = SOx emission factor (g/kW-hr)
Sact = actual fuel sulfur level (weight ratio)
BSFC = brake specific fuel consumption in g/kW-hr
0.97753 is the fraction of fuel sulfur converted to SO2 and
2 is the ratio of molecular weights of SO2 and S.=64/32 = 2

The CO_2 emission factor is based on the following equation:

[1] *www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance*

Equation 2.6

$$CO_2 \text{ EF} = \text{BSFC} \times \text{CCF}$$

Where:

CO2 EF = COx emission factor (g/kW-hr)
BSFC = brake specific fuel consumption in g/kW-hr
CCF= carbon content factor as a function of fuel type (CO2/g fuel)
= 3.206 for MGO/MDO
= 3.114 for HFO

For regulatory purposes, all diesel cycle fuel oil/marine distillate fueled engines are divided into Tier 0 to Tier III as per the NOx standards and by engine rated speed, in revolutions per minute or rpm, as listed below:

- Slow speed engines: less than 130 rpm
- Medium speed engines: between 130 and 2,000 rpm
- High speed engines: greater than or equal to 2,000 rpm

Per IMO regulation, NOx emission factors vary by engine Tier.

All vessels transiting the study region are subject to the IMO North American Emissions Control Area (ECA) which requires 0.1% or less sulfur (S) content fuel. For this analysis, all vessels are assumed using 0.1% sulfur content marine gas oil or marine distillate oil (MGO/MDO) fuel. The emission factors for MGO/MDO with 0.1% sulfur content are shown in tables 2.2 and 2.3.

Table 2.1 shows BSFC by engine type used in the equations for PM, SOx, and CO_2 emission factors.

Table 2.1: BSFC by Engine Type (g/kWhr)

Using 0.1% S MGO Fuel Engine Category	IMO Tier	Model Year Range	BSCF
Slow speed propulsion	All	All	195
Medium speed propulsion	All	All	215
Medium speed auxilliary	All	All	227
High speed auxiliary	All	All	227
Steam Propulsion engine and boiler	All	All	305
Gas Turbone	All	All	305

Table 2.2: Emission Factors for Diesel Propulsion Engines (g/kWhr)

Using 0.1% S MGO Fuel Engine Category	IMO Tier	Model Year Range	PM	DPM	NO_x	SOx
Slow speed propulsion	Tier 0	1999 and older	0.255	0.255	17.01	0.389
Slow speed propulsion	Tier I	2000 to 2010	0.255	0.255	15.98	0.389
Slow speed propulsion	Tier II	2011 to 2015	0.255	0.255	14.38	0.389
Slow speed propulsion	Tier III	2016 and newer	0.255	0.255	3.38	0.389
Medium speed propulsion	Tier 0	1999 and older	0.255	0.255	13.16	0.426
Medium speed propulsion	Tier I	2000 to 2010	0.255	0.255	12.22	0.426
Medium speed propulsion	Tier II	2011 to 2015	0.255	0.255	10.53	0.426
Medium speed propulsion	Tier III	2016 and newer	0.255	0.255	2.63	0.426
Gas turbine	na	All	0.009	0.000	5.73	0.611
Steam propulsion engine and boiler	na	All	0.136	0.000	1.97	0.611

Table 2.3: GHG Emission Factors for Propulsion Engines (g/kWhr)

Using 0.1% S MGO Fuel Engine Category	IMO Tier	Model Year Range	CO_2	N_2O	CH_4
Slow speed propulsion	Tier 0	1999 and older	593	0.029	0.012
Slow speed propulsion	Tier I	2000 to 2010	593	0.029	0.012
Slow speed propulsion	Tier II	2011 to 2015	593	0.029	0.012
Slow speed propulsion	Tier III	2016 and newer	593	0.029	0.012
Medium speed propulsion	Tier 0	1999 and older	657	0.029	0.010
Medium speed propulsion	Tier I	2000 to 2010	657	0.029	0.010
Medium speed propulsion	Tier II	2011 to 2015	657	0.029	0.010
Medium speed propulsion	Tier III	2016 and newer	657	0.029	0.010
Gas turbine	na	All	962	0.075	0.002
Steam propulsion engine and boiler	na	All	962	0.075	0.002

2.5. Propulsion Engines Low Load Emission Factor Adjustments

In general terms, diesel-cycle engines are not as efficient when operated at low loads compared with higher load operation. An EPA study[2] prepared by Energy and Environmental Analysis, Inc. (EEAI) established a formula for calculating emission factors for 2-stroke slow speed diesel engines at engine loads below 20%, conditions such as those encountered during harbor maneuvering and when traveling slowly at sea (e.g. in the reduced speed zone) This formula was later used and described in a study conducted for the EPA by ENVIRON.[3] While mass emissions

[2] EPA, *Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data,* February 2000

[3] EPA, *Commercial Marine Inventory Development,* July 2002

in pounds per hour tend to go down as vessel speeds and engine loads decrease, the emission factors in g/kW-hr increase.

Equation 2.7 is the equation developed by EEAI to generate emission factors for the range of load factors from 2% to 20% for each pollutant:

Equation 2.7

$$\boldsymbol{y = a\,(fractional\ load)^{-x} + b}$$

Where:

y = emissions, g/kW-hr
a = coefficient, dimensionless
b = intercept, dimensionless
x = exponent, dimensionless
fractional load = propulsion engine load factor (2% - 20%), derived from the Propeller Law, percent

Table 2.4 presents the variables for equation 3.7.

Table 2.4: Low-Load Emission Factor Regression Equation Variables

Pollutant	Exponent (x)	Intercept (b)	Coefficient (a)
PM	1.5	0.2551	0.0059
NO_x	1.5	10.4496	0.1255
CO	1.0	0.1548	0.8378
HC	1.5	0.3859	0.0667

The base emission factors used in the development of the low-load regression equation are not the currently accepted emission factors for Ocean Going Vessel (OGV) propulsion engines. Therefore, low-load adjustment (LLA) multipliers were developed by dividing the emission factors for each load increment between 2% and 20% by the emission factor at 20% load. These LLA multipliers are listed in Table 2.5. In keeping with the emission estimating practice of assuming a minimum propulsion engine load of 2%, the table of LLA factors does not include values for 1% load. During emission estimation, the LLA factors are multiplied by the latest emission factors for 2-stroke (slow speed) non-MAN diesel propulsion engines, adjusted for fuel differences between the actual fuel and the fuel used when the emission factors were developed. Adjustments to N_2O and CH_4 emission factors are made based on the NO_x and HC low load adjustments, respectively. Load adjustment factors for slow speed MAN diesel engines are discussed later in this section. The LLA adjustments are applied only to non-MAN engines at loads less than 20%. Low load emission factor adjustments do not apply to medium speed diesel engines, steamships or gas turbines because the EPA study referenced above only observed an increase in emissions from 2-stroke slow speed diesel engines.

Table 2.5: Low Load Adjustment Multipliers for Slow Speed non-MAN Diesel Emission Factors[4]

Load	PM	NO_x	SO_2	CO	HC	CO_2	N_2O	CH_4
2%	7.29	4.63	3.30	9.68	21.18	3.28	4.63	21.18
3%	4.33	2.92	2.45	6.46	11.68	2.44	2.92	11.68
4%	3.09	2.21	2.02	4.86	7.71	2.01	2.21	7.71
5%	2.44	1.83	1.77	3.89	5.61	1.76	1.83	5.61
6%	2.04	1.60	1.60	3.25	4.35	1.59	1.60	4.35
7%	1.79	1.45	1.47	2.79	3.52	1.47	1.45	3.52
8%	1.61	1.35	1.38	2.45	2.95	1.38	1.35	2.95
9%	1.48	1.27	1.31	2.18	2.52	1.31	1.27	2.52
10%	1.38	1.22	1.26	1.96	2.18	1.25	1.22	2.18
11%	1.30	1.17	1.21	1.79	1.96	1.21	1.17	1.96
12%	1.24	1.14	1.17	1.64	1.76	1.17	1.14	1.76
13%	1.19	1.11	1.14	1.52	1.60	1.14	1.11	1.60
14%	1.15	1.08	1.11	1.41	1.47	1.11	1.08	1.47
15%	1.11	1.06	1.09	1.32	1.36	1.08	1.06	1.36
16%	1.08	1.05	1.06	1.24	1.26	1.06	1.05	1.26
17%	1.06	1.03	1.05	1.17	1.18	1.04	1.03	1.18
18%	1.04	1.02	1.03	1.11	1.11	1.03	1.02	1.11
19%	1.02	1.01	1.01	1.05	1.05	1.01	1.01	1.05
20%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Emissions from MAN 2-stroke propulsion (main) engines were adjusted as a function of engine load using test data from the San Pedro Bay Ports' (SPBP) *MAN Slide Valve Low-Load Emissions Test Final Report* (Slide Valve Test)[5] completed under the SPBP Technology Advancement Program (TAP) in conjunction with MAN and Mitsui. The following enhancements are incorporated into the emissions estimates for applicable propulsion engines:

- Emission factor adjustment (EFA) is applied to pollutants for which test results were significantly different in magnitude than the base emission factors. A slide valve EFA (EFASV) is applied only to vessels equipped with slide valves (SV), which include 2004 or newer MAN 2-stroke engines. A conventional nozzle (C3) EFA (EFAC3) is used for all other MAN 2-stroke engines, which are typically older than 2004 vessels. EFAs were developed

[4] The LLA multipliers for N_2O and CH_4 are based on NO_x and HC, respectively.

[5]*https://cleanairactionplan.org/download/231/final-reports/5109/ogv-slide-valve-low-load-emissions-test-final-report-2013.pdf*

by compositing the test data into the E3 duty cycle load weighting and comparing them to the E3-based EFs used in the inventories. The following EFAs are used:

a. NOx:	EFASV = 1.0	EFAC3 = 1.0
b. PM:	EFASV = 1.0	EFAC3 = 1.0
e. CO2:	EFASV = 1.0	EFAC3 = 1.0

- Load adjustment factors (LAF) are calculated and applied to the EF x EFA across all loads (0% to 100%). The LAF is pollutant based and valve specific (SV or C3), using the same criteria as stated above for EFA. The adjusted equation for estimating Ocean Going Vessel MAN propulsion engine emissions is:

Equation 2.8

Ei = Energy x EF x EFA x LAFi x FCF

Where,

Ei = Emission by load i, g
Energy = Energy demand by mode, kW-hr
EF = default emission factor (E3 duty cycle by pollutant or GHG), g/kW-hr
EFA = emission factor adjustment by pollutant or GHG, dimensionless
LAFi = test-based EFi (by valve type and pollutant or GHG) at load i / test-based composite EF (E3 duty cycle), dimensionless
FCF = fuel correction factor by pollutant or GHG, dimensionless

The LAFs used across the entire engine load range are shown in the Appendix.

2.6. Propulsion Engine Power Rating

OGVs transiting the region are matched by IMO number with the most current IHS Markit[6] data to determine propulsion engine power ratings. For vessels missing propulsion engine power rating, vessel class specific average values are used.

2.7. Auxiliary Engine Emission Factors

OGVs are equipped with the following types of auxiliary engines:

- Medium speed diesel engines (most common), having maximum engine speeds over 130 rpm (typically greater than 400 rpm) and less than 2,000 rpm.
- High speed diesel engines, having maximum engine speeds equal to or greater than 2,000 rpm.

[6] *See: www.ihsmarkit.com/products/maritime-world-ship-register.html*

Emission factors for all engine types used in this study were obtained from equations or values included in USEPA's EI Guidance document. Equations used to calculate PM, DPM, SOx and CO2 are the same as included in for propulsion engines. The emission factors for MDO/MGO fuel with 0.1% sulfur content shown in tables 2.8 and 2.9.

Table 2.6: Pollutant Emission Factors for Auxiliary Engines (g/kWhr)

Using 0.1% S MGO Fuel						
Engine Category	**IMO Tier**	**Model Year Range**	**PM**	**DPM**	**NOx**	**SOx**
Medium speed auxiliary	Tier 0	1999 and older	0.189	0.189	13.82	0.424
Medium speed auxiliary	Tier I	2000 to 2010	0.189	0.189	12.22	0.424
Medium speed auxiliary	Tier II	2011 to 2015	0.189	0.189	10.53	0.424
Medium speed auxiliary	Tier III	2016 and newer	0.189	0.189	2.63	0.424
High speed auxiliary	Tier 0	1999 and older	0.189	0.189	10.90	0.424
High speed auxiliary	Tier I	2000 to 2010	0.189	0.189	9.78	0.424
High speed auxiliary	Tier II	2011 to 2015	0.189	0.189	7.71	0.424
High speed auxiliary	Tier III	2016 and newer	0.189	0.189	1.97	0.424

Table 2.7: GHG Emission Factors for Auxiliary Engines (g/kWhr)

Using 0.1% S MGO/MDO Fuel					
Engine Category	**IMO Tier**	**Model Year Range**	**CO_2**	**N_2O**	**CH_4**
Medium speed auxiliary	Tier 0	1999 and older	696	0.029	0.008
Medium speed auxiliary	Tier I	2000 to 2010	696	0.029	0.008
Medium speed auxiliary	Tier II	2011 to 2015	696	0.029	0.008
Medium speed auxiliary	Tier III	2016 and newer	696	0.029	0.008
High speed auxiliary	Tier 0	1999 and older	696	0.029	0.008
High speed auxiliary	Tier I	2000 to 2010	696	0.029	0.008
High speed auxiliary	Tier II	2011 to 2015	696	0.029	0.008
High speed auxiliary	Tier III	2016 and newer	696	0.029	0.008

2.8. Auxiliary Engine Load Defaults

The IHS Markit (IHS) database contains limited installed power information for auxiliary engines and no information on use by mode. Due to the lack of information in IHS, the primary data source for auxiliary load data is from Starcrest's Vessel Boarding Program (VBP) program where vessels are boarded at various ports and information related to auxiliary engine load is collected on vessel operations by mode. Vessel data for sister-ships of the boarded vessels are also collected and utilized. When estimating auxiliary engine emissions, VBP operational data is first applied on a vessel-by-vessel basis if the vessel was boarded, or it is a sister-ship to a boarded vessel. If the vessel is not in the VBP database, average auxiliary engine load defaults are derived from the VBP data and applied by vessel type.

The averages based on the Port of Los Angeles and Port of Long Beach default loads was used when VBP data was not available. Auxiliary engine default loads from the Port of Los Angeles' 2021 Emissions Inventory[7] are used. These are based on VBP data for vessels visiting the Port of Los Angeles in 2021 (the most recent year of data). Tables 2.10 present the auxiliary engine load defaults by vessel type used to estimate emissions.

[7] See: *https://www.portoflosangeles.org/environment/air-quality/air-emissions-inventory* and *https://polb.com/environment/air/#emissions-inventory*

Table 2.8: Auxiliary Engine and Boiler Default Loads

Vessel Type	Auxiliary Engine (kW)	Boiler (kW)	Boiler - diesel electric (kW)
Auto Carrier	527	82	87
Bulk	222	63	35
Bulk - Heavy Load	255	35	35
Container1000	913	90	106
Container2000	1287	188	149
Container3000	920	203	164
Container4000	1419	180	179
Container5000	1594	266	247
Container6000	1558	248	206
Container7000	1580	345	412
Container8000	1635	210	253
Container9000	1634	448	341
Container10000	1634	368	314
Container11000	1727	193	193
Container12000	1740	127	127
Container13000	1589	241	227
Container14000	1553	266	251
Container15000	1850	259	259
Container16000	1793	206	206
Container17000	1735	152	216
Container18000	1500	216	216
Container19000	1950	355	460
Container23000	2048	373	373
Cruise	7290	282	557
General Cargo	489	77	56
Reefer	1416	89	95
RoRo	434	67	67
Tanker - Aframax	448	179	0
Tanker - Chemical	498	90	0
Tanker - Handysize	659	143	0
Tanker - Panamax	480	223	0
Tanker - Suezmax	860	144	0
Tanker - VLCC	0	0	0
Bulk - Self Discharging	0	0	0

Note, not all of the vessel type classifications (VTCs) are used in this analysis as their type did not transit the region during the study period. The five VTCs that did not transit the region were larger container ships above 15,000 TEU (Container 16000 to Container 23000).

2.9. Auxiliary Boiler Emission Factors

In addition to the auxiliary engines that are used to generate electricity for on-board uses, most vessels have one or more auxiliary boilers used for fuel heating and for producing hot water and steam. Emission factors for the steam boilers listed in tables 2.11 and 2.12 are the same as for steam powered propulsion engines.

Table 2.9: Pollutant Emission Factors for Auxiliary Boilers, g/kW-hr

Using 0.1% S MGO Fuel									
Engine Category	IMO Tier	Model Year Range	PM_{10}	$PM_{2.5}$	DPM	NOx	SOx	CO	ROG
Steam boiler	na	All	0.202	0.186	0.000	2.0	0.587	0.2	0.1

Table 2.10: GHG Emission Factors for Auxiliary Boilers, g/kW-hr

Using 0.1% S MGO Fuel					
Engine Category	IMO Tier	Model Year Range	CO_2	N_2O	CH_4
Steam boiler	na	All	962	0.075	0.002

The auxiliary boiler fuel consumption data collected from vessels during the VBP is converted to equivalent kilowatts using specific fuel consumption (SFC) factors found in the 2002 Entec report. The average SFC value for distillate fuel is 290 grams of fuel per kW-hour, and 305 grams of fuel per kW-hour for residual fuel. The average kW for auxiliary boilers using distillate fuel is calculated using the following equation.

Equation 2.9

$$\boldsymbol{Average\ kW = ((daily\ fuel/24) \times 1,000,000)/290}$$

Where:

Average kW = average energy output of boilers, kW
daily fuel = boiler fuel consumption, tonnes per day

As with auxiliary engines, the IHS database does not provide boiler engine load or fuel consumption data. The primary source of auxiliary boiler fuel consumption data is from the VBP, and direct values for vessels boarded are used on an individual basis for vessels boarded and their sister ships. For vessels not boarded or vessels that did not have any sister vessels boarded through the VBP, average loads presented in the Port of Los Angeles 2021 emissions inventory are applied.

2.10. Vessel Slowdown Program Emissions Benefits Calculations

The emissions benefits of the voluntary slowdown program are calculated by comparing the emissions generated in the slowdown zones during the slowdown season to those that would have occurred in the absence of the slowdown program (baseline emissions). Slowdown and baseline emissions are calculated using the same slowdown season (June through October 2022) reported data. Vessel specific parameters (engine size and type, design speed, engine and boiler loads, etc.) are determined from the vessel's IMO identification number and used with the reported speeds to determine the slowdown emissions for each transit using the methodologies described earlier in this chapter. The same information with the reported speed adjusted to baseline speeds using speed correction factors (discussed in the next paragraph) are used to calculate the baseline emissions for each transit. The vessel transit's emission benefit is calculated by subtracting the slowdown emissions from the baseline emissions (if the emissions benefit is negative – slowdown emission is larger than the baseline emissions - it is set to zero or no benefit). Each transit's emissions benefit is summed to calculate the slowdown season emissions benefits.

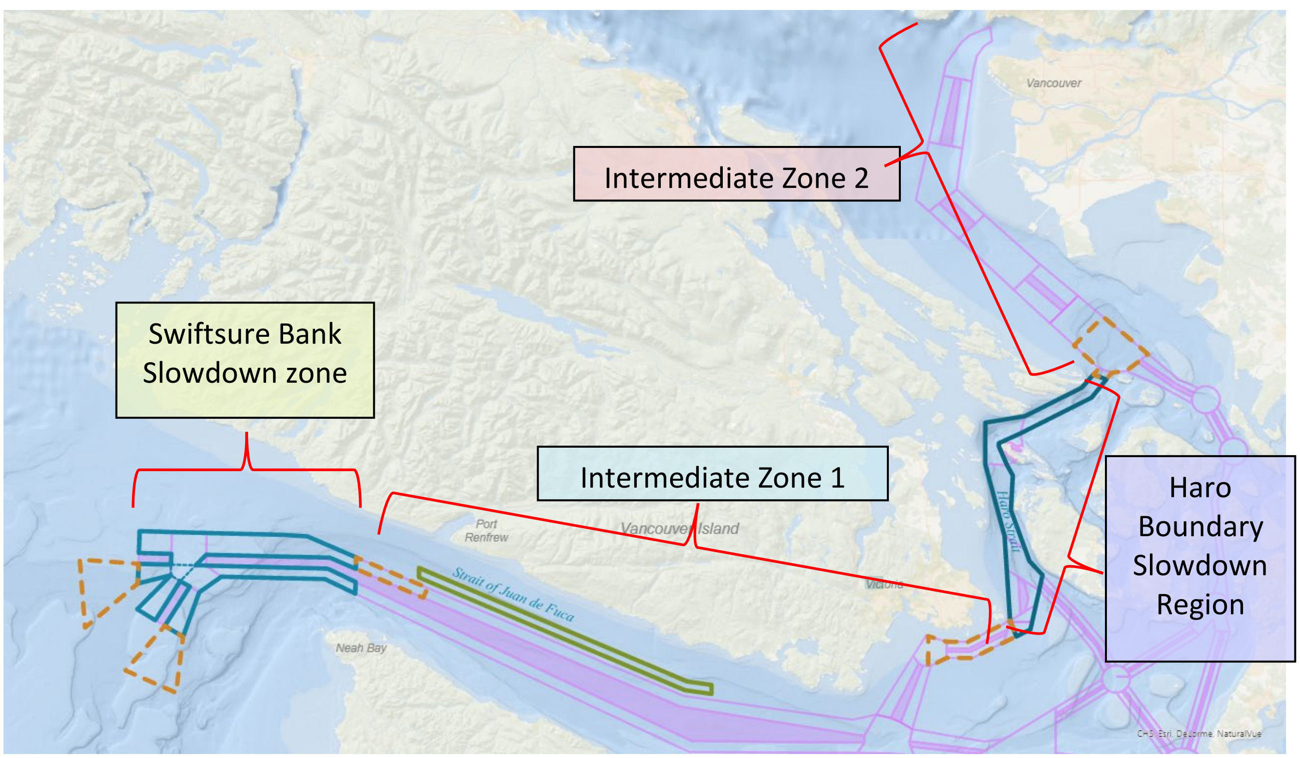
SCFs are derived from the non-slowdown season (March through May 2022) reported data by grouping the vessel transits into the VTCs shown in Table 2.8 above and averaging the ratios of each vessel's transit reported speed to its design speed. The resulting values for the 29 VTCs in each the slowdown regions and by direction of transit are shown in Chapter 4. Conversion of the reported slowdown speed to baseline speed is made by multiplying the vessel's design speed by the appropriate SCF.

3. Sensitivity of Total Air Emissions Due to Vessel Behavior in Non-Slowdown Regions of the Georgia Air Shed

Air emissions are not spatially limited to their emission location. Starcrest was tasked to evaluate how sensitive total air emissions are to vessel speed between the slowdown regions on a representative transit within the Georgia Basin air shed. The scenarios were selected based on analysis of the slowdowns and baseline periods for the 2022 voluntary slowdown. For each scenario the representative transit was considered from Swiftsure Bank to English Bay. Within this representative transit, speed scenarios are to be considered in the four Zones as shown in Figure 3.1.

1. Swiftsure Bank Slowdown Zone
2. Intermediate Zone 1
3. Haro Boundary Slowdown Zone
4. Intermediate Zone 2

Figure 3.1 Georgia Basin Air Shed Transit Zones



The ECHO Program does not collect AIS data within the intermediate zones, however, the operation of vessels within these zones may have a significant impact on overall air emissions within the air shed. To consider how sensitive total air emission within the air shed is to vessel speed within these intermediate zones, three speed conditions are evaluated as a simple sensitivity analysis. For this sensitivity study, the baseline and slowdown speeds through water within Swiftsure Bank were used to define the scenario speeds through water for Intermediate Zone 1. The baseline and slowdown speeds within Haro Boundary slowdown zone were used to define the scenario speeds for Intermediate Zone 2. The selection of these speeds is outlined below. In all three scenarios the vessels are assumed to maintain the vessel category average slowdown speeds within the three slowdown regions. For simplicity, the speed through water is assumed to match the speed over ground.

The first scenario assumes that vessels will resume speeds in the intermediate zones consistent with their average baseline speed within the slowdown regions. For this sensitivity study the speeds within the intermediate zones was set to the baseline speeds within the slowdown regions for each vessel class as shown in Equation 3.1.

Equation 3.1

$$\boldsymbol{V(stw)_{Scenario\ 1} = V(stw)_{Slowdown} + (V(stw)_{Baseline} - V(stw)_{slowdown})}$$

The second scenario assumes that vessels will speed up relative to the slowdown period but will maintain a reduced speed within the intermediate zones. For this sensitivity study the speeds within the intermediate zones are set to the slowdown speed plus 75% of the difference between the baseline and slowdown speed for each vessel class as shown in Equation 3.2.

Equation 3.2

$$\boldsymbol{V(stw)_{Scenario\ 2} = V(stw)_{Slowdown} + {}^{3}/_{4}\,(V(stw)_{Baseline} - V(stw)_{slowdown})}$$

The third scenario assumes that vessels will attempt to make up time lost during transit through the slowdown regions and will speed up to the slowdown speed plus 125% of the difference between the baseline and slowdown speeds for each vessel class as shown in Equation 3.3.

Equation 3.3

$$\boldsymbol{V(stw)_{Scenario\ 3} = V(stw)_{Slowdown} + {}^{5}/_{4}\,(V(stw)_{Baseline} - V(stw)_{slowdown})}$$

The 2022 voluntary slowdown season speed data was used to generate the speeds for the three scenarios. Scenario 2 speeds ranged from 2% to 5% lower than the baseline speeds (scenario 1) and scenario 3 speeds ranged from 2% to 5% higher than the baseline speeds depending on the vessel type. The speeds through water (in knots) for the slowdown and scenarios are shown in Table 3.1.

Table 3.1: Sensitivity analysis - Scenario speed through water (knots) – STW equals SOG

ECHO Vessel Class	Swiftsure Bank Slowdown Zone	Intermediate zone 1			Haro-Boundary Slowdown Zone	Intermediate zone 2		
		Scenario 1	Scenario 2	Scenario 3		Scenario 1	Scenario 2	Scenario 3
Bulk Carrier	10.76	11.43	11.26	11.60	11.74	12.93	12.63	13.23
Car Carrier	14.09	16.40	15.82	16.97	15.08	17.22	16.69	17.76
Container Ship	13.22	14.07	13.86	14.28	14.57	17.94	17.10	18.78
Passenger Ship	14.97	16.58	16.18	16.98	14.02	17.06	16.30	17.82
Tanker Ship	10.78	12.06	11.74	12.38	11.37	12.17	11.97	12.37

The distances of the zones for this evaluation were set as:

Swiftsure Bank Slowdown Zone	19.0 Nautical Miles
Intermediate Zone 1	65.2 Nautical Miles
Haro Boundary Slowdown Zone	29.6 Nautical Miles
Intermediate Zone 2	40.8 Nautical Miles

The effect of current on vessel speed was ignored and the speed through water was assumed to be the same as speed over ground.

The different speeds for each of the scenarios are used to modify the transit times and engine loads to generate the emissions for the intermediate zones only. These are added to the slowdown zones emissions to estimate the total emissions by all vessels transiting the Swiftsure Bank to English Bay transit during the 2022 slowdown season. The total emissions from the three scenarios are compared to better understand the effect of vessel speeds on the emissions reduction benefits of the ECHO Program's seasonal slowdown.

4. RESULTS

4.1. Baseline Speed Correlation Factors

Speed Correlation Factors (SCFs) are used to convert the slowdown speeds reported during the slowdown season to the baseline speeds which are then used to estimate the baseline emissions. SCFs are developed by averaging the ratios of the baseline speed to design speed of all vessels in a VTC. Non-slowdown season (March through May) speeds are assumed to represent the baseline speeds. The ratios are determined for each vessel transit during the non-slowdown season. The ratios are then grouped by transit direction, slowdown zone, and VTCs and then averaged. To improve the results of the study, the VTCs were further refined from 5 ECHO vessel types to 29 VTCs typically used by Starcrest for vessel emissions calculations to ensure the most accurate operational and design parameters are used for each vessel. The baseline speed is then estimated by multiplying the vessels maximum design speed by the appropriate SCF. The SCF values are shown in Table 4.1.

4.2. Vessel Slowdown Emission Reductions

As described in section 2.10, the emission benefits of the voluntary vessel slowdown program are determined by comparing the baseline emissions to the slowdown emissions. The comparison is done at the transit level for all vessel transits that occurred during the slowdown season (June through October 2022) and summed across all transits to determine the emissions benefits. The reported speeds, time in zone, and vessel IMO identification number were used to determine the engine parameters and transit distance (slowdown speed multiplied by the time in zone) for each of the vessel transits. The methodologies described in chapter 2 were used to determine the slowdown and baseline emissions for each of the slowdown regions. Slow down emissions were calculated using the reported vessel speeds and times in zone, and the baseline emissions were calculated using the baseline speeds derived from the SCFs, the time in zone determined from the transit distance and the baseline speed (transit distance divided by the baseline speed). The emissions benefit for each transit is determined by subtracting the slowdown emission from the baseline emissions. All transits with positive emissions benefits (i.e., the slowdown emissions are less than the baseline emissions) were summed to determine the emissions benefits for the season by VTC, direction, and slowdown zone.

The results are further summarized by consolidating the 29 VTCs into the five ECHO program vessel types with the General Cargo grouped with the bulk vessel type, the RoRo grouped with the Car Carriers, and the reefers grouped with the container ships. Additionally, the Haro Strait and Boundary Pass emission reductions were summed and presented as Haro Boundary emission reductions due to their proximity and to simplify reporting. The emission reductions in the slowdown regions achieved by the 2022 ECHO program are shown in Table 4.2.

Table 4.1: Speed Correlation Factors

Vessel Type Category	Northbound/Inbound			Southbound/Outbound		
	Boundary Pass	Haro Straight	Swiftsure Bank	Boundary Pass	Haro Straight	Swiftsure Bank
Auto Carrier	0.82	0.803	0.64	0.849	0.81	0.76
Bulk	0.872	0.879	0.772	0.833	0.784	0.731
Bulk - Heavy Load	0.829	NA	0.607	0.841	NA	0.713
Bulk - Self Discharging	NA	NA	0.823	NA	NA	0.804
Container1000	0.827	0.821	0.779	0.846	0.82	0.828
Container2000	0.791	0.784	0.632	0.786	0.786	0.723
Container3000	0.716	0.684	0.636	0.731	0.754	0.782
Container4000	0.701	0.706	0.464	0.74	0.706	0.626
Container5000	0.663	0.676	0.46	0.717	0.726	0.625
Container6000	0.691	0.69	0.44	0.725	0.706	0.543
Container7000	0.7	0.654	0.535	0.739	0.725	0.663
Container8000	0.748	0.72	0.491	0.756	0.74	0.596
Container9000	0.708	0.728	0.491	0.74	0.715	0.523
Container10000	0.733	0.776	0.492	0.757	0.72	0.545
Container11000	0.721	0.777	0.442	0.671	NA	0.592
Container12000	0.797	NA	0.475	0.874	0.86	0.576
Container13000	0.75	0.752	0.465	0.641	0.649	0.535
Container14000	0.675	0.678	0.521	0.682	0.707	0.691
Container15000	0.752	NA	0.349	0.744	NA	0.729
Cruise	0.584	0.662	0.714	0.759	0.94	0.76
General Cargo	0.866	0.878	0.745	0.877	0.829	0.764
Reefer	NA	NA	0.714	NA	NA	0.78
RoRo	0.91	NA	0.845	NA	NA	0.848
Tanker - Aframax	0.879	0.841	0.751	0.711	0.622	0.775
Tanker - Chemical	0.836	0.82	0.764	0.803	0.765	0.805
Tanker - Handysize	0.819	0.742	0.713	0.786	0.682	0.637
Tanker - Panamax	0.805	NA	0.729	0.594	0.544	0.824
Tanker - Suezmax	NA	NA	0.783	NA	NA	0.887
Tanker - VLCC	NA	NA	0.738	NA	NA	0.771

Table 4.2: Emission Reductions from 2022 ECHO Program

	PM (tons)	DPM (tons)	NOx (tons)	SOx (tons)	CO2 (tons)
HB	**1.27**	**1.28**	**75.39**	**2.19**	**3,589**
Bulk	0.52	0.52	25.38	0.69	1,126
Car Carrier	0.06	0.06	4.71	0.11	183
Container	0.58	0.58	38.54	1.11	1,829
Passenger	0.08	0.08	5.09	0.23	370
Tanker	0.03	0.03	1.67	0.05	82
SS	**1.26**	**1.28**	**90.06**	**2.73**	**4,478**
Bulk	0.30	0.30	16.23	0.54	894
Car Carrier	0.25	0.25	17.30	0.53	868
Container	0.18	0.19	23.65	0.60	978
Passenger	0.32	0.32	19.83	0.69	1,133
Tanker	0.21	0.21	13.05	0.37	605
Grand Total	**2.53**	**2.55**	**165.45**	**4.92**	**8,067**

The Swiftsure Bank and Haro Boundary zones have similar magnitudes of emission reductions during the slowdown season. For comparison, the baseline emissions in each of the zones during the vessel slowdown period are shown in Table 4.3**.**

Table 4.3 2022 Baseline Vessel Emissions During Slowdown Season

Row Labels	PM (tons)	DPM (tons)	NOx (tons)	SOx (tons)	CO2 (tons)
HB	**5.06**	**5.04**	**439.53**	**11.41**	**18,708**
Bulk	2.17	2.17	177.74	4.58	7,513
Car Carrier	0.29	0.29	25.50	0.60	982
Container	1.79	1.77	183.65	4.38	7,177
Passenger	0.60	0.60	36.12	1.40	2,295
Tanker	0.20	0.20	16.53	0.45	740
SS	**9.83**	**9.74**	**817.63**	**22.95**	**37,623**
Bulk	1.86	1.86	171.18	4.46	7,312
Car Carrier	0.84	0.84	65.18	1.84	3,010
Container	2.42	2.36	271.22	6.20	10,167
Passenger	3.78	3.75	230.35	8.34	13,668
Tanker	0.93	0.93	79.70	2.11	3,466
Grand Total	**14.89**	**14.78**	**1257.16**	**34.36**	**56,331**

The baseline emissions are approximately twice as high in the Swiftsure Bank region versus the Haro Boundary region which is consistent with the higher activity in the Swiftsure Bank zone (approximately twice the number of vessel transits). The emission reductions are close to the same for both regions which was not expected as the emission reductions should correlate with the number of vessel transits. However, further review showed that the operational characteristics of the vessels in the two slowdown zones differ, with many vessels in the Haro Boundary slowing approximately 50% more than the vessels do in the Swiftsure Bank region. This additional slowing results in more emissions benefits per vessel transit. The reductions as a percent of the baseline emissions are shown in Table 4.4 again showing that the Haro Boundary zone reduction percentages are approximately 50% larger than those experienced by the Swiftsure Banks zone due to the additional slowing of the vessels in the Haro Boundary zone.

Table 4.4 Reductions as Percent of Baseline Vessel Emissions

Row Labels	PM	DPM	NOx	SOx	CO2
HB	**25%**	**25%**	**17%**	**19%**	**19%**
Bulk	24%	24%	14%	15%	15%
Car Carrier	22%	22%	18%	19%	19%
Container	32%	33%	21%	25%	25%
Passenger	13%	13%	14%	16%	16%
Tanker	16%	16%	10%	11%	11%
SS	**13%**	**13%**	**11%**	**12%**	**12%**
Bulk	16%	16%	9%	12%	12%
Auto Carrier	30%	30%	27%	29%	29%
Container	8%	8%	9%	10%	10%
Passenger	8%	9%	9%	8%	8%
Tanker	22%	22%	16%	17%	17%
Grand Total	**17%**	**17%**	**13%**	**14%**	**14%**

Overall, the program resulted in emission reductions between 13 and 17% in the slowdown regions depending on the pollutant.

4.3. Effect of Vessel Behavior in Non-Slowdown Zones on Regional Emissions

The sensitivity analysis investigated three scenarios where vessels operating outside the slowdown zones increased speeds to their normal baseline speeds or to speeds slightly above or below their baseline speeds. Scenario 1 assumed the vessels traveled at their baseline speeds in the intermediate zones. Scenario 2 and 3 assumed the vessels traveled 2% to 5% below or above their baseline speeds. The three scenarios were calculated as defined in equation 3.1 to 3.3 in Chapter 3. Table 4.5 shows the average energy weighted speeds in each of the two slowdown zones and the two intermediate zones to illustrate the magnitude of the changes in speed used in the analysis. Energy usage correlates well with emissions and the average could also be thought of as emissions weighted average speeds. Weighting the speeds by energy/emissions is appropriate as changes in speeds for the categories with the higher emissions will create greater changes in overall emissions.

Table 4.5: Emissions Weighted Average Speeds (nm/hr)

	Swiftsure Bank	Inter Zone 1	Haro Boundary	Inter Zone 2
Scenario 1	13.2	14.4	13.2	15.4
Scenario 2	13.2	14.1	13.2	14.8
Scenario 3	13.2	14.7	13.2	15.9
Percent change from baseline				
Scenario 2	0	-2.1%	0	-3.6%
Scenario 3	0	2.1%	0	3.6%

These speed changes are four times less than those observed in the slowdown zones during the slowdown season (Swiftsure Bank -8.5% and Haro Boundary -14.3%). The smaller changes are appropriate as the vessels in the intermediate zones are not motivated by a voluntary program to change their behavior in the intermediate regions. Smaller speed changes would be expected if they were to occur.

The emissions change relative to the baseline conditions (where baseline represents the vessel speed behavior in the absence of the slowdown program) associated with each of scenarios for each of the zones are shown in Table 4.6 and for the total Airshed in Table 4.7.

Table 4.6: Emission Changes for the Three Scenarios by Zone

	Swiftsure Bank					Intermediate Zone 1				
	PM (ton)	DPM (ton)	NOx (ton)	SOx (ton)	CO2 (ton)	PM (ton)	DPM (ton)	NOx (ton)	SOx (ton)	CO2 (ton)
Baseline	0	0	0	0	0	0	0	0	0	0
Scenario 1	-0.9	-0.9	-87.3	-2.2	-3946	0.0	0.0	0.0	0.0	0
Scenario 2	-0.9	-0.9	-87.3	-2.2	-3946	-0.8	-0.9	-78.6	-2.0	-3,582
Scenario 3	-0.9	-0.9	-87.3	-2.2	-3946	0.9	0.9	81.0	2.1	3,709
	Haro Boundary					Intermediate Zone 2				
	PM	DPM	NOx	SOx (ton)	CO2	PM (ton)	DPM	NOx	SOx (ton)	CO2 (ton)
Baseline	0	0	0	0	0	0	0	0	0	0
Scenario 1	-1.3	-1.3	-152.6	-3.4	-6161	0.0	0.0	0.0	0.0	0
Scenario 2	-1.3	-1.3	-152.6	-3.4	-6161	-0.5	-0.5	-56.5	-1.3	-2,296
Scenario 3	-1.3	-1.3	-152.6	-3.4	-6161	0.5	0.5	59.1	1.3	2,407

Table 4.7: Total Airshed Emission Changes for the Three Scenarios

Georgia Airshed					
	PM (ton)	DPM (ton)	NOx (ton)	SOx (ton)	CO2 (ton)
Scenario 1	-2.3	-2.3	-240.0	-5.6	-10,106
Scenario 2	-3.6	-3.6	-375.1	-8.8	-15,984
Scenario 3	-0.9	-0.9	-99.9	-2.2	-3,990
Percent Change from Scenario 1					
Scenario 2	59%	59%	56%	58%	58%
Scenario 3	-62%	-62%	-58%	-61%	-61%

Note that the sensitivity analysis goals are different than those for the slowdown emissions benefits study described earlier and uses different assumptions (i.e., effect of currents is not included, transits are the same distance, the Haro Boundary distance includes the non-slowdown area between the Haro Strait and Boundary Pass zones), therefore the emission reductions shown here for the slowdown zones are not directly comparable to the results shown earlier.

The results illustrate that relatively small changes in vessel speeds in the non-slowdown zones have substantial effects on the emission benefits of achieved in the slowdown zones when considered over the totality of the Georgia air shed. Speed changes in the non-slowdown regions at 25% of those realized in the slowdown regions increased or decreased the slowdown zone emissions benefits by approximately 60%. This result is not surprising since slowdown zone transit distance is a little over 2 times less than the non-slowdown zone transit distances, roughly doubling the impact on overall emissions of vessel behavior in the non-slowdown regions. The results indicate that air emissions co-benefits of the ECHO program are fairly sensitive to how vessels behave in the non-slowdown regions but without evaluation of actual traffic behavior in these intermediate zones the total benefit of air emissions within the air shed due to the seasonal slowdowns are unknown.

Appendix

Load Adjustment Factors for MAN 2-Sroke Propulsion Engines

Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Slide Valves

Load	PM	DPM	NO_x	SO_x	CO_2	N_2O	CH_4
1%	0.36	0.36	1.90	1.10	1.10	1.90	1.36
2%	0.37	0.37	1.86	1.10	1.10	1.86	1.32
3%	0.38	0.38	1.82	1.09	1.09	1.82	1.28
4%	0.38	0.38	1.78	1.09	1.09	1.78	1.24
5%	0.39	0.39	1.74	1.09	1.09	1.74	1.20
6%	0.40	0.40	1.70	1.08	1.08	1.70	1.17
7%	0.41	0.41	1.67	1.08	1.08	1.67	1.14
8%	0.41	0.41	1.63	1.08	1.08	1.63	1.11
9%	0.42	0.42	1.60	1.07	1.07	1.60	1.08
10%	0.43	0.43	1.57	1.07	1.07	1.57	1.05
11%	0.44	0.44	1.53	1.07	1.07	1.53	1.02
12%	0.45	0.45	1.50	1.07	1.07	1.50	0.99
13%	0.45	0.45	1.47	1.06	1.06	1.47	0.97
14%	0.46	0.46	1.45	1.06	1.06	1.45	0.94
15%	0.47	0.47	1.42	1.06	1.06	1.42	0.92
16%	0.48	0.48	1.39	1.06	1.06	1.39	0.90
17%	0.49	0.49	1.37	1.05	1.05	1.37	0.88
18%	0.49	0.49	1.34	1.05	1.05	1.34	0.86
19%	0.50	0.50	1.32	1.05	1.05	1.32	0.84
20%	0.51	0.51	1.30	1.05	1.05	1.30	0.82
21%	0.52	0.52	1.28	1.04	1.04	1.28	0.81
22%	0.53	0.53	1.26	1.04	1.04	1.26	0.79
23%	0.54	0.54	1.24	1.04	1.04	1.24	0.78
24%	0.54	0.54	1.22	1.04	1.04	1.22	0.76
25%	0.55	0.55	1.20	1.03	1.03	1.20	0.75

Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Slide Valves (cont'd)

Load	PM	DPM	NO_x	SO_x	CO_2	N_2O	CH_4
26%	0.56	0.56	1.19	1.03	1.03	1.19	0.74
27%	0.57	0.57	1.17	1.03	1.03	1.17	0.73
28%	0.58	0.58	1.16	1.03	1.03	1.16	0.72
29%	0.59	0.59	1.14	1.03	1.03	1.14	0.71
30%	0.60	0.60	1.13	1.02	1.02	1.13	0.70
31%	0.60	0.60	1.12	1.02	1.02	1.12	0.70
32%	0.61	0.61	1.10	1.02	1.02	1.10	0.69
33%	0.62	0.62	1.09	1.02	1.02	1.09	0.69
34%	0.63	0.63	1.08	1.02	1.02	1.08	0.68
35%	0.64	0.64	1.07	1.02	1.02	1.07	0.68
36%	0.65	0.65	1.06	1.01	1.01	1.06	0.68
37%	0.66	0.66	1.05	1.01	1.01	1.05	0.67
38%	0.67	0.67	1.05	1.01	1.01	1.05	0.67
39%	0.68	0.68	1.04	1.01	1.01	1.04	0.67
40%	0.69	0.69	1.03	1.01	1.01	1.03	0.67
41%	0.70	0.70	1.03	1.01	1.01	1.03	0.67
42%	0.70	0.70	1.02	1.01	1.01	1.02	0.68
43%	0.71	0.71	1.02	1.01	1.01	1.02	0.68
44%	0.72	0.72	1.01	1.00	1.00	1.01	0.68
45%	0.73	0.73	1.01	1.00	1.00	1.01	0.69
46%	0.74	0.74	1.00	1.00	1.00	1.00	0.69
47%	0.75	0.75	1.00	1.00	1.00	1.00	0.70
48%	0.76	0.76	1.00	1.00	1.00	1.00	0.70
49%	0.77	0.77	0.99	1.00	1.00	0.99	0.71
50%	0.78	0.78	0.99	1.00	1.00	0.99	0.71

Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Slide Valves (cont'd)

Load	PM	DPM	NO_x	SO_x	CO_2	N_2O	CH_4
51%	0.79	0.79	0.99	1.00	1.00	0.99	0.72
52%	0.80	0.80	0.99	1.00	1.00	0.99	0.73
53%	0.81	0.81	0.99	1.00	1.00	0.99	0.74
54%	0.82	0.82	0.99	1.00	1.00	0.99	0.75
55%	0.83	0.83	0.98	0.99	0.99	0.98	0.75
56%	0.84	0.84	0.98	0.99	0.99	0.98	0.76
57%	0.85	0.85	0.98	0.99	0.99	0.98	0.77
58%	0.86	0.86	0.98	0.99	0.99	0.98	0.78
59%	0.87	0.87	0.98	0.99	0.99	0.98	0.80
60%	0.88	0.88	0.98	0.99	0.99	0.98	0.81
61%	0.89	0.89	0.98	0.99	0.99	0.98	0.82
62%	0.90	0.90	0.98	0.99	0.99	0.98	0.83
63%	0.91	0.91	0.99	0.99	0.99	0.99	0.84
64%	0.92	0.92	0.99	0.99	0.99	0.99	0.85
65%	0.93	0.93	0.99	0.99	0.99	0.99	0.87
66%	0.94	0.94	0.99	0.99	0.99	0.99	0.88
67%	0.95	0.95	0.99	0.99	0.99	0.99	0.89
68%	0.97	0.97	0.99	0.99	0.99	0.99	0.91
69%	0.98	0.98	0.99	0.99	0.99	0.99	0.92
70%	0.99	0.99	0.99	0.99	0.99	0.99	0.93
71%	1.00	1.00	0.99	0.99	0.99	0.99	0.95
72%	1.01	1.01	0.99	0.99	0.99	0.99	0.96
73%	1.02	1.02	0.99	0.99	0.99	0.99	0.98
74%	1.03	1.03	0.99	0.99	0.99	0.99	0.99
75%	1.04	1.04	0.99	0.99	0.99	0.99	1.00

Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Slide Valves (cont'd)

Load	PM	DPM	NO_x	SO_x	CO_2	N_2O	CH_4
76%	1.05	1.05	0.99	0.99	0.99	0.99	1.02
77%	1.06	1.06	0.99	0.99	0.99	0.99	1.03
78%	1.07	1.07	0.99	0.99	0.99	0.99	1.05
79%	1.09	1.09	0.99	0.99	0.99	0.99	1.06
80%	1.10	1.10	0.99	0.99	0.99	0.99	1.08
81%	1.11	1.11	0.99	0.99	0.99	0.99	1.09
82%	1.12	1.12	0.99	0.99	0.99	0.99	1.10
83%	1.13	1.13	0.98	0.99	0.99	0.98	1.12
84%	1.14	1.14	0.98	0.99	0.99	0.98	1.13
85%	1.15	1.15	0.98	0.99	0.99	0.98	1.15
86%	1.16	1.16	0.98	0.99	0.99	0.98	1.16
87%	1.18	1.18	0.97	0.99	0.99	0.97	1.18
88%	1.19	1.19	0.97	0.99	0.99	0.97	1.19
89%	1.20	1.20	0.96	0.99	0.99	0.96	1.20
90%	1.21	1.21	0.96	0.99	0.99	0.96	1.22
91%	1.22	1.22	0.95	1.00	1.00	0.95	1.23
92%	1.23	1.23	0.95	1.00	1.00	0.95	1.24
93%	1.25	1.25	0.94	1.00	1.00	0.94	1.25
94%	1.26	1.26	0.93	1.00	1.00	0.93	1.27
95%	1.27	1.27	0.93	1.00	1.00	0.93	1.28
96%	1.28	1.28	0.92	1.00	1.00	0.92	1.29
97%	1.29	1.29	0.91	1.00	1.00	0.91	1.30
98%	1.31	1.31	0.90	1.00	1.00	0.90	1.31
99%	1.32	1.32	0.89	1.00	1.00	0.89	1.32
100%	1.33	1.33	0.88	1.00	1.00	0.88	1.34

Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Conventional Valves

Load	PM	DPM	NO_x	SO_x	CO_2	N_2O	CH_4
1%	0.84	0.84	1.91	1.11	1.11	1.91	2.53
2%	0.83	0.83	1.86	1.11	1.11	1.86	2.45
3%	0.83	0.83	1.82	1.10	1.10	1.82	2.37
4%	0.82	0.82	1.77	1.10	1.10	1.77	2.30
5%	0.82	0.82	1.72	1.10	1.10	1.72	2.23
6%	0.81	0.81	1.68	1.09	1.09	1.68	2.16
7%	0.81	0.81	1.64	1.09	1.09	1.64	2.10
8%	0.80	0.80	1.60	1.09	1.09	1.60	2.03
9%	0.80	0.80	1.56	1.08	1.08	1.56	1.97
10%	0.79	0.79	1.52	1.08	1.08	1.52	1.91
11%	0.79	0.79	1.49	1.08	1.08	1.49	1.86
12%	0.78	0.78	1.45	1.07	1.07	1.45	1.80
13%	0.78	0.78	1.42	1.07	1.07	1.42	1.75
14%	0.78	0.78	1.39	1.07	1.07	1.39	1.70
15%	0.77	0.77	1.36	1.06	1.06	1.36	1.65
16%	0.77	0.77	1.33	1.06	1.06	1.33	1.61
17%	0.77	0.77	1.30	1.06	1.06	1.30	1.56
18%	0.77	0.77	1.28	1.06	1.06	1.28	1.52
19%	0.76	0.76	1.25	1.05	1.05	1.25	1.48
20%	0.76	0.76	1.23	1.05	1.05	1.23	1.44
21%	0.76	0.76	1.20	1.05	1.05	1.20	1.41
22%	0.76	0.76	1.18	1.05	1.05	1.18	1.37
23%	0.76	0.76	1.16	1.04	1.04	1.16	1.34
24%	0.75	0.75	1.14	1.04	1.04	1.14	1.31
25%	0.75	0.75	1.12	1.04	1.04	1.12	1.28

Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Conventional Valves (cont'd)

Load	PM	DPM	NO_x	SO_x	CO_2	N_2O	CH_4
26%	0.75	0.75	1.11	1.04	1.04	1.11	1.25
27%	0.75	0.75	1.09	1.04	1.04	1.09	1.22
28%	0.75	0.75	1.07	1.03	1.03	1.07	1.20
29%	0.75	0.75	1.06	1.03	1.03	1.06	1.17
30%	0.75	0.75	1.05	1.03	1.03	1.05	1.15
31%	0.75	0.75	1.03	1.03	1.03	1.03	1.13
32%	0.75	0.75	1.02	1.03	1.03	1.02	1.11
33%	0.75	0.75	1.01	1.02	1.02	1.01	1.09
34%	0.75	0.75	1.00	1.02	1.02	1.00	1.08
35%	0.76	0.76	0.99	1.02	1.02	0.99	1.06
36%	0.76	0.76	0.98	1.02	1.02	0.98	1.05
37%	0.76	0.76	0.98	1.02	1.02	0.98	1.04
38%	0.76	0.76	0.97	1.02	1.02	0.97	1.02
39%	0.76	0.76	0.96	1.01	1.01	0.96	1.01
40%	0.76	0.76	0.96	1.01	1.01	0.96	1.00
41%	0.77	0.77	0.95	1.01	1.01	0.95	0.99
42%	0.77	0.77	0.95	1.01	1.01	0.95	0.99
43%	0.77	0.77	0.94	1.01	1.01	0.94	0.98
44%	0.78	0.78	0.94	1.01	1.01	0.94	0.97
45%	0.78	0.78	0.94	1.01	1.01	0.94	0.97
46%	0.78	0.78	0.94	1.01	1.01	0.94	0.96
47%	0.79	0.79	0.94	1.00	1.00	0.94	0.96
48%	0.79	0.79	0.93	1.00	1.00	0.93	0.96
49%	0.79	0.79	0.93	1.00	1.00	0.93	0.96
50%	0.80	0.80	0.93	1.00	1.00	0.93	0.96

Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Conventional Valves (cont'd)

Load	PM	DPM	NO_x	SO_x	CO_2	N_2O	CH_4
51%	0.80	0.80	0.94	1.00	1.00	0.94	0.95
52%	0.81	0.81	0.94	1.00	1.00	0.94	0.95
53%	0.81	0.81	0.94	1.00	1.00	0.94	0.95
54%	0.82	0.82	0.94	1.00	1.00	0.94	0.95
55%	0.82	0.82	0.94	1.00	1.00	0.94	0.96
56%	0.83	0.83	0.94	1.00	1.00	0.94	0.96
57%	0.84	0.84	0.95	1.00	1.00	0.95	0.96
58%	0.84	0.84	0.95	1.00	1.00	0.95	0.96
59%	0.85	0.85	0.95	1.00	1.00	0.95	0.96
60%	0.86	0.86	0.95	0.99	0.99	0.95	0.97
61%	0.86	0.86	0.96	0.99	0.99	0.96	0.97
62%	0.87	0.87	0.96	0.99	0.99	0.96	0.97
63%	0.88	0.88	0.96	0.99	0.99	0.96	0.98
64%	0.89	0.89	0.97	0.99	0.99	0.97	0.98
65%	0.89	0.89	0.97	0.99	0.99	0.97	0.98
66%	0.90	0.90	0.98	0.99	0.99	0.98	0.99
67%	0.91	0.91	0.98	0.99	0.99	0.98	0.99
68%	0.92	0.92	0.98	0.99	0.99	0.98	0.99
69%	0.93	0.93	0.99	0.99	0.99	0.99	1.00
70%	0.94	0.94	0.99	0.99	0.99	0.99	1.00
71%	0.94	0.94	0.99	0.99	0.99	0.99	1.00
72%	0.95	0.95	1.00	0.99	0.99	1.00	1.01
73%	0.96	0.96	1.00	0.99	0.99	1.00	1.01
74%	0.97	0.97	1.00	0.99	0.99	1.00	1.01
75%	0.98	0.98	1.01	0.99	0.99	1.01	1.01

Load Adjustment Factors for MAN 2-Stroke Propulsion Engines with Conventional Valves (cont'd)

Load	PM	DPM	NO_x	SO_x	CO_2	N_2O	CH_4
76%	0.99	0.99	1.01	0.99	0.99	1.01	1.01
77%	1.00	1.00	1.01	0.99	0.99	1.01	1.01
78%	1.01	1.01	1.01	0.99	0.99	1.01	1.01
79%	1.03	1.03	1.02	0.99	0.99	1.02	1.01
80%	1.04	1.04	1.02	0.99	0.99	1.02	1.01
81%	1.05	1.05	1.02	0.99	0.99	1.02	1.01
82%	1.06	1.06	1.02	0.99	0.99	1.02	1.01
83%	1.07	1.07	1.02	0.99	0.99	1.02	1.01
84%	1.08	1.08	1.02	0.99	0.99	1.02	1.00
85%	1.10	1.10	1.02	0.99	0.99	1.02	1.00
86%	1.11	1.11	1.02	0.99	0.99	1.02	0.99
87%	1.12	1.12	1.02	0.99	0.99	1.02	0.99
88%	1.13	1.13	1.02	0.99	0.99	1.02	0.98
89%	1.15	1.15	1.01	0.99	0.99	1.01	0.97
90%	1.16	1.16	1.01	0.99	0.99	1.01	0.97
91%	1.17	1.17	1.01	0.99	0.99	1.01	0.96
92%	1.19	1.19	1.00	0.99	0.99	1.00	0.94
93%	1.20	1.20	1.00	0.99	0.99	1.00	0.93
94%	1.22	1.22	0.99	0.99	0.99	0.99	0.92
95%	1.23	1.23	0.99	0.99	0.99	0.99	0.91
96%	1.24	1.24	0.98	0.99	0.99	0.98	0.89
97%	1.26	1.26	0.97	1.00	1.00	0.97	0.87
98%	1.28	1.28	0.97	1.00	1.00	0.97	0.86
99%	1.29	1.29	0.96	1.00	1.00	0.96	0.84
100%	1.31	1.31	0.95	1.00	1.00	0.95	0.82

Estimated effect of the 2022 ECHO Program voluntary ship slowdowns on whale ship strikes

Pacific Whale Watch Association

March 28th, 2023

R. Cotton Rockwood and Jaime Jahncke

Point Blue Conservation Science

Suggested Citation

Rockwood, R.C. and J. Jahncke. March 2023. Estimated effect of the 2022 ECHO Program voluntary ship slowdowns on whale ship strikes. Unpublished Report to the Port of Vancouver ECHO Program. 8 pp.

Point Blue Conservation Science – Point Blue's 160 scientists work to reduce the impacts of climate change, habitat loss, and other environmental threats while developing nature-based solutions to benefit both wildlife and people. Visit Point Blue on the web www.pointblue.org.

Overview and Background

The Port of Vancouver Enhancing Cetacean Habitat and Observation (ECHO) Program goal is to decrease the cumulative effect of commercial shipping and ship traffic on whales through quantifiable initiatives. One initiative of the program institutes seasonal voluntary ship slowdowns in Haro Strait, Boundary Pass and Swiftsure Bank. The primary purpose of these efforts is to reduce underwater noise impacts on marine life, especially for southern resident killer whales (SRKW), but slowing vessels also decreases the incidence of collisions with whales providing program conservation co-benefits. The objective of this analysis is to quantify the proportional decrease in whale mortality risk from ship strikes achieved when vessels slowed during the program relative to the speeds they would otherwise have traveled within these regions. This assessment is done cumulatively across all slowdown regions as well as separately for each individual slowdown region (Haro Strait/Boundary Pass and Swiftsure Bank). While Haro Strait/Boundary Pass are reported as a single unit, the analysis does not include the precautionary turning area between the two regions since slowdowns are optional in that portion of the traffic separation scheme and not monitored. In addition, the results are parsed according to ECHO specified ship types to understand which classes of vessel contribute most to strike reduction by slowing their speeds.

This study assesses relative risk reduction for humpback and fin whales, baleen whale species that frequent the waters of the slowdown areas and are at significant risk of ship strikes. The models used are modified from previous efforts to quantify both spatially-explicit ship strike risk and estimates of mortality from strikes[1,2]. Rockwood et al. 2017 parameterized the proportion of time in the strike zone, whale size and whale avoidance components of the models based on data from archival tags and available literature. However, these components (especially a reliable estimate of avoidance) are not quantified for SRKW or transient killer whales, making the analysis of strike risk reductions attributable with the slowdown for these species infeasible at this time.

Key message: The transits of vessels participating in the slowdowns posed 21% less strike mortality risk to whales than if those vessels had not slowed in cooperation with the program. Slower participating transits in Haro Strait and Boundary Pass areas presented 17% and 18%

---

[1] Martin, J., Sabatier, Q., Gowan, T. A., Giraud, C., Gurarie, E., Calleson, C. S., ... & Koslovsky, S. M. (2016). A quantitative framework for investigating risk of deadly collisions between marine wildlife and boats. *Methods in Ecology and Evolution*, *7*(1), 42-50.

[2] Rockwood, R. C., Calambokidis, J., & Jahncke, J. (2017). High mortality of blue, humpback and fin whales from modeling of vessel collisions on the US West Coast suggests population impacts and insufficient protection. *PLoS One*, *12*(8), e0183052.

lower mortality risk to whales, respectively, than if ships did not decrease speed. Mortality risk was lowered 27% in the Swiftsure Bank area. While not the initial goal of the ECHO vessel slowdown, according to our analysis, decreasing strike risk to whales is a significant co-benefit.

Methods

To evaluate the effect slower vessel speeds (due to the ECHO Program initiatives) had on strike mortality risk, this study incorporates parts of the full, spatially-explicit ship strike model from Rockwood *et al.* 2020[3]. The Rockwood *et al.* 2020 model built upon the model developed in Rockwood et al. 2017 by applying the strike calculation to each vessel's unique track rather than to a raster grid of model variables summarized for each grid cell and then summed to provide a total strike calculation. This improvement, while computationally intensive, provides more accurate results since it eliminates error that comes from applying the non-linear model functions to mean raster cell values rather than each individual track. The track-wise model has been used to evaluate the effect of voluntary speed reductions (VSRs) in central[3] and southern[4] California.

For post-hoc analysis of the VSRs in California, periods of vessel traffic data during times when the VSR was not in effect to provide 'baseline' speeds representing the rate vessels would likely travel if no slowdown was requested. The same approach was taken here. Specifically, since the intent was to estimate the effect of a speed slowdown program, the components of the model which depend on speed were isolated. These include the encounter rate between whales and vessels, the probability of mortality given a collision and the probability of active avoidance by whales. Each of these model components were combined into an equation which allows calculation of the proportional decrease in model mortality risk between transits of a vessel at two different speeds. That is, assuming other features of the vessel (e.g., beam, draught) and its route are the same, the calculated strike mortality risk is decreased when traveling at a slower speed. In this way, the effect of a slow-down program on strike risk could be isolated and quantified while controlling for other fleet characteristics. Mortality risk is calculated as:

$$Mortality\ Risk = \lambda_e \cdot \left(1 - P(Avoidance|v_b)\right) \cdot P(Mortality|v_b)\ ,$$

where λ_e is the encounter rate, $\left(1 - P(Avoidance|v_b)\right)$ is the probability of no successful avoidance given the vessel's speed, v_b, and $P(Mortality|v_b)$ is the probability of mortality in the event of a strike as a function of the vessel's speed. The function for probability of

[3] R. Cotton Rockwood et al., "Estimating Effectiveness of Speed Reduction Measures for Decreasing Whale-Strike Mortality in a High-Risk Region," *Endangered Species Research* 43 (2020): 145–66, https://doi.org/10.3354/ESR01056.

[4] Rockwood, R. C., Adams, J. D., Hastings, S., Morten, J., & Jahncke, J. (2021). "Modeling whale deaths from vessel strikes to reduce the risk of fatality to endangered whales". *Frontiers in Marine Science*, *8*, 649890.

avoidance is based on studies of close encounters between vessels and whales and the resulting behavioral responses[5,6] and is explained in detail in Rockwood et al. 2020. The relationship between probability of mortality and vessel speed is derived from a published analysis of a global database of ship strike records[7] and has been used in numerous assessments of ship strike risk and is also explained in greater detail in Rockwood *et al.* 2017.

Encounter rate is calculated as:

$$\lambda_e = \frac{2r_c}{S}\int_{v_m} I(v_m,\ v_b)\, v_m \mathrm{d}v_m\ ,$$

where r_c is the critical radius (a distance defining the strike risk zone in the horizontal plane), S is the cell area, v_m is the species-specific average whale swim velocity as derived from satellite tags, v_b is the vessel velocity through the water based on AIS and water current data, and $I(v_m,\ v_b)$ is an increasing function of the velocities as derived from encounter theory. The encounter rate is a per-time estimate of the number of potential collision interactions between a single whale and ship within a defined area. In order to estimate strike mortality as was done in Rockwood *et al.* 2020 and 2021, this rate can be scaled by the number of whales predicted withing that area (usually via statistical species distribution models). However, in this case density estimates are not available across the entire area of interest, so encounter rate is used as a risk scalar and we calculate only proportional changes in risk rather than absolute estimates of changes in strike mortality.

For this analysis, the ECHO program collected and processed AIS reports from the slowdown areas and provided AIS vessel data including the vessel draft, beam, and speed through water. Speed through water was calculated using the Salish Sea Cast Model[8] a detailed tidal current model to adjust the vessel speed over ground reported in the AIS data. This was necessary because of the strong tidal currents in the study region. Since the slow-down program is seasonal, with the request for reduced vessel speeds from June to October, the remainder of the year provides a control period to derive 'baseline' or 'normal' vessel transit speeds. Using AIS-derived transits of vessels through the initiative areas in 2022, the effect of the slowdown

[5] McKenna, M. F., Calambokidis, J., Oleson, E. M., Laist, D. W., & Goldbogen, J. A. (2015). Simultaneous tracking of blue whales and large ships demonstrates limited behavioral responses for avoiding collision. *Endangered Species Research*, *27*(3), 219-232.

[6] Gende, S. M., Hendrix, A. N., Harris, K. R., Eichenlaub, B., Nielsen, J., & Pyare, S. (2011). A Bayesian approach for understanding the role of ship speed in whale–ship encounters. *Ecological Applications*, *21*(6), 2232-2240.

[7] Conn, P. B., & Silber, G. K. (2013). Vessel speed restrictions reduce risk of collision-related mortality for North Atlantic right whales. *Ecosphere*, *4*(4), 1-16.

[8] Soontiens, N., Allen, S., Latornell, D., Le Souef, K., Machuca, I., Paquin, J.-P., Lu, Y., Thompson, K., Korabel, V., 2016. Storm surges in the Strait of Georgia simulated with a regional model. Atmosphere-Ocean, 54, 1-21. https://dx.doi.org/10.1080/07055900.2015.1108899

program was isolated by using vessel speeds from the period when the slowdown is not requested (March-May; “baseline period”). Due to challenges with data availability, processed AIS data was not available for several periods in Haro Strait (May 22-29; June 5-12; Jun 19-26) and Boundary Pass (June 25 – July 9). Since the analysis estimates proportional change in strike risk, it is unlikely that these short periods with missing data would significantly alter the results. Only if there were major systematic differences in speeds or fleet characteristics during these specific times would there be any notable influence on proportional strike risk estimates.

In addition, the ECHO Program classified each transiting vessel into six types: Vehicle carriers (including Roll on/roll off vessels), Container ships, Passenger ships, Bulkers (this category included both Bulkers and general cargo vessels), Tankers and Tugs. These designations allowed model results to be summarized according to the proportional change in risk attributable to each vessel class. However, there were few transits of Tugs during the baseline period (March-May) which made robust re-sampling of speeds impossible. For this reason, we do not report modeled strike risk change for Tugs. Similarly, in Haro Strait, there were few Passenger vessel transits during the baseline period. To enable analysis of Passenger ships in Haro Strait, we used the baseline speeds from Boundary Pass as the re-sampling pool, but this means that the results for Passenger ships in Haro Strait should be taken with caution.

To estimate the impact of the slowdown, 100 sets of simulated control vessel data were created by assigning a speed to each vessel track collected during the slowdown period, and randomly re-sampled from the population of vessel speeds during April-March, the non-slowdown period. The re-sampling scheme only assigned speeds from the same vessel class and slowdown area, to ensure systematic differences in vessel operation and spatial variation in the fleet were minimized. To further control for the random nature of the speed assignment, 100 re-sampling iterations (each corresponding to the 100 simulated data sets) were run.

The strike model was run on both the actual vessel data and the 100 simulated data sets and the risk was summed across all tracks for each data set. This processed allowed for the calculation of the proportional difference between modeled risk based on the true speeds (actual risk) and modeled risk based on simulated speeds (baseline risk) and these differences were then averaged across all 100 iterations. The results represent the proportional change mortality risk resulting from the slower speeds during the slowdown period when compared to the non-slowdown baseline period.

Results and Discussion

For humpback whales, the percent decrease in strike mortality risk was -21.1% for the combined area, and higher in the Swiftsure Bank area (-27.4%) than in Haro Strait (-17.8%) and Boundary Pass (-18.1%). For fin whales, Haro Strait and Swiftsure Bank were slightly lower at -17.6% and -27.2%, respectively. In the model, both humpback whales and fin whales have identical avoidance strategies and mortality risk due to a strike. As a result the only model component that varied between species was their size, which has a very minor effect on encounter rate. Therefore, the proportional change in mortality risk predicted by this calculation was very similar for both species evaluated.

Table 1. Percent decrease in strike mortality risk for vessel transits participating in the slowdown compared to the strike mortality risk that would have occurred had they traveled at normal speeds recorded during periods with no slowdown.

	Distance-weighted mean speed (knots)		**Percent change in strike risk**	
Region	No slowdown	Active slowdown	Humpback whale	Fin whale
Boundary Pass	14.6	12.8	-18.1 %	-18.1 %
Haro Strait	15.0	12.7	-17.8 %	-17.6 %
Swiftsure Bank	12.9	11.8	-27.4 %	-27.2 %
Combined area	14.2	12.4	-21.1 %	-21.0 %

In addition, the study calculated changes in risk by vessel class. It was found that Vehicle carrier vessels had the greatest proportional decrease in strike risk, while Passenger ship risk showed the lowest proportional change in strike risk when participating in the slowdown versus normal vessel behavior during the non-slowdown periods (Table 2).

One key aspect of strike risk that plays out in these results is the non-linear relationship between strike risk and vessel speed. The same increment of speed decrease at slower speeds has a greater mitigating effect on strike risk than it does at higher speeds. This effect can be seen in the greater proportional decrease in risk for tankers (which have a smaller decrease in speed during the slowdown) vs container ships. Since container ships travel faster than tankers (both during and outside of the slowdown period), they have a lower proportional decrease in strike risk despite a slightly higher decline in average speeds. This also contributes to the higher

Table 2. Proportional decrease in strike risk for different vessel classes participating in the voluntary slowdown.

	Distance-weighted mean speed (knots)		**Percent change in strike risk**	
Vessel Class	No slowdown	Active slowdown	Humpback whale	Fin whale
Vehicle carriers	16.6	14.4	-21.8 %	-21.8 %
Container ships	15.0	13.6	-17.7 %	-17.6 %
Passenger ships	15.7	14.9	-9.5 %	-9.5 %
Bulkers and cargo vessels	12.1	11.2	-13.7 %	-13.6 %
Tankers	12.0	11.0	-20.7 %	-20.7 %

proportional risk reduction in Swiftsure Bank compared to Haro Strait and Boundary Pass; the Swiftsure vessels achieve lower average speeds during the slowdown which compensates for the smaller absolute change in speed compared to the Haro and Boundary areas. Thus, proportional change in risk depends on a combination of the change in speed *and* the non-slowdown rate of travel. In addition, these factors act at the individual transit level so that the specific distribution of baseline speeds and changes in speed within a fleet or vessel class can affect the total strike risk significantly. Detailed discussion of the non-linearity of speeds and strike risk including how it is represented in this strike model can be found in the supplement of Rockwood *et al.* 2020.

Model Limitations

The changes in proportional risk reported above are the estimated relative decline in risk as a result of the ECHO Program slowdowns. However, it is important to be clear that the models did not estimate the change in the absolute number of whales struck because of the lack of cetacean density data. What that means is that the absolute benefit in terms of numbers of whales saved by the slowdowns could be different across the regions analyzed and even between different vessel classes despite having similar percentage reductions in risk. This is because, the number of whales saved is the product of the proportional reduction and the density of whales present in the area evaluated. Thus, a lower proportional reduction in risk could still result in a greater number of whales saved if the area in question has a much higher whale density. Similarly, if the different vessel classes overlap more or less with whales (e.g. certain vessel types tend to travel through Swiftsure Bank, but not Haro Strait and Boundary Pass because they are more often bound for the Port of Tacoma), that vessel class might avoid high-density humpback whale areas in Haro Strait/Boundary Pass and therefore have a lower absolute conservation benefit from the slowdown program than a vessel class that more often travels to the Port of Vancouver.

Though this simplified risk assessment cannot estimate the absolute mortality avoided, as can be done with the full model[1], proportional change is a more consistent measure for assessing slowdown effects across years and seasons. This is because variation in vessel characteristics, routes and whale distribution and density, which were unknown, can have significant effects on absolute risk and mortality but proportional effects of a program will remain much more consistent. Based on this analysis approach, the strike mortality risk for the two species analyzed from vessels traversing the slowdown areas was cut 21% because of the vessel cooperation with the slowdown initiative.

Future Directions

This analysis provides an estimate of the slowdown co-benefit of reducing ship strikes to whales. Because spatial models of whale density are not available covering the slowdown areas, we could not estimate strike mortality or the absolute change in mortality as a result of the slowdowns. Similarly, we were not able to identify varying risk of collision due to whale density changes throughout the slowdown region. To enable these more detailed analyses and metrics, it would be necessary to conduct spatial modeling and prediction of whale density for species of interest in the region. If reliable data or methods become available to parameterize SRKW avoidance, then the study could be expanded to cover additional species. Additionally, analysis was conducted based on actual speeds seen during both the baseline and slowdown periods and give a representation of proportional risk reduction based on current parameters and participation. Since the analysis used in this report is based on computer simulation it is also possible to consider how vessels traveling at a range of speeds effects strike risk which could inform any future decisions to change the requested slowdown speed.