COMPOSITION AND ANALYSIS OF VESSEL SPEEDS
OFF THE COAST OF WASHINGTON STATE

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Geographic Information Science

by

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CERTIFICATION OF APPROVAL

I certify that I have read *Composition and Analysis of Vessel Speeds off the Coast of Washington State* by Nathaniel Cameron Greig, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Science in Geographic Information Science at San Francisco State University.

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Most species of whales are vulnerable to vessel collisions, and the probability of lethality increases logistically with vessel speed. Spatially explicit risk assessments can inform the marine management process about the potential for vessel collisions. We used Satellite Automatic Identification Systems data from 2013 and 2014 to calculate vessel speed over ground around the Olympic Coast National Marine Sanctuary. Nearby shipping lanes connecting the Ports of Vancouver, Seattle, Tacoma, and Portland have the greatest density of vessel traffic, and these densely traveled routes continue outside the US Exclusive Economic Zone. We characterized speed and density based on vessel type and for areas of interest, including the Cetacean Density and Distribution Working Group's Biologically Important Areas. Cargo and tanker vessels constitute the majority of distance traveled at the greatest speeds. We found that calculated speed is higher and less variable than broadcast speed for most vessel types. Temporal gaps in the SAIS data led to uncertainty in transit path and a resulting systematic underestimation of vessel speed. Calculating vessel speed is important so that risk to cetaceans from collisions is not underestimated by using broadcast speed in risk assessments.

I certify that the Abstract is a correct representation of the content of this thesis.

Chair, Thesis Committee Date

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Part 1. Introduction

1.1 Vessel Collisions and Spatial Risk Assessments

Collisions between vessels and whales, or ship strikes, are a dangerous source of anthropogenic mortality to whales. Most species of whales are potentially vulnerable to collisions, which can account for a large proportion of whale strandings in some geographic areas (Clapham, Young, and Brownell 1999; Laist et al. 2001; Berman-Kowalewski et al. 2010). Most collisions happen near continental shelves or when prey aggregations are located in shipping lanes or areas with high ship density, and with slow-moving whales that spend a large proportion of their time near the surface (Clapham, Young, and Brownell 1999; Laist et al. 2001; Berman-Kowalewski et al. 2010). Spatial bottlenecks of highly concentrated densities of both vessels and whales pose the greatest relative risk of collisions (Williams and O'Hara 2010).

Methods of reducing the likelihood of vessel collisions include vessel speed reduction, rerouting vessels in time and space, mariner education, and technology aimed at detection and warning (Vanderlaan et al. 2008; Asaro 2012; Laist, Knowlton, and Pendleton 2014). The effectiveness of species-specific management areas relies on knowledge of spatial and temporal habitat use by the target species with the caveat that risk management for one species of cetacean does not mean risk reduction for another species (Redfern et al. 2013; Laist, Knowlton, and Pendleton 2014).

Spatial risk assessments, which allow for rapid and broad scale analysis of potential hazards posed to the marine environment by correlating anthropogenic pressures with ecosystem sensitivity, can increase our understanding of vessel collisions (Hope 2006; Stelzenmüller, Ellis, and Rogers 2010; Grech, Coles, and Marsh 2011). Risk assessments can predict where collisions are most likely to occur and can be investigated through vessel tracking technologies (Williams and O'Hara 2010; van der Hoop, Vanderlaan, and Taggart 2012). A thorough understanding of the spatial and temporal patterns of vessel traffic is a fundamental step in a risk assessment of vessel collisions. The objective of this research is to delineate spatial locations where vessel traffic density is high in known areas of cetacean concentrations.

1.2 Cetaceans, BIAs, and Strandings

There are two species of baleen whales that have designated Biologically Important Areas (BIAs) in our research area off the coast of the state of Washington (Calambokidis et al. 2015). The BIAs are species, region, and time specific marine areas where cetacean populations are seasonally concentrated for reproduction, feeding, migrating, or small and residential populations (Ferguson et al. 2015). The National Oceanic and

Atmospheric Administration (NOAA) Fisheries, Cetacean Density and Distribution Working Group defined these areas within United States Exclusive Economic Zone (EEZ) waters for cetaceans only.

There are six gray whale (*Eschrichtius robustus*) and one humpback whale (*Megaptera novaeangliae*) BIAs within our research area. The humpback whale BIAs are based on surveys and opportunistic sources about highly concentrated feeding animals, while the gray whale BIAs are based on migratory corridors between annual feeding and reproductive areas, from numerous survey methods and expert opinion (Calambokidis et al. 2015).

Large whale strandings with evidence of vessel collisions have been recorded all over the world and with a variety of vessel types (Laist et al. 2001; Jensen and Silber 2004). The detection probability of vessel collisions is low (Jensen and Silber 2004). In the state of Washington, 19 of 130 (15%) strandings from 1980 to 2006 showed evidence of collisions with vessels, but numerous biases lead to underestimates in true number of mortalities (Douglas et al. 2008). The fine scale behavior of whales in response to large vessels in close proximity is not well understood, and whales show varied and limited behavioral responses to approaching vessels (Gende et al. 2011; Harris et al. 2012; McKenna et al. 2015; Szesciorka 2015). Whales are subject to striking from both the bulbous bow and the propeller of the vessel, and vessel speed is correlated with forces exhibited on a whale (Knowlton et al. 1995; Silber, Slutsky, and Bettridge 2010).

1.3 Vessel Traffic, Speed, and Monitoring Technologies

Maritime shipping presents a direct pressure to many species of whales (NMFS 1991; NMFS 1998, NMFS 2010). Shipping is a highly globalized industry, is an important component of international trade, and is correlated with global economic patterns (Schwehr and McGillivary 2007; Rodrigue 2010, Frisk 2012). The number, size, and speed of vessels are increasing over time (Silber, Slutsky, and Bettridge 2010). This research site is offshore from the important West Coast ports of Vancouver, Seattle, Tacoma, and Portland.

Vessel speed is an important component of shipping’s potential impact on cetaceans (Gende et al. 2011; Conn and Silber 2013). The conservation benefit to whales by reducing vessel speed is well established, and is generally expressed as a simple logistic relationship between vessel speed and probability of lethality (Pace and Silber 2005; Vanderlaan and Taggart 2007; Gende et al. 2011; Wiley et al. 2011; Conn and Silber 2013). There is a significant positive relationship, and the greatest rate of change generally occurs between 9 and 15 knots, corresponding roughly to an increase in probability of lethality from 0.2 to 0.8 (see Vanderlaan and Taggart 2007). Vessel speed limits help to reduce the anthropogenic mortality risk and possibly collision probability (Gende et al. 2011; Conn and Silber 2013).

Automatic Identification Systems (AIS) is a technology that can be used to analyze vessel traffic patterns, informing us about the anthropogenic pressures from shipping by quantifying speed and density. AIS is a non-proprietary, autonomous vessel communication, navigation, and tracking technology, standardized by the International Telecommunications Union and required for most vessels by the International Maritime Organization's Safety of Life at Sea Convention (Tetreault 2005; USCG 2008). By gathering data from connected GPS, gyrocompass, and user input, AIS provides information such as vessel identity, position, speed, and status to other ships, shore-based stations, aids to navigation, and aircraft, and receives such information from other AIS-transmitting units over two maritime Very High Frequency (VHF) bands (USCG 2008; Schwehr 2011). These data can also be collected by any AIS receiver, and then processed and analyzed in a geographic information system.

Under most configurations, VHF transmissions are limited roughly to line-of-sight, or about 50 nautical miles (nm) (Calder and Schwehr 2009). While most of the coastal waters of the United States are covered by the network of United States Coast Guard (USCG) receivers, coverage does not extend well into the open ocean (Silber, Adams, and Fonnesbeck 2014). Satellite AIS (SAIS) can help overcome the terrestrial line-of-sight limitation by collecting AIS broadcasts from a constellation of low earth orbiting satellites (Ball 2013).

Both regular AIS and SAIS are not without limitation and potential error, including human input, data corruption, signal noise, GPS faults, and gyrocompass or other instrument failure (Aarsæther and Moan 2009; McGillivary, Schwehr, and Fall 2009; Silber and Bettridge 2010). For SAIS specifically, the spatial coverage is theoretically more complete in global scale terms, but the present constellation of SAIS satellites cannot capture all AIS broadcasts as there are not enough satellites to ensure continuous full global coverage, leading to temporal gaps. Most vessels are required to broadcast AIS messages every few seconds while under way, but preliminary data analyses showed SAIS gaps of several hours to be common.

1.4 Research Scope and Questions

This research informs about traffic patterns off the coast of Washington state and provides a baseline understanding of the marine traffic patterns and foundation to future risk assessments, as the use of SAIS-derived data allows for vessel tracking much further from the coast than is possible with terrestrial receivers. This research is novel in its use of a derived, or calculated, speed over ground (SOG) rather than relying on the broadcasted SOG from the AIS data (Jensen et al. 2015).

Extensive research on North Atlantic right whales on the US Eastern seaboard has shown the effectiveness of active management practices in reducing whale mortality from vessel collisions (Laist, Knowlton, and Pendleton 2014). Off the coast of British Columbia, risk to several species of cetaceans has been investigated (Williams and O'Hara 2010). However, the area within US waters outside the Strait of Juan de Fuca has still not been studied. Multiple species of large whales off the coast of Washington state are vulnerable to collisions, and vessel traffic is increasing over time (Douglas et al. 2008; Silber, Slutsky, and Bettridge 2010). This geographic focus area is important due to its connections to several primary ports and the presence of multiple species of slow-reproducing whales recovering from past population declines.

This work will serve as a baseline understanding of the relative risk posed to cetaceans from vessel traffic off the coast of Washington state by analyzing and characterizing vessel speed and density. First, what are the traffic patterns characteristic to each vessel type? Which are most common and which travel at the highest speeds? Second, which spatial locations have the greatest densities of vessels and vessels traveling at the highest speeds? Third, within the active months of the BIAs when whale concentrations are highest, which areas experience the greatest densities and speeds?

Part 2. Methods

2.1 Study Area

The study area is between the 46^{th} and 49^{th} parallels north and the 124^{th} and 127^{th} meridians west, and defines the extent of SAIS data collection (Figure 1). Reaching 90 to 125 nm offshore of the state of Washington in the northwestern US, the study area extends from roughly the mouth of the Columbia River in the south to the Strait of Juan de Fuca and southern Vancouver Island in the north.

Figure 1. Location of the study area along the Pacific Northwest coast of the contiguous United States and southwest Vancouver Island in Canada.

Inside the Strait of Juan de Fuca are the Ports of Tacoma and Seattle, major US shipping ports, and Port Metro Vancouver (Figure 1). Port Metro Vancouver is the largest Canadian port, handling roughly the same amount of total tonnage as the Port of New York and more than Seattle and Tacoma combined (Port Metro Vancouver 2015; USACE 2016). Tacoma and Seattle ranked 7th and 10th, respectively, in the United States for total container traffic in 2013 and 29th and 31st, respectively, for total tonnage in the US in 2014. (USACE 2015; USACE 2016). These ports connect internationally to East and

Southeast Asia, and domestically to Alaska, Hawaii, and the West Coast of the US Additionally, the Port of Portland is located inland from the mouth of the Columbia River. Portland ranked 25th among US ports for total container traffic in 2013 and 28th for total tonnage in 2014 (USACE 2015; USACE 2016).

Within the full 75,367 km^2 study area, 88% is open water and 12% is land. Administrative areas in the study area include the NOAA administered Olympic Coast National Marine Sanctuary (OCNMS), an IMO designated Area to be Avoided (ATBA), and part of the USCG controlled Juan de Fuca Traffic Separation Scheme (TSS) (Figure 2).

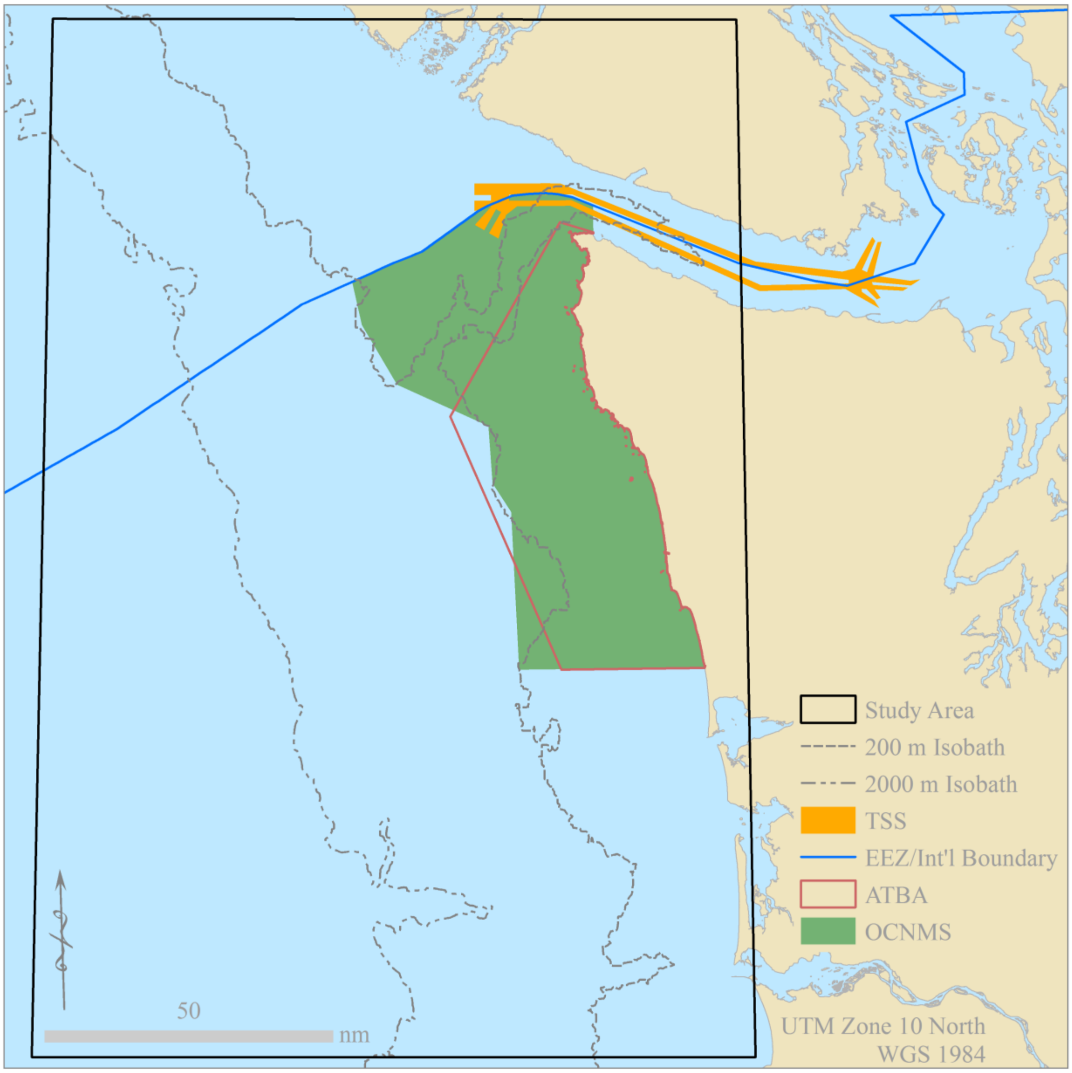


Figure 2. Bathymetric and administrative areas in the Study Area.

Thirty one percent of the marine section of the study area is above the continental shelf, less than 200 m deep. Thirty seven percent is between 200 and 2000 m deep, and thirty two percent is greater than 2000 m deep (Figure 2). Within the study area, there are seven Biologically Important Areas, six for gray whales and one for humpback whales (Table 1 and Figure 3).

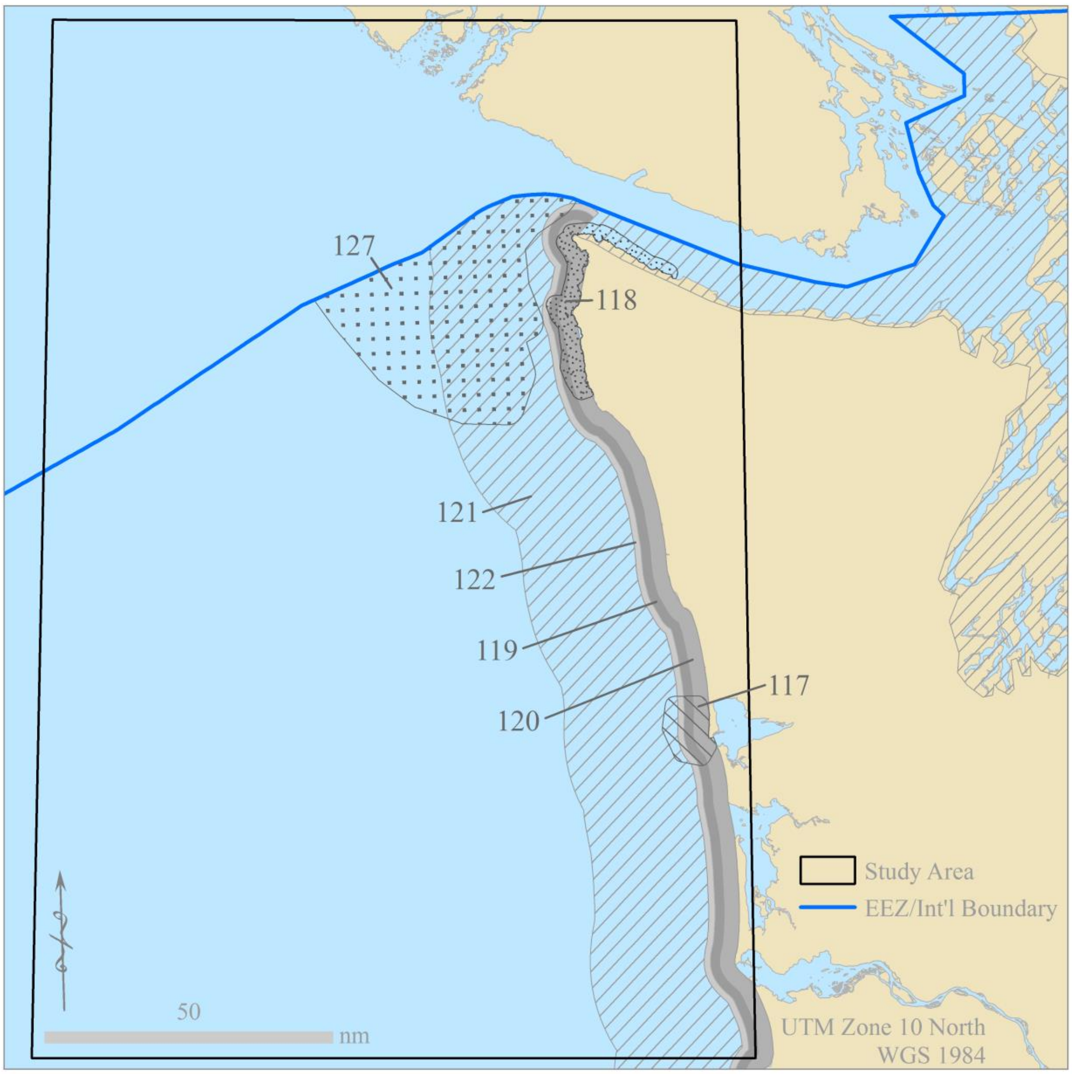


Figure 3. Biologically Important Areas (see Table 1 for species and type) for gray and humpback whales along the coast of the North American Pacific Northwest. The United States Exclusive Economic Zone and international boundary is the blue line.

Table 1. Summary of Biologically Important Areas within the North American Pacific Northwest.

Number	Species	Name	Type	Months	Area within Study Area (nm^2)	Description
117	Gray whale	Grays Harbor	Feeding	April-November	86.8	Outside Grays Harbor
118	Gray whale	Northwest Washington	Feeding	May-November	150.1	Northwest tip of Olympic Peninsula
119	Gray whale	Northbound Phase A	Migration	January-July	652.3	Within 8 km of coast
120	Gray whale	Northbound Phase B	Migration	March-July	393.8	Within 5 km of coast
121	Gray whale	Potential Presence	Migration	Jan.-July, Oct.-Dec.	4111.8	Within 47 km of coast
122	Gray whale	Southbound	Migration	October-March	828.7	Within 10 km of coast
127	Humpback whale	Northern Washington	Feeding	May-November	989.2	Northern part of U.S. EEZ

2.2 SAIS Information

SAIS data were collected by exactEarth Ltd (Cambridge, Ontario, Canada) for the calendar years 2013 and 2014, and received from the OCNMS. Each record in the tables corresponds to an individual AIS broadcast. AIS information is comprised of static information that does not change over the course of a voyage, and dynamic information that changes potentially as frequently as every AIS broadcast (Table 2).

Table 2. Examples of AIS static and dynamic broadcast information.

Static Information		Dynamic Information	
Vessel Name	Length	Date and Time	Heading
VIN	Draft	Latitude	Navigation Status
VIN Type	Beam	Longitude	Trip ID
MMSI	Gross Tonnage	Speed Over Ground	Source
Vessel Type	Country Flag	Course Over Ground	Message Type
Vessel Category	Call Sign	Rate of Turn	

The original SAIS data that were received had 3,045,407 records for the year 2013 and 2,941,900 for 2014. The years 2013 and 2014 had consistent fuel sulfur regulations (10,000 ppm or 1.0%) for vessels operating within the North America Emissions Control Area, 200 nm from the coast (EPA 2010). Thus, there were no temporal changes in traffic patterns based on emissions controls standards (Jensen et al. 2015). The use of SAIS data is necessary because only 56.4% of the study area water is within the potential range of terrestrial AIS.

2.3 Data Preparation

I conducted data quality control, starting with removing duplicate SAIS records, defined as records having the same Maritime Mobile Service Identity (MMSI), latitude, longitude, and time. The MMSI is a unique, regulated, and coded identifier for a ship. The second quality control step was to remove all records with a missing or null MMSI. The third quality control step was to create a tabular relationship between dynamic SAIS information and static vessel information, using the MMSI as a primary key.

2.4 Python Scripting for Transit Lines

I used ArcGIS geoprocessing and the programming language Python (Python Software Foundation 2012) running in PyScripter (K. Vlahos 2015) to write or modify numerous Python scripts.

The first script reprojected the point data into the Universal Transverse Mercator (UTM) Zone 10 North projection based on the Geographic Coordinate System (GCS) World Geodetic System (WGS) 1984, which allows distance to be measured in meters. AIS latitude and longitude are collected from a GPS receiver, which is based on GCS WGS 1984. The second Python script ran a spatial selection of only the SAIS points that were broadcasted from the water, and eliminated random error points located on land (Jensen et al. 2015). I added and calculated new fields for season and day/night based on the time stamp (Jensen et al. 2015). Seasons were defined as Winter (January-March), Spring (April-June), Summer (July-September), and Autumn (October-December). Day and night were defined by using published nautical twilight times from the US Naval Observatory, Astronomical Applications Department for Forks, WA and Ocean Shores, WA for the years 2013 and 2014. The nautical twilight was defined per month by using the average time from the 15th of each month (Jensen et al. 2015).

I created ship transit line segments, calculated SOG, and evaluated transit contiguity (Jensen et al. 2015). I joined SAIS data from sequential points from the same vessel to create straight line segments between points. The time difference and distance between sequential points defined the calculated speed over ground. The final part of the script evaluated transit contiguity, a single vessel on a continuous transit, based on MMSI, Trip ID, time between broadcasts, and heading difference.

I merged all 24 months of line segments and the 22 OCNMS-specified vessel types (Table 3) together to create complete transit lines. I analyzed the years 2013 and 2014 together to simplify calculations, despite differences in overall mean vessel speeds (Figure 4). I assumed these differences to arise from incomplete SAIS data. In 2013, 42.8% of the data were removed due to duplicate records, whereas this was only 5.8% for 2014. Separating by year would have added an extra level of dimensionality to the analysis. I conducted analyses at the vessel type level to minimize inherent inter-type vessel differences.

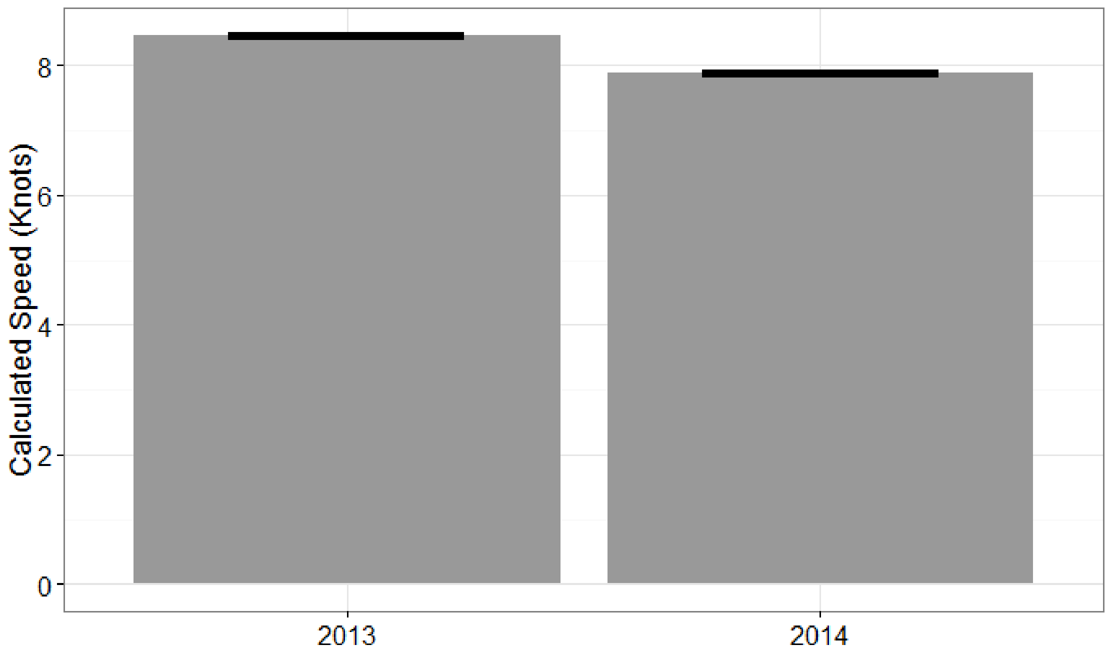


Figure 4. Mean calculated vessel speed over ground between years 2013 and 2014 with standard error bars shown.

Table 3. Twenty-two vessel types, as specified by the Olympic Coast NMS, grouped into six vessel categories.

Cargo	**Fishing**
Bulk Carrier	Fishing Vessel
Cargo Ship	**Passenger**
Container Ship	Passenger Ship
Refrigerated Cargo	**Miscellaneous**
Roll-On Roll-Off (RORO) Cargo Ship	Cable Layer
Vehicle Carrier	Dredger
Tanker	Drill Ship
Chemical Carrier	Pollution Control
Liquefied (Liquified) Gas Carrier	Private Vessel
Oil Tanker	Public Vessel
Tug	Research Ship
Articulated Tug Barge (ATB)	Supply Ship
Tug	Unknown

2.5 Calculated Speed Truncation

Truncation of calculated SOG values, an attempt to enumerate the highest possible legitimate speed per vessel type, was necessary because of infrequent errors in the data or processing that led to implausible SOG values and means. Truncation meant removing any record where the calculated speed was greater than a given threshold, from the following equation:

$$TT_{\alpha} = \bar{x}_{\alpha} + (3 \times \sigma_{\alpha})$$

where TV_{α} is the truncation threshold for vessel type α, $\bar{x}_{\alpha}$ is the mean non-0 broadcast SOG value for type α, and σ_{α} is the standard deviation of non-0 broadcast SOG values for type α. This equation was derived from examining histograms and statistics of broadcast SOG values and validated by expert opinion (G. Galasso, pers. comm.). The use of non-0 broadcast SOG values was necessary because 36.7% of all broadcast SOG values were 0, skewing the mean and inflating the standard deviation.

2.6 Areas of Interest

I examined vessel transit lines with truncated average speed values across a range of areas of interest. This included the entire space and time of the study area, and spatial subsets that included the OCNMS, ATBA, and the BIAs during active months. I examined temporal subsets that included day versus night and the four seasons.

2.7 Hexagon Average Speed and Density

The Olympic Coast NMS has used hexagons, one square statute mile in area, as a unit of measurement or observation as part of their spatial planning process (N. Wright, pers. comm.). There are 29,542 homogenous hexagons for the entire study area, including the ONMS. I calculated mean SOG and number of vessel transits per month for vessel transits across each hexagon that intersects the BIAs.

Part 3. Results

3.1 Truncation Threshold per Vessel Type

Public vessels, primarily armed forces vessels from both the US and Canada, had the highest truncation threshold at 37 knots, followed by roll-on roll-off (RORO) cargo ships at 31 knots, passenger and supply ships at 30 knots, and container ships at 28 knots (Table 4). Tugs, fishing vessels, and dredgers had the lowest truncation threshold, 15 knots.

Table 4. Truncation thresholds by vessel type. Truncation thresholds are an estimate of maximum attainable speed for each vessel type.

Vessel Type	**Truncation Value (Knots)**	**Percent Truncated**
Cargo		
Bulk Carrier	21	1.32
Cargo Ship	21	1.45
Container Ship	28	2.59
Refrigerated Cargo	17	9.32
RORO Cargo Ship	31	3.06
Vehicle Carrier	26	1.55
Tanker		
Chemical Carrier	21	1.76
Liquefied Gas Carrier	21	1.24
Oil Tanker	21	1.65
Tug		
Articulated Tug Barge	16	1.10
Tug	15	1.31
Fishing		
Fishing Vessel	15	0.56
Passenger		
Passenger Ship	30	1.66
Miscellaneous		
Cable Layer	20	0.24
Dredger	15	1.58
Drill Ship	19	0.27
Pollution Control	20	0.13
Private Vessel	23	0.97
Public Vessel	37	2.16
Research Ship	18	0.61
Supply Ship	30	4.97
Unknown	17	1.07

All vessel types in the tanker category had truncation thresholds at 21 knots, while the cargo category ranged from 17-31 knots. Articulated tug barges (ATBs) and tugs had similar truncation thresholds, 16 and 15 knots, respectively. Liquefied gas carriers, cable layers, and pollution control vessels all had maximum calculated speeds of less than one knot under the truncation threshold.

Overall, 1.28% of the data were truncated. Pollution control vessels had the least proportion of truncated data, 0.13%, and refrigerated cargo had the most, 9.32%. Container ships, RORO cargo ships, public vessels, and supply ships were the only other vessel types with more than 2% of their data truncated.

3.2 Total Transits and Distance Traveled

The 42,629 sum total transits of all vessels in the years 2013 and 2014 covered 2,694,197 nm. Fishing vessels account for the most total vessel transits, at 26.9%, followed by bulk carriers at 23.5% (Table 5). The only other vessel type to have greater than 10% of the total transits is container ships (10.4%).

The cargo category made up 41.7% of total transits, the most of any category. With the exception of public vessels and private vessels, most vessel types in the miscellaneous category registered very few transits. The remaining seven vessel types in the miscellaneous category only account for 2.2%. Vessels in the cargo and tanker categories average 27.7 transits per day.

Bulk carriers accounted for the most distance traveled by any one vessel type (32.0%). Only fishing vessels (16.8%) and container ships (13.2%) accounted for more than 10% of total distance traveled. Cargo category vessels traveled more than half (56.0%) of all distance traveled. The miscellaneous category accounts for only 5.1% of total distance traveled, and passenger only 2.3%. Excluding private and public vessels again, the miscellaneous category only accounts for 1.2% of total distance.

Table 5. Total transits and distance traveled by vessel type for 2013 and 2014 combined.

Vessel Type	Total Transits	Percent of Total Transits	Total Distance Traveled (nm)	Total Distance Traveled (%)
Cargo	17756	41.7	1508615.4	56.0
Bulk Carrier	10018	23.5	862409.7	32.0
Cargo Ship	921	2.2	79166.3	2.9
Container Ship	4453	10.4	370728.4	13.8
Refrigerated Cargo	47	0.1	3573.8	0.1
RORO Cargo Ship	609	1.4	39459.0	1.5
Vehicle Carrier	1708	4.0	153278.1	5.7
Tanker	2479	5.8	250400.9	9.3
Chemical Carrier	485	1.1	47961.5	1.8
Liquefied Gas Carrier	42	0.1	2486.5	0.1
Oil Tanker	1952	4.6	199952.9	7.4
Tug	4223	9.9	282482.2	10.5
Articulated Tug Barge	772	1.8	90554.2	3.4
Tug	3451	8.1	191928.0	7.1
Fishing	11478	26.9	452249.7	16.8
Fishing Vessel	11478	26.9	452249.7	16.8
Passenger	872	2.0	62352.6	2.3
Passenger Ship	872	2.0	62352.6	2.3
Miscellaneous	5821	13.7	138096.6	5.1
Cable Layer	27	0.1	1676.4	0.1
Dredger	115	0.3	6418.6	0.2
Drill Ship	4	0.0	401.3	0.0
Pollution Control	522	1.2	2016.1	0.1
Private Vessel	1605	3.8	35289.0	1.3
Public Vessel	3276	7.7	69160.2	2.6
Research Ship	193	0.5	19262.5	0.7
Supply Ship	56	0.1	3201.6	0.1
Unknown	23	0.1	670.8	0.0

3.3 Overall Average Calculated Speed over Ground

Passenger ships show the greatest average calculated SOG, 18.2 knots (Table 6). These are followed by RORO cargo ships (16.9 knots), container ships (16.1 knots), and vehicle carriers (14.0 knots). The five vessel types with the greatest average calculated SOG also have the five greatest average broadcast. Supply ships are the only miscellaneous category vessel type to average greater than 10 knots (10.4 knots). Public vessels have the greatest variability of speeds, with a standard deviation of 8.1 knots, followed by supply ships (6.6 knots) and RORO cargo ships (5.7 knots).

With the exceptions of three vessel types (cable layer, drill ship, and supply ship), all vessel types have a greater calculated SOG than broadcast SOG. Further, with the exception of four vessel types (fishing vessels, dredgers, pollution control, and research ships), all vessel types have an equal or greater broadcast SOG standard deviation (SD) than calculated SOG standard deviation (Table 6). While calculated vessel speeds remained similar between the two years or among the four seasons, they were not identical (Table 7).

Table 6. Overall calculated and broadcast speed over ground by vessel type for 2013 and 2014 combined. The asterisk (*) indicates a statistically significantly higher mean SOG ($\alpha = 0.05$) when comparing calculated versus broadcast SOG within a vessel type.

	Calculated Speed Over Ground			Broadcast Speed Over Ground		
Vessel Type	**Mean (Knots)**	**SD (Knots)**	**Count**	**Mean (Knots)**	**SD (Knots)**	**Count**
Cargo						
Bulk Carrier	10.5 *	4.1	963279	8.5	5.4	976195
Cargo Ship	11.2 *	3.8	77292	9.5	5.2	78431
Container Ship	16.1 *	4.7	382776	13.4	7.3	392957
Refrigerated Cargo	11.7 *	2.6	2851	8.4	5.3	3144
RORO Cargo Ship	16.9 *	5.7	45424	14.0	8.1	46857
Vehicle Carrier	14.0 *	4.9	194421	11.5	6.8	197485
Tanker						
Chemical Carrier	11.8 *	3.7	51393	9.8	5.5	52312
Liquefied Gas Carrier	13.5 *	3.8	2627	12.8	4.5	2660
Oil Tanker	12.4 *	3.4	198504	10.3	5.5	201838
Tug						
Articulated Tug Barge	9.1 *	2.7	85510	7.5	4.3	86458
Tug	6.7 *	3.2	317997	5.4	3.9	322224
Fishing						
Fishing Vessel	3.0 *	3.6	1400609	2.5	3.4	1408449
Passenger						
Passenger Ship	18.2 *	4.7	50239	15.8	7.8	51086
Miscellaneous						
Cable Layer	8.1	5.1	2056	8.3	5.1	2061
Dredger	3.6 *	3.7	50877	2.5	3.4	51693
Drill Ship	3.0	4.4	750	3.2	4.4	752
Pollution Control	0.6 *	1.9	55869	0.4	1.8	55941
Private Vessel	7.5 *	5.3	24783	6.2	5.6	25025
Public Vessel	6.5 *	8.1	276096	6.2	8.4	282194
Research Ship	5.0 *	4.4	37174	4.4	4.3	37404
Supply Ship	10.4	6.6	4306	10.9 *	6.7	4531
Unknown	3.8 *	3.9	833	3.1	3.9	842

Table 7. Mean calculated speed over ground (knots) by year and season for each vessel type.

	2013 and 2014 Combined					2013					2014				
Vessel Type	**Overall**	**Winter**	**Spring**	**Summer**	**Autumn**	**Overall**	**Winter**	**Spring**	**Summer**	**Autumn**	**Overall**	**Winter**	**Spring**	**Summer**	**Autumn**
Cargo															
Bulk Carrier	10.5	10.2	11.4	11.1	9.7	10.6	10.7	11.4	10.9	9.8	10.4	9.9	11.4	11.3	9.6
Cargo Ship	11.2	10.8	11.9	11.4	10.7	11.5	10.4	12.1	11.8	11.5	11.0	11.0	11.8	11.2	10.4
Container Ship	16.1	15.9	16.5	16.4	15.8	16.4	16.0	16.7	16.7	16.3	15.9	15.9	16.4	16.1	15.3
Refrigerated Cargo	11.7	10.6	11.8	11.3	12.4	11.3	10.6	11.6	11.1	11.9	11.9		11.9	11.5	12.9
RORO Cargo Ship	16.9	16.4	17.2	17.7	16.4	16.5	16.3	16.8	18.1	15.6	17.1	16.5	17.4	17.5	17.0
Vehicle Carrier	14.0	14.0	14.0	14.5	13.8	14.1	14.3	14.0	13.9	14.2	14.0	13.8	14.0	14.9	13.5
Tanker															
Chemical Carrier	11.8	12.0	12.6	12.0	11.0	12.4	12.2	12.7	12.9	11.8	11.3	11.7	12.4	11.5	10.5
Liquefied Gas Carrier	13.5	11.5	14.1	14.1	12.1	13.8	1.8	13.8	14.9	12.1	13.3	11.6	14.7	13.8	
Oil Tanker	12.4	12.7	12.6	12.9	11.8	12.7	12.9	12.8	12.7	12.4	12.3	12.5	12.5	13.1	11.4
Tug															
Articulated Tug Barge	9.1	9.2	9.3	9.3	8.7	9.3	9.5	9.5	9.2	9.0	9.0	9.0	9.1	9.4	8.6
Tug	6.7	6.6	7.0	7.2	6.3	7.0	6.9	6.9	7.3	6.9	6.5	6.4	7.0	7.1	5.9
Fishing															
Fishing Vessel	3.0	2.8	3.7	3.2	2.5	3.2	2.9	4.3	3.1	2.6	3.0	2.7	3.3	3.3	2.4
Passenger															
Passenger Ship	18.2	13.4	18.5	18.8	12.9	18.5	14.7	18.3	19.4	14.0	18.0	10.6	18.6	18.5	12.4
Miscellaneous															
Cable Layer	8.1	11.6	8.7	7.1	14.0	9.9	11.6	10.0	9.6	14.0	7.3		8.2	6.2	
Dredger	3.6	6.7	3.5	3.4	3.9	3.2		3.0	2.9	4.4	4.0	6.7	4.3	4.0	3.6
Drill Ship	3.0	8.1	2.2			3.0	8.1	2.2							
Pollution Control	0.6	0.7	0.6	1.0	0.3	2.3	1.5	4.3	3.2	0.8	0.4	0.5	0.3	0.8	0.3
Private Vessel	7.5	8.7	9.3	5.6	9.5	6.8	9.9	9.6	4.7	8.3	8.3	6.7	9.1	6.8	10.8
Public Vessel	6.5	7.1	6.8	7.0	5.5	7.1	8.4	6.9	7.7	5.8	6.2	6.4	6.8	6.6	5.3
Research Ship	5.0	7.4	4.4	5.4	5.3	4.7	7.1	4.1	4.7	6.1	5.4	8.9	4.7	6.9	5.0
Supply Ship	10.4	11.1	11.6	9.2	8.4	9.6	10.7	9.2	9.5	9.5	11.3	11.3	14.4	8.9	6.9
Unknown	3.8		9.3	2.8	5.4	2.3			2.3		7.0		9.3	10.4	5.4

3.4 Biologically Important Areas

There are three feeding BIAs in the study area, each of which is transited by most vessel types (Figure 5). The most frequented areas of the BIAs by vessels are the western and northern regions of the humpback whale feeding BIA. The southeastern part of this BIA is inside the IMO-designated ATBA, which specifies an area that all ships greater than

400 gross tonnage should avoid for safety and environmental concerns. The shipping lanes entering and exiting the Strait of Juan de Fuca have the highest density of vessels. Vessels in the Grays Harbor and Northwest Washington feeding BIAs for gray whales are not as common, with the exception of the Strait of Juan de Fuca. Commercial vessels infrequently transit the Grays Harbor BIA.

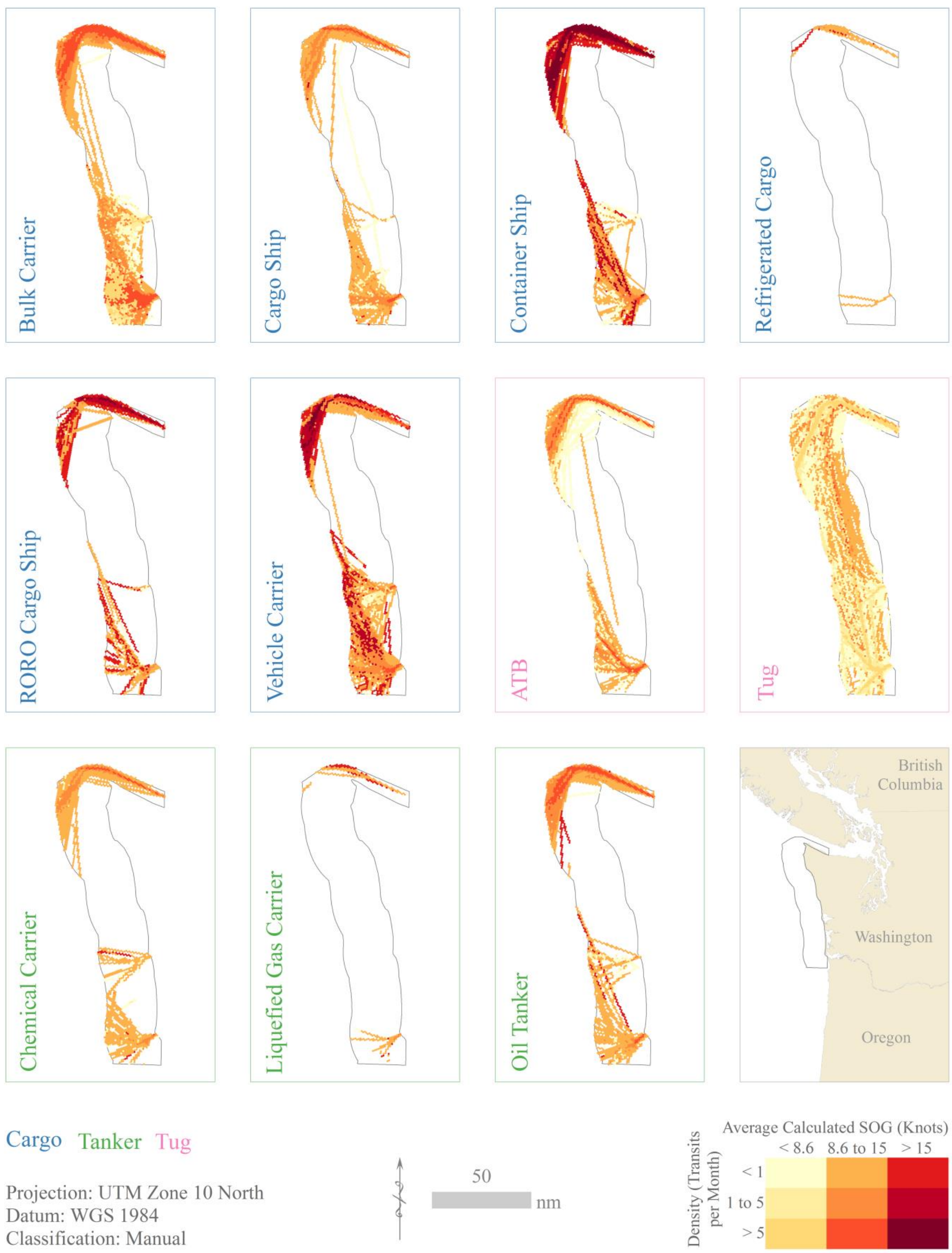

Bulk Carrier
Cargo Ship
Container Ship
Refrigerated Cargo
RORO Cargo Ship
Vehicle Carrier
ATB
Tug
Chemical Carrier
Liquefied Gas Carrier
Oil Tanker
British Columbia
Washington
Oregon
Cargo
Tanker
Tug
Projection: UTM Zone 10 North
Datum: WGS 1984
Classification: Manual
50
nm
Average Calculated SOG (Knots)
< 8.6
8.6 to 15
> 15
Density (Transits per Month)
< 1
1 to 5
> 5


Cable Layer
Dredger
Drill Ship
Pollution Control
Private Vessel
Public Vessel
Research Ship
Supply Ship
Unknown
Fishing Vessel
Passenger Ship
Gray Whale
Northwest Washington
May-November
Humpback Whale
Northern Washington
May-November
Gray Whale
Grays Harbor
April-November
Miscellaneous Fishing Passenger
Projection: UTM Zone 10 North
Datum: WGS 1984
Classification: Manual
50
nm
Average Calculated SOG (Knots)
< 8.6 8.6 to 15 > 15
Density (Transits per Month)
< 1
1 to 5
> 5

Figure 5. Average calculated speed over ground and vessel transits per month in the feeding Biologically Important Areas for gray and humpback whales for 2013 and 2014. Darker colors represent faster average speeds and more transits per month, for each vessel type. The unit of observation is the square mile hexagon.

There are four gray whale migration BIAs within the study area. The Northbound Phase A, Northbound Phase B, and Southbound migration BIAs are located within eight, five, and ten kilometer buffers of the coast, respectively. Due to this coastal proximity and the ATBA, there are relatively few vessels in any of these BIAs. However, the Potential Presence BIA extends 47 km from the coast and is transited by all vessel types (Figure 6). Fishing vessels, tugs, private vessels, public vessels, and research ships utilize the entire area, while most vessels in the cargo and tanker categories avoid the ATBA, which overlaps with a large portion of the central part of this BIA.

Container ships have the greatest combined average SOG and density, particularly in the northern region of the BIA. The northern portion of the BIA that is at the mouth of or inside the Strait of Juan de Fuca has the highest densities of most vessel types. Drill ships and unknown vessel types are very uncommon in the Potential Presence BIA. Tugs and ATBs show very different movement patterns. Tugs traverse the entire BIA, but ATBs follow the pattern of commercial vessels and avoid the ATBA.


Bulk Carrier
Cargo Ship
Container Ship
Refrigerated Cargo
RORO Cargo Ship
Vehicle Carrier
ATB
Tug
Chemical Carrier
Liquefied Gas Carrier
Oil Tanker
British Columbia
Washington
Oregon
Cargo Tanker Tug
Projection: UTM Zone 10 North
Datum: WGS 1984
Classification: Manual
50
nm
Average Calculated SOG (Knots)
< 8.6
8.6 to 15
> 15
Density (Transits per Month)
< 1
1 to 5
> 5

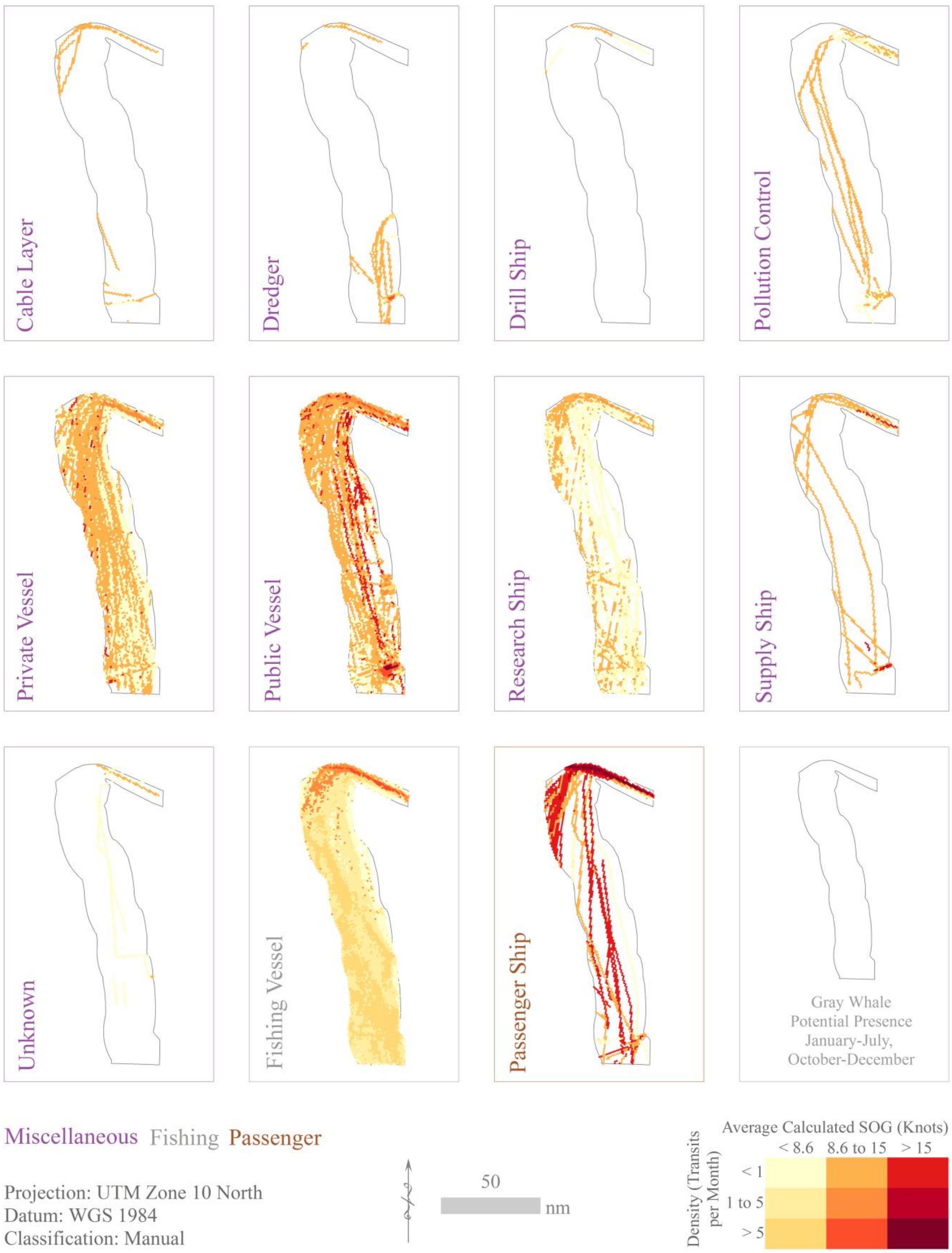

Cable Layer
Dredger
Drill Ship
Pollution Control
Private Vessel
Public Vessel
Research Ship
Supply Ship
Unknown
Fishing Vessel
Passenger Ship
Gray Whale
Potential Presence
January-July,
October-December
Miscellaneous Fishing Passenger
Projection: UTM Zone 10 North
Datum: WGS 1984
Classification: Manual
50
nm
Average Calculated SOG (Knots)
< 8.6 8.6 to 15 > 15
Density (Transits per Month)
< 1
1 to 5
> 5

Figure 6. Average calculated speed over ground and vessel transits per month in the gray whale Potential Presence Biologically Important Area for 2013 and 2014. Darker colors represent faster average speeds and more transits per month, for each vessel type. The unit of observation is the square mile hexagon.

A full tabular statistical summary for calculated SOG in the four BIAs analyzed can be found in the Appendix. Most transits for most vessel types across the BIAs occur at less than 15 knots (Table 8). Notable exceptions are the fastest vessel types outlined previously (container ship, RORO cargo ship, vehicle carrier, and passenger ship). Grays Harbor has the greatest proportion of vessel speeds below 15 knots. This BIA is just offshore, so vessels are approaching or leaving port at slower speeds.

Table 8. Percent of calculated SOG values less than 15 knots, for the entire research area and for each of the BIAs within for 2013 and 2014.

		Biologically Important Areas			
Vessel Type	**Overall**	**Grays Harbor**	**NW Washington**	**Potential Presence**	**N Washington**
Cargo					
Bulk Carrier	95.2	99.4	98.3	94.7	93.4
Cargo Ship	92.2	100.0	100.0	91.3	86.2
Container Ship	33.8	55.2	30.7	40.6	32.8
Refrigerated Cargo	89.7		100.0	89.7	79.5
RORO Cargo Ship	33.7	77.8	26.9	47.4	34.8
Vehicle Carrier	44.8	90.2	67.4	53.1	32.5
Tanker					
Chemical Carrier	90.2	98.8	92.0	91.7	90.7
Liquefied Gas Carrier	61.1		0.0	82.2	75.7
Oil Tanker	83.6	100.0	97.0	86.5	87.1
Tug					
Articulated Tug Barge	99.7		100.0	99.7	99.8
Tug	100.0	100.0	100.0	100.0	100.0
Fishing					
Fishing Vessel	100.0	100.0	100.0	100.0	99.9
Passenger					
Passenger Ship	17.7	100.0	34.8	25.5	17.0
Miscellaneous					
Cable Layer	98.6			98.1	99.3
Dredger	100.0	100.0	100.0	99.9	100.0
Drill Ship	100.0			100.0	100.0
Pollution Control	99.9	100.0	99.2	99.5	100.0
Private Vessel	93.2	99.1	93.7	91.2	85.4
Public Vessel	84.0	93.1	58.9	68.3	83.7
Research Ship	99.3	100.0	99.8	99.5	99.7
Supply Ship	83.3	100.0	98.2	71.8	100.0
Unknown	100	100.0	100.0	100.0	100.0

Part 4. Discussion

4.1 Truncation Threshold per Vessel Type

The truncation threshold is an estimate of the maximum plausible and attainable speed for each vessel type. The maximum calculated speed of liquefied gas carriers, cable layers, and pollution control vessels were less than one knot under the truncation threshold. Further, the three vessel types in the tanker category had identical truncation thresholds. Combined, these relative measures of accuracy and precision indicate that the truncation threshold method was a workable approximation for maximum speed.

Public vessels have highly variable rates of speed, which causes a large truncation threshold. However, the nature of armed forces vessel transits and how frequently they are not subject to AIS regulations is unknown.

The overall truncation rate of 1.28% shows the vast majority of data were retained for further analysis. However, truncation was necessitated in almost 55,000 records, due to either anomalous location or time stamp broadcasts.

Several vessel types with the highest truncation thresholds (supply ship, container ship, RORO cargo ship, and public vessel) also had some of the highest rates of data truncation. The source of these high rates of truncation and any possible correlation within SAIS is unclear.

4.2 Total Transits and Distance Traveled

The commercial ports of Vancouver, Seattle, Tacoma, and Portland drive much of the vessel traffic in the study area. Bulk carriers have the most cargo transits, and their transits also tend to be longer. Fishing is also a dominant use, and accounts for a plurality of vessel transits, but transits tend to be shorter. Miscellaneous category vessels without private and public vessels account for a very small proportion of vessel transits and distance traveled.

4.3 Overall Average Calculated Speed over Ground

Most vessel types had a greater average calculated SOG than average broadcast SOG. It is important to use calculated SOG in any analysis so that the risk from potential vessel collisions is not underestimated by using broadcast SOG. Bulk carriers, cargo ships, refrigerated cargo, and chemical carriers have an average broadcast SOG less than 10 knots, but an average calculated SOG greater than 10 knots, the speed limit for North Atlantic right whale seasonal management areas. Similarly, container ships and RORO cargo ships cross the 15 knot threshold when average calculated SOG is considered instead of average broadcast SOG. Exceeding these thresholds could have important management implications. More research is needed to document the difference between broadcast and calculated SOG when using SAIS data.

Container ships are one of the fastest and most common vessel types. Although passenger ships do not comprise a large proportion of transits or total distance, they are the fastest vessel type, and thus warrant special consideration in any potential future risk assessment. Fishing vessels and bulk carriers, the most common vessel types, have average calculated SOG less than or near the 10 knot speed restrictions that are commonly used in whale management areas (Laist, Knowlton, and Pendleton 2014). All other cargo and tanker ships have average calculated SOG values above this threshold. Vessel categories that transit across the study area (cargo, tanker, and passenger) tend to have greater average speeds than those working within the study area (fishing, miscellaneous). These categories should therefore also warrant potentially differing policy and analysis considerations. Tugs and ATBs have characteristically different patterns, with more common tugs behaving like small vessels and less common ATBs behaving like larger cargo ships. ATBs are generally much larger than tugs, and are likely subject to ATBA restrictions.

4.4 Biologically Important Areas

In reviewing the data, the northern-most portion of the BIAs had the highest concentration of vessel traffic and the fastest average vessel speeds. The Northern Washington feeding BIA for humpback whales has the greatest number of transits among the feeding BIAs, due to its location just offshore of the TSS. While this BIA does not extend north of the US EEZ to cover the shipping lanes between the Strait of Juan de Fuca and Alaska and Asia, it does overlap the shipping lanes towards the US West Coast and Hawaii. The Northwest Washington feeding BIA for gray whales is infrequently transited, as it is located close to shore. The Grays Harbor feeding BIA for gray whales is transited most commonly by tugs, fishing, public, and private vessels. Commercial traffic in this area is uncommon.

The Potential Presence migration BIA for gray whales is spatially extensive and located from the mouth of the Strait of Juan de Fuca south along the coast, so it is transited by all vessel types. The majority of large, commercial vessels abide by the ATBA restrictions. Notable vessel types inside the ATBA are tug, public, private, research, and fishing vessels. Each of these vessel types has a low average calculated SOG, and should not be engaged in the transport of oil or hazardous cargo.

The other gray whale migration BIAs are located within several kilometers of the coast (Table 1 and Figure 3). Exploratory analyses showed relatively few vessels transits in these areas, so they were not considered for further analysis.

The Biologically Important Areas were designated solely within the US EEZ and do not cross international boundaries (Calambokidis et al. 2015). However, the shipping routes between the Strait of Juan de Fuca and Asia and Alaska continue north and west of the US EEZ, in an area with frequent humpback whale sightings (Calambokidis et al. 2015). The study area extends to cover Canadian waters, and vessel speed and density remain high in the shipping routes extending toward Asia and Alaska (dark red in Figure 7). We recommend that future analyses or management planning concerning whales or vessel traffic, including risk analyses, should be considered a transboundary effort.

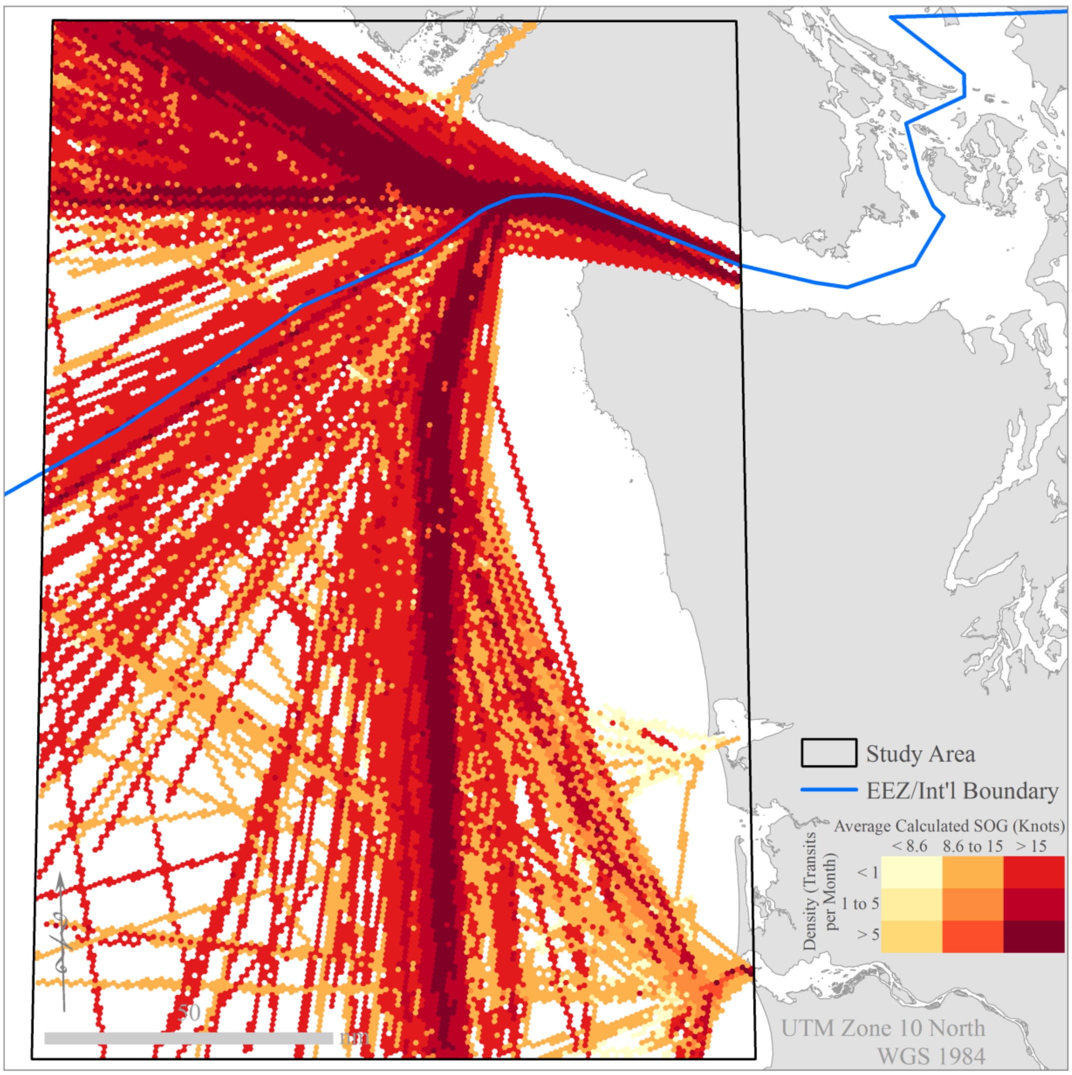


Figure 7. Container ship calculated speed over ground and transits per month for 2013 and 2014. The area northwest of the blue EEZ line exhibits high vessel speed and density, although it was not included in the BIA designations.

4.6 Marine Spatial Planning

Using AIS in the risk analysis process is one potential tool in marine management (Wiley et al. 2013). Marine Spatial Planning (MSP) is designed as an adaptive spatial planning process to help manage current and future human activities in the marine environment to meet a variety of objectives and minimize user-user and user-environment interactions by engaging multiple stakeholders (Ehler and Douvere 2007; Ehler 2008; Foley et al. 2010; Redfern et al. 2013). Recent examples of successful MSP are the shifts in the TSS outside Boston, Massachusetts, and San Francisco Bay, California (Wiley et al. 2013, USCG 2013). The scientific processes used stakeholder involvement throughout, created numerous alternatives, showed how challenges can help the process, and used AIS to evaluate and monitor results (Wiley et al. 2013). The findings of the present research, including calculated SOG and SAIS data, should be important considerations in the MSP process off the coast of the state of Washington and British Columbia in Canada. The SAIS data, within its limitations and at small scale, is an effective means to delineate areas of high use for vessel traffic, even across international boundaries. Calculating vessel speed is critical to avoid underestimating vessel speed and the probability of a lethal vessel and cetacean collision.

4.7 Limitations

One of the main limitations of this research is the temporal resolution of the available SAIS data. The ability to precisely track vessel movement decreases with increasing time between sequential points. Vessels can potentially transit around corners, but large amounts of time between SAIS broadcasts can make transit lines appear to cut those corners. This is evident in many vessel types on the northwestern tip of the Olympic Peninsula and the near-shore BIAs (see Figure 8 as an example). This introduces the potential for a vessel to appear to cross a BIA when in fact it did not. The TSS, controlled by the USCG and used by vessels for insurance and accident coverage purposes, never intersects the Northwest Washington BIA. However, the TSS circumnavigates this BIA, and it is therefore possible that a vessel remaining in the TSS could appear to transit through the BIA. This results in calculated transits across the BIA, sometimes at high SOG, that never actually occurred. The other BIAs, the TSS, ATBA, and OCNMS are also susceptible to this limitation.

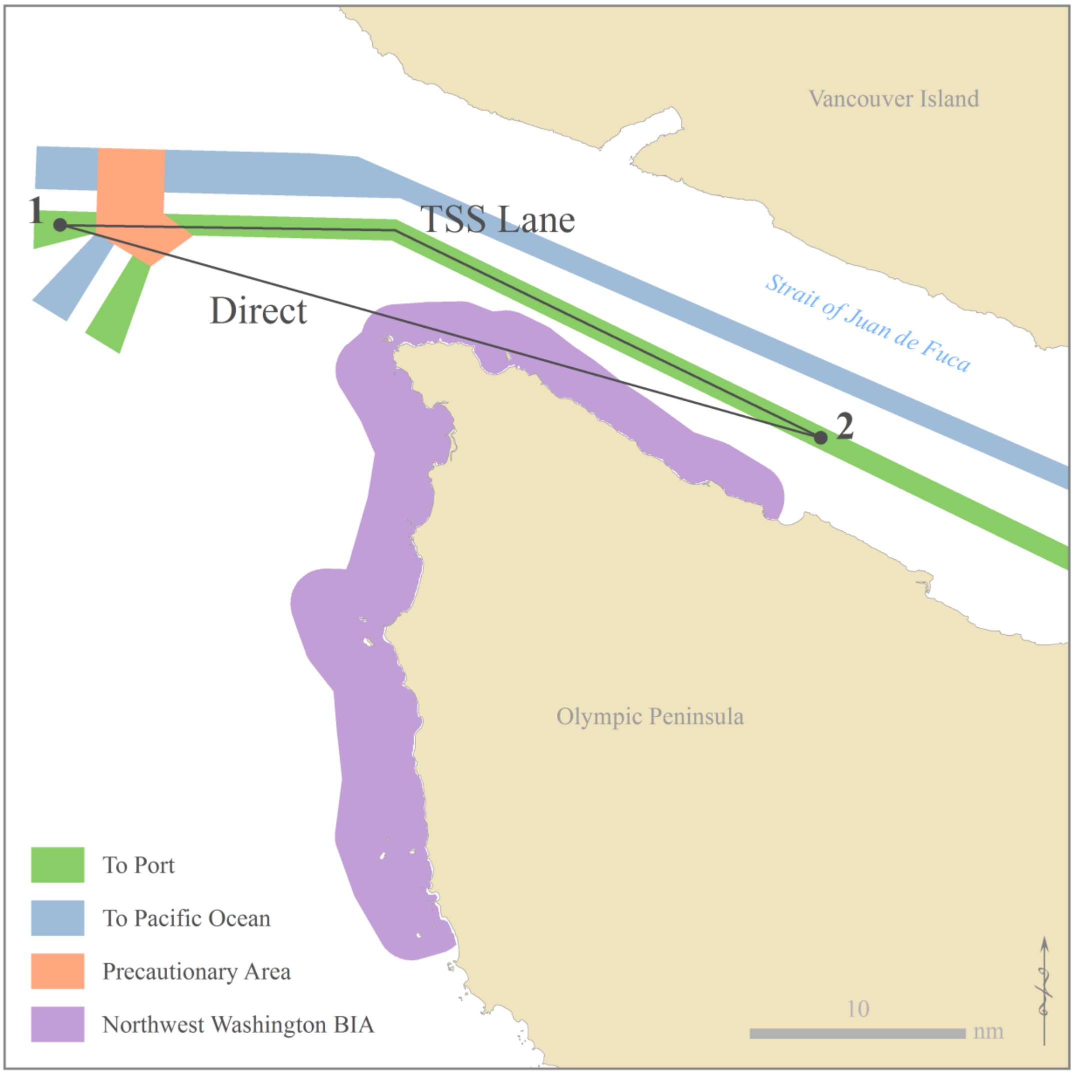


Figure 8. Potential vessel transit lines cutting across the Northwest Washington BIA due to temporal gaps between sequential points in the SAIS data, (1) and (2). The vessel could actually remain inside the TSS, but could appear to cut across the BIA, leading to false transits.

Since the shortest distance between two points is a line and the time between points remains identical despite the actual path taken, the calculated SOG, while faster than broadcast SOG, is still a systematic underestimation of true SOG, assuming random GPS error. As distance increases for a vessel to traverse around a corner and time remains the same, speed also must increase. Using the example in Figure 8, the TSS lane distance and speed are greater than the direct distance and speed between points 1 and 2. Although we may be overestimating the number of transits through some administrative areas, this would be correlated with an underestimation of SOG. Most vessels are required to broadcast every few seconds while under way using engine, but the time gap between SAIS records is frequently on the order of minutes or hours. The uncertainty in vessel path is unknown, but will increase with path sinuosity.

As an emerging technology, current SAIS presents tremendous opportunities for research, but caution should be used and uncertainty should be addressed when using the technology for large scale applications. Temporal gaps in vessel transits add uncertainty to transit path and calculated SOG that was not quantified in this research. Duplicate records accounted for 42.8% of total SAIS records for the year 2013. Broadcast SOG values were zero in 36.7% of all records. There were numerous time, location, and missing value errors that had to be addressed prior to data analysis. Units of measurement for vessel length were also not consistent. These factors cast into question the reliability of individual values and the present quality of SAIS data as a whole, and add uncertainty to automated aggregate calculations. SAIS data in its current state should not be used in a policy enforcement context or for documenting individual presence or absence in an administrative area at large scale. However, SAIS data can be helpful to assess general or overall compliance within an area of interest. As calculated SOG is an underestimation of true vessel speed, SAIS can be helpful in documenting minimum vessel speeds across large geographic areas, especially beyond the reach of terrestrial AIS receivers. It is useful in examining vessel density at small scale, and could be used to assess basin-wide open ocean routes. Future additional satellite platforms with AIS receivers will only increase the quality of SAIS data and decrease the amount of temporal gaps. This will open potential research questions involving larger scale questions of specific areas.

Cargo and tanker category vessels have the most transits and greatest calculated average speeds. Passenger ships do not account for a large proportion of transits, but travel at the greatest average speed. The calculated SOG for most vessel types is greater than the broadcast SOG in the SAIS data, despite the calculated SOG being a systematic underestimation of true vessel speed. The SAIS data used in this analysis have large temporal gaps, which increase uncertainty in calculated SOG, and also in vessel transit paths. Within the BIAs, the mouth of the Strait of Juan de Fuca and the shipping routes connecting the US West Coast ports have the most vessel transits and fastest mean calculated SOG. The area immediately north and west of the US EEZ, along routes connecting Asia and Alaska, has a high density of fast-moving vessels, but was not considered in the BIA analysis. Future risk analyses should be transboundary. Caution should be used with current SAIS data, but future improvements to the technology will enable better large scale research.

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Part 8. Appendix

Appendix Table 1. Calculated SOG statistics for each BIA by vessel type. The three feeding BIAs and the gray whale potential presence area were analyzed.

Vessel Type, BIA	Calculated Speed Over Ground				Distance
	Mean (Knots)	SD (Knots)	Max (Knots)	Count	Traveled (nm)
Cargo					
Bulk Carrier					
Gray - Grays Harbor	7.3	3.6	20.4	1404	1997.4
Gray - NW Washington	12.1	1.6	16.1	464	24851.9
Gray - Potential Presence	9.9	4.3	21.0	219608	517643.6
Humpback - N Washington	12.1	2.4	21.0	40563	154408.7
Cargo Ship					
Gray - Grays Harbor	9.6	1.7	11.5	27	27.7
Gray - NW Washington	11.3	2.1	13.7	49	2433.7
Gray - Potential Presence	11.1	3.6	21.0	18112	43625.1
Humpback - N Washington	12.6	2.6	20.7	4134	15730.4
Container Ship					
Gray - Grays Harbor	11.2	4.8	18.6	29	53.4
Gray - NW Washington	16.3	2.9	23.9	375	19996.0
Gray - Potential Presence	15.7	4.3	28.0	72249	280408.3
Humpback - N Washington	16.5	3.8	28.0	27069	110430.9
Refrigerated Cargo					
Gray - Grays Harbor					
Gray - NW Washington	8.3	1.6	9.7	4	154.9
Gray - Potential Presence	11.6	2.1	17.0	493	1699.5
Humpback - N Washington	12.8	2.2	17.0	220	1233.0
RORO Cargo Ship					
Gray - Grays Harbor	10.6	4.0	18.1	27	81.5
Gray - NW Washington	18.2	4.1	23.2	67	2634.7
Gray - Potential Presence	15.6	4.9	30.9	8308	32771.6
Humpback - N Washington	15.4	4.8	30.9	2765	10761.6
Vehicle Carrier					
Gray - Grays Harbor	9.9	3.9	25.4	1344	2228.8
Gray - NW Washington	14.2	2.2	19.9	89	4183.4
Gray - Potential Presence	13.7	4.5	26.0	50409	101994.7
Humpback - N Washington	15.6	3.1	26.0	14051	32209.6
Tanker					
Chemical Carrier					
Gray - Grays Harbor	6.3	4.1	15.7	85	214.5
Gray - NW Washington	12.3	1.6	15.2	25	1509.7
Gray - Potential Presence	11.7	3.1	21.0	9986	25125.5
Humpback - N Washington	12.4	2.4	21.0	4454	10792.8
Liquefied Gas Carrier					
Gray - Grays Harbor					
Gray - NW Washington	15.2		15.2	1	22.6
Gray - Potential Presence	13.1	2.3	19.2	724	1883.1
Humpback - N Washington	13.9	1.5	19.0	235	768.9
Oil Tanker					
Gray - Grays Harbor	5.4	3.8	11.3	104	384.5
Gray - NW Washington	13.2	1.3	16.9	100	4897.7
Gray - Potential Presence	12.3	3.0	21.0	38696	105620.8
Humpback - N Washington	12.7	2.4	21.0	17321	48891.1
Tug					
Articulated Tug Barge					
Gray - Grays Harbor					
Gray - NW Washington	7.1	1.5	12.0	145	1726.5
Gray - Potential Presence	9.2	2.3	16.0	27971	44553.8
Humpback - N Washington	9.4	2.0	15.9	9460	19547.4
Tug					
Gray - Grays Harbor	6.0	2.8	14.9	1905	2260.7
Gray - NW Washington	1.4	3.2	15.0	18771	7577.3
Gray - Potential Presence	6.0	3.7	15.0	161497	96007.1
Humpback - N Washington	7.8	2.3	15.0	23013	22941.0

Vessel Type, BIA	Calculated Speed Over Ground				Distance
	Mean (Knots)	SD (Knots)	Max (Knots)	Count	Traveled (nm)
Fishing					
Fishing Vessel					
Gray - Grays Harbor	7.4	2.1	15.0	10511	18881.8
Gray - NW Washington	0.5	1.7	15.0	76548	9580.9
Gray - Potential Presence	3.9	3.7	15.0	368875	179898.4
Humpback - N Washington	5.4	3.8	15.0	42386	32762.9
Passenger					
Passenger Ship					
Gray - Grays Harbor	6.0	0.0	6.0	3	99.3
Gray - NW Washington	15.8	4.8	29.9	155	2451.3
Gray - Potential Presence	17.7	5.6	30.0	11048	30813.8
Humpback - N Washington	18.5	3.9	30.0	7387	27887.8
Miscellaneous					
Cable Layer					
Gray - Grays Harbor					
Gray - NW Washington					
Gray - Potential Presence	7.5	5.6	17.3	533	754.4
Humpback - N Washington	10.6	1.9	15.0	144	351.0
Dredger					
Gray - Grays Harbor	3.2	2.7	14.9	7218	760.7
Gray - NW Washington	9.1	6.3	12.7	3	30.6
Gray - Potential Presence	4.8	3.8	15.0	14204	3861.8
Humpback - N Washington	10.1	3.8	13.3	52	287.6
Drill Ship					
Gray - Grays Harbor					
Gray - NW Washington					
Gray - Potential Presence	8.4	0.9	10.8	63	217.0
Humpback - N Washington	8.7	0.3	9.1	5	81.2
Pollution Control					
Gray - Grays Harbor	3.6	3.8	12.1	69	14.7
Gray - NW Washington	2.2	3.6	19.5	1207	222.4
Gray - Potential Presence	4.9	4.6	19.5	2397	1165.6
Humpback - N Washington	7.5	3.3	12.2	103	109.4
Private Vessel					
Gray - Grays Harbor	7.2	3.4	21.7	227	1981.1
Gray - NW Washington	5.5	5.3	22.2	1500	6515.1
Gray - Potential Presence	9.3	4.3	23.0	10671	34560.2
Humpback - N Washington	10.2	4.5	22.1	1388	5624.6
Public Vessel					
Gray - Grays Harbor	8.4	5.0	36.0	3781	3135.6
Gray - NW Washington	12.1	9.4	36.8	2554	3746.8
Gray - Potential Presence	12.2	8.3	37.0	58590	44730.6
Humpback - N Washington	10.3	5.3	36.1	5025	11013.2
Research Ship					
Gray - Grays Harbor	4.7	3.3	12.1	304	510.3
Gray - NW Washington	3.5	3.9	17.4	578	1057.4
Gray - Potential Presence	5.3	3.9	18.0	13651	12719.3
Humpback - N Washington	4.5	3.9	17.3	5695	4609.2
Supply Ship					
Gray - Grays Harbor	9.8	0.3	10.3	8	20.4
Gray - NW Washington	4.0	3.8	17.0	57	134.2
Gray - Potential Presence	11.9	7.3	29.9	1736	2219.4
Humpback - N Washington	11.3	1.7	14.1	116	499.6
Unknown					
Gray - Grays Harbor	7.2	2.4	10.6	63	161.1
Gray - NW Washington	5.0	2.4	7.9	23	190.6
Gray - Potential Presence	7.4	2.4	14.8	200	1081.0
Humpback - N Washington	6.4	0.0	6.4	2	31.8

Appendix 2.

I used frequency histograms of positive broadcast speed over ground to help establish the truncation threshold equation. Select vessel types are shown below, with one knot bins.