Rescue Tug Analysis Model Description

Tug escort and ERTV Projects

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1 Overview

The Rescue Tug Analysis Model (Model) is a set of tools used to perform the tug escort and ERTV analyses. The objective of the Model is to test, through simulations, the impacts of different tug escort and ERTVs scenarios on drift groundings. Simulation modeling is a common approach to generate data when experimentation is not possible, cost prohibitive, or time-consuming.

Each simulation in the Model follows the same general approach. At every minute, each vessel moves following trajectories based on the historical traffic data. Loss of propulsion and loss of steering events occur with given probabilities. Vessel drift trajectories from the loss of propulsion incidents are generated. Then, the Model evaluates actions and interventions for preventing a drift grounding, and generates oil spill risk metrics for each simulated drift grounding.

The Model is structured as five discrete modules: Vessel Movement, Vessel Accident, Momentum and Drift, Oil Spill Risk, and Vessel Rescue Analysis. The Vessel Movement Module generates similar vessel traffic levels to what was observed but allows for unique combinations of vessel routes and travel times not observed.

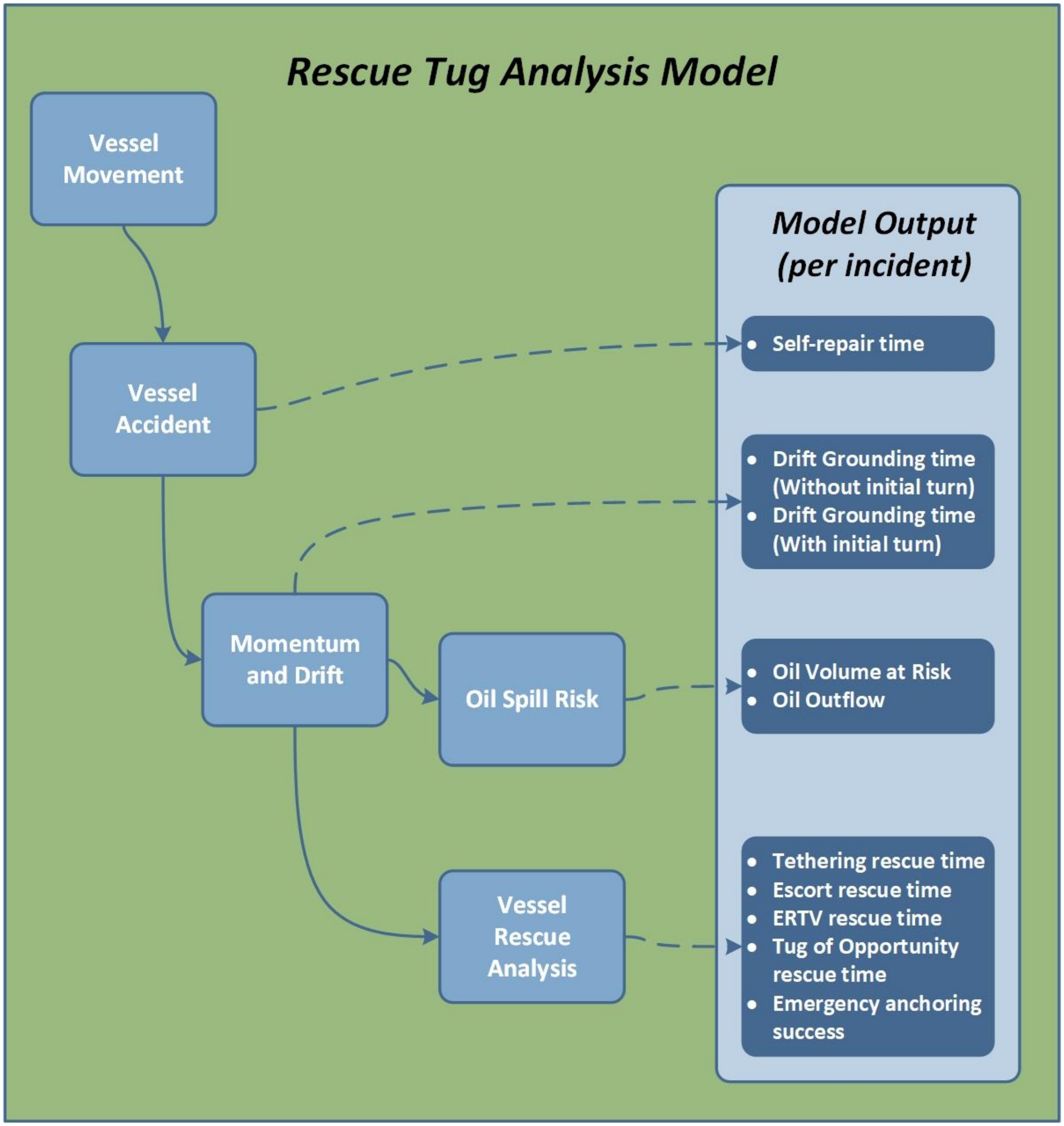
Using probabilities based on existing data, the Vessel Accident Module generates loss of propulsion and loss of steering incidents, identifying the time and location for the incident for a simulated vessel. The Vessel Accident Module also determines an amount of time for the crew to self-repair.

The Momentum and Drift Module plots a drift trajectory and a drift grounding location for a simulated ship that loses propulsion, based on vessel characteristics, wind and current data, and bathymetry. For each loss of propulsion event, the Momentum and Drift Module plots two drift trajectories. One trajectory includes an initial turn to avoid readily apparent grounding hazards and another drift trajectory without an initial turn.

For each drift grounding, the Oil Spill Risk Module generates a value for the maximum amount of potential oil on board the simulated vessel (oil volume at risk) and an oil spill volume. The Oil Spill Risk Module generates the oil spill volume using data from historical spills.

The Vessel Rescue Analysis Module evaluates a vessel drift trajectory for successful emergency anchoring, Emergency Response Towing Vessel (ERTV) rescue, and tug of opportunity rescue. The Vessel Rescue Analysis Module also evaluates the immediate benefits of escorting and tethering for an adrift vessel. This model structure allows us to independently assess the relative impacts of ship actions and interventions, including self-repair, emergency anchoring, escort tugs, tugs of opportunity, and ERTVs, to prevent drift groundings.

Figure 1: Rescure Tug Analysis Model



1.1 Model Domain

The model domain is bounded on the west by an arc approximately 20 nautical miles past the J buoy, and to the north with a line from Nanoose Bay to Sechelt (Figure 2).

Interior waterways within the ports of Seattle and Vancouver, such as the Fraser River, portions of the Duwamish River, and Lake Washington, are outside the model domain. The maritime traffic patterns in these areas are either not directly relevant to the scope of our analysis or too complex to simulate effectively.

Additionally, the model domain is restricted in the north to include only lower Howe Sound due to a lack of consistent vessel traffic data in the upper portion.

Figure 2: Model domain

2 Data Processing and Analysis

All of the Model's components, mechanisms, and tools are based on data. We used data to build the foundation for the Model's vessel traffic simulation, for defining key Model parameters, and for analysis to inform Model rules. In many cases, the data underwent significant processing and analysis. We primarily acquired data from government agencies through public data portals or Freedom of Information Act requests. When necessary, we acquired proprietary datasets to supplement our existing data. Our general approach to data processing was to transform and modify source data as little as possible to still meet the needs of the Model. Similarly, when analyzing data, we relied upon empirical results as much as possible and attempted to minimize our use of derived values or "rules of thumb."

2.1 AIS Data

AIS transmissions include a ship's position along with other information, such as speed, course, status, and heading. AIS transmitters also broadcast additional vessel details, including Maritime Mobile Service Identity number (MMSI), vessel type, International Maritime Organization (IMO) number, call sign, and vessel dimensions. Vessels transmit this information with different frequency ranging from a few seconds to several minutes. The frequency depends on the type of AIS unit, vessel status, course, and speed. Most commercial vessels are required to carry AIS under United States Coast Guard (USCG), IMO, and Transport Canada regulations. Only vessels that carry AIS are represented in the Model.

For this analysis, the project team acquired AIS data from MarineCadastre.gov for the years 2015 through 2019. MarineCadastre.gov, a partnership between National Oceanic and Atmospheric Administration (NOAA) and the Bureau of Ocean Energy Management (BOEM), provides AIS data received by land-based antennas from the USCG's national network of receivers. MarineCadastre.gov filters the raw AIS messages to one minute. Beginning in 2015, MarineCadastre.gov used the USCG's Authoritative Vessel Identification Service (AVIS) to correct static vessel information for fields with missing or inaccurate values.

The project team developed a number of scripts and transfer tools to handle the AIS data. A Python script selected AIS messages within a bounding box encompassing the model domain. Custom data transfer tools imported these AIS messages into a Microsoft SQL Server 2016 database and then split into two tables. One table included dynamic movement information (latitude, longitude, speed, course, heading, and navigation status). The other contained static vessel information (MMSI, vessel name, IMO number, call sign, vessel type, length, width, and draft). Database scripts split the dynamic movement data into separate tables for each model vessel type (section 2.3.1) and year.

2.2 Environmental Data

2.2.1 Bathymetry

The Model uses bathymetry data for determining drift groundings and the potential for emergency anchoring. We acquired bathymetry data from NOAA. The bathymetry layer used in the Model was a composite dataset stitched together from multiple bathymetric products to provide coverage for the entire model domain. The list of bathymetric data sources is listed below:

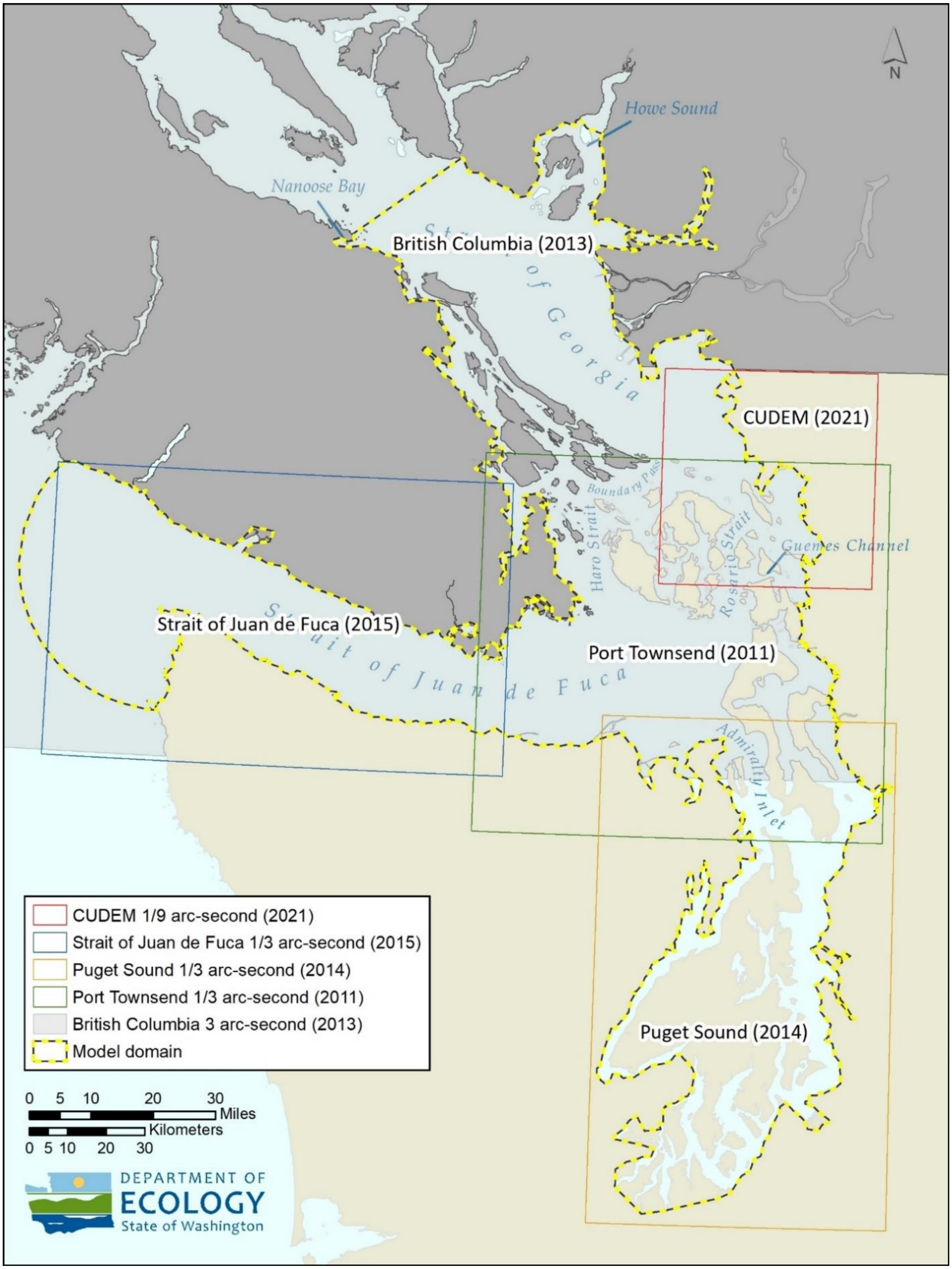
Table 1: Bathymetry data sources

Dataset	Year	Horizontal Resolution	Vertical Datum for Source Bathymetry[1]
Continuously Updated Digital Elevation Model (CUDEM) – 1/9 Arc-Second Resolution Bathymetric-Topographic Tiles	2021 (downloaded)	1/9 arc-seconds (approx.. 3 m)	MHW
Strait of Juan de Fuca 1/3 arc-second NAVD 88 Coastal Digital Elevation Model	2015	1/3 arc-seconds (approx.. 10 m)	MHW
Puget Sound 1/3 arc-second NAVD 88 Coastal Digital Elevation Model	2014	1/3 arc-seconds (approx.. 10 m)	MHW
Port Townsend, Washington 1/3 Arc-second NAVD 88 Coastal Digital Elevation Model	2011	1/3 arc-seconds (approx.. 10 m)	MHW
British Columbia 3 arc-second Bathymetric Digital Elevation Model	2013	3 arc-seconds (approx. 90 m)	MLLW, LLWLT, MSL, or assumed MSL (no common vertical datum reference due to large cell size)

There was overlapping spatial coverage for the datasets. When creating the composite bathymetry dataset preference, elevations for overlapping area were selected by first prioritizing greater horizontal resolution, then year of publication (Figure 3).

[1] Mean lower low water (MLLW), Lower Lower Water Large Tide (LLWLT), Mean sea level (MSL), and Mean high water (MHW) are local referenced tidal datums and are transformed to a standard vertical datum (NAVD 88) for consistency of elevation values within and across bathymetric datasets.

Figure 3: Bathymetry sources



2.2.2 Wind and Current Data

The Model uses wind and current data to determine vessel drift trajectories. The Model uses wind and current hindcast data from LiveOcean. LiveOcean is a computer modeling simulating ocean properties and is integrated with Weather Research and Forecasting (WRF) wind data (MacCready et al. 2021). Dr. Parker MacCready of the University of Washington Coastal Modeling Group provided LiveOcean data and the WRF wind input data from 2017 to 2021.

2.3 Vessel Data

The Model simulates vessels based on AIS messages transmitted within the model domain from 2015 to 2019. Vessel attribute data used in the Model came from four databases: IHS-Markit Seaweb, USCG's Vessel Documentation System (VDS), the Transportation Safety Board of Canada's Marine Safety Information System (MARSIS), and the USCG's AVIS. Information from company and industry websites supplemented the vessel database sources.

2.3.1 Vessel Types

The Model simulates movement for three broad sets of vessels: route based, dependent, and ferries. These vessel sets are distinguished by their behavior. Route based vessels predominantly operate on a set of common routes throughout the system and contain the majority of deep draft commercial vessels. Dependent vessels' movements rely on the presence of another vessel. For instance, vessels providing escort, assist, or bunkering services. The third general group is ferries which exclusively includes car ferries.

2.3.1.1 Route based vessel types

The model simulates the following vessel types as route-based:

Table 2: Definitions of route-based vessel types

Model Vessel Type	Definition
ATB	Tugs that almost exclusively travel with a linked tank barge.
Bulk Carrier	A commercial ship that carries bulk (non-liquid) cargo.
Container Ship	A commercial ship that carries containerized cargo.
Cruise Ship	A large overnight passenger vessel with a tonnage over 2000 ITC.
Fishing Vessel (Large)	A commercial fishing vessel over 40 meters
General/Other Cargo Ship (Large)	A commercial ship that carries cargo and is more than 100 meters long. This category includes break-bulk cargo vessels, mixed containerized and bulk ships, and others.
Tanker (Chemical)	A tank ship that carries oil (or substances defined as oil) as cargo, and also could carry non-oil liquid cargo
Tanker (Crude)	A crude tanker is designed to carry unrefined oil.
Tanker (Liquefied Gas)	A commercial ship that carries liquefied gas, including natural gas (LNG) and liquefied petroleum gas (LPG).
Tanker (Product)	A tank ship that carries refined oil in bulk.
Towing Vessel (Oil)	Tugs that generally operate with a tow (ahead or astern) that contains oil as cargo.
Vehicle Carrier	A commercial ship that carries vehicles as cargo, and loads and discharges via a ramp.

2.3.1.2 Ferry vessels

In the Model, Ferry (Car) is the only vessel type is this category. These vessels carry vehicles and passengers on set routes between established ferry terminals. This category also includes the Seaspan Intermodal Ferries, which include a few ATBs that run intermodal cargo (not oil) on set runs.

2.3.1.3 Dependent vessels

Table 3: Definitions of dependent vessel types

Model Vessel Type	Definition
Towing Vessel (Oil) – Bunkering	Tugs that generally operate with a tow (ahead or astern) that contains oil as cargo and engage in bunkering of other vessels. This category does include one self-propelled bunkering vessel.
Tug (Assist & Escort)	Tugs that generally do not operate with a tow. These tugs run light and assist/escort other vessels. Generally over 50 feet long.

2.3.2 Vessel Categorization

Traffic patterns vary by vessel type within the system. In order to represent this in our simulation, it was necessary to establish a vessel categorization system. Though many maritime datasets organize vessels into categories based on vessel type, there is no unifying typology. None of the existing categorization systems were ideal for the needs of the Model. As a result, the project team created a vessel taxonomy. The new vessel taxonomy first classified vessels based on a list of individually classified vessels before using existing classifications and vessel length found in IHS-Markit Seaweb, VDS, MARSIS, and AVIS.

2.3.3 Vessel Categorization Algorithm

1) Manual assignment to a vessel category.
   a) For all vessel types, we built a table for manual identification. For any vessel that was uniquely identifiable based on organizational or expert knowledge, we assigned a type in these tables.
   b) For a subset of vessel types that were too specific to be identified using vessel databases, we used these tables exclusively. Those vessel types included **Towing Vessel (Oil), Towing Vessel (Oil) – Bunkering,** and **Tug (Assist & Escort)**.
2) Vessels assigned to a model category based on specific IHS-Markit vessel categories.

Table 4: IHS-Markit vessel category groupings

IHS-Markit Vessel Category	Model Vessel Type
Passenger/Ro-Ro Ship (Vehicles)	Ferry (Car)
Articulated Pusher Tug	ATB
Bulk Carrier Bulk Carrier, Laker Only Bulk Carrier, Self-discharging Bulk Carrier, Self-discharging, Laker Bulk/Caustic Soda Carrier (CABU) Open Hatch Cargo Ship Wood Chips Carrier	Bulk Carrier
Container ship (Fully Cellular)	Container Ship
Crude Oil Tanker Asphalt/Bitumen Tanker	Tanker (Crude)
LNG Tanker LPG Tanker	Tanker (Liquefied Gas)

IHS-Markit Vessel Category	Model Vessel Type
Vehicles Carrier	Vehicle Carrier
Crude/Oil Products Tanker Products Tanker Replenishment Tanker	Tanker (Product)
Chemical/Products Tanker	Tanker (Chemical)

3) Based on specific IHS-Markit vessel categories and additional criteria

Table 5: IHS-Markit vessel category groupings with additional criteria

IHS-Markit Vessel Category	Additional criteria	Model Vessel Type
Passenger/Cruise Cruise Ship, Inland Waterways	Gross tonnage (ITC) >= 2000	Cruise Ship
Fish Factory Ship Fishery Research Vessel Fishery Support Vessel	Vessel length > 40 m	Fishing Vessel (Large)
General Cargo Ship General Cargo Ship (with Ro-Ro facility) Heavy Load Carrier, semi-submersible Hospital Vessel Landing Craft Livestock Carrier Rail Vehicles Carrier Refrigerated Cargo Ship Ro-Ro Cargo Ship	Vessel length > 100 m	General/Other Cargo Ship (Large)

4) Based on a specific type in the Marine Exchange, Chamber of Shipping (British Columbia), or Transportation Safety Board (TSB) of Canada.

Table 6: Marine Exchange, the Chamber of Shipping, and TSB vessel category groupings

Vessel Category [Source]	Model Vessel Type
Bulk Carrier [Marine Exchange, TSB] Wood-chip [Marine Exchange] Barge Carrier [Marine Exchange]	Bulk Carrier
Container [Marine Exchange] General Cargo with Container Capacity [Marine Exchange] Container Ship (Fully Cellular) [Marine Exchange] Container Ship [TSB]	Container Ship
Car Carrier [Marine Exchange, Chamber of Shipping] Vehicle Carrier [Marine Exchange, Chamber of Shipping] Vehicles [Marine Exchange, Chamber of Shipping]	Vehicle Carrier

5) Based on a specific type in the Marine Exchange or USCG's VDS **and** additional criteria.

Table 7: Marine Exchange and VDS vessel category groupings with additional criteria

Vessel Category [Source]	Additional criteria	Model Vessel Type
General Cargo [Marine Exchange] Catamaran Tug [Marine Exchange]	Vessel length > 100 m	General/Other Cargo Ship (Large)

Vessel Category [Source]	Additional criteria	Model Vessel Type
Freight ship [VDS]		
Fishing [Marine Exchange] Commercial Fishing Vessel [VDS] Fishery Support Vessel [VDS]	Vessel length > 40 m	Fishing Vessel (Large)

6) Based on AIS vessel type and additional criteria, in some cases.

Table 8: AIS vessel type code groupings

AIS Vessel Type Code	Additional criteria	Model Vessel Type
80 to 89	No additional criteria	Tanker (Chemical)
70 to 79	Vessel length > 100 m	General/Other Cargo Ship (Large)
30	Vessel length > 40 m	Fishing Vessel (Large)

2.4 Vessel Attributes

The Model requires specific vessel attributes to simulate vessel momentum and drift and for generating oil spill risk outputs. We populated vessel attributes from previously mentioned data sources. Complete sets of attributes were not available for all vessels. We performed regression analysis based on known values to fill data gaps for displacement tonnage and fuel capacity. Where insufficient data existed to perform regression analysis, we assigned default values.

Each vessel type uses the following attributes:

Table 9: Required vessel attributes

Model Vessel Type	Length	Width	Draft	Fuel Capacity	Cargo Capacity	Tons (DWT)	Tons (displ.)
ATB	Yes	Yes	Yes	Yes	No	Yes	Yes
Bulk Carrier	Yes	Yes	Yes	Yes	No	Yes	Yes
Container Ship	Yes	Yes	Yes	Yes	No	Yes	Yes
Cruise Ship	Yes	Yes	Yes	Yes	No	Yes	Yes
Ferry (Car)	Yes	Yes	Yes	Yes	No	Yes	Yes
Fishing Vessel (Large)	Yes	Yes	Yes	Yes	No	Yes	Yes
General/Other Cargo Ship (Large)	Yes	Yes	Yes	Yes	No	Yes	Yes
Tanker (Chemical)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tanker (Crude)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tanker (Liquefied Gas)	Yes	Yes	Yes	Yes	No	Yes	Yes
Tanker (Product)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Towing Vessel (Oil)	Yes	Yes	Yes	No	No	No	No
Towing Vessel (Oil) – Bunkering	Yes	Yes	Yes	No	No	No	No
Tug (Assist & Escort)	Yes	Yes	Yes	Yes	No	No	No
Vehicle Carrier	Yes	Yes	Yes	Yes	No	Yes	Yes

Barge attributes are also required to supplement vessel characteristics for towing vessels. The Model uses the following attributes for ATB, Towing Vessel (Oil), and Towing Vessel (Oil) – Bunkering vessels:

- Barge length
- Barge width
- Barge draft
- Barge cargo capacity
- Barge dead weight tonnage
- Barge displacement

2.4.1 Barge Attributes

In the case of barge attributes, we used the following default values if known values were not available.

Table 10: Barge attributes

Barge Attribute	ATB	Towing Vessel (Oil)	Towing Vessel (Oil) - Bunkering
Length (m)	150	125	80
Width (m)	22	30	18
Draft (m)	N/A; use tug draft	6.5	5.5
Cargo capacity (m^3)	26,402	14,024	6,713

If barge displacement was not known, we used the following formula:

Equation 1

$$C = L \cdot W \cdot D \cdot c_b \cdot \rho$$

Where:

- C – vessel cargo capacity;
- L – vessel length;
- W – vessel width;
- D – vessel draft,
- $c_b = 0.90$ – block coefficient;
- $\rho = 1.025\ t/m^3$- seawater density

The estimated value for block coefficient is based on the maximum block coefficient for tankers listed in Elements of Modern Ship Construction (House 2010).

2.4.2 Displacement Tonnage Calculations

We used regression analysis based on deadweight tonnage to fill data gaps for displacement tonnage. We considered several regression models and chose the no-intercept polynomial regression model. This model had the smallest Root Mean Squared Errors (RMSE). RMSE measures how far from the regression line the data points are and the model with the smallest RMSE is generally the one with the best predictive power.

No-intercept polynomial regression model for displacement tonnage:

Equation 2

$$D = \beta_1 W + \beta_2 W^2$$

Where:

- D – vessel displacement;
- W – vessel DWT;
- β_1 and β_2 - regression coefficients.

The following table shows the coefficients for the no-intercept polynomial regression models:

Table 11: Regression coefficients for vessel displacement using DWT

Model Vessel Type	β_1	β_2
ATB	3.09	-8.53×10^{-4}
Bulk Carrier	1.19	-3.28×10^{-7}
Container Ship	1.36	-4.25×10^{-7}
Cruise Ship	5.64	6.87×10^{-6}
Ferry (Car)	3.68	1.23×10^{-4}
Fishing Vessel (Large)	3.14	-1.87×10^{-4}
General/Other Cargo Ship (Large)	1.74	-7.91×10^{-6}
Tanker (Chemical)	1.28	-1.15×10^{-6}
Tanker (Crude)	1.20	-1.59×10^{-7}
Tanker (Liquefied Gas)	1.35	2.36×10^{-7}
Tanker (Product)	1.24	-6.70×10^{-7}
Vehicle Carrier	2.04	-9.67×10^{-6}

2.4.3 Fuel Capacity Calculations

We used regression analysis based on vessel length to fill data gaps for fuel capacity. We examined three models: linear, no-intercept linear, and the no-intercept polynomial. Following the same criteria as for the displacement regression models (section 2.4.2), the no-intercept polynomial models were chosen.

No-intercept polynomial regression model for fuel capacity:

Equation 3

$$F = \beta_1 L + \beta_2 L^2$$

Where:

- F – vessel fuel capacity;
- L – vessel length;
- β_1 and β_2 - regression coefficients.

The following table shows the coefficients for the no-intercept polynomial regression models:

Table 12: Regression coefficients for fuel capacity using vessel length

Model Vessel Type	β_1	β_2
ATB	-5.65	0.48
Bulk Carrier	-1.84	0.06
Container Ship	-13.11	0.14
Cruise Ship	3.02	0.03
Ferry (Car)	-0.41	0.03
Fishing Vessel (Large)	-2.18	0.14
General/Other Cargo Ship (Large)	0.21	0.06
Tanker (Chemical)	5.49	0.02
Tanker (Crude)	-10.96	0.10
Tanker (Liquefied Gas)	-14.19	0.13
Tanker (Product)	2.48	0.04
Tug (Assist & Escort)	-1.20	0.22
Vehicle Carrier	2.77	0.08

2.5 Laden Status Determination

Determining whether a tank ship or oil barge is carrying oil or liquefied gas (LG) is a critical component of the Model, as it allows the Model to know when an escort tug may be required. The project team examined historical transits for model vessel types known to transport oil as cargo or LG. To develop rules that we used in the Model, we used visits to facilities handling oil, the type of facility visited, and in some cases, the presence or absence of a tug escort.

Six model vessel types regularly require an escort while they are in the system. They are as follows: ATB, Tanker (Chemical), Tanker (Crude), Tanker (Liquefied gas), Tanker (Product), and Towing Vessel (Oil). There is one additional type that transports oil as cargo but does not require an escort: Towing Vessel (Oil) - Bunkering.

For vessels that have historically used escorts while laden with oil, like Tanker (Chemical), Tanker (Crude), and Tanker (Product) vessels, we used the presence or absence of an escort while in an escort zone as a proxy for ladenness. Liquefied gas tankers are also required to use escorts while laden, and we used the same approach for them as well.

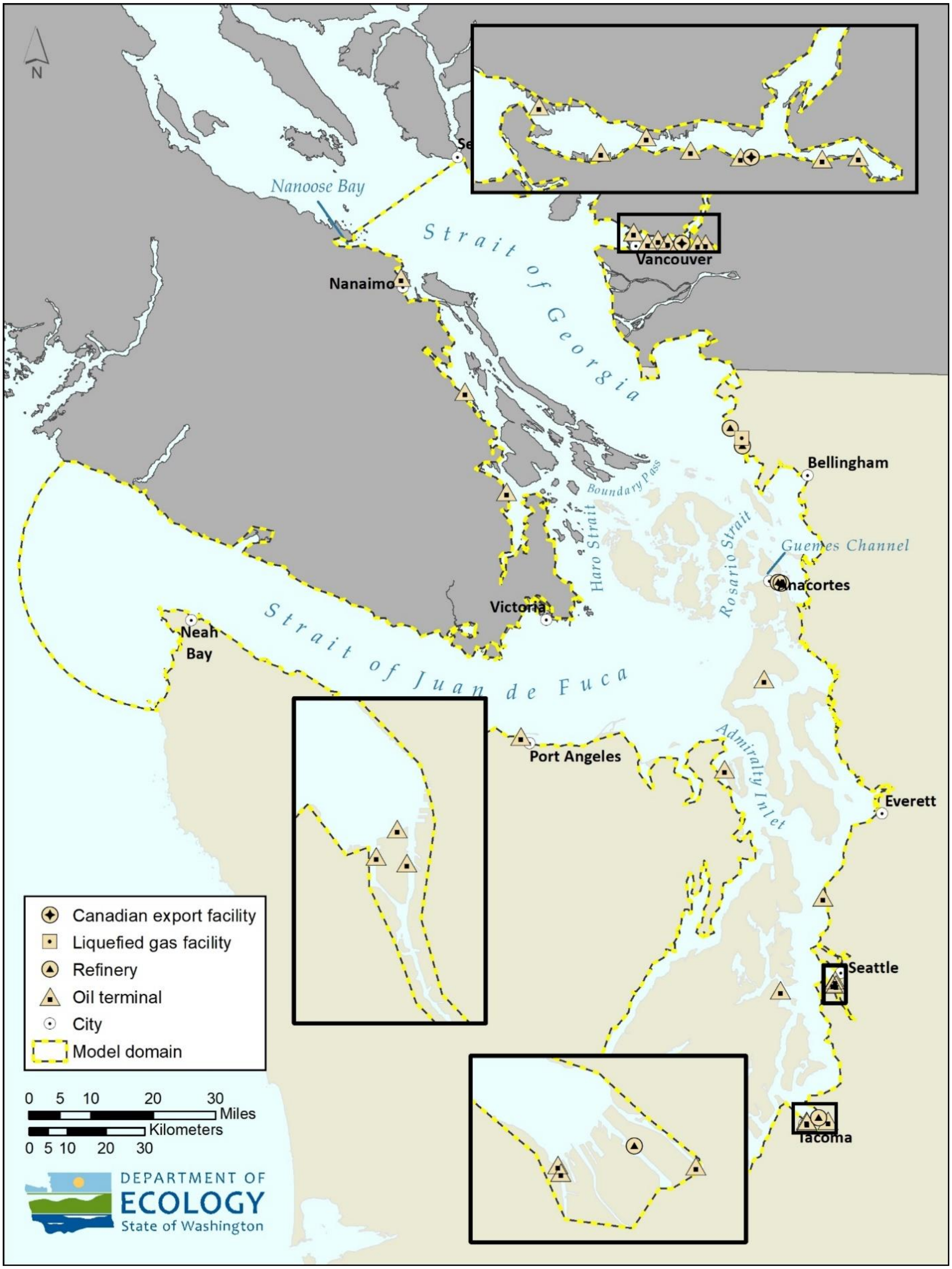
ATBs and towed tank barges have been required to use escorts while laden since late 2020. However, we did not have processed AIS data from that period, so we were not able to use the same method that we used for tankers to estimate ladenness. In addition, the area where escorts are required for ATB and towed tank barges is a small part of the overall system, and it would be problematic to extrapolate the data from that area to the whole system, even if the data was available. Additional details on ATB and towed tank barge laden status determination in in section 2.5.4.6.

2.5.1 Oil Handling Facilities

We identified the names and locations of oil handling facilities operating from 2015 to 2019 based on Ecology facility records, aerial imagery, and publicly available company documentation. **Error! Reference source not found.** shows the locations of oil handling facilities used in the Model. We categorized facilities as:

- Refinery
- Canadian Export Facility (Westridge Marine Terminal)
- Liquefied Gas Facility
- Oil Terminal

Figure 4: Oil handling facilities



2.5.2 Liquefied Gas, Product, Chemical, and Crude Tankers

Using 2018 AIS data, we identified 200 entries into the study area by chemical tankers, 185 entries by crude tankers, 182 entries into the system by product tankers and 19 by Liquefied Gas (LG) tankers. Some of the entries were relatively simple, with just one port of call before departing again. Other ships visited a number of different facilities before departing.

To support our estimation of how likely tankers are to be laden, we grouped their transits based on their behavior in the system. Options include facilities visited, first facility visited, last facility visited, facility and type visited.

Based on a review of those options, we characterized LG, product and crude tanker visits by "first facility visited." Grouping the tanker visits in this way gives us enough visibility into where they are going but is not so granular as to eliminate our chance to use a sampling approach to the review of data.

For chemical tankers we characterized their visits based on whether they called on a Canadian Export Facility, a Refinery, or an "other" berth at any time during their visit.

For each sampled entry, project team members independently determined the laden status of its inbound and outbound transits, using a historical replay of AIS information to identify if the transits were escorted. Escorted transits were determined based not only on proximity of an escort tug but also its behavior before during and after the escorted transit. After making initial determinations, the team reviewed any mismatches and selected a consensus answer.

We visually inspected all transits for vessel types with less than 20 transits. For vessel types with more than 20 transits, we visually examined a simple random sample of 20 transits.

To facilitate our sampling approach, we grouped the possible "first facilities" into our facility types.

Under that categorization, we saw the following number of transits from outside of the system to a facility type.

Table 13: First facility visited

Vessel Type	Refinery	Canadian Export Facility	LG Facility	Other Berths (including Oil Terminal)
Product Tanker	115	30	0	11
Crude Tanker	148	17	0	2
LG Tanker	0	0	19	0

For chemical tankers we grouped possible visits using our facility types. We saw the following number of transits from outside the system for each visit category.

Table 14: Chemical tanker facility visits

Vessel Type	Refinery	Canadian Export Facility	LG Facility	Other Berths (including Oil Terminal)
Chemical Tanker	67	5	0	144

2.5.3 Review of Inbound and Outbound Transits

The following set of estimates for percentage laden per vessel type, per route type were established. Percentages refer to the percentage of vessels that are laden not the percentage of cargo aboard a vessel.

The following table specifies the percent of transits laden with oil cargo on the inbound leg of a journey.

Table 15: Inbound laden transits, percentage of vessels that are laden

Vessel Type	Refinery	Canadian Export Facility	LG Facility	Other (including Oil Terminal)
Product Tanker	55%	35%	N/A	N/A
Crude Tanker	100%	0%	N/A	N/A
Chemical Tanker	45%	100%	N/A	5%
LG Tanker	N/A	N/A	0%	N/A

The following table specifies the percent of transits laden with oil cargo on the outbound leg of a journey.

Table 16: Outbound laden transits, percentage of vessels that are laden

Vessel Type	Refinery	Canadian Export Facility	LG Facility	Other (including Oil Terminal)
Product Tanker	85%	84%	N/A	N/A
Crude Tanker	43%	100%	N/A	N/A
Chemical Tanker	80%	40%	N/A	10%
LG Tanker	N/A	N/A	100%	N/A

2.5.4 Other Transit Types

There were transits that could not be grouped by the first facility visited. They include:

- Where crude or product tanker visits an “other berth” on their entry or exit from the system
- Internal transits
- Transits that do not call on a facility
- Partial journeys

2.5.4.1 Crude and product tanker visits to “other berths”

Of the 367 combined product and crude tanker entries in the system, 13 went first to an “other berth.” These berths were generally oil terminals—import, export and holding locations for petroleum products. Instead of a data-based approach for these visits, we established a set of basic assumptions based on an understanding of the role of oil terminals in petroleum transportation.

- Inbound to Oil Terminal – 100% are laden
- Outbound from Oil Terminal – 0% are laden

2.5.4.2 Crude and product tanker internal transits

Due to the complexity of the movements, and the presence of too many confounding vessels, the escort status of internal transits (movements between berths, anchorages, and between berths and anchorages) could not be determined visually. Using escorts as a proxy for ladenness works best when target vessels are transiting relatively open waters within an escort area. An open stretch of water allows the reviewer a clear area for review that is free from confounding vessels like assist tugs or transiting tugs. These confounding vessels are much harder to deal with when trying to evaluate short transits between berths or between anchorages and berths. This means internal transits (movements between berths, anchorages, and between berths and anchorages) require a different approach.

Instead of a data-based approach for these internal transits, we established a set of assumptions on laden status:

- From Refinery/Canadian Export Facility to Refinery/Canadian Export Facility/Oil Terminal – 100% are laden
- From Oil Terminal To Oil Terminal – 100% are laden
- From Oil Terminal to Refinery/Canadian Export Facility – 0% are laden

2.5.4.3 Crude and product tanker transits that do not visit a facility

Some tankers entering the system only visit Port Angeles anchorage before departure. Since their entry does not cross any areas where laden tankers are required to take an escort, we cannot use our established method for determining ladenness. To address this, we established a set of assumptions on laden status for this type of movement. Although there is the potential for lightering activity during these types of calls, most of these trips are associated with bunkering. As such we established the following rule:

- From System Edge to Port Angeles and Back – 100% are Laden

2.5.4.4 Crude and product tanker partial journeys

For some tankers, their historical visit may have been split across calendar years resulting in "partial journeys." A partial journey is a vessel movement that does not start and end at the edge of the study area. Instead, it may start or end, or start *and* end at locations within the study area. Since our ladenness determinations are all based on knowing either the destination or the origin of a given transit, partial journeys present a problem. Some partial journeys may not contain enough information to allow us to use our determination rules. With that in mind, we established the following rules:

- Partial journeys for Product and Crude Tankers – 100% are laden

2.5.4.5 Chemical tanker transits

The laden status of chemical tankers presents an interesting problem. Chemical tankers move a wider variety of products, not all of which are oil, and they do not only call on facilities that handle oil. Their unique behaviors led us to develop an unique approach for the determination of ladenness for this vessel type.

Chemical tanker journeys that include a refinery, Canadian export facility, or other berth are broken into two portions, the portion preceding the visit to the refinery, export facility or "other" berth, and the portion following. The preceding portion is assigned a ladenness status using the probability for inbound transits for that visit type (see Table 15). The portion of the journey following the visit is assigned a ladenness status using the probability for outbound transits for that visit type.

Any internal transit, or partial journey follows the same rules. If the chemical tanker does not visit a refinery, Canadian export facility, or other berth during their journey, the entire transit is marked as unladen.

2.5.4.6 ATBs and towed oil barges

The laden status of ATBs and towed oil barges is difficult to determine from existing data. Since barges do not carry separate AIS transmitters, determining if a tug was burdened presented an additional difficulty. As a result, we adopted rules of thumb based on a general understanding of how those vessel types transport oil within the system. For ATBs and towed tank barges, we established the following rules:

- Inbound to first facility – 0% are laden
- Internal transits, partial journeys, and any other journey that is not the initial inbound journey to the first facility – 100% are laden

2.6 Hazard Probabilities

The Vessel Accident Module requires hazard probabilities to identify when and where a loss of propulsion or loss of steering occurs. To estimate a probability, two measures are required, the number of observed occurrences and an exposure variable. For these analyses, the project team used operating minutes underway as our exposure variable.

2.6.1 Hazard Vessel Types

Not every model vessel type has been assigned its own unique hazard probability. Due to a limited number of observed hazards, we consolidated some model vessel types. We consolidated Cruise and Ferry vessel types because the incident databases did not differentiate them sufficiently to allow for separate hazard counts. We consolidated General Cargo and Vehicle Carrier vessel types for the same reason. The following table indicates the relationship between hazard vessel types and model vessel types.

Table 17: Vessel types for hazard probability calculations

Hazard Vessel Type	Model Vessel Types
Tank Ship	Tanker (Chemical), Tanker (Crude), Tanker (Liquefied Gas), Tanker (Product)
Tank Barge and ATB	ATB, Towing Vessel (Oil), Towing Vessel (Oil) - Bunkering
Passenger Ship (Cruise & Ferry)	Cruise Ship, Ferry (Car)
Container Ship	Container Ship
General Cargo Ship	General/Other Cargo Ship (Large), Vehicle Carrier
Bulk Carrier	Bulk Carrier
Large Fishing Vessel	Fishing (Large)
Escort Tugs	Tug (Assist & Escort)

MISLE categorizes vessels by Vessel Class and a more specific Vessel Type. We mapped MISLE vessel categories to the Model hazard vessel types according to the following table.

Table 18: Mapping MISLE vessel types to model hazard vessel types

Hazard Vessel Type	MISLE Vessel Types	MISLE Vessel Classes
Tank Ship	Petroleum Oil Tank Ship, Chemical Tank Ship, Petroleum Oil Tank Ship, Gas Carrier	
Tank Barge and ATB	Articulated Tug and Barge (Tug), Bulk Liquid Cargo (Tank) Barge	
Passenger Ship (Cruise & Ferry) [over 300 GT]	Ocean Cruise Vessel, Ferry, River Cruise Vessel	Passenger Ship
Container Ship	Container Ship	
General Cargo Ship	Ro-Ro/Container, Livestock Carrier, Vehicle Carrier	General Dry Cargo Ship, Ro-Ro Cargo Ship, Refrigerated Cargo Ship
Bulk Carrier	Combination Carrier (e.g. OBO), Barge Carrier (e.g. LASH), Cement Carrier, Woodchip Carrier	Bulk Carrier
Large Fishing Vessel [over 300 GT]	Fishing Catching/Processing, Vessel, Fishing Support Vessel	Fishing Vessel
Escort Tugs [over 50 feet]	Harbor/Ship Assist (Tug), Ship/Harbor Assist, Towing Astern, Towing Behind (Tug)	Towing Vessel

Similar to MISLE, MARSIS includes two levels of vessel categorization, Type and Subtype. We mapped MARSIS vessel categorizes into the Model hazard vessel types according to the following table.

Table 19: Mapping MARSIS vessel types to model hazard vessel types

Hazard Vessel Type	MARSIS Vessel Subtypes	MARSIS Vessel Types
Tank Ship	PRODUCT/CHEMICAL TANKER, PRODUCT TANKER, CHEMICAL TANKER, CRUDE TANKER (INCL BITUMEN/ASPHALT, LIQUIFIED GAS CARRIER	TANKER - CHEMICAL/ORE/OIL/CRUDE, TANKER - OTHER
Tank Barge and ATB	BARGE – PRODUCT, BARGE - COMBINATION OIL/CARGO/RO-RO	BARGE - LIQUID CARGO
Passenger Ship (Cruise & Ferry) [over 300 GT]	PASSENGER/VEHICLE PASSENGER – CARGO, PASSENGER ONLY, PASSENGER PASSENGER/TRAIN	Passenger Vessel, tour boat, ferry, PASSENGER
Container Ship	CONTAINER SHIP	Container Ship
General Cargo Ship	GENERAL CARGO, REFRIGERATED CARGO, HEAVY LOAD CARRIER, COMBINATION CARRIER (OBO), RO-RO CARGO	
Bulk Carrier	BULK CARRIER	

Hazard Vessel Type	MARSIS Vessel Subtypes	MARSIS Vessel Types
Large Fishing Vessel [over 300 GT]	TROLLER, LONG LINER, PACKER/TENDER, GILLNETTER, TRAWLER, SEINER, AQUACULTURE, FISHERIES, PROCESSOR/FACTORY	Fishing Vessel
Escort Tugs [over 50 feet]		TUG

2.6.2 Calculated Hazard Probabilities for Simulated Vessels

Hazard probabilities are expressed as a number of occurrences per minute underway. Note that $1x10^{-6}$ is 0.000001 or one occurrence per million minutes. The confidence intervals give an indication of uncertainty by providing a range in which the true probability is likely to fall 95% of the time.

The following table displays the probabilities for loss of propulsion events.

Table 20: Loss of propulsion probabilities

Hazard Vessel Type	Probability (LOP)	Confidence Interval (lower bound)	Confidence Interval (upper bound)
Tank Ship	$1.69 x10^{-6}$	$1.15 x10^{-6}$	$2.38 x10^{-6}$
Tank Barge and ATB	$7.13 x10^{-8}$	$2.32 x10^{-8}$	$1.66 x10^{-7}$
Passenger Ship (Cruise & Ferry)	$1.09 x10^{-6}$	$9.52 x10^{-7}$	$1.25 x10^{-6}$
Container Ship	$2.34 x10^{-6}$	$1.83 x10^{-6}$	$2.94 x10^{-6}$
General Cargo Ship	$1.56 x10^{-6}$	$9.66 x10^{-7}$	$2.39 x10^{-6}$
Bulk Carrier	$1.44 x10^{-6}$	$1.15 x10^{-6}$	$1.78 x10^{-6}$
Large Fishing Vessel	$2.10 x10^{-6}$	$1.09 x10^{-6}$	$3.67 x10^{-6}$

The following table displays the probabilities for loss of steering events for each hazard vessel type.

Table 21: Loss of steering probabilities

Hazard Vessel Type	Probability (LOS)	Confidence Interval (lower bound)	Confidence Interval (upper bound)
Tank Ship	$1.58 x10^{-7}$	$3.26 x10^{-8}$	$4.62 x10^{-7}$
Tank Barge and ATB	$2.85 x10^{-8}$	$3.45 x10^{-9}$	$1.03 x10^{-7}$
Passenger Ship (Cruise & Ferry)	$2.86 x10^{-7}$	$2.16 x10^{-7}$	$3.72 x10^{-7}$
Container Ship	$6.41 x10^{-8}$	$7.76 x10^{-9}$	$2.31 x10^{-7}$
General Cargo Ship	$1.49 x10^{-7}$	$1.80 x10^{-8}$	$5.37 x10^{-7}$
Bulk Carrier	$1.34 x10^{-7}$	$5.78 x10^{-8}$	$2.64 x10^{-7}$
Large Fishing Vessel	$1.75 x10^{-7}$	$4.43 x10^{-9}$	$9.76 x10^{-7}$

The following table displays the hazard probabilities for escort tugs.

Table 22: Escort tug hazard probabilities

Hazard Type	Probability	Confidence Interval (lower bound)	Confidence Interval (upper bound)
Allisions/Collisions	$2.31 x10^{-7}$	$1.73 x10^{-7}$	$3.03 x10^{-7}$

Hazard Type	Probability	Confidence Interval (lower bound)	Confidence Interval (upper bound)
Groundings	7.12×10^{-8}	4.07×10^{-8}	1.16×10^{-7}
Sinking/Capsize	1.78×10^{-8}	4.85×10^{-9}	4.56×10^{-8}
Other	1.09×10^{-6}	9.54×10^{-7}	1.23×10^{-6}

2.6.3 Hazard Counts

We counted hazards using the USCG's MISLE and Canada's MARSIS incident databases. We looked at incidents that occurred between 2002 and 2019 in the model domain (Figure 2). The tables below include the counts for hazards used to calculate the hazard probabilities used by the Model.

Table 23: Loss of propulsion and loss of steering incident counts by vessel type

Hazard Vessel Type	Counts (LOP)	Counts (LOS)
Tank Ship	32	3
Tank Barge and ATB	5	2
Passenger Ship (Cruise & Ferry)	214	56
Container Ship	73	2
General Cargo Ship	21	2
Bulk Carrier	86	8
Large Fishing Vessel	12	1

The following table includes hazard counts for escort tugs (see Table 18 and Table 19 for which vessel types from MISLE and MARSIS are included).

Table 24: Hazard counts for escort tug hazard probabilities

Hazard Type	Counts
Allisions/Collisions	52
Groundings	16
Sinking/Capsize	4
Other	244

2.6.4 Methods and Hazard Mapping

Hazard categories differed in the two databases. To count incidents in each hazard category, we mapped hazard counts in the databases to the categories used in the model.

The MARSIS dataset assigns each occurrence one accident or incident type, while the MISLE dataset assigns each occurrence one or more event types. Information about incidents is also available in various free-text fields in both databases. We also processed IHS incident descriptions to help with the mapping.

We generally accepted the MARSIS assigned accident type and MISLE primary event type as the primary hazard for the purposes of hazard counting. However, since there was no specific MARSIS category for loss of propulsion (LOP) or loss of steering (LOS), LOP and LOS events were linked in the database to other hazards. We used information in the summary field to identify which hazards also included LOP and LOS events.

Since MISLE used multiple event types for some incidents, we reviewed every event type associated with a given incident to determine if they referenced other hazards of interest. While only LOP or LOS hazard probabilities are used in the Model simulation, the tug escort analysis requires a review of additional hazard types for a supplemental analysis of risk presented by additional tug escorts.

The full list of hazard types counted is listed below.

- Allision
- Capsize
- Collision
- Loss of Propulsion (LOP)
- Loss of Steering (LOS)
- Other
- Power Grounding
- Sinking

2.6.4.1 MISLE

Our incident mapping process first queries incidents by initial Event Type. For some initial Event Types, we applied additional criteria to determine the model hazard type. When possible, we integrated summary information from MISLE and IHS-Markit databases. We employed the field mapping strategy employed shown in the following table.

Table 25: USCG MISLE database query parameters

MISLE Event Type	Additional Criteria	Model Hazard Type
Abandonment	Direct categorization	Other
Capsize	Direct categorization	Capsize
Grounding	Direct categorization	Power Grounding
Loss of Electrical Power	Direct categorization	LOP
Sinking	Direct categorization	Sinking
Allision	Direct categorization	Allision
Collision	Direct categorization	Collision
Loss/Reduction of Vessel Propulsion/Steering	Summary contains: *los|casualty|failure* AND *power|prop|engine* OR *engine* AND *break|broke|failure* OR *lop|disable|drift*	LOP
Loss/Reduction of Vessel Propulsion/Steering	Summary contains: *mechanical|rudder|steering* AND *failure* OR *steering* AND *broke|jam|trouble|los|casualty* OR *damaged navigation*	LOS
Set Adrift	Summary contains: *sink|sunk|sank|submerge*	Sinking
Set Adrift	Summary contains: *capsiz_*	Capsize
Set Adrift	Not classified as Sinking or Capsize	Other
Cargo/Fuel Transfer/Shift Damage to Cargo Discharge/Release - Pollution Explosion	Summary contains: *Loss/Reduction of Vessel Propulsion/Steering AND los|casualty|failure* AND *power|prop|engine* OR *engine* AND *break|broke|failure* OR *lop|disable|drift*	LOP

Fire - Initial Fire - Reflash Flooding - Initial Flooding - Progressive Fouling Implosion Loss of Stability Material Failure/Malfunction Vessel Manuever Vessel Yaw/Pitch/Roll/Heel Wave(s) Strikes/Impacts		
Cargo/Fuel Transfer/Shift Damage to Cargo Discharge/Release - Pollution Explosion Fire - Initial Fire - Reflash Flooding - Initial Flooding - Progressive Fouling Implosion Loss of Stability Material Failure/Malfunction Vessel Manuever Vessel Yaw/Pitch/Roll/Heel Wave(s) Strikes/Impacts	Summary contains: *Loss/Reduction of Vessel Propulsion/Steering AND* *mechanical|rudder| steering* AND *failure* OR *steering* AND *broke|jam|trouble|los| casualty* OR *damaged navigation*	LOS
Cargo/Fuel Transfer/Shift Damage to Cargo Discharge/Release - Pollution Explosion Fire - Initial Fire - Reflash Flooding - Initial Flooding - Progressive Fouling Implosion Loss of Stability Material Failure/Malfunction Vessel Manuever Vessel Yaw/Pitch/Roll/Heel Wave(s) Strikes/Impacts	Summary contains: *allision*	Allision
Cargo/Fuel Transfer/Shift Damage to Cargo Discharge/Release - Pollution Explosion Fire - Initial Fire - Reflash Flooding - Initial Flooding - Progressive Fouling Implosion	*Summary contains: collision_|collid_*	Collision

Loss of Stability Material Failure/Malfunction Vessel Manuever Vessel Yaw/Pitch/Roll/Heel Wave(s) Strikes/Impacts		
Cargo/Fuel Transfer/Shift Damage to Cargo Discharge/Release - Pollution Explosion Fire - Initial Fire - Reflash Flooding - Initial Flooding - Progressive Fouling Implosion Loss of Stability Material Failure/Malfunction Vessel Manuever Vessel Yaw/Pitch/Roll/Heel Wave(s) Strikes/Impacts	*Summary contains: ground*	Power Grounding
Cargo/Fuel Transfer/Shift Damage to Cargo Discharge/Release - Pollution Explosion Fire - Initial Fire - Reflash Flooding - Initial Flooding - Progressive Fouling Implosion Loss of Stability Material Failure/Malfunction Vessel Manuever Vessel Yaw/Pitch/Roll/Heel Wave(s) Strikes/Impacts	*Summary contains: sink|sank|sunk|submerge*	Sinking
Cargo/Fuel Transfer/Shift Damage to Cargo Discharge/Release - Pollution Explosion Fire - Initial Fire - Reflash Flooding - Initial Flooding - Progressive Fouling Implosion Loss of Stability Material Failure/Malfunction Vessel Manuever Vessel Yaw/Pitch/Roll/Heel Wave(s) Strikes/Impacts	*Summary contains: capsiz_*	Capsize
Cargo/Fuel Transfer/Shift	Does not meet any of above criteria	Other

Damage to Cargo Discharge/Release - Pollution Explosion Fire - Initial Fire - Reflash Flooding - Initial Flooding - Progressive Fouling Implosion Loss of Stability Material Failure/Malfunction Vessel Maneuver Vessel Yaw/Pitch/Roll/Heel Wave(s) Strikes/Impacts		

2.6.4.2 MARSIS

For each incident, the MARSIS database records a single hazard. Our incident mapping process started by querying incidents by the Hazard Type. For each MARSIS hazard, we checked if the recorded hazard was preceded by a different hazard or if it was the "final" hazard associated with a given event. The full mapping strategy is displayed below.

Table 26: TSB MARSIS database query parameters

MARSIS Hazard Type	Additional Criteria	Model Hazard Type
COLLISION - Struck by vessel COLLISION - With another vessel or other floating object	Direct categorization	Collision
STRIKING - Allision with a fixed object (striking - includes berthed/docked vessels)	Direct categorization	Allision
GROUNDING - Not under power (includes drifting) (non-intentional)	Summary contains: *lop OR los|casualty|failure AND power|prop|engine OR engine AND break|broke OR disable OR drift*	LOP
GROUNDING - Not under power (includes drifting) (non-intentional)	Summary contains: *mechanical|rudder|steering AND failure OR steering AND broke|jam|trouble|los|casualty OR damaged navigation*	LOS
GROUNDING - Under power (non-intentional)	Summary contains: *mechanical|rudder|steering AND failure OR steering AND broke|jam|trouble|los|casualty OR damaged navigation*	LOS
GROUNDING - Under power (non-intentional)	ELSE	Power Grounding
Bottom Contact	Summary contains: *mechanical|rudder|steering AND failure OR steering AND broke|jam|trouble|los|casualty OR damaged navigation*	LOS

MARSIS Hazard Type	Additional Criteria	Model Hazard Type
Bottom Contact	Summary contains: *lop OR los|casualty|failure AND power|prop|engine OR engine AND break|broke OR disable OR drift*	LOP
Bottom Contact	*ELSE*	Power Grounding
Capsizes	Summary contains: *mechanical|rudder|steering AND failure OR steering AND broke|jam|trouble|los|casualty OR damaged navigation*	LOS
Capsizes	Summary contains: *lop OR los|casualty|failure AND power|prop|engine OR engine AND break|broke OR disable OR drift*	LOP
Capsizes	ELSE	Capsize
SANK - Flooding SANK - Founders (taking on water above the waterline)	Summary contains: *mechanical|rudder|steering AND failure OR steering AND broke|jam|trouble|los|casualty OR damaged navigation*	LOS
SANK - Flooding SANK - Founders (taking on water above the waterline)	Summary contains: *lop OR los|casualty|failure AND power|prop|engine OR engine AND break|broke OR disable OR drift*	LOP
SANK - Flooding SANK - Founders (taking on water above the waterline)	ELSE	Sinking
Abandoned CARGO SHIFT/CARGO LOSS - Cargo lost overboard CARGO SHIFT/CARGO LOSS - Cargo shifted DANGEROUS GOODS RELEASED - From the ship DANGEROUS GOODS RELEASED - On board ship EXPLOSION FIRE FOULS UNDERWATER OBJECT INTENTIONAL BEACHING/GROUNDING/ ANCHORING to avoid occurrence SUSTAINS DAMAGE RENDER UNSEAWORTHY/ UNFIT FOR PURPOSE - Unfit for purpose - ice, weather, etc. TOTAL FAILURE OF ANY MACHINERY OR TECHNICAL SYSTEM	Summary contains: *mechanical|rudder|steering AND failure OR steering AND broke|jam|trouble|los|casualty OR damaged navigation*	LOS
Abandoned CARGO SHIFT/CARGO LOSS - Cargo lost overboard CARGO SHIFT/CARGO LOSS - Cargo shifted DANGEROUS GOODS RELEASED - From the ship DANGEROUS GOODS RELEASED - On board ship EXPLOSION FIRE	Summary contains: *lop OR los|casualty|failure AND power|prop|engine OR engine AND break|broke OR disable OR drift*	LOP

MARSIS Hazard Type	Additional Criteria	Model Hazard Type
FOULS UNDERWATER OBJECT INTENTIONAL BEACHING/GROUNDING/ ANCHORING to avoid occurrence SUSTAINS DAMAGE RENDER UNSEAWORTHY/ UNFIT FOR PURPOSE - Unfit for purpose - ice, weather, etc. TOTAL FAILURE OF ANY MACHINERY OR TECHNICAL SYSTEM		
Abandoned CARGO SHIFT/CARGO LOSS - Cargo lost overboard CARGO SHIFT/CARGO LOSS - Cargo shifted DANGEROUS GOODS RELEASED - From the ship DANGEROUS GOODS RELEASED - On board ship EXPLOSION FIRE FOULS UNDERWATER OBJECT INTENTIONAL BEACHING/GROUNDING/ ANCHORING to avoid occurrence SUSTAINS DAMAGE RENDER UNSEAWORTHY/ UNFIT FOR PURPOSE - Unfit for purpose - ice, weather, etc. TOTAL FAILURE OF ANY MACHINERY OR TECHNICAL SYSTEM	ELSE	Other

2.6.5 Exposure Counts

We used AIS data from 2018 to count minutes underway for each vessel type. Due to the inconsistency or lack of AIS data for the entirety of the temporal range (2002-2019) we used an estimation approach to adjust 2018 counts for other years.

Specifically, we used Vessel Entries and Transit (VEAT) data from 2002-2019 to create annual multipliers based on the percent difference in traffic levels for each year compared to 2018 levels. This relies on the assumption that exposure counts for each vessel type are proportional to overall traffic levels captured in the VEAT data.

For example, we found that overall traffic captured in VEAT in 2008 was 95% of that in 2018. The exposure counts from 2018 AIS data for each vessel category are multiplied by 0.95 to estimate exposures for 2008. We summed these estimated exposures for the period 2002-2019 to create the total exposure minutes for that vessel type. Overall traffic levels captured in VEAT remained fairly static over the period 2002-2019 as can be seen in table below.

Table 27: Annual vessel traffic multipliers

Year	Percent of 2018 Traffic	Year	Percent of 2018 Traffic
2002	99.2	2011	98.7

Year	Percent of 2018 Traffic	Year	Percent of 2018 Traffic
2003	99.7	2012	100.0
2004	99.2	2013	100.3
2005	99.3	2014	99.9
2006	99.8	2015	100.2
2007	99.2	2016	100.4
2008	94.9	2017	99.7
2009	97.7	2018	100.0
2010	98.9	2019	100.5

Total calculated exposure counts for model vessel types for 2002-2019:

Table 28: Exposure counts by vessel type

Vessel Categories	Counts (minutes underway)
Tank Ship	18,961,115
Tank Barge and ATB	70,127,573
Passenger Ship (Cruise & Ferry)	195,577,926
Container Ship	31,222,345
General Cargo Ship	13,456,884
Bulk Carrier	59,704,524
Large Fishing Vessel	5,708,788

The following table includes calculated exposure counts for escort tugs:

Table 29: Exposure counts for escort tugs

Vessel Categories	Counts (minutes underway)
Tug (Assist & Escort)	224,757,316

2.7 Self-Repair

We developed this probability distribution function by reviewing loss of propulsion incidents from two datasets: The Washington Board of Pilotage Commissioners Marine Safety Occurrence records from 2007-2020, and Neah Bay ERTV callout records from 1999-2017. In our review of these two datasets, we identified 103 events that involved a vessel in the Salish Sea or the entrance to the Strait of Juan de Fuca that met our definition of any reduction in propulsion that affects maneuverability.

Our review of associated investigation reports, class reports, and contemporaneous notes allowed us to estimate the duration of loss of propulsion for 98 of those 103 incidents. For incidents where propulsion was never restored, we used a duration of 24 hours (1440 minutes). From that dataset, we reviewed the goodness of fit of four distributions: Log Normal, Weibull, Gamma, and Exponential. The Log Normal distribution does the best job of representing the bimodal aspect of the dataset. The Log Normal function is unbounded in its upper range and can theoretically generate infinitely high predicted values.

Table 30 shows the observed durations found in our incident review, as well as the times predicted by the Log Normal distribution. Twenty-five-percent of the values fall below the 1st quartile. Fifty-percent of the values fall below the median, and 75% of the values fall below the 3rd quartile. Predicted values are the summary of 100,000 predicted values generated from the Log Normal function.

Table 30: Loss of propulsion durations

Loss of Propulsion Duration (min.)	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
Observed	2	8	36	266	325	1,440
Predicted	0	12	47	364	181	740,656

2.8 Oil Spill Probabilities

The Model requires oil spill probabilities to identify if an oil spill occurs when a drift grounding occurs. To estimate a probability, two measures are required, the number of observed occurrences and an exposure variable. For these analyses, the project team used the number of groundings as our exposure variable.

We estimated oil spills probabilities using the USCG's MISLE and Canada's MARSIS incident databases. We looked at incidents that occurred between 2000 and 2020 in both databases. To ensure that we would find enough oil spills, we consolidated vessel types. The mapping followed the procedures used in the hazard counts estimation (section 2.6.3).

The table below includes the consolidated vessel types for oil spill probabilities from groundings, as well as the observed counts of groundings, observed counts of oil spills, and the probabilities of oil spills from groundings.

Table 31: Oil spills from groundings

Oil Outflow Vessel Type	Model Vessel Types	Count of Groundings	Count of Oil Spills	Probability of an Oil Spill Per Grounding
Non Tank Commercial Ship	Cruise Ship, Ferry (Car), Container Ship, General/Other Cargo Ship (Large), Bulk Carrier, Fishing (Large), Vehicle Carrier	1456	14	0.0096
Tank Ship	Tanker (Chemical), Tanker (Crude), Tanker (Liquefied Gas), Tanker (Product)	380	2	0.0053
Tank Barge and ATB	ATB, Towing Vessel (Oil), Towing Vessel (Oil) - Bunkering	1636	13	0.0080

2.8.1 Oil Spill Volumes

When a simulated grounded ship spills oil, an oil volume is generated from a distribution of observed oil spills for the respective vessel type. We estimated oil spills volumes using the USCG's MISLE and Canada's MARSIS incident databases. We looked at incidents that occurred between 2000 and 2020 in both databases. We did not apply any geographic filter. To ensure that we would find enough oil spills per vessel type, we consolidated vessel types and used oil spills observed in the database for all incident types, except other or unknown. The mapping followed the procedures used in the hazard counts estimation (section 2.6.3).

The table below includes the consolidated vessel types for oil spill probabilities from groundings, as well as summary statistics of the observed oil spills in gallons. The table shows that the smallest 25% (1st quartile) of the spills, are under 2 gallons. The smallest 75% of the spills (3rd quartile) are under 42 gallons. The average spill size ranges from 561 to 1467 gallons, depending on vessel type.

Table 32: Oil outflow volumes (in gallons)

Oil Outflow Vessel Type	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
Non Tank Commercial Ship	0.1	2.0	10.0	561.8	42.3	48,151.0
Tank Ship	0.1	1.0	5.0	1318.1	25.0	100,000.0
Tank Barge and ATB	0.1	1.0	10.0	1467.4	39.8	282,828.0

3 Tug Escort Scenarios

This analysis includes three tug escort scenarios:

- Scenario 1 reflects the tug escort requirements immediately prior to the 2020 expansion.
    - This is the minimum requirement for upcoming rulemaking allowed under the Oil Transportation Safety Act of 2019.
- Scenario 2 reflects the current tug escort requirements as implemented in 2020 following the Oil Transportation Safety Act of 2019.
    - This is our scenario representing current practice.
- Scenario 3 extends the 2020 expanded rules to the entire study area.
    - This scenario encompasses the maximum extent of tug escort requirements allowed under the Oil Transportation Safety Act of 2019.

These scenarios capture the full range of possible tug escort requirements allowed by the Oil Transportation Safety Act of 2019. The tables below elaborate on the specific tug escort requirements under each scenario.

Table 33: Tug escort scenarios applicability

Location	Laden Tank Ships (including LPG and LNG ships) over 40,000 DWT	Laden Tank Ships (including LPG and LNG ships) between 5,000 and 40,000 DWT	Laden Towed Tank Barges over 5,000 DWT	Laden ATBs over 5,000 DWT
Admiralty Inlet	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Boundary Pass	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Colvos Passage	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Central Strait of Juan de Fuca	Scenario 1 Scenario 2 Scenario 3	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3
Eastern Strait of Juan de Fuca	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Guemes Channel and Saddlebags	Scenario 1 Scenario 2 Scenario 3	Scenario 2 Scenario 3	Scenario 2 Scenario 3	Scenario 2 Scenario 3
Haro Strait	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Possession Sound and Saratoga Passage	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3

Location	Laden Tank Ships (including LPG and LNG ships) over 40,000 DWT	Laden Tank Ships (including LPG and LNG ships) between 5,000 and 40,000 DWT	Laden Towed Tank Barges over 5,000 DWT	Laden ATBs over 5,000 DWT
Puget Sound	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Rich Passage And Sinclair Inlet	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Rosario Strait	Scenario 1 Scenario 2 Scenario 3	Scenario 2 Scenario 3	Scenario 2 Scenario 3	Scenario 2 Scenario 3
South Sound to Olympia	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Strait of Georgia	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3
Waters East (Of Rosario)	Scenario 1 Scenario 2 Scenario 3	Scenario 2 Scenario 3	Scenario 2 Scenario 3	Scenario 2 Scenario 3
Other WA Waters Inside Line from Discovery Island Light to New Dungeness Light	Scenario 1 Scenario 2 Scenario 3	Scenario 3	Scenario 3	Scenario 3

4 Vessel Movement Module

The Vessel Movement Module (VMM) generates marine traffic based on historical vessel movement observed in Automatic Identification System (AIS) data. The module simulates the equivalent of multiple years of vessel traffic data. Each year is unique, but based on observed patterns such as the mix of vessel types, berth and anchorage use, and daily traffic levels. The objective of the VMM is to simulate different random traffic configurations that reproduce the macro-characteristics of the system (such as vessel traffic volume by vessel characteristics and waterway characteristics) while changing various micro-characteristics, such as timing and speed of individual vessel journeys.

4.1 Simulating Vessel Movement

This section covers a number of different aspects of vessel movements. It starts with a list of the components of a vessel movement. Then it describes the process for the creation of tracks out of raw AIS data. The process for identification and assignment of vessel attributes is also described in this section.

4.1.1 Vessel Journeys

A journey is a vessel's entire visit to the model domain. For example, a typical journey for a crude tanker would start at the western entrance to the Strait of Juan de Fuca. The journey would continue as it transits the Salish Sea, calls at a berth, or visits an anchorage. The tanker's journey ends when it departs the Salish Sea. For the Model, a journey translates to the collection of vessel tracks that represent a vessel's trip in the system. A track is the collection of AIS messages (in chronological order) for one vessel for one route. A route is a direction of travel between model locations or nodes. The Model identifies routes with a starting and ending node. Another component of a journey is a stay. A stay is the time a vessel spends at a node.

4.1.2 Nodes

Nodes are locations that represent the start or end of a route. Berths, anchorages, waypoints, edge of model areas, escort areas, and extended study areas are all types of nodes.

4.1.2.1 Berths

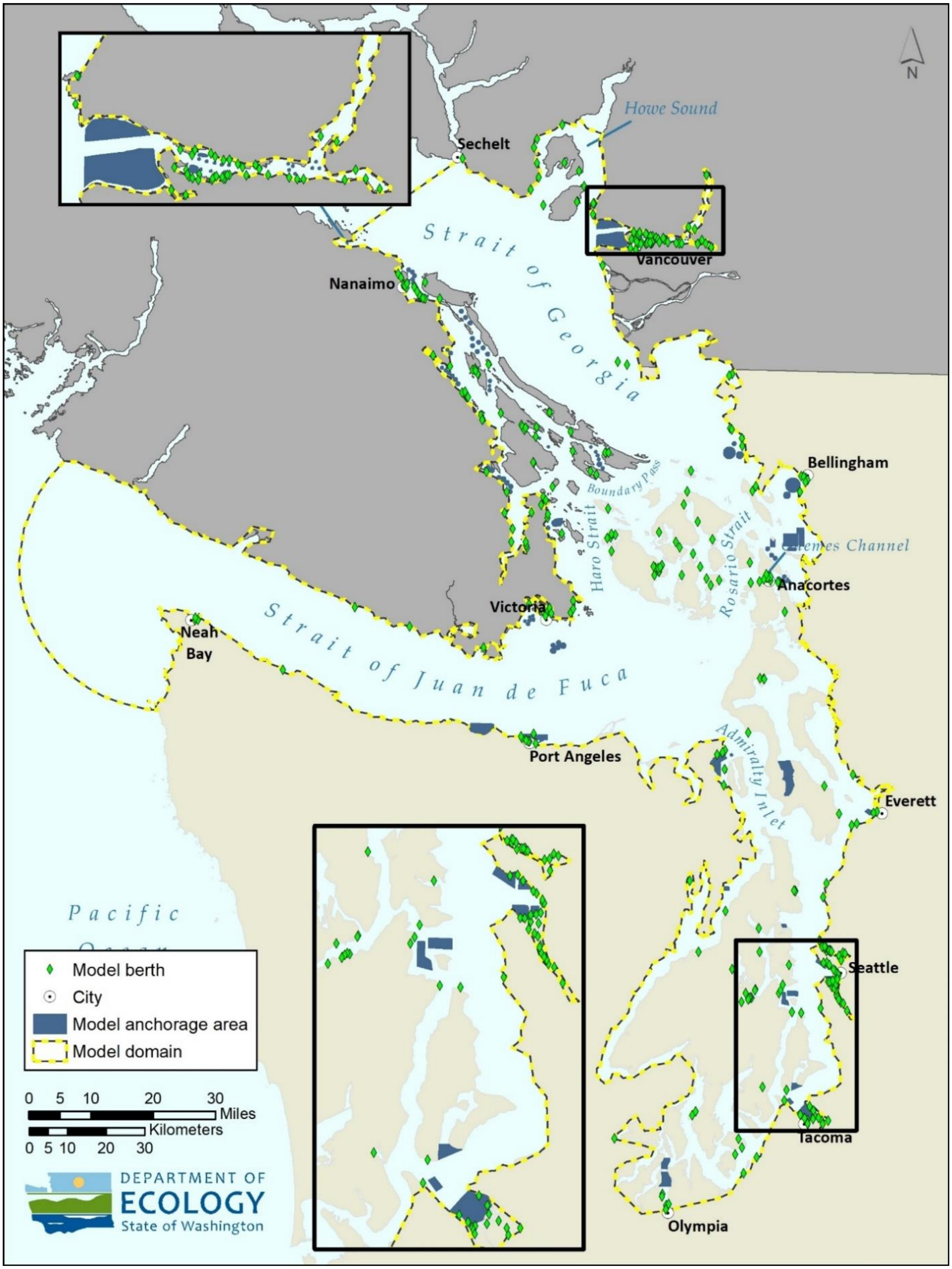
A berth is a node defined by one or more spatial points. Berths typically refer to specific terminals or docks. We identified berth locations from existing Ecology datasets, through visual inspection of aerial imagery, port maps, and AIS data.

4.1.2.2 Anchorages

Anchorages are defined by a spatial polygon. Model anchorages include official and unofficial anchorage areas used by deep draft commercial vessels. We identified official anchorages from the Puget Sound Harbor Safety Plan and the Pacific Pilotage Authority. We identified unofficial anchorages through a visual review of AIS data. Each model anchorage can only be used by one deep draft vessel at a time.

We created anchorage groups for areas where multiple individual anchorages are available. We assigned maximum occupancy values to these groups based on local rules. The Model combines anchorages into anchorage groups for selecting routes. If a first choice anchorage group is fully occupied, the next preferred anchorage groups are called Alternative Anchorages. The only model anchorage areas that can take more than one vessel at a time are the tug and barge anchorages.

Figure 5: Model berths and anchorages



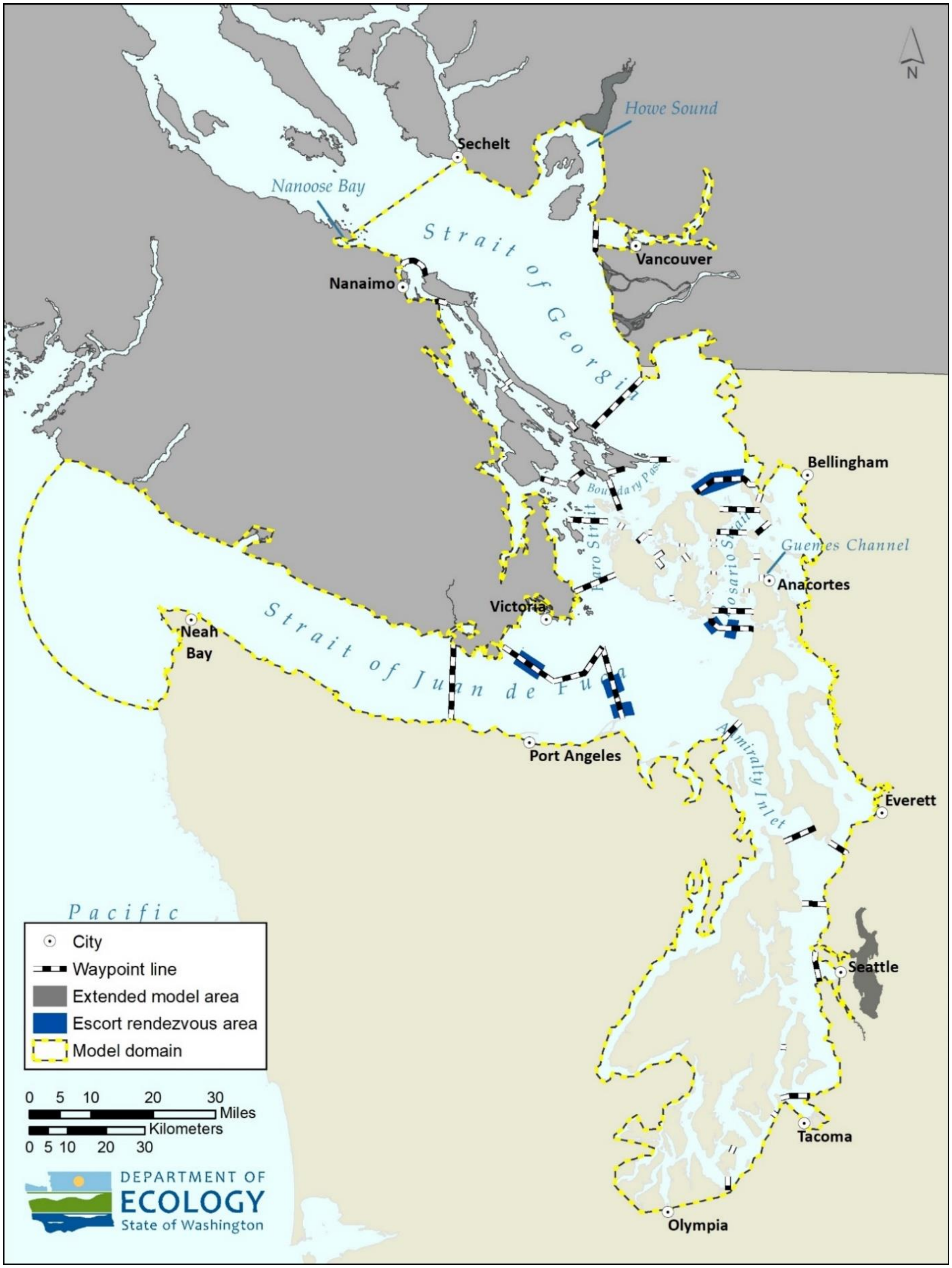
4.1.2.3 Waypoints
Waypoints are virtual lines within waterways. They are used to split tracks and provide more flexibility for simulating a diversity of vessel routes and incorporating some model components. We defined waypoints based on a review of AIS traffic.

4.1.2.4 Edge of model areas
Edge of model areas are locations where the model domain ends. There are two edge of model areas. One is the arc 20 miles west of the J Buoy at the western entrance to the Strait of Juan de Fuca and one is in the Strait of Georgia, at the line from Nanoose Bay to Sechelt.

4.1.2.5 Escort rendezvous areas
Escort rendezvous areas are delineated by a spatial polygon. Escort rendezvous areas are where escort tugs either meet or leave laden underway tank vessels. We identified escort rendezvous areas through an examination of tug escort requirements, and a review of AIS.

4.1.2.6 Extended model areas
Extended model areas are located adjacent to the model domain and the model does not simulate traffic within them. The Model treats these areas like berths for track, route, and stay length purposes. These areas include interior waterways within the ports of Seattle and Vancouver, such as the Fraser River and the Duwamish River. Other examples include Upper Howe Sound, Fraser River North, Fraser River South, Duwamish River, and Lake Washington.

Figure 6: Model waypoints, escort rendezvous areas, and extended model areas



4.1.3 AIS Track Creation

The first step in the track creation process for all vessel types was selecting AIS messages whose position was within the model domain. The AIS message selection was expanded to include AIS messages immediately outside the model domain. Including these AIS messages was useful when creating tracks near the margins of the model domain.

4.1.3.1 Route-based vessels

After selecting AIS messages within the model domain, messages were associated with nodes. We performed spatial comparisons to identify the closest berth or anchorage within 500 meters. For each unique MMSI, AIS messages were connected chronologically to create a line. Virtual AIS messages were created at the intersection of any line segment with a waypoint line, edge of model area, and extended study area. The virtual AIS messages were associated with the node feature that prompted their creation. Lines were split into vessel tracks when one of the following conditions were met:

- an AIS message was associated with a node;
- the reported vessel speed decreased below 0.2 knots;
- the reported vessel speed increased above 0.2 knots;
- the calculated vessel speed was less than 0.25 meters per second (approx. 0.5 knots);
- the calculated vessel speed was greater than 50 meters per second (approx. 100 knots);
- the distance to previous AIS message was greater than 5 km;
- the duration since last AIS message was greater than 10 minutes;

For AIS messages associated with berths or anchorages, the final node selection was done as follows:

1) If AIS message is within 200 meters of berth, then the final node selection is a berth.
2) If AIS message is more than 200 meters from a berth, then the final node is whichever is closer, the berth or anchorage node.

The result was a series of tracks with starting and ending nodes. AIS messages were then generated at one-minute intervals along the track.

4.1.3.2 Dependent vessels

4.1.3.2.1 Tug (Assist & Escort)

We processed AIS messages and created tracks following two different procedures to meet the simulation needs of the VMM. The VMM generates separate sets of traffic for Tug (Assist & Escort) vessels for each tug escort scenario.

The track creation for escort and assist vessels used the same procedure as with route-based vessels, but with a different set of nodes. For escort tracks, the nodes used for the spatial comparisons were berths, anchorages, and escort rendezvous areas. After lines were created for each unique MMSI connecting the AIS messages in chronological order, they were split into vessel tracks using the same conditions as with route-based vessels. The assignment of starting and ending nodes for tracks also follows the same steps as with route-based vessels. AIS messages were then generated at one-minute intervals along each track.

The majority of the observed vessel tracks for this vessel type do not follow a clear pattern of traveling from node to node. In an attempt to account for this irregular movement, daily tracks were created for each vessel. A daily track was defined as all AIS messages for a given message for a single calendar day.

All AIS messages with a reported vessel speed less than or equal to 0.2 knots were removed. The remaining AIS messages were rounded to the nearest minute. Any temporal gaps (no messages at any one-minute increment) were filled in by repeating the previous AIS message. The resulting track represented a daily track.

4.1.3.2.2 Towing Vessel (Oil) – Bunkering

For this vessel type, AIS messages were only associated with berths or anchorages. The rest of the track creation process was the same as with route-based vessels, including generating AIS messages at one-minute intervals along each track.

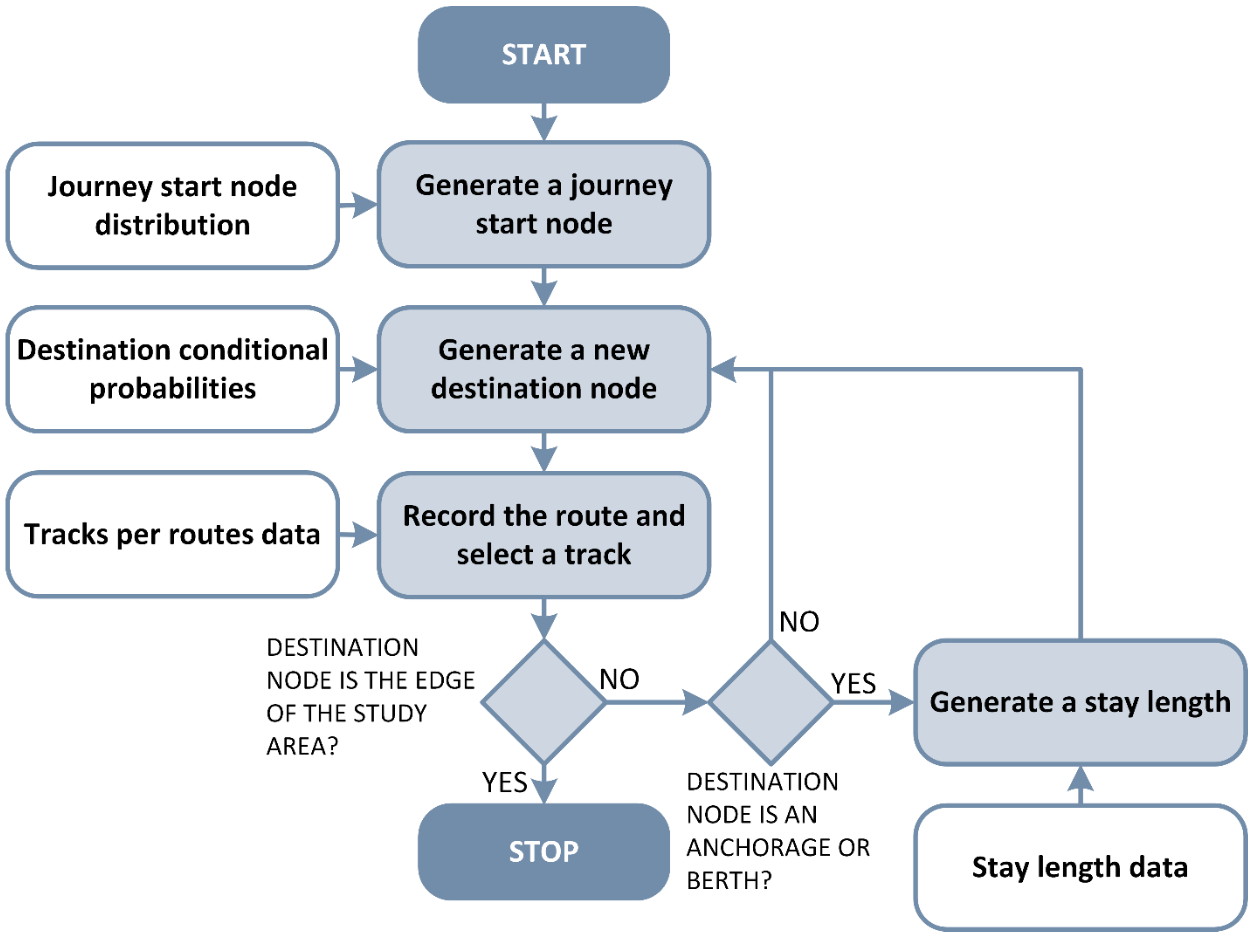
4.1.3.3 Ferry (Car)

Daily tracks were created for this vessel category. First, all AIS messages with a reported vessel speed less than or equal to 0.2 knots were removed. Remaining AIS messages were rounded to the nearest minute. Any temporal gaps were filled by repeating the previous AIS message.

4.1.4 Simulating Movements for Route-Based Vessels

When a route-based vessel visits the system, it follows a series of routes that combine to form a journey. A vessel's journey starts with its appearance at a node. A vessel selects a route from that node based on the distribution of observed tracks from that node. When selecting routes, the model factors in the previous two nodes visited to prevent vessels from becoming trapped in loops. A vessel continues to select routes until it leaves the system or the model year ends. Route-based vessels travel between berths, anchorages, waypoints, edge of model areas, and extended model areas.

Figure 7: Route generation process (simplified)



4.1.4.1 Vessel journey starts

A vessel journey starts with a vessel's appearance in the Model. This is determined from the observed AIS. In the observed AIS, a vessel journey start occurs when a vessel track starts at the edge of model area or when the first valid track is observed for that vessel for that year. A valid track has a start and end node.

4.1.4.2 Simulating journeys

The first step in simulating vessel traffic for route-based vessels is determining how many vessel journeys to simulate for a model year. This is determined by randomly selecting a number for each vessel type between the annual minimum number of observed vessel journeys and the annual maximum number of observed vessel journeys across all years of data. That number of journey starts is then selected from the distribution of journey start locations and times (month, day, and time).

Next, a starting track is selected from a distribution of tracks starting from the journey start location. A set of vessel attributes is randomly selected for that vessel type from the model vessels dataset. Once the initial track is selected, the Model selects subsequent tracks factoring in the vessel's previous two destinations. Subsequent routes and tracks are selected until a vessel leaves the model domain or the model year is over.

4.1.4.3 Berths, including extended model areas

When vessels travel to berths or extended model areas, the module must determine how long the vessel will remain at that location. Stay length is determined by selecting from the observed stay lengths for that location. The module does not track berth occupancy, so there is no restriction on the number of vessels that could be at a berth or extended model area at the same time. The module does not track vessel location while at berths or extended model areas.

4.1.4.4 Anchorages

In the VMM, there are two types of anchorages, standard anchorages and tug and barge anchorages. Standard anchorages in the model are common anchorages primarily used by commercial, deep-draft vessels. The following route-based model vessel types visit them:

- ATB
- Bulk Carrier
- Container Ship
- Cruise Ship
- General/Other Cargo Ship (Large)
- Tanker (Chemical)
- Tanker (Crude)
- Tanker (Liquefied Gas)
- Tanker (Product)
- Vehicle Carrier

Tug and barge anchorages are anchorages specially designated for use by tugs and barges. The following route-based model vessel types visit them:

- ATB
- Towing Vessel (Oil)

Similar to berths, when a vessel travels to an anchorage, the VMM determines how long the vessel will remain at that location. Occupancy is tracked for standard anchorages and each anchorage group has a maximum occupancy based on local rules or regulations. If a vessel route is selected for an anchorage group that cannot accommodate an additional vessel, a new vessel route is selected to an alternative anchorage group. Each anchorage group has been assigned one or more alternative anchorage groups. Occupancy is not restricted for tug and barge anchorages.

The VMM simulates the location and movement of vessels while at anchor. Stay duration and vessel movement at anchor is determined by selecting an observed vessel track for that anchorage location.

4.1.4.5 Vessels that take escorts

A laden tank vessel may require escort tugs for portions of its journey. The rules defined in tug escort scenarios (section 0) determine the portions of journeys that require tug escorts. The following model vessel types may have tug escorts:

- ATB
- Tanker (Chemical)

- Tanker (Crude)
- Tanker (Liquefied Gas)
- Tanker (Product)
- Towing Vessel (Oil)

4.1.4.6 Vessels that use assist tugs

Some vessels require assist tugs when arriving or leaving a berth. ATBs use one assist tug, all other vessel types use two assist tugs. The following model vessel types use tug assists:

- ATB
- Bulk Carrier
- Container Ship
- General/Other Cargo Ship (Large)
- Tanker (Chemical)
- Tanker (Crude)
- Tanker (Liquefied Gas)
- Tanker (Product)
- Vehicle Carrier

4.1.4.7 Vessels that use bunkering services

The VMM determines if a vessel will receive fuel from bunkering vessels at berths and anchorages. Bunkering vessels can provide fuel to the following route-based vessels at some berths and anchorages.

- ATB
- Bulk Carrier
- Container Ship
- Cruise Ship
- General/Other Cargo Ship (Large)
- Tanker (Chemical)
- Tanker (Crude)
- Tanker (Liquefied Gas)
- Tanker (Product)
- Vehicle Carrier

The project team identified berths and anchorages where bunkering is allowed and those locations where it is prohibited. We used the following criteria to determine that a location allows vessel to vessel bunkering:

- It is a berth or anchorage where bunkering is specifically allowed by that port authority.
- It is a Washington location where a vessel to vessel transfer has been recorded in Ecology's Advance Notice of Oil Transfer System (ANTS).
- It is a Puget Sound VTS Anchorage.
- It is a berth that is otherwise not specifically prohibited from allowing bunkering.

We used the following criteria to determine that a location does not allow vessel to vessel bunkering:

- Bunkering is functionally or actually prohibited at that location by port authority.
- It is a ferry dock or fuel dock.
- It is a non Puget Sound VTS anchorage.
- It is a refinery berth.
- It is a WA berth where no vessel to vessel transfers has been recorded in in Ecology's Advance Notice of Oil Transfer System (ANTS).
- It is an exposed anchorage.

Bunkering frequency was determined by reviewing oil transfer data for 2018 from Ecology's Advance Notice of Oil Transfer System (ANTS) and berth and anchorage visits (stays) observed in AIS. We only counted stays at Washington locations where we determined bunkering is allowed. The bunkering rate is the number of vessel to vessel transfers divided by the number of stays at berths and anchorages where bunkering is allowed. In 2018, the counts were 1564 transfers and 3943 stays. The rate was 0.397 transfers per stay. If bunkering occurs, it begins when the ship arrives at the berth or anchorage. Each transfer is instantaneous for simulation purposes.

4.1.5 Simulating Movements for Dependent Vessels

In the Model, dependent vessels are vessels that perform some support function for route-based vessels. This includes assist, escort, and bunkering vessels. When required, dependent vessels travel to the location where the dependent activity begins. When the dependent activity has concluded, the dependent vessel leaves. Dependent vessels are available on demand. They "appear" in the system when needed and then "disappear" after their dependent activity is concluded.

4.1.5.1 Simulating movements for Tug (Assist & Escort)

This category includes vessels that are engaged in two different behaviors, escorting and assisting. The VMM simulates these vessels both as dependent journeys and as background traffic. The number of dependent escort and assist tracks simulated for each model year is recorded and subtracted from the overall number of background traffic tracks that will be simulated. Background traffic is simulated using the daily tracks described in section 4.1.3.2.1. A separate set of simulated traffic (dependent and background) is created for each tug escort scenario for each simulation.

4.1.5.1.1 Tug escorts

When the need for an escort is identified (section 4.1.4.5), a track is selected from the distribution of observed Tug (Assist & Escort) tracks traveling to the location where the escort job begins. The movement of the tug while escorting is simulated by replicating the movement of the route-based vessel from the rendezvous location to the end of the escort job. The start time for the escorting tug track is delayed by one minute. At the end of the escort job, a track is selected from the distribution of observed Tug (Assist & Escort) tracks traveling from the location where the escort job ends. Escort jobs can begin or end at berths, extended study areas, anchorages, and escort rendezvous areas.

4.1.5.1.2 Tug assists

When a tug assist is required, the VMM first evaluates if the vessel is escorted. If the vessel is escorted, the escort tug is assumed to provide assist services reducing the number of assist tugs required by one. To simulate tug assists, the required number of assist tracks are selected from the distribution of observed Tug (Assist & Escort) tracks traveling to the berth visited by the route-based vessel. The start time for the tug assist track is modified so it arrives at the berth at the same time as the route-based vessel. The movement of the dependent vessel while assisting is not simulated. Once the assist tug arrives at the berth, it immediately departs.

The return trip for tug assists is simulated by selecting from the observed Tug (Assist & Escort) tracks traveling from the berth visited by the route-based vessel. When the route-based vessel leaves from the berth, the VMM selects tracks for the assist tugs from the distribution of tracks to the berth. The subsequent return trip for the assist tugs begins one hour after the route-based vessel leaves the berth. The VMM selects return tracks for assist tugs from the distribution of tracks from that berth. If the route-based vessel requires an escort tug when leaving the berth, then the number of assist tugs required is reduced by one.

4.1.5.2 Simulating movements for Towing Vessel (Oil) - Bunkering

Based on the rate of bunkering per stay at berth or anchorage described in section 4.1.4.7, the VMM simulates the movement of Towing Vessel (Oil) – Bunkering vessels to the bunkering location and from the bunkering location. The VMM simulates movement to the bunkering location by selecting a track from the distribution of observed Towing Vessel (Oil) – Bunkering tracks to the bunkering location. The return trip begins immediately after arriving at the bunkering location (bunkering is instantaneous in the Model) and is simulated by selecting a track from the distribution of observed Towing Vessel (Oil) – Bunkering tracks from the bunkering location. If there is not an observed track to or from the bunkering location, then bunkering does not occur.

4.1.6 Simulating movements for Ferry (Car)

Ferry (Car) movements are simulated by replicating an entire year of Ferry (Car) AIS tracks. For the VMM, each simulation will choose at random a year of traffic from the available years of AIS data (2015 to 2019).

4.1.7 Implemented Rules for Ladenness

For purposes of coding, we used the following set of rules to establish ladenness for tank vessels based on tank vessel type, destination, and origin.

4.1.7.1 Tanker (Chemical)

- If visits Canadian Export Facility, then:
    - Transit before Canadian Export Facility visit – 100% are laden
    - Transit after Canadian Export Facility visit – 40% are laden
- If does not visit Canadian Export Facility **and** does visit Refinery, then:
    - Transit before Refinery visit – 45% are laden
    - Transit after Refinery visit – 80% are laden
- If does not visit Canadian Export Facility **and** does not visit Refinery, then:
    - Transit before Other Berth – 5% are laden
    - Transit after Other Berth – 10% are laden

4.1.7.2 Tanker (Crude)

- Inbound to Canadian Export Facility – 0% are laden
- Inbound to Refinery – 100% are laden
- Outbound from Canadian Export Facility – 100% are laden
- Outbound from Refinery – 43% are laden
- Inbound to Oil Terminal - 100% are laden
- From Refinery/Canadian Export Facility to Oil Terminal – 100% are laden

- From Oil Terminal to Oil Terminal – 100% are laden
- From Refinery/Canadian Export Facility to Refinery/Canadian Export Facility – 100% are laden
- Outbound from Oil Terminal – 0% are laden
- From Oil Terminal to Refinery/Canadian Export Facility – 0% are laden
- Does not call on an Oil Handling Berth - 100% are laden

4.1.7.3 Tanker (Liquefied Gas)

- Inbound to Ferndale Facility – 0% are laden
- Outbound from Ferndale Facility – 100% are laden
- Ferndale Facility to Ferndale Facility – 100% are laden
- Outbound from Anchorage – 100% are laden
- Anchorage to Ferndale – 0% are laden

4.1.7.4 Tanker (Product)

- Inbound to Canadian Export Facility – 35% are laden
- Inbound to Refinery – 55% are laden
- Outbound from Canadian Export Facility – 84% are laden
- Outbound from Refinery – 85% are laden
- Inbound to Oil Terminal – 100% are laden
- From Refinery/Canadian Export Facility to Oil Terminal – 100% are laden
- From Oil Terminal to Oil Terminal – 100% are laden
- From Refinery/Canadian Export Facility to Refinery/Canadian Export Facility – 100% are laden
- Does not call on an Oil Handling Berth - 100% are laden
- Outbound from Oil Terminal – 0% are laden
- From Oil Terminal to Refinery/Canadian Export Facility – 0% are laden

4.1.7.5 ATB and Towing Vessel (Oil)

- Enter the system unladen
- Exit the system laden
- Considered laden after first visit to oil terminal
- If vessel does not leave the system, all subsequent transits are laden

4.1.7.6 Towing Vessel (Oil) - Bunkering

- Laden from appearance to bunkering rendezvous
- Unladen for return trip after completing the bunkering job

4.2 Determining Need for Escort

Whether a laden vessel requires a tug escort is dictated by the rules associated with a given tug escort scenario. In the VMM, the escort zones (areas of the waterways where escort requirements apply) are identified by the routes where escort rendezvous areas are located. Any simulated vessel route is considered to be within the escort zone if it occurs after a route where a tug escort would join and before a route where a tug escort would leave. Slight modifications of these general rules were required during implementation to ensure that vessels with partial journeys took escorts where appropriate.

5 Vessel Accident Module

The Vessel Accident Module generates marine incidents for further analysis. The Model applies a probability of loss of propulsion (LOP) and loss of steering (LOS) on a minute-by-minute basis to the simulated traffic from the Vessel Movement Module. Hazard probabilities are based on observed occurrences in the USCG Marine Information for Safety and Law Enforcement (MISLE) and Transportation Safety Board of Canada's Marine Safety Information System (MARSIS) databases.

5.1.1 Application of Hazard Probabilities in Model

We established probabilities for loss of propulsion (LOP) and loss of steering (LOS) per operating minute. Using the calculated probabilities, the Model evaluates each simulated track to determine if a hazard occurs and at what 1-minute time step it occurs. If one of these hazards occurs, the Model logs the incident time and location for subsequent analysis.

5.1.2 Self-Repair

When a simulated vessel experiences a loss of propulsion event, the model first determines if the loss of propulsion was total. To do so, the Model applies a probability of 0.347 that the event resulted in a complete loss of propulsion. Then, for ships that experience a total loss of propulsion, the Model selects a duration without propulsion using the following probability distribution function.

Equation 4

$$X \sim Lognormal(meanlog = 3.834073, sdlog = 2.03378)$$

Section 2.7 describes the self-repair function in more detail.

6 Momentum and Drift Module

The Momentum and Drift Module (MDM) plots a drift trajectory for a simulated ship that loses propulsion. The model incorporates vessel dimensions and characteristics, wind and current data, and bathymetry. For each loss of propulsion event, the MDM identifies a drift duration, speed, and location of grounding.

6.1 Data Inputs

The MDM uses simulated vessel movement and attributes along with wind, current, and bathymetry data to calculate a drift trajectory. The vessel movement data is fed from the Vessel Accident Module that includes information about the time and location of the loss of propulsion event. The Vessel Accident Module also identifies the simulated vessel involved allowing the MDM to bring in relevant vessel attributes, such as displacement tonnage and dimensions.

6.2 Initial Turn Application

When ships lose propulsion they can briefly retain the ability to control their heading and avoid hazards using momentum. We incorporated this real-world behavior into the MDM with these steps:

1) Create a 120-degree hazard evaluation area centered on the vessel's coordinates and using the vessel speed to determine radius of the arc.
   a) The radius of the arc corresponds to the distance that vessel will travel at its current speed in 20 minutes.
2) Divide the 120-degree hazard evaluation area into 10 equal wedges.
3) Evaluate wedges for potential grounding hazards.
   a) If the water depth is equal to or less than the draft of the vessel anywhere within the wedge, then a hazard is identified.
4) Select the largest group of contiguous wedges without hazards.
5) If there are multiple groups of the same number, select the wedge group closest to the original course.
6) Set new course to the middle of the selected wedge group.

For each vessel that loses power, a drift trajectory is first calculated without applying the initial turn. If for that same vessel an initial turn was required, an additional drift trajectory is calculated after applying the initial turn course change.

6.3 Drift Modeling

No existing drift model fully met our requirements. We developed a new drift model to account for the vessel momentum, vessel type, wind, current, and wave effects. For Towing Vessel (Oil) and Towing Vessel (Oil) – Bunkering vessels, only the barge is modeled for drifting.

6.3.1 Drift Modeling Approach

The drift modeling process has three main objectives:

1) To include the major environmental forces acting on a ship (wind, current, and waves) in a generalized form;

2) To account for the vessel momentum as a potential influencing force in restricted waters;
3) To account for vessel type where possible.

To achieve this, the drift model balances ship momentum with environmental drag forces:

Equation 5

$$(m + m')\frac{dv}{dt} = F_{res,air} + F_{res,water} + F_{wind} + F_{current} + F_{wave}$$

Where:

- m is vessel mass
- m' is added mass from acceleration of water particles along the hull
- $\frac{dv}{dt}$ is vessel acceleration
- $F_{res,air}$, $F_{res,water}$ are the air and water resistance opposed to the direction of vessel movement
- $F_{wind}, F_{current}, F_{wave}$ are the wind drag force acting on the vessel, the current drag force acting on the vessel, and the wave drag force acting on the vessel

The forces are generally proportional to the velocity of the object in a fluid. This function depends on the vessel characteristics and its speed relative to the external forces. In general, the drag force is exponentially proportional to speed (Ni et al. 2010). As an approximation, the generic formulas for the air and water resistance forces and the drag wind, current and wave drag forces are:

Equation 6

$$F_{res,air} = \frac{1}{2} c_{air} \rho_{air} A_{air} {v_{ship}}^2$$
$$F_{current} = \frac{1}{2} c_{water} \rho_{water} A_{water} {v_{ship}}^2$$
$$F_{wind} = \frac{1}{2} c_{air} \rho_{air} A_{air} {v_{air}}^2$$
$$F_{current} = \frac{1}{2} c_{water} \rho_{water} A_{water} {v_{water}}^2$$
$$F_{wave} = \frac{1}{2} c_{wave} \rho_{water} g L a^2$$

Where:

- $c_{air}, c_{water}, c_{wave}$ are the drag coefficients for air, water, and waves
- ρ_{air}, ρ_{water} are the air and water densities
- A_{air}, A_{water} are the areas exposed to wind and water
- $v_{ship}, v_{air}, v_{water}$ are the ship's velocity, the relative wind velocity, and the relative current velocity
- g is the Earth's gravitational acceleration
- L is the length of the waterline
- a is the wave amplitude (1/2 of the wave length)

6.3.2 Inclusion of Vessel Momentum

In the restricted waters considered in our analyses, the early moments after a loss of propulsion are important. Over this period, a vessel could travel 1 nm or more after losing propulsion. The inertial stopping distance could be longer, depending on the vessel type, size and speed. Moreover, this is the period of time when the pilot maneuvering the ship could influence the direction of the vessel trajectory. For these reasons, we deemed vessel momentum as an essential component of our drift model.

6.3.3 Input Parameters

There are a number of parameters required by our approach. The assumed model structure is as described by Equation 5 and Equation 6 in section 6.3.1 and requires the following inputs:

- Vessel location
- Course
- Speed
- Time of the loss-of-propulsion event
- Vessel characteristics
- Wind and current speed and direction
- Wave direction and amplitude

The MDM also requires estimates for five vessel-dependent parameters: air drag, water drag, wave drag, added mass, ratio of wind to air exposed areas. Discussion for calculating these five parameters follows.

6.3.3.1 Wind drag coefficients

Wind drag forces depend on the angle of attack (angle between vessel heading and wind direction), wind speed, and vessel characteristics. Many studies have focused on estimation of the wind drag forces or wind drag coefficients for various vessel types.

There are three types of wind drag models documented in the literature: experimental, statistical, and mathematical. After review, we selected a mathematical model based on the Helmholtz-Kischhoff plate theory as used by (Blenderman 1994).

(Blenderman 1994) applied a load concept to compute wind coefficients. The wind load functions use four parameters: longitudinal resistance CD_l, transversal resistance CD_t, the cross-force parameter δ, and the rolling moment factor K.

6.3.3.2 Current drag coefficients

The current drag coefficients depend on the angle of attack (relative angle between vessel heading and current direction), current speed relative to the vessel, vessel characteristics, vessel orientation into the current (port or starboard), and the ratio of water depth to vessel draft.

There are few studies dedicated to the estimation of the current drag forces or current drag coefficients than wind drag. A 1994 study by Oil Companies International Marine Forum (OCIMF 1994) provides the only approach to estimating current drag forces based on extensive research, and it was ultimately chosen for the MDM.

The formulas are designed to estimate current force on stationary objects. In our model the relative current speeds may be higher than the ones for which the (OCIMF 1994) was built, but only for a short period of time when the vessel still has momentum and is not fully driven by the wind and current velocity vectors combined.

6.3.3.3 Wave drag coefficients

In Equation 6, wave force requires the calculation of a wave-drag coefficient, of the length of the waterline, and the wave amplitude. The most common approach in drift modeling is to ignore wave effects. For example, (Breivik and Allen 2008) assumed that wave drag forces are negligible for the objects modeled, and already captured by the regression coefficients since wave direction predominantly followed the direction of the wind.

(Ni et al. 2010) showed that the wave effects can be ignored if the wave amplitude is less than 1/30th of the length of the vessel. (Yang et al. 2018) showed the maximum wave height in the Salish Sea is about 2.5 m with most frequent wave heights being between 0.25 – 0.5 m. The most common wave amplitudes in Salish Sea are therefore 0.125 – 0.25 m, with maximum of approximately 1.25 m. Wave forces are therefore negligible in terms of their influence on drift path for vessels longer than 37.5 m under virtually all conditions. As a result, we determined that wave action in the study area likely has no significant impact on drift for covered vessels and therefore excluded it.

6.3.3.4 Estimating "added mass"

A vessel accelerating or decelerating in a fluid accelerates or deflects some volume of surrounding fluid as it moves. This is typically modeled as a volume of fluid moving with the vessel, which effectively increases the vessel inertia. This effect is called the added mass (Breivik and Allen 2008).

There are many approaches for calculating added mass. (Tveitnes 2001) conducted an extensive review of the historical approaches. They include both theoretical and experimental methods. There are 36 components of the added mass corresponding to combinations of the six vessel movements: surge, sway, heave, roll, pitch, and yaw. In the MDM, we are only interested in the added mass for surge, which is the longitudinal motion along the x-axis. We are only interested in surge since only the forward momentum is modeled and the vessel heading is approximated by the course over ground.

(Zhang et al. 2019) indicates that the longitudinal added mass coefficient is small compared with the mass of the ship – about 0.02 to 0.07. (Zhang et al. 2019) also suggest that for simplicity or in case of absence of detailed vessel information a value of 0.05 can be used. Following that rationale, the MDM uses a value of 0.05 multiplied by the vessel's displacement to approximate added mass.

6.3.3.5 Estimating "water-exposed vessel area" and "wind-exposed vessel area"

To estimate the water exposed area and the wind exposed area, the model relies on the approach in (Jurdzinski 2020). This is the assumption that the general ratio of above to below the waterline area is 5:1 for vessel types with large windage areas and 1:5 for vessels types that have low freeboard.

The vessel area exposed to the current is calculated first as the product of the vessel draft and the vessel length for longitudinal area, and the product of the vessel draft and vessel beam for the lateral area. This is an overestimate of the true values.

The wind exposed area will be five times larger than the current exposed area for vessels with large windage areas and $1/5^{th}$ of the current exposed area for vessels with low free board. The modeled vessel types are classified as high and low windage as follows.

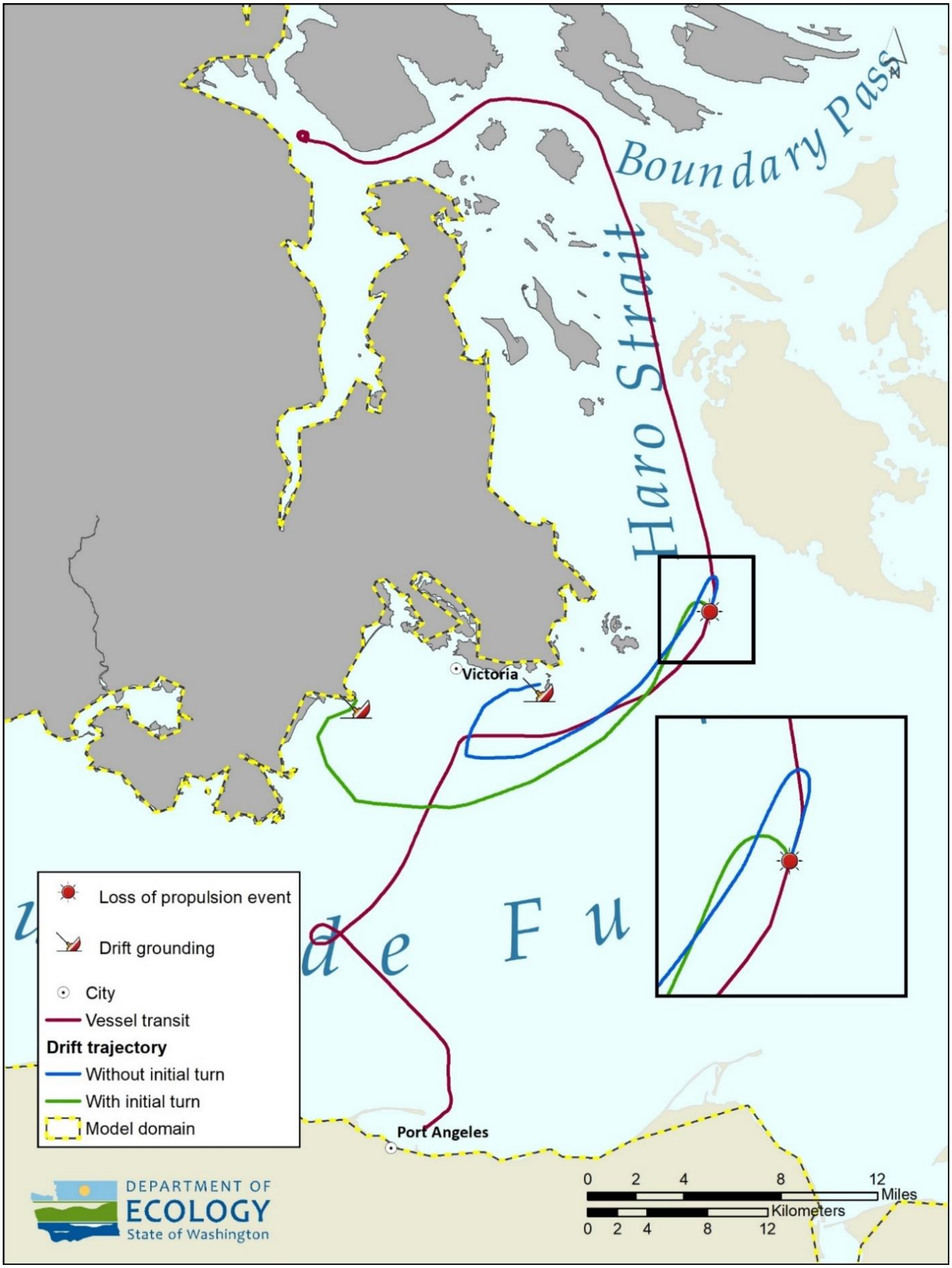
Table 34: Windage classification

Model Vessel Type	Windage Category
ATB	Low
Bulk Carrier	Low
Container Ship	High
Cruise Ship	High
Ferry (Car)	High
Fishing Vessel (Large)	High
General/Other Cargo Ship (Large)	High
Tanker (Chemical)	Low
Tanker (Crude)	Low
Tanker (Liquefied Gas)	Low
Tanker (Product)	Low
Towing Vessel (Oil)	Low
Towing Vessel (Oil) - Bunkering	Low
Vehicle Carrier	High

6.4 Determining Drift Grounding

Vessel drift trajectories are simulated for 48-hour periods or until a drift grounding event occurs. The MDM identifies drift grounding events by performing a spatial intersection between the vessel drift trajectory and bathymetry depth contours equal to or less than the vessel design draft. The intersection of the drift trajectory with a bathymetry contour identifies the location and time of grounding. The MDM passes grounding events to the Vessel Rescue Analysis Module. Figure 8 provides an illustration of the complete functionality of the MDM with the initial turn applied, drift trajectories with and without an initial turn, and drift groundings.

Figure 8: Map of drift trajectory examples



7 Oil Spill Risk Module

In addition to the drift groundings simulated by the MDM, the Oil Spill Risk Module (OSRM) generates additional oil related risk metrics for further analysis. The two additional risk metrics are an estimate of oil outflow, and a representation of the oil volume at risk in an incident.

7.1 Oil Outflow

To estimate oil outflow, the model applies a probability of an oil spill to each drift grounding incident. Then, if an oil spill occurs, it generates an oil spill volume. Oil spill probabilities and volumes are based on observed occurrences in the US Coast Guard Marine Information for Safety and Law Enforcement (MISLE) and Transportation Safety Board of Canada's Marine Safety Information System (MARSIS) databases. See section 2.8.1 for more details.

7.1.1 Oil Spill Volume Generation

During the simulation, the OSRM generates an oil spill volume from the observed distribution of groundings that released oil, following the 2-step procedure below:

- Step 1: Select a quartile interval:
    - Minimum to 1st Quartile
    - 1st Quartile to Median
    - Median to 3rd Quartile
    - 3rd Quartile to Maximum
- Step 2: for the interval selected, randomly select an oil spill volume between the boundaries of the interval, limited by the vessel's total oil capacity. The upper limit is equal to the fuel capacity or, in the case of a laden tank vessel, the sum of fuel and oil cargo capacity.

7.2 Oil Volume at Risk

Oil Volume at Risk is a second oil spill risk metric. It is designed to represent the catastrophic potential represented by the carriage of large quantities of oil. To calculate the Oil Volume at Risk for a given incident, the model uses maximum volume of oil carried by a vessel as fuel and cargo. The volume is generated from simulated vessel fuel and cargo capacity.

7.3 Fuel Capacity Value

For calculation of Oil Volume at Risk, the OSRM uses the fuel capacity value from the vessel attributes table.

7.4 Cargo Capacity Value

For calculation of Oil Volume at Risk, the model uses the 98% of the cargo capacity value from the vessel attributes table. This follows 46 CFR § 154.1844, which limits the maximum amount for filling liquid cargo tanks to 98% to allow for thermal expansion and to avoid overfilling during loading. When tank ships are not laden, the oil volume at risk only includes fuel capacity, not oil cargo capacity.

8 Vessel Rescue Analysis Module

The Momentum and Drift Model calculates a path when a vessel loses power until it grounds. Few loss of propulsion incidents actually result in drift groundings, so the Model evaluates a series of ship actions for self-rescue to estimate a realistic likelihood of a drift grounding, absent outside intervention. The Model incorporates some of these ship actions into other modules. These are:

- **Initial turn using residual momentum –** The ability of a ship to adjust its heading immediately following the loss of propulsion (Momentum and Drift Module)
- **Self-repair –** The time that it takes a ship to recover propulsion after losing it (Vessel Accident Module)

The Vessel Rescue Analysis Module (VRAM) include one ship action.

- **Emergency anchoring –** The ability of a ship to arrest its drift by dropping anchor

The Model also evaluates the ability of rescue tugs to intervene and prevent drift grounding when a ship loses propulsion. This is the core of our analyses and allows us to test the relative benefits of tug escorts, tugs of opportunity, and ERTVs.

For each drifting ship, the total time required for a tug to perform a rescue will be calculated. This "time to save" is calculated based on the travel and control time of the nearest escort tug, tug of opportunity, or ERTV. This time is compared to the drift duration to determine if the tug could have prevented that drift grounding.

8.1 Emergency Anchoring Function

A modeled vessel that is adrift following a loss of propulsion will attempt to anchor. At every one-minute interval along the drift trajectory, the Model checks if the drift speed is 3 knots or less. If it is, the Model checks water depth and distance to grounding depth to determine if emergency anchoring is available. The Model defines the grounding depth as the point along the drift trajectory where the ship's design draft equals the water depth.

If the following conditions are met, the drifting vessel is able to anchor:

- Speed is 3 knots or less
- Water depth is 60m or less
- Distance to grounding contour must be greater than ship length plus 500m
    - 100m for anchor to hold
    - 300m anchor rode
    - 100m safety margin

This emergency anchoring function is adapted from (Fowler and Sorgard 2000).

8.2 Tug of Opportunity Identification

When a simulated ship loses propulsion, the Model will capture the location of all escort and assist tugs in the system at the time of the LOP. This excludes assist tugs engaged in maneuvering a ship. The Model considers each of these potentially capable of responding to a disabled vessel. No other tugs, for instance, those engaged in towing barges, will be considered by the Model as potential tugs of opportunity.

8.3 Transit Route and Time Calculation

After the Model identifies the location of all assist and escort tugs at the time of the LOP, the Model calculates a transit time dataset for each potential tug of opportunity and ERTV. The Model generates the transit time dataset using a custom Python script and ESRI ArcGIS spatial analysis tools. The Model assumes the tug travels at an average speed of 10 knots and will take the shortest feasible route from the tug's location to where the interception point with the drifting ship is plotted.

8.4 Interception of Drifting Ship

The Model determines the interception point by comparing the disabled vessel's drift trajectory to the tug's transit time dataset. The Model identifies the tug transit time to all points along the disabled vessel's drift trajectory. Since the tug must arrive such that there is sufficient time to connect and control before grounding, the Model adds the tug's time to connect and time to control to its transit times. The model identifies the earliest point on the drift trajectory where a tug could arrive in time for a save.

The Model uses the following assumptions for tug rescue:

- Tug time to connect: 15 minutes
- Tug time to control of disabled vessel: 15 minutes

8.5 ERTV

An ERTV has a 20-minute mobilization time added to its transit from the stationing location to point of interception with the drifting ship. The 20-minute mobilization time is the planning standard for the existing ERTV in Neah Bay as defined in RCW 88.46.135 – 1(a). The VRAM evaluates ERTV rescue from the existing ERTV staging location at Neah Bay and 6 additional locations, suggested in Nuka Research and Planning Group's 2021 study of vessel drift and response analysis (Robertson et al. 2021) (Figure 9). Other than the mobilization time, ERTVs have the same response capabilities as tugs of opportunity described above.

Figure 9: Map of ERTV locations

8.6 Tethering

Modeled escort tugs can be tethered or untethered. Tethering refers to the practice of escorting a ship with a towline connected. If the escort is untethered, the time to save an escorted vessel is 30 minutes. That value is the sum of time to connect and time to control. If an escort is tethered the time to save is 15 minutes, as only the time to control applies.

8.7 Model Output for Loss of Propulsion Events

The end result for every loss of propulsion event is a series of simulated and calculated values. Taking the example illustrated in Figure 8, the Model would produce the following output:

Table 35: Model output examples

Model Output	Without initial turn	With Initial turn
Time to drift grounding	489 minutes	402 minutes
Time to rescue, escorted without tethering	30 minutes	30 minutes
Time to rescue, escorted with tethering	15 minutes	15 minutes
Time to rescue, ERTV (Anacortes)[2]	228 minutes	279 minutes
Time to rescue, ERTV (DeltaPort)[2]	315 minutes	358 minutes
Time to rescue, ERTV (Neah Bay)[2]	351 minutes	322 minutes
Time to rescue, ERTV (Port Angeles)[2]	170 minutes	149 minutes
Time to rescue, ERTV (Roche Harbor)[2]	125 minutes	159 minutes
Time to rescue, ERTV (Sidney)[2]	158 minutes	182 minutes
Time to rescue, ERTV (Victoria)[2]	102 minutes	93 minutes
Time to rescue, closest tug of opportunity[3]	152 minutes	130 minutes
Self-repair time	37 minutes	37 minutes
Emergency anchoring	Success (after 470 minutes adrift)	Success (after 347 minutes adrift)
Oil at risk volume	1,319,302 gallons	1,319,302 gallons
Oil spill volume for drift grounding	4,020 gallons	4,020 gallons

Figure 10 displays the location of tugs of opportunity in the example from Figure 8. Figure 11 illustrates the earliest points along the drift trajectories that the ERTVs and closest tug of opportunity would arrive.

[2] Rescue time for ERTV includes mobilization time, time to connect, and time to control.

[3] Rescue time for tug of opportunity includes time to connect and time to control. Hypothetical tug location is based on the location of the closest tug to the historical vessel when it experienced a hypothetical loss of propulsion event.

Figure 10: Map showing tugs of opportunity when loss of propulsion occurs

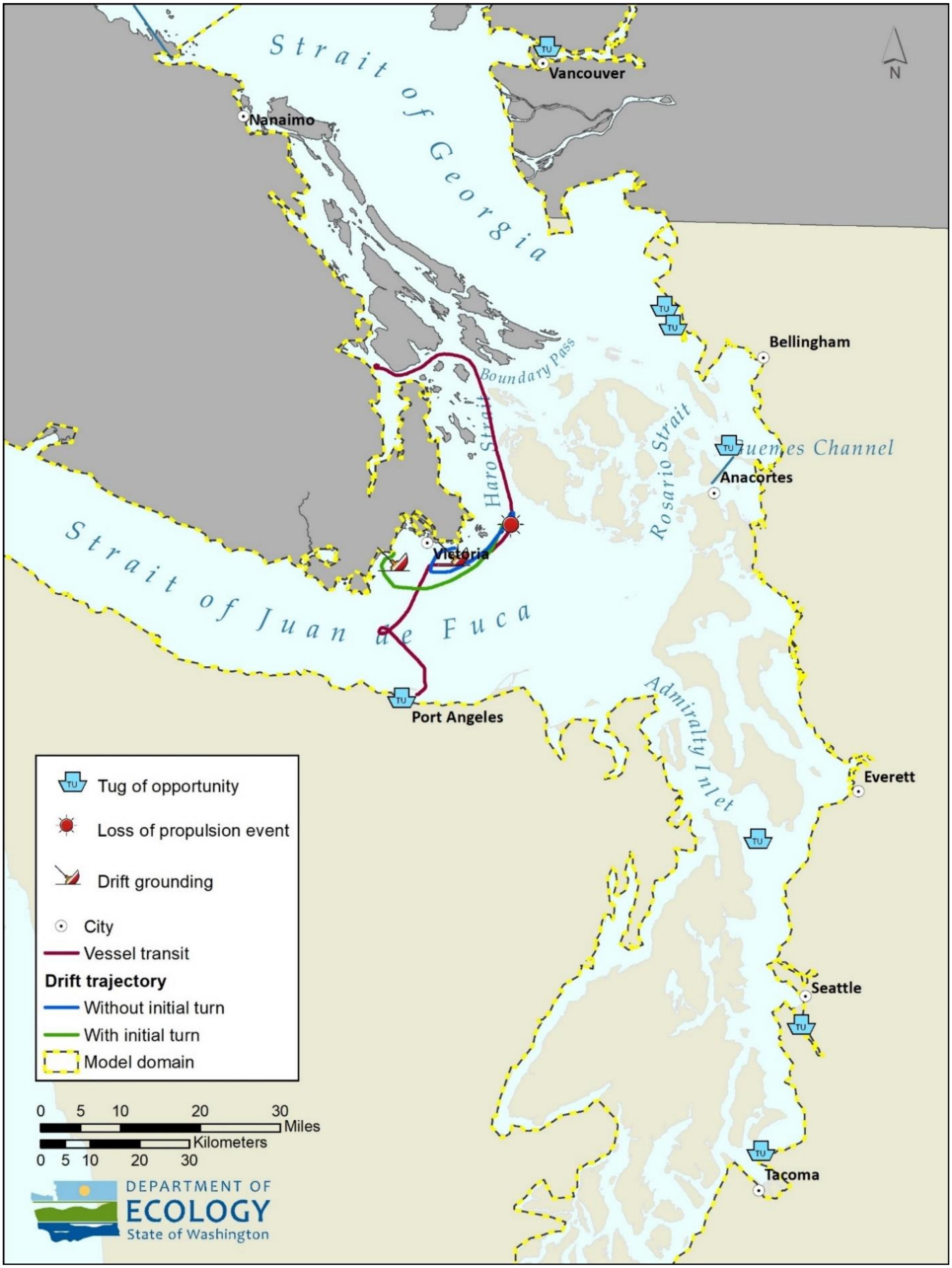
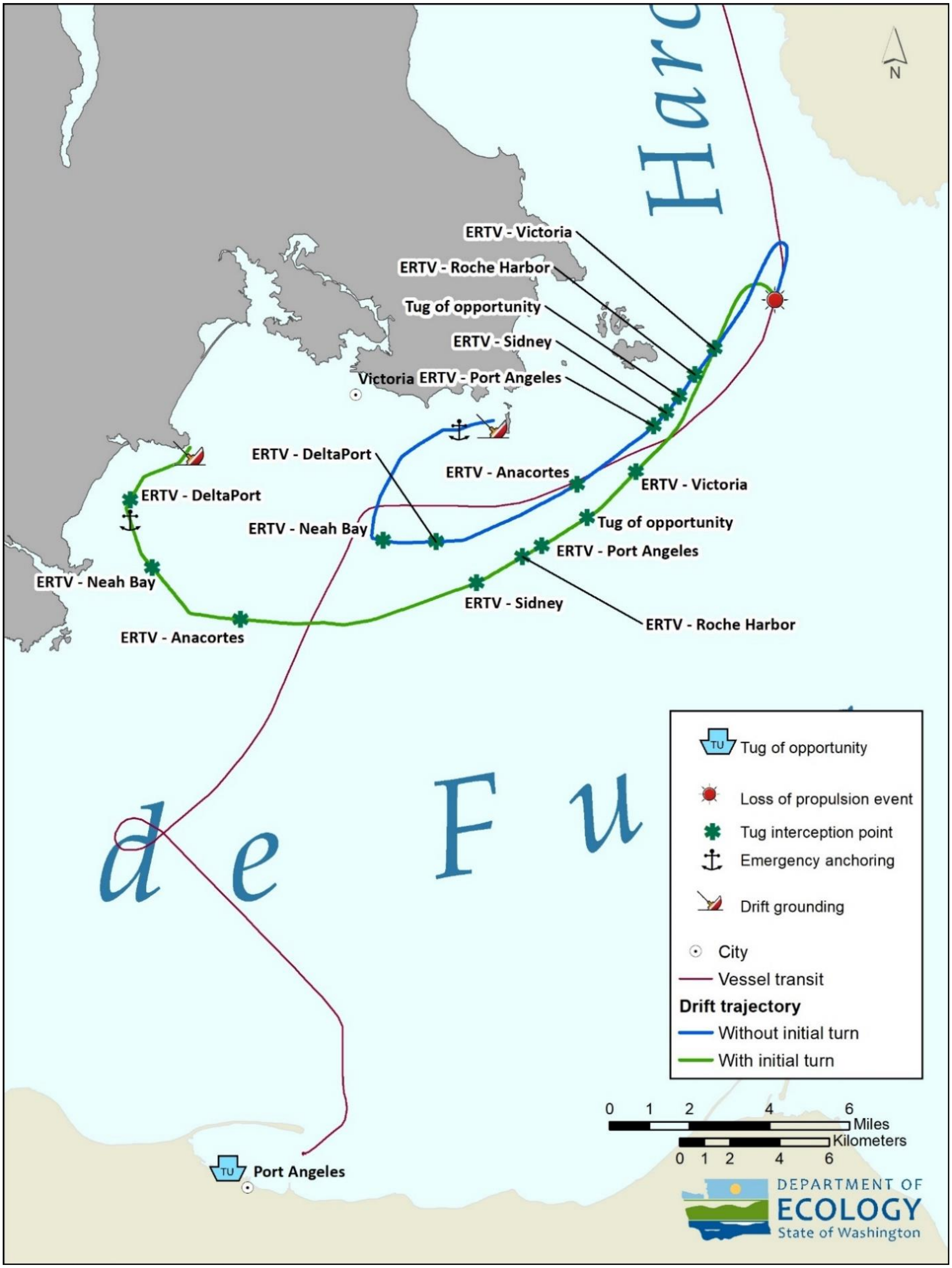


Figure 11: Map showing rescue tug interception points along drift trajectories



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