Emergency Towing Vessel Needs Assessment

September 2018

Clear Seas
CENTRE FOR RESPONSIBLE MARINE SHIPPING

About Us

Clear Seas Centre for Responsible Marine Shipping is an independent, not-for-profit research centre that provides impartial and fact-based information about marine shipping in Canada.

Led by a Board of Directors and advised by a Research Advisory Committee, Clear Seas' work focuses on identifying and sharing best practices for safe and sustainable marine shipping in Canada, encompassing the human, environmental and economic impacts of the shipping industry.

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About this Report

This report presents the results of an emergency towing vessel needs assessment for high windage and large ships, undertaken by Vard Marine Inc. (VARD) on behalf of Clear Seas Centre for Responsible Marine Shipping (Clear Seas). This study is part of the Marine Transportation Corridors project sponsored by Clear Seas to provide stakeholders, interested parties and responsible agencies with an understanding of the risks and issues involved in responding to disabled ships, particularly off the Pacific Coast of Canada.

Board of Directors of Clear Seas Centre for Responsible Marine Shipping

Message from the Executive Director

When a commercial ship is disabled and drifting offshore an effective emergency response requires towing assets with sufficient capabilities to be able to render useful assistance. The emergency towing vessel (ETV) must be able to arrive on scene in a timely manner, successfully attach a tow line, and have sufficient power to tow the disabled ship to a safe location for assessment and repair.

This report, the second element of the Marine Transportation Corridors Project, contains the results of a study commissioned by Clear Seas and conducted by Vard Marine Inc. of Ottawa, to examine the capabilities which a single ETV should have to be able to render assistance effectively to a disabled ship drifting onto Canada's Pacific coast.

It is intended to inform decision makers, response professionals and the public regarding the extensive capabilities that are required to be able to respond to emergency towing scenarios in the North Pacific Ocean.

Clear Seas' *Vessel Drift and Response Analysis for Canada's Pacific Coast* study published in March 2018 examined the risk that a ship which has become disabled due to engineering breakdown, collision or other cause could drift aground on Canada's Pacific coast before help arrives. Inspired in part by the 2014 incidents of the *M/V Simushir* ship-drift and emergency tow off of Haida Gwaii, British Columbia and *M/V John I* ship-grounding at Rose-Blanche, Newfoundland, this study demonstrated that significant reductions to the risk profile of Canada's Pacific coast could be achieved through the acquisition and deployment of rescue assets (referred to as ETVs or more commonly as tugs). The study noted that while such occurrences are relatively rare events, they could entail significant impacts.

As a follow-on to that study, the current report describes what that "help" ought to be able to do. It describes the characteristics that an ETV requires to be effective in assisting seven different types of ships that commonly operate off the British Columbia coast—whether bound for Canadian ports or engaged in passage between other countries.

The seven ship types were selected because they are representative of current and future merchant traffic off Canada's Pacific coast or because they tend to have large windage areas (ship area above the waterline) and therefore are more prone to high wind-driven drift rates than other ship types. Analysis conducted for Clear Seas' *Vessel Drift and Response Analysis for Canada's Pacific Coast* study indicates that the load placed on a disabled ship by wind has by far the most impact on its drift speed and trajectory. Ships with high windage are therefore the most susceptible to accelerated drift rates and potential grounding if disabled. Their large size and profiles also make them more difficult to take and manoeuvre under tow.

The study does not address the probability of a ship suffering a breakdown or accident; the selection of these ships is not meant to imply anything regarding their reliability. It is recognized that these are very infrequent events; however, the *Simushir* and *John I* incidents and also the recent *MOL Prestige* (2018) and *Laura Maersk* (2017) ship-drift events in the North Pacific, both of which were prevented from grounding by emergency towing assets, indicate clearly that emergency towing capability contributes to the security and sustainability of a marine transportation network vital to the welfare and prosperity of Canada and its trading partners. This report answers the question: How capable do these tugs have to be to operate in the harsh conditions common off Canada's Pacific coast and be effective in response to ship drift events?

While other studies have examined tug requirements for specific ships that were associated with specific projects, or extreme weather conditions and smaller ships, these studies did not examine the worst-case scenarios with respect to large ships and severe weather. This study examines specifically the characteristics that make for an effective rescue tug in the harsh environment of Canada's Pacific EEZ (exclusive economic zone). The analysis uses historical weather data and computer modelling to determine the capabilities required to respond in different meteorological and ocean conditions. The report goes beyond simply articulating the propulsion power and bollard pull needs and highlights other characteristics such as vessel reach and endurance as well as human factors. This analysis does not consider the scenario of two or more ETVs responding to a disabled ship; a multiple ETV response is a complex scenario that requires further consideration.

The analysis examines five weather cases ranging from the 50th to the 99th percentiles and establishes that ETV requirements vary significantly with the intensity of weather. For instance, some of the requirements to be effective in 99th percentile weather conditions can be more than 50% greater than the requirements at the 95th percentile. Although the worst-case scenario of severe weather and very large, disabled ships has a low likelihood of occurrence, understanding the requirements for response is important for planning and decision-making purposes. The report concludes that effective ETVs need to be big, powerful vessels of such size and seakeeping ability that they could be used for other purposes such as sovereignty operations or research in addition to emergency towing.

In this report, the study of a range of ship types is valuable not only to assess the different ETV capabilities required, but also to assess the differing abilities of large ships to receive and sustain a tow. Only tankers are required by International Maritime Organization regulations to have bollard attachment points with sufficient strength to sustain an emergency tow. Most other ships have attachment points suitable for berthing operations which may be insufficient for emergency open-ocean conditions.

The results presented in this report are drawn from traffic transiting Canada's Pacific coast, but the conclusions are relevant elsewhere in Canada, as similar types of ships encounter comparable wind and wave conditions in the Atlantic region.

Executive Summary

This report presents the results of an emergency towing needs assessment for high windage and large ships, undertaken by Vard Marine Inc. (VARD) on behalf of Clear Seas Centre for Responsible Marine Shipping (Clear Seas). This study is part of the Marine Transportation Corridors project sponsored by Clear Seas to provide stakeholders, interested parties and responsible agencies with an understanding of the risks and issues involved in responding to disabled ships, particularly off the Pacific coast of Canada.

The work involved three main tasks:

1. Collecting data to analyze selected ships of interest.
2. Assessing emergency towing capability requirements for these ships.
3. Developing design and operational requirements for potential emergency response vessels.

Seven ships were selected, to represent container ships, LNG carriers, vehicle carriers, passenger ships (cruise ships), bulk carriers and oil tankers. The ships selected either operate in Canadian coastal waters or are expected to do so in the near future. The ships selected are intended to illustrate worst-case or near worst-case candidates for emergency towing scenarios. Worst-case scenarios, from an emergency towing perspective, are determined by severe weather conditions combined with ships with large windage (or ship area above water). The analysis used Pacific coast wind and wave data of varying severity to identify towing needs for different scenarios.

Towing force requirements, measured as bollard pull, were analyzed for turning the ship into the wind, holding position, and making slow progress upwind and into head seas. The turning manoeuver was simulated to show the time required and the drift downwind for the operation. Maximum forces were then matched to the capabilities required by an emergency towing vessel (ETV), taking into account the loss of towing efficiency in higher sea states. An illustration of the results is shown in Figure 1; in the worst case scenario, these forces can exceed 200 tonnes for a very large, loaded container ship.

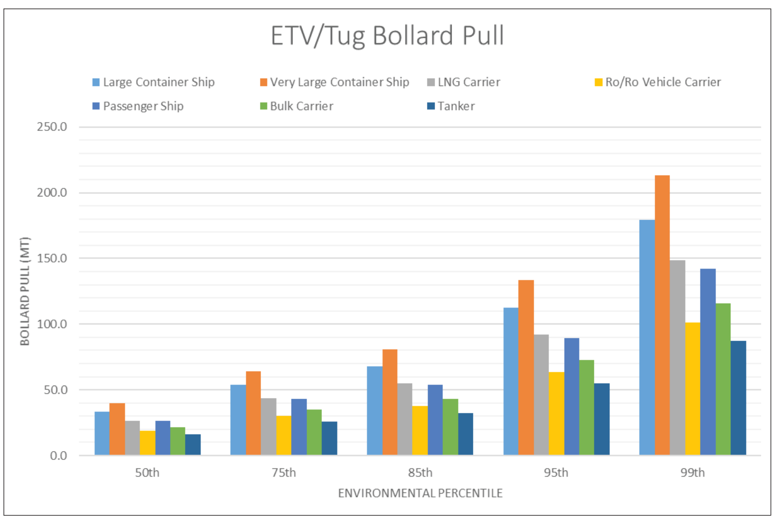

Figure 1. ETV bollard pull required in response to weather conditions

The report describes desirable characteristics for ETVs, emphasizing the need to have relatively large and powerful vessels equipped with trained crew and sufficient equipment to cope with Pacific coast conditions. It also notes that ships other than tankers are not required by regulation to have deck fittings or towing equipment of sufficient strength for a worst-case emergency towing situation.

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Emergency Towing Vessel Needs Assessment

1.0 Introduction

This report presents the results of an emergency towing vessel needs assessment for high windage and large ships, undertaken by Vard Marine Inc. (VARD) on behalf of Clear Seas Centre for Responsible Marine Shipping (Clear Seas). This study is one of a series sponsored by Clear Seas to provide stakeholders, interested parties and responsible agencies with an understanding of the risks and issues involved in responding to disabled ships, particularly off the Pacific coast of Canada. This study complements the analysis contained in Clear Seas' "Vessel Drift and Response Analysis for Canada's Pacific Coast" report and provides insight into what is needed to save a disabled ship from drifting aground. Specifically, this study determines what towing capabilities and operating capacities are potentially needed by a single Emergency Towing Vessel (ETV) or rescue tug responding to an emergency towing situation. The merchant ships selected by Clear Seas for analysis would represent worst-case or near worst-case scenarios if disabled in severe weather conditions, based on current and anticipated ship traffic in Canada's territorial waters and economic exclusion zone (EEZ).

1.1 Purpose and Scope

The purpose of this emergency towing vessel needs assessment was to determine the characteristics a tug or offshore vessel would require to effectively respond to the worst-case or near-worst case scenario of a large, high windage ship disabled and drifting toward Canada's Pacific coast in severe wind and wave conditions. The results from this analysis and the larger Marine Transportation Corridors project may inform policy decisions about managing vessel traffic, selecting and stationing rescue assets, and other mitigation measures aimed at reducing the potential for accidents along Canada's Pacific coast.

1.2 Structure and Organization

The structure of this report reflects the three main tasks VARD completed:

1. Collecting data to analyze selected ships of interest.
2. Assessing emergency towing capability requirements for these ships.
3. Developing design and operational requirements for potential emergency response vessels.

Section 2 includes detailed information for the selected ship types, the wind and wave conditions considered in the analysis, and towing efficiency considerations as well as the capabilities of the selected ship types to receive and sustain a tow. Section 3 contains the methodology used and the results of the analysis conducted to simulate steady state and turning sequences for the selected ship types under the five wind and wave scenarios. Section 4 describes the considerations applied to determine ETV requirements, such as ship size, speed, endurance, and range; the propulsion system, tow handling equipment; and crew training and other factors affecting emergency response. Section 5 summarizes the findings and the appendices provide detailed simulation results.

The units used to present data in this report follow customary practice; most forces and towing equipment capacities are given in kilonewtons (kN), while towing vessel bollard pulls and tow winch capabilities are given in metric tonnes (tonnes). Where it is necessary for clarity, both values are presented together. Conversions from one to the other use the relationship 9.81kN = 1 tonne of 'bollard pull'.

2.0 Data Collection

2.1 Ships of Interest

Seven ships of interest were selected for assessment. Six of these are among the largest ships of their respective types which call at Western Canadian ports or may do so in future based on current and projected ship traffic patterns:

- Large Container Ship (14,500 TEU or twenty-foot equivalent unit)
- Very Large Container Ship (21,413 TEU)
- LNG Carrier (~265,000 m^3)
- Vehicle Carrier (138,000 m^3)
- Passenger Ship (~4,000 passengers)
- Bulk Carrier (221,478 m^3)
- Aframax Tanker (124,167 m^3)

The selections should not be taken to imply that these reference ships are themselves considered as at high risk for any incident—they are purely illustrative. These ships are shown in Figure 2 through Figure 8. A summary of their particulars is given in Table 1.

Figure 2. 'Large Container Ship' [Image courtesy of Claus Gaser, MarineTraffic.com]

Figure 3. 'Very Large Container Ship' [Image courtesy of KARooL, MarineTraffic.com]

Figure 4. 'LNG Carrier' [Image courtesy of MarineTraffic.com]

Figure 5. 'Vehicle Carrier' [Image courtesy of WW, MarineTraffic.com]

Figure 6. 'Passenger Ship' [Image courtesy of Wolfgang Plapp, MarineTraffic.com]

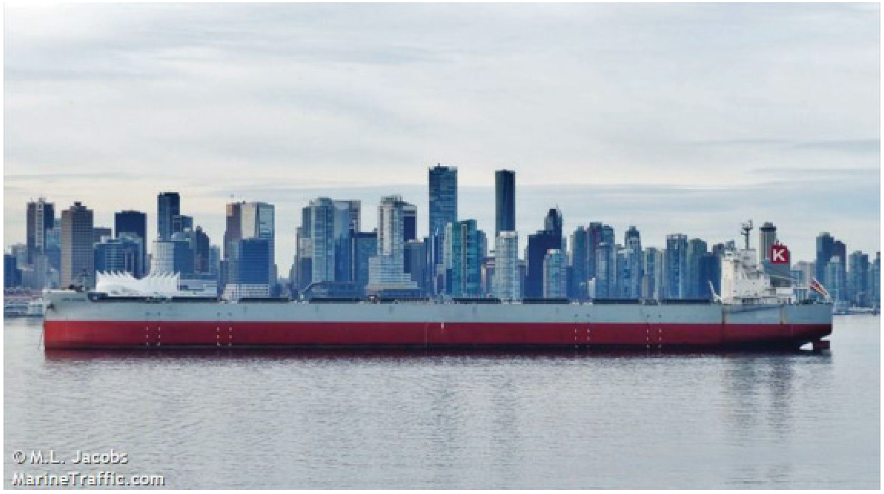

Figure 7. ‘Bulk Carrier’ [Image courtesy of M.L. Jacobs, MarineTraffic.com]

Figure 8. ‘Aframax Tanker’ [Image courtesy A Mackinnon, MarineTraffic.com]

Table 1. Particulars of ships used in analysis

Ship Details	Ship #1 Large Container Ship	Ship #2 Very Large Container Ship	Ship #3 LNG Carrier	Ship #4 Vehicle Carrier	Ship #5 Passenger Ship	Ship #6 Bulk Carrier	Ship #7 Aframax Tanker
Type of Ship	Container Ship	Container Ship	LNG Carrier (Q-Max)	Vehicle Carrier	Passenger Ship	Bulk Carrier	Aframax Tanker
Size	14,500 TEU	21,413 TEU	~265,000 m^3	138,000 m^3	~4,000 passengers	221,478 m^3	124,167 m^3
Year Built	2017	2017	2008	2011	2018	2014	2005
Length Overall (m)	366	399.9	345.3	265	329.8	299	249.9
Beam (m)	51	58.8	53.83	32.27	41.5	50	43.9
Gross Tonnage (tonnes)	154,300	210,890	163,922	75,251	167,800	107,054	62,929
Deadweight (tonnes)	153,811	191,422	130,102	41,820	11,700	209,996	115,525
Comment	Largest container ship to call on a Canadian Port (Prince Rupert, Nov 2017).	World's largest container ship, not currently operating in Canadian waters.	Largest LNG carrier identified in "LNG Canada" TERMPOL Review.	MARK V Class is one of the largest vehicle carriers in operation today.	Largest passenger ship to call in Vancouver in 2018.	Currently the largest bulk carrier to call on Canada's Pacific Ports.	Typical of large tankers entering the Port of Vancouver.

2.2 Data Sources and Assumptions

2.2.1 Ships

The methodology used to conduct the scenario analysis is described in Section 3.0. The scenarios require data for each ship, including measurements for the following characteristics:

- Length Between Perpendiculars
- Length Overall
- Length Water Line
- Draught Fore and Aft
- Breadth
- Projected Area (Front View) Above and Below Water
- Projected Area (Profile View) Above and Below Water
- Centroid of the Profile Area Above Water

While much of this information is publicly available, the areas and centroid values, along with some of the lengths, had to be estimated. A set of outline sketches was developed for each ship to support the estimation of these values, working from photographs and from typical hull form parameters for each ship type. These sketches are shown in summary versions in Figure 9. Features such as shafts, rudders and bulbous bows were included, again using typical values for the ship type. Areas and centroids were calculated using AutoCAD functions. All of this information has been included in this report (refer to Table 4), allowing for future researchers to either replicate the work or to use more accurate numbers as and if these become available. The level of accuracy achieved in the current estimate is considered adequate for the needs of this project.

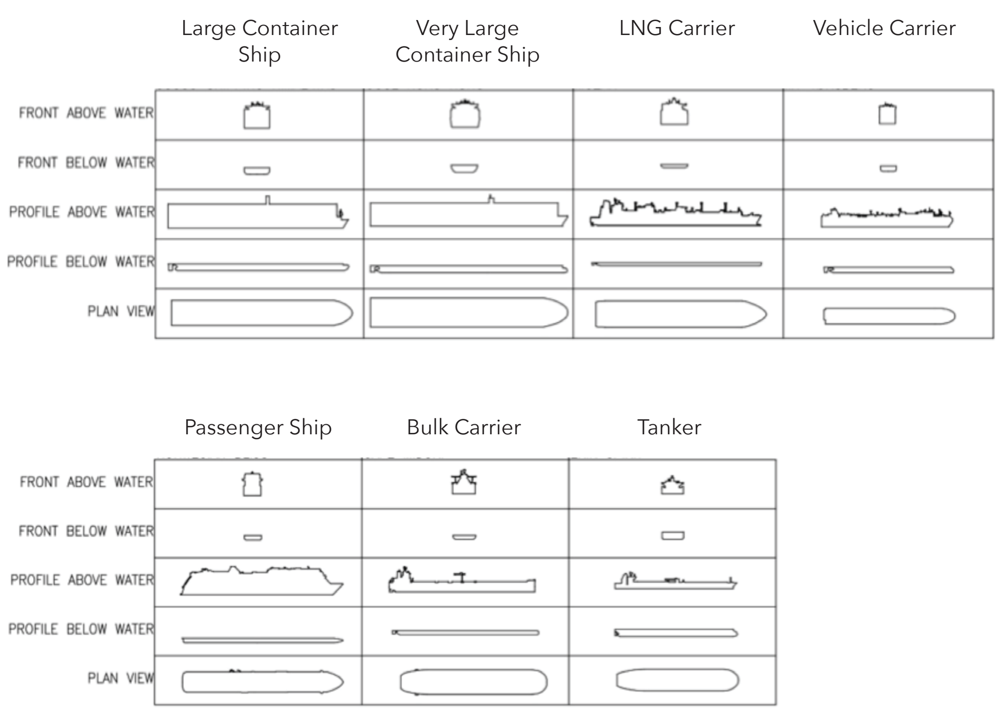

Figure 9. All ship views

2.2.2 Metocean Conditions

This study includes combinations of wind and wave conditions based on environmental statistics previously gathered for waters off the Canadian Pacific coast. These are based on year-round statistics considering all environmental directions, drawn from Environment and Climate Change Canada's weather buoy number 46205 located north-west of Haida Gwaii (refer to Figure 10), which represents one of the most severe locations along the Pacific coast. The conditions selected for this study correspond to the specified percentiles for wind and waves provided in Table 2, and these percentiles are quoted throughout the report. However, the actual percentiles associated with given environmental conditions will vary by geographic region, direction, and season, and may be subject to climate change in the future.

Table 2. Metocean conditions for the towing needs assessment

	50th Percentile	75th Percentile	85th Percentile	95th Percentile	99th Percentile
Mean Wind Speed (kn)	14	19	22	27	33
Mean Significant Wave Height (m)	2.3	3.4	4.1	5.6	7.8
Modal Wave Period (s)	10.7	12.8	14.2	16	18.3

It is typical to see partial, but not complete, correlation between wind and wave conditions. For example, wind-driven waves arise during a storm. However, the wave height in a storm typically lags behind the wind speed, and an underlying swell is not typically correlated with wind. Therefore, for the purposes of this analysis, the application of a given percentile wind speed with the same percentile waves is an imperfect, but reasonable, approximation.

Figure 10 shows how the wind conditions vary across the study area. These year-round wind roses were developed for Clear Seas' "Vessel Drift and Response Analysis for Canada's Pacific Coast" and more detailed information can be found in that report. In Figure 10, the wind roses show the influence of directionality due to a tendency for the most severe winds to blow nearly parallel to the shoreline. From the perspective of emergency towing, open-ocean towing and towing near a shore sheltered from the wind present different requirements and challenges. The data show that in many emergency scenarios there will be ample sea room for open-ocean towing. However, if considering the subset of scenarios in which there is limited sea room (i.e. near a sheltered shore), it would be important to re-examine the environmental statistics. From Figure 10 it can be inferred that, if the environmental data were restricted to the directions resulting in sheltered conditions (i.e. generally from the SW in open ocean, or from most directions in the straits), the conditions having a 1% chance of being exceeded (the 99th percentile case) would be less severe than the 99th percentile case used in this study.

A 1 knot (kn) current has been added for some of the analyses and is also assumed to be aligned with the wind and waves. This is much less probable, but as discussed in Section 3.0, the influence on most results is relatively minor.

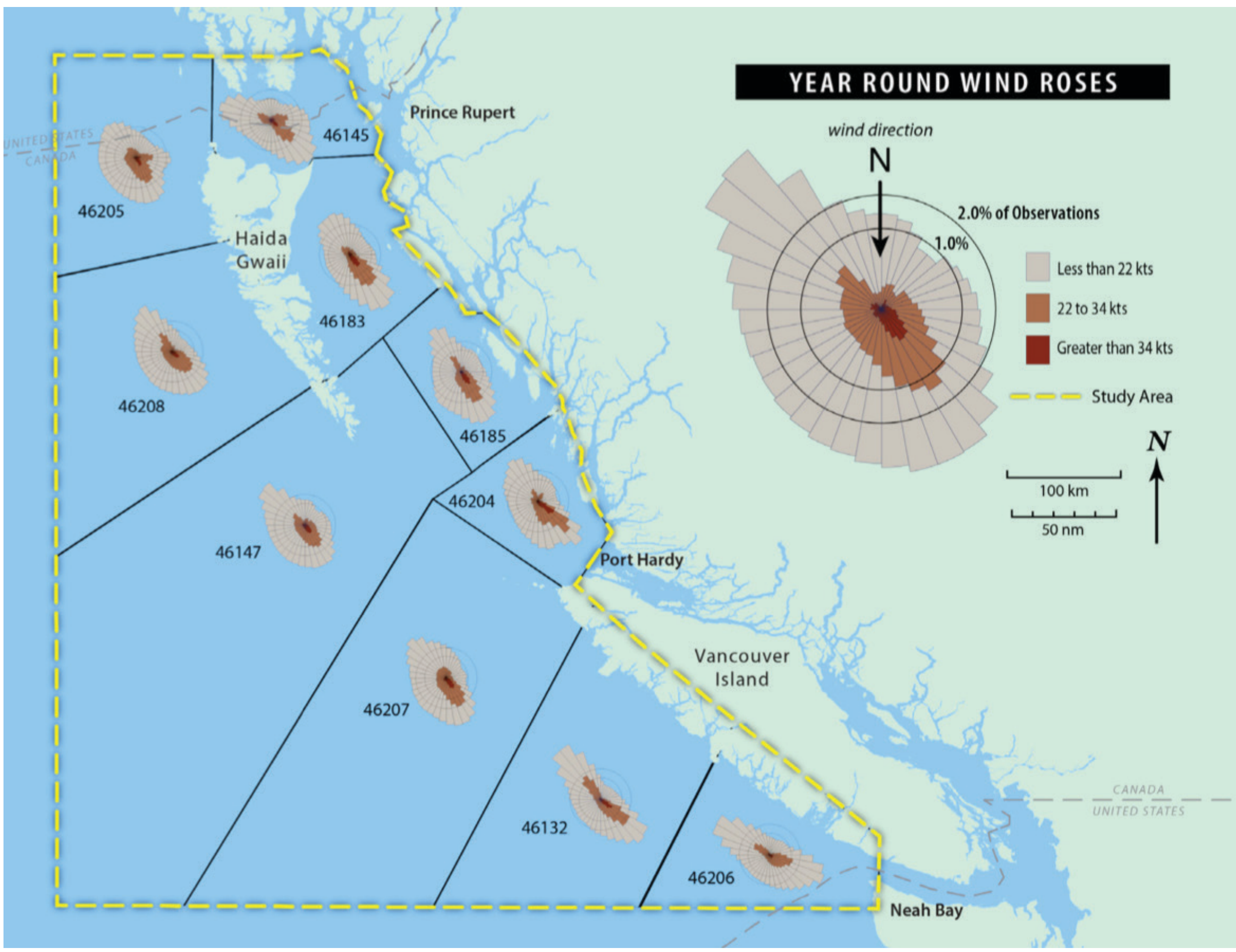

Figure 10. Wind speed statistics, by location and direction

2.3 Additional Considerations

2.3.1 Tug and Emergency Towing Vessel Towing Efficiency

The nominal or theoretical bollard pull (BP) of any emergency towing vessel (ETV) or other ship is an idealized value, measured in calm conditions pulling on a bollard fixed to the shore. Often the value is an analytical estimate, as the test conditions can be difficult to set up.

The effective BP is typically lower than the nominal BP, reduced by real-world conditions and by the tug's own self-propulsion needs. Vessel motion reduces the thrust that the propulsors can generate and the intended direction of motion.

This is well known in a qualitative sense, but there is little good data to support the selection of efficiency factors, particularly for larger vessels in open ocean conditions. One of the most frequently cited formulations is provided by DNV in its Sea Transport Operations standard and shown below. The equation calculates a "tug efficiency factor" by considering the tug's overall length up to a maximum of 45 m, the tug's expected bollard pull up to a maximum of 100 tonnes, and the wave height between 1 m and 5 m, as shown below:

$$yTE=[80-(18-0.0417 * LOA * \sqrt{(BP-20)} * (Hs-1)/100$$

Where yTE = tug efficiency factor

LOA = overall length; [where LOA=45 m to be used for all vessels over 45 m]

BP = tug bollard pull; [where BP=100 tonnes to be used for all BP>100 tonnes]

$1m \leq Hs \leq 5m$: [where Hs=Wave Height]

Applying this formula would give a tug efficiency factor of 80% for a 100 tonne BP tug of 60 m length operating in 1 m wave height or of 66% in 5 m wave height.

These values are lower than those cited in other studies (see for example RAL 2014 and Sasi 2016), which give efficiencies of around 75% for this vessel in higher sea states than 5 m. The differences in results emphasize the uncertainties involved, which themselves increase with increasing sea state. The values that have been included in our analyses are shown in Figure 11; these values are based on averages drawn from published information.

Efficiency estimates were generated for a significant wave height of 2 m (80%), 5 m (75%), and 8 m (60%), encompassing all five significant wave heights specified for this analysis. Once plotted, these points were fitted with a quadratic trendline. Tug efficiency factors were then interpolated from the graph for each of the five environmental conditions determined by Clear Seas.

The evaluation of tug efficiency in varying sea states is an area in which more research and data collection would be very beneficial.

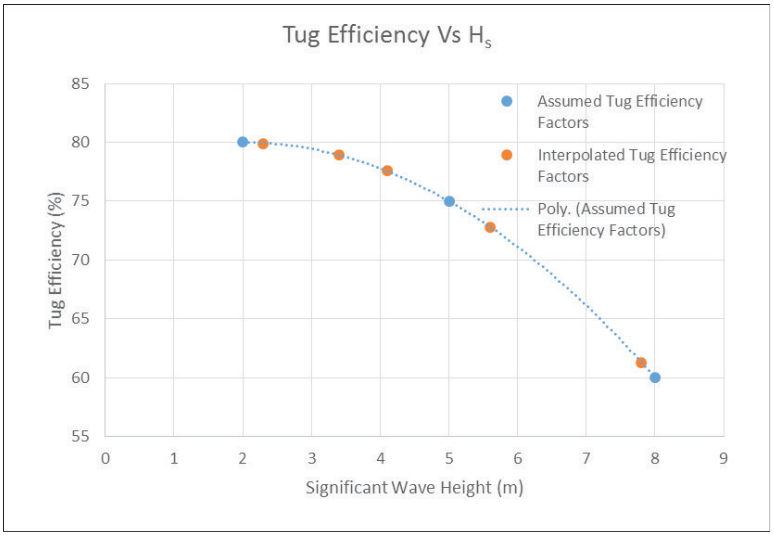

Figure 11. Tug efficiency factors

2.3.2 Towed Ship Capabilities

The ability of the ship to receive and sustain a tow line also needs to be considered.

International concerns over tanker spills due to groundings and other incidents has resulted in tankers being subjected to a variety of special requirements by the International Maritime Organization (IMO). Tankers are required by the IMO's SOLAS Convention to be fitted with strong points for towing line connection and with towing arrangements that can be deployed easily and rapidly in emergencies. The requirements, which are defined in IMO Circular MSC 35(63), are summarized in Table 3.

Table 3. SOLAS tanker emergency towing gear

Item	Forward	Aft	Strength Requirements (SWL)
Pick-up gear	Optional	Yes	
Towing pennant	Optional	Yes	1000 or 2000 kN[1]
Chafing gear	Yes	Depending on design	1000 or 2000 kN[1]
Fairlead	Yes	Yes	1000 or 2000 kN[1]
Strongpoint	Yes	Yes	1000 or 2000 kN[1]
Roller pedestal	Yes	Depending on design	

Note 1. Use '1000 kN' value for tankers 20,000 DWT to 50,000 DWT; Use '2000 kN' value for tankers >50,000 DWT

Note 2. 9.81 kN = 1 tonne of bollard pull

The strength values in Table 3 are specified as being half of the ultimate strength; i.e. a large tanker is required to be able to handle an expected tow force of 2000 kN or just over 200 tonnes, close to three times the capacity expected for other ship types.

Non-tanker ship types are required to have towing plans, but the level of capacity is not specified. The capacities of bollards, winches and capstans are generally based on the equipment number for anchoring and mooring, which itself is set on the basis of an assumed 25 m/s (50 kn) wind speed and 2.5 m/s (5 kn) current.

The "equipment number" (EN) is a parameter to determine the size and number of anchors and cables for a new ship, including bollards and other towing equipment. The EN is intended for the temporary mooring of a vessel within a harbour or sheltered area, such as when the vessel is awaiting berth. The EN is not an indicator of a ship's ability to sustain a tow in rough weather. Most operators are unlikely to know how to interpret the EN or the associated load capacities. The installed equipment is rarely tested; approval is based on drawings and limited analysis. In-service testing of bollard strength is rare. EN calculation is standardized by the International Association of Classification Societies (IACS), but its application differs somewhat among class societies. As an example, under Lloyd's Register rules, towlines for large ships (i.e. the ships in this study) are advised to have a minimum breaking strength of 1471 kN (150 tonnes) and towing points must have a safe working load that matches this breaking strength.

Two of the vessels ('large container ship" and "very large container ship") analyzed in the 99th percentile weather conditions would have experienced an estimated bollard pull force greater than the advised minimum breaking strength rating of 150 tonnes; however, this does not indicate that these vessels would be unable to receive and sustain an emergency tow in a 99th percentile scenario. These results simply indicate that the tow force was greater than the minimum recommended breaking strength. More vessel-specific information would be required to make any assessment related to the likelihood of failure in an extreme weather situation.

Alaska has implemented a variety of measures to enhance its ability to respond to incidents off the coast of the Aleutian Islands, which are close to many major shipping routes. Amongst these is the development and storage at various locations of emergency towing kits, which can be deployed either by helicopter or by ETV. The kit is illustrated in Figure 12; more information on its deployment can be found at http://dec.alaska.gov/media/8131/ets-after-action-report.pdf. The Canadian Coast Guard is in the process of acquiring a number of these kits under the Government of Canada's Ocean Protection Plan, and also investing in new ETV capability.

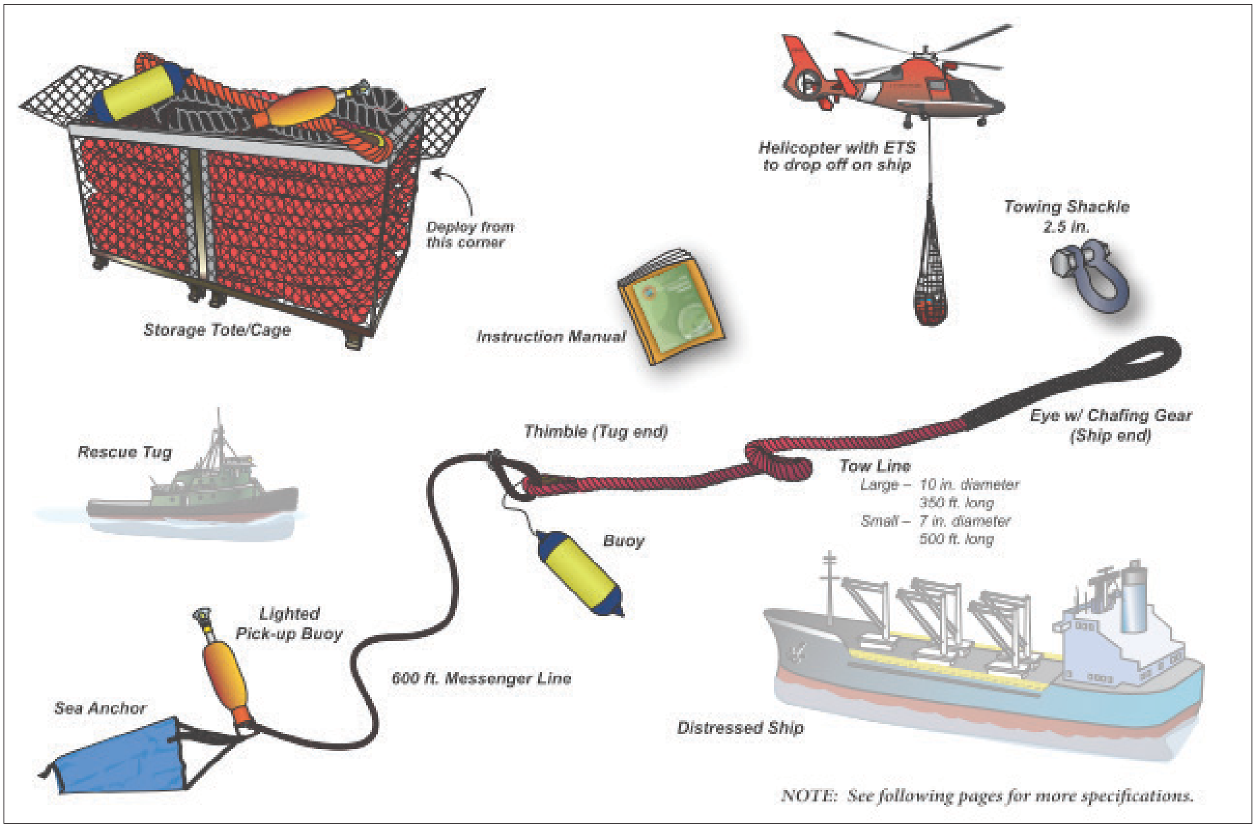

Figure 12. Aleutian Islands emergency towing kits

Other similar deployable towing kits have also been developed, for example on behalf of the Alaska Maritime Prevention and Response Network. Links are included in Section 6.0.

3.0 Analysis and Assessment

The analysis considered a number of force systems that may act on a disabled ship. Normally, after loss of power, most ships will drift parallel to the prevailing wind and waves (beam sea), subjecting the largest areas of the ship to wind and wave forces, resulting in high drift speeds. VARD calculated the beam sea forces but not the drift speeds under this project, as drift speeds are addressed in Clear Seas' "Vessel Drift and Response Analysis for Canada's Pacific Coast" report (Clear Seas/Nuka, 2018).

To arrest the ship, an ETV will need to turn the disabled ship perpendicular to (head or stern facing) the wind and waves, and then tow it away from danger and towards a safe refuge. Bringing the ship under control by turning it and overcoming its downwind inertia has to be considered dynamically, as the force system changes constantly through the turning process (further described in Section 3.1.2).

Once turned, the towing force can be treated quasi-statically. The project has considered two levels of force: one to hold position in the prevailing conditions and the other to make slow progress upwind (assumed in these analyses to be at 1 kn). As discussed in Section 2.3.1, all these forces must be supplied by an ETV that loses towing efficiency as weather conditions worsen.

3.1 Methodologies

3.1.1 Steady State

The force and power analysis was carried out by applying wind, wave, and current forces as calculated with DPLab, a software developed by Force Technologies of Denmark. DPLab was developed as a dynamic positioning prediction program intended primarily for determining the limiting environmental conditions in which a dynamically positioned ship can maintain station and heading. An important capability of the program is the ability to predict the steady environmental forces acting on a ship. This is done using environmental force coefficients included in the program's internal library of example ships for which more detailed model tests or analyses were completed.

While DPLab's development was not targeted at towing force prediction, its methodologies are directly applicable to the work required, and the values generated can easily be duplicated or extended to other ships and ship types. The force coefficients are not directly relevant to all the ship types covered by the project, but most of the approximations involved are considered small in comparison to other uncertainties and assumptions involved in the work. DPLab includes the ability to enter values directly, where the user has better data than the default values included in the program libraries. One aspect that was adjusted for greater accuracy was the wind coefficients, where VARD generated input values based on the ship sketch drawings described in Section 2.0.

Figure 13 shows a screenshot of DPLab's data entry screen, in this case for the example of the Large Container Ship.

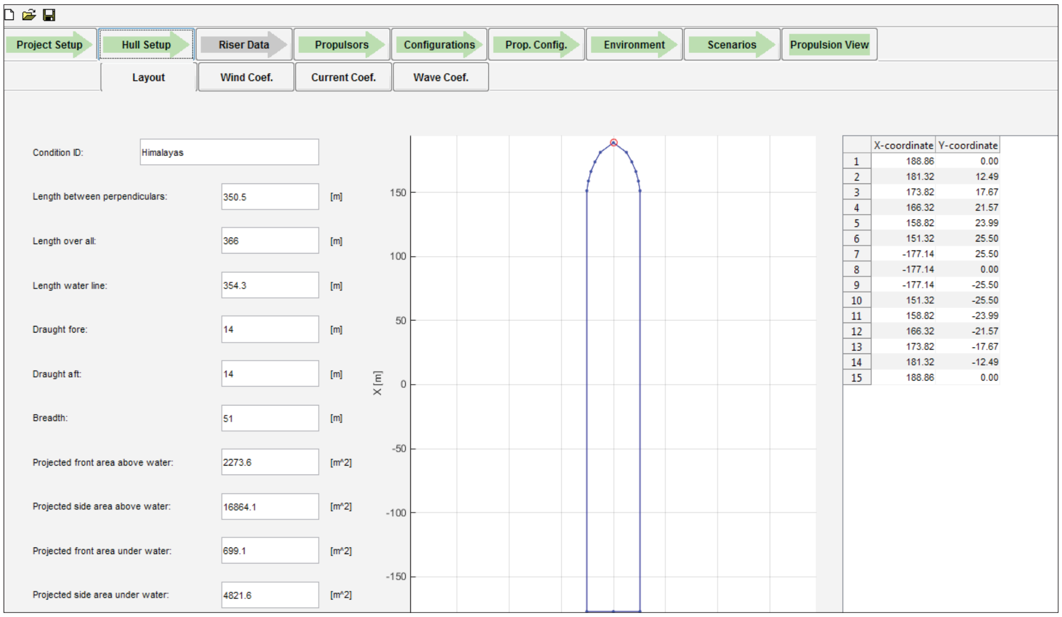

Figure 13. DPLab inputs for Large Container Ship

The forces on ships are affected by loading condition. The analyses aimed to use the worst-case conditions for environmental forces, which in most cases is a lightly loaded ship with high windage areas. For the container ships, the containers themselves form a large part of the windage area, and so the heavily loaded condition is the most severe. For the tankers and bulk carriers, there can also be a significant variation in trim over their loading conditions, and so the analysis examined both a level trim and an extreme trim case. The results were not significantly different, so for consistency all results presented in the main report use the level trim condition.

The input data for all ships used in the DPLab analysis is summarized in Table 4 (for reference, Appendix A provides all data) and includes ship particulars along with information about the loading conditions and windage areas. This information was used in DPLab and in a local spreadsheet to correct for some environmental conditions.

Table 4. DPLab inputs by ship

Particulars	Units	Large Container Ship	Very Large Container Ship	LNG Carrier	Vehicle Carrier	Passenger Ship	Bulk Carrier	Aframax Tanker
Length Between Perpendiculars	m	350.5	383	332	250	300	296	240
Length Overall	m	366	399.9	345.3	265	333.45	299	249.9
Length Water Line	m	354.3	389.4	337	257.8	309.3	299	242.9
Draught Fore	m	14	14.6	6	11	8.4	8.11	14.9
Draught Aft	m	14	14.6	6	11	8.4	8.11	14.9
Breadth	m	51	58.8	53.83	32.27	41.5	50	43.9
Projected Front Area Above Water	m^2	2,273.6	2,680.6	2,201.2	1,172.9	1,516.3	1,474.2	1,049.9
Projected Side Area Above Water	m^2	16,864.1	17,907.0	10,565.9	6,753.5	15,010.1	6826.6	3,739.0
Projected Front Area Below Water	m^2	699.1	707.4	309.5	344.1	293.5	359.4	650.2
Projected Side Area Below Water	m^2	4,821.6	5,662.6	2,010.0	2,786.1	2,737.2	2,389.4	3,667.3
Centroid of Side Area Above Water	m^2	175.3	206.4	159.7	133.0	163.6	140.2	113.9
Loading Condition	–	Fully Loaded	Fully Loaded	Lightly Loaded	Lightly Loaded	Standard Cruising Draught	Lightly Loaded	Fully Loaded
Longitudinal Centroid Reference Point	–	From aft end	From aft end	From aft end	From aft end	From aft end	From aft end	From aft end

DPLab requires coefficients to be loaded for wind, current, and waves. The environmental force coefficients are based on the DPLab library of coefficients for representative ships; the project used the following pre-existing ship attributes "DPLab #107-xxxx2" for both wind and current coefficients, and ship "DPLab #109-xxxx1" for wave drift coefficients (these ships are identified by the numbers shown in the User Manuals). To account for the superstructure position and size, the wind moment coefficients were adjusted based on the longitudinal centroid of the side windage area, as determined from the estimated profile drawing for each ship. The wind moment coefficient adjustment works as a longitudinal shift in the line of action of the wind force vector, such that in a beam wind it passes through the centroid of the windage area. That is,

$$C'_N = C_N + C_Y \frac{LCA'\text{-}LCA}{\mathrm{LOA}}$$

Where:

- C'_N is the adjusted wind moment coefficient,
- C_N and C_Y are the original wind moment and lateral force coefficients from the DPLab library,
- *LOA* is the length overall,
- *LCA'* is the longitudinal centre of area of the profile windage area of the ship,
- *LCA* Is the same quantity for the ship in the DPLab library.

This was calculated as

$$\mathrm{LCA} = LOA\ C_{N,90}/C_{Y,90}$$

where inclusion of ",90" in the subscripts refers to the coefficient values for a beam wind.

The formulae above apply because the non-dimensionalisation of C_N in DPLab includes division by LOA. Table 5 shows an example of the correction table from 0 to 90 degrees for the Large Container Ship. The first four columns were directly pasted from DPLab using #107-xxxx2 from the DPLab wind coefficient repository. The fifth column shows the corrected wind coefficient values. The final column contains data that was saved as a text file to later be imported back into DPLab.

Table 5. Wind coefficient correction

Heading	Cx	Cy	Cn	CnCORR	For DPLab Import File
0	-1.276	-0.008	-0.003	-0.003	0 -1.2760 -0.0082 -0.0032
10	-1.205	-0.143	-0.02	-0.021	10 -1.2045 -0.1429 -0.0214
20	-1.274	-0.307	-0.036	-0.038	20 -1.2741 -0.3071 -0.0382
30	-1.313	-0.486	-0.047	-0.051	30 -1.3129 -0.4864 -0.0506
40	-1.259	-0.676	-0.051	-0.055	40 -1.2592 -0.6761 -0.0553
50	-1.166	-0.826	-0.046	-0.052	50 -1.1663 -0.8259 -0.0517
60	-0.967	-0.981	-0.035	-0.042	60 -0.9665 -0.9806 -0.0415
70	-0.724	-1.089	-0.023	-0.031	70 -0.7243 -1.0887 -0.0311
80	-0.442	-1.121	-0.005	-0.013	80 -0.4423 -1.1207 -0.0128
90	-0.159	-1.112	0.014	0.006	90 -0.1589 -1.1116 0.0057

3.1.2 Turning Simulations

The force required to turn the disabled ship into the weather has been determined via simulations in time. This more advanced technique is necessary because during the turning manoeuvre, the tow force will tend to accelerate the ship, which will cause the ship's velocity through the water to change in time. The hydrodynamic forces associated with the ship's motion while turning influence the remainder of the manoeuvre. This will occur even if the tow line pulls directly into the weather, without attempting cross-wind towing to intentionally develop forward speed. A simple static analysis, as used for the other items above, would require some assumptions regarding the net drift velocity and associated hydrodynamic forces, as well as the point about which yaw moments are calculated. These assumptions would have a dominant effect on such a static analysis, such that different assumed inputs could be used to arbitrarily select any desired output.

The time simulations of turning into the weather have been completed using a VARD in-house simulation methodology which was successfully used for predicting low-speed manoeuvres of other vessels, such as the Canadian Coast Guard Offshore Oceanographic Science Vessel (OOSV). The simulation methodology determines the net force using a methodology based on DPLab: it effectively re-applies the same environmental force coefficients as used in the static analyses to determine the net force on the ship at each instant in the simulation. This includes consideration for the ship's relative motion through the water and air, and the hydrodynamic forces due to the rotation of the ship is determined by extension of the lateral current force coefficients. The net force is used to determine the ship accelerations, motions, and trajectory in the horizontal plane. This includes the influence of hydrodynamic added mass and centripetal effects.

The basic process for the simulations is as follows:

1. Solve for the free drifting condition for the ship before the tow is initiated, including the ship heading and drift velocity. This represents the condition as the tow line is being attached, immediately before the tow vessel begins pulling.
2. Apply a steady assumed tow force directly to windward. This is assumed to linearly increase from zero to the full tow force during the first 30 s of the simulation.
3. Continue the simulation to predict the trajectory of the ship under the combined tow force and environmental forces. This includes determining the ship accelerations, velocities, and positions as they change in time.
4. Stop the simulation when it has demonstrated whether the manoeuvre was successful or not.
5. Repeat the above (from #2) for a series of different tow forces to determine the minimum tow force required to successfully complete the manoeuvre. A numerical solver is used to determine the tow force to within 1%.

At step 4 above, the manoeuvre has been determined to be successful if all the following criteria are met:

1. A heading of perpendicular to wind and waves has been achieved; this is considered met if the heading passes through head seas, as some oscillations are expected;
2. The ship is no longer moving downwind;
3. The maximum drift motion is less than 2 nm (3704 m); and
4. The elapsed time is less than 1 hour.

The drift motion and time limits are somewhat arbitrary. They are intended to represent a reasonable tolerance for sea room, changing weather conditions in time, and the tow vessel operator's patience in continuing with one apparently unsuccessful approach before trying a new recovery tactic. Insight into the suitability of these limits can be gleaned from the results, which show how these values change with tow force.

The displacement of the ships has been estimated based on typical block coefficients for each ship type. In all cases, the ship's centre of gravity is assumed to be located 2% aft of amidships. The added mass of the ships has been estimated based on the ship dimensions. The displacement and added mass values used are shown in Table 6.

Table 6. Ship displacement and added mass

Vessel	Displacement [Tonne]	Surge added mass [Tonne]	Sway added mass [Tonne]	Yaw added mass [Tonne-m²]	Sway-Yaw added mass [Tonne-m]
Large Container Ship	156,000	4.3×10^3	8.8×10^4	6.8×10^8	3.1×10^6
Very Large Container Ship	206,000	5.7×10^3	1.1×10^5	9.6×10^8	4.0×10^6
LNG Carrier	89,000	1.3×10^3	1.5×10^4	1.1×10^8	5.1×10^5
Vehicle Carrier	61,000	1.5×10^3	3.9×10^4	1.5×10^8	9.7×10^5
Passenger Ship	77,000	1.5×10^3	2.7×10^4	1.5×10^8	8.2×10^5
Bulk Carrier	103,000	1.9×10^3	2.5×10^4	1.4×10^8	7.4×10^5
Aframax Tanker	130,000	3.8×10^3	6.9×10^4	2.5×10^8	1.6×10^6

Note: Analysis considered 'light operational conditions', not max displacement for a number of the ships. This was done because windage has a bigger effect on the force results than displacement, and light operational conditions results in increased windage.

3.2 Results

3.2.1 Steady State Results

As described in 3.1.1, wind, wave and current force components were generated using DPLab. An example output screen is shown in Figure 14. These values were downloaded into an excel spreadsheet for further processing. An example of the information is provided in Table 7, showing the total force values derived from the summation of each component. The full set of results including all force components is presented in Appendix B.

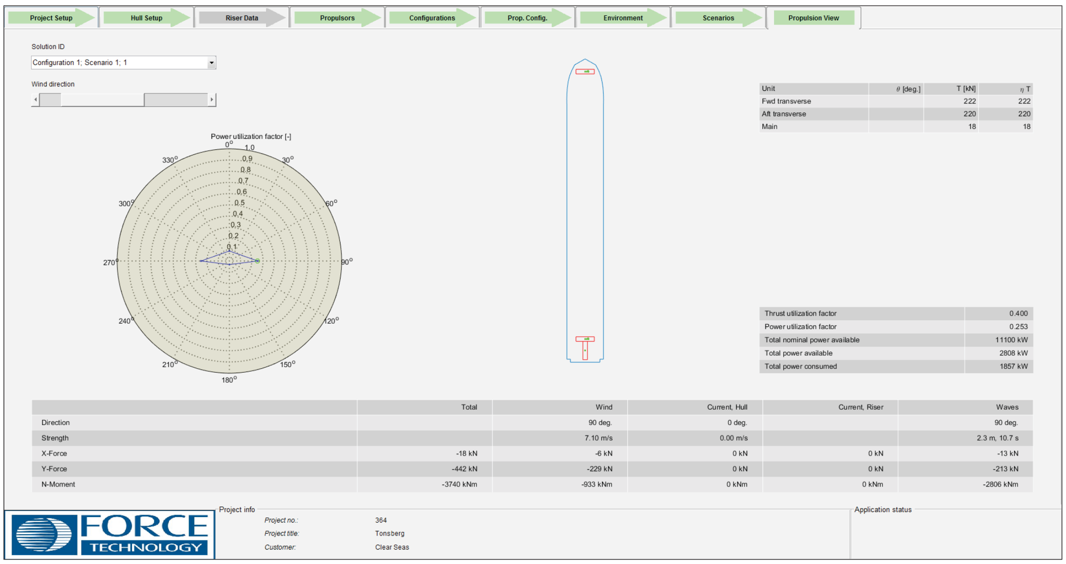

Figure 14. Vehicle Carrier data; beam seas in the 50th percentile of environmental conditions

Table 7. DPLab beam seas condition data – total force vs MET-Ocean condition

Beam Seas – Total Force (kN) vs MET-Ocean Conditions (%)					
Vessel	**50th Percentile**	**75th Percentile**	**85th Percentile**	**95th Percentile**	**99th Percentile**
Large Container Ship	-870	-1435	-1798	-2682	-3858
Very Large Container Ship	-933	-1535	-1921	-2862	-4114
LNG Carrier	-641	-1017	-1247	-1828	-2591
Vehicle Carrier	-442	-690	-838	-1218	-1715
Passenger Ship	-753	-1244	-1560	-2329	-3351
Bulk Carrier	-484	-742	-893	-1288	-1800
Aframax Tanker	-331	-488	-573	-807	-1106

Note: 9.81 kN = 1 tonne of bollard pull

3.2.2 Turning Simulation Results

This section presents results for the dynamic simulations of turning the subject ships to be perpendicular to conditions (into head seas), including consideration for arresting the downwind motion of the ship and limits for both drift motion and overall time as discussed in Section 3.1.2. Due to the number of ships, environmental intensities, and tow forces explored in this study, a large number of simulations have been completed. This report includes summarized results, and samples of the individual simulation results. Table 8 provides a summary of the minimum tow force required to complete the manoeuvre for each example ship in each environmental condition.

Table 8. Minimum feasible tow force [kN] from turning simulations

	Minimum feasible tow force [kN], by environmental percentile				
Ship	**50th Percentile**	**75th Percentile**	**85th Percentile**	**95th Percentile**	**99th Percentile**
Large Container Ship	262	419	517	802	1080
Very Large Container Ship	312	498	614	953	1280
Lng Carrier	206	338	417	658	892
Vehicle Carrier	146	234	287	453	609
Passenger Ship	207	332	409	638	855
Bulk Carrier	170	270	327	520	695
Aframax Tanker	126	200	246	391	523

Note: 9.81 kN = 1 tonne of bollard pull

Figure 15 and Figure 16 below show an example of an individual simulation of the large container ship in the 50th percentile environment, with a 349 kN tow force. Figure 15 shows the trajectory of the ship's centre of gravity, with the ship outline shown every minute of simulated time, and the wind and seas from the top of the figure. Figure 16 shows time traces of various parameters predicted by the simulation. The relatively high drift rate from the initial condition dominates the first part of the simulation while the tow force ramps up. The direction of motion of the ship remains similar to the original direction for much of the simulation. As the ship turns further, the cross-wind component of the environmental force causes the ship to accelerate towards the right-hand side of the figure. The tow force gradually arrests the downwind motion, and finally the turn to perpendicular completes at about the same time.

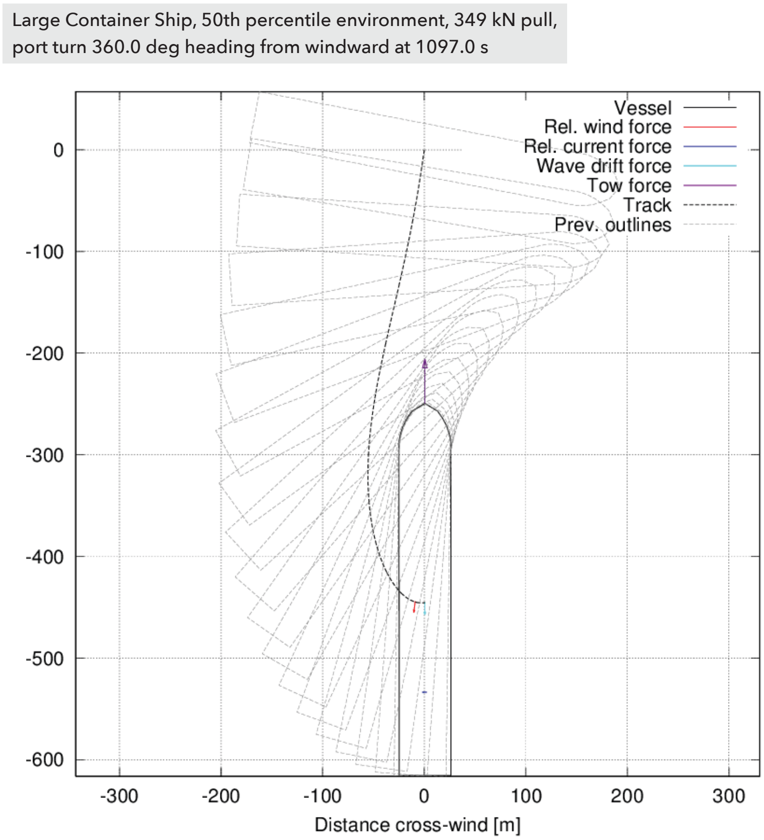

Figure 15. Large Container Ship example simulation trajectory

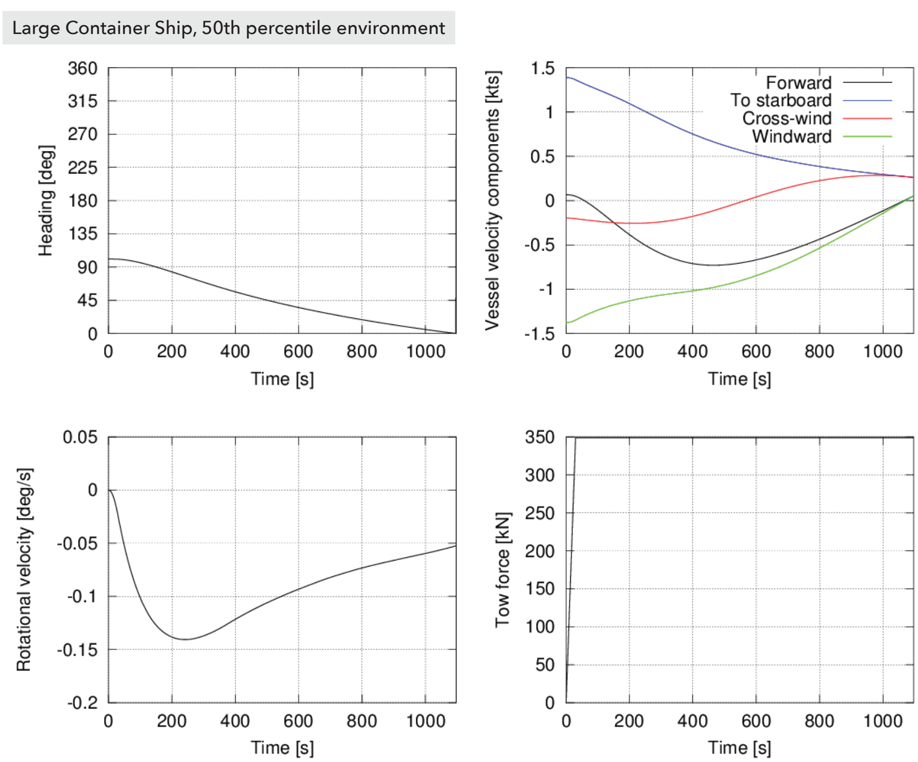

Figure 16. Large Container Ship example simulation time traces

With a larger tow force in the same environment, the ship turns more rapidly and with less downwind drift. With a lesser tow force, the results become more pessimistic until the manoeuvre is unable to be completed in a reasonable amount of time or sea room. Figure 17 shows the influence of tow force on the maximum drift motion and the time required to turn perpendicular and arrest the ship, for the same ship and environmental conditions. Referring to Figure 17, the time to turn the ship perpendicular corresponds to the time at which the heading (black curve in the upper-left plot) first becomes zero, and the time to arrest the downwind motion corresponds to the time at which the green curve (windward velocity component) in the upper-right plot of Figure 16 crosses through zero. The trends for these indices versus tow force in Figure 17 show a dramatic increase in the drift motion and time as the tow forces reduce to the identified minimum value (262 kN). This asymptotic behaviour is characteristic with all of the ships. One could make arguments for selecting a practical minimum tow force based on other specified limits for drift motion and time. Based on the relatively sharp turn in this curve, selecting other criteria could, for example, identify a practical minimum tow force which is on the order of 10% to 30% higher than the identified minimum. A complete set of these plots has been included in Appendix B.

The simulation of the large container ship in the same environment with the minimum feasible tow force is shown in Figure 18 and Figure 19. These figures show an extended period of time after the initial heading change during which the ship heading changes quite slowly. This occurs when the heading is around 45°, where the environmental yaw moments are quite large.

As expected, the minimum feasible tow force to complete the turn and arrest the ship increases with increasing environmental intensity. The plots in Appendix B show that at the minimum feasible tow force, the drift motion also increases with increasing environmental intensity, however this effect is not sufficiently strong to cause excessive drift motion in the stronger environments. The time to achieve head seas remains the limiting criterion for determining the minimum feasible tow force. There is also a slight trend for the knuckle in the time to head seas and time to arrest curves to move slightly downwards in plots similar to Figure 17; the implications for this are that if a time limit different from 1 hour were applied, the percent influence this would have on the required tow force would be slightly lesser in more intense environments. The ship trajectories in more intense environments have similar features, but generally use more space. There is a tendency for the overall drift to the right side of the plots to become more apparent with increasing environmental intensity. In the most extreme environment assessed (99th percentile), the minimum feasible tow force is 1078 kN, and the maximum drift motion is 2560 m (1.38 nm). Details of these effects can be seen in the plots in Appendix B.

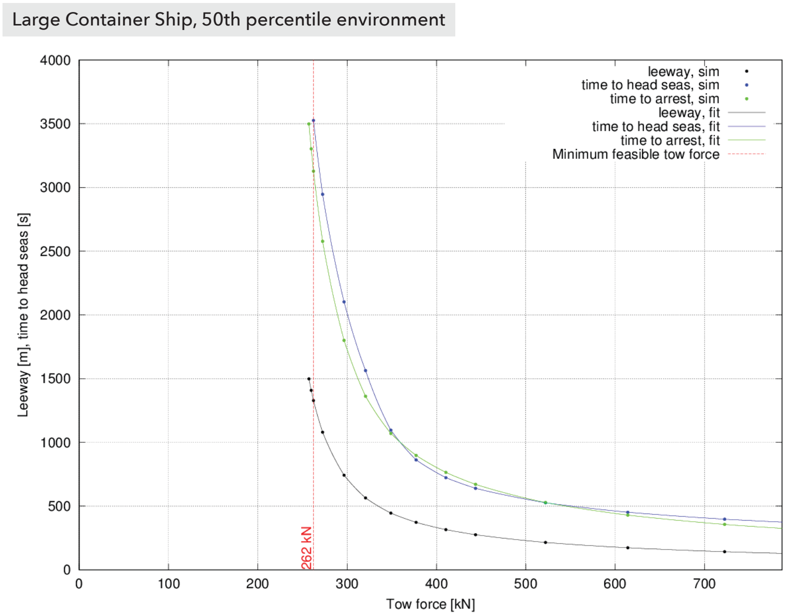

Figure 17. Larger Container Ship effect of tow force, 50th percentile environment

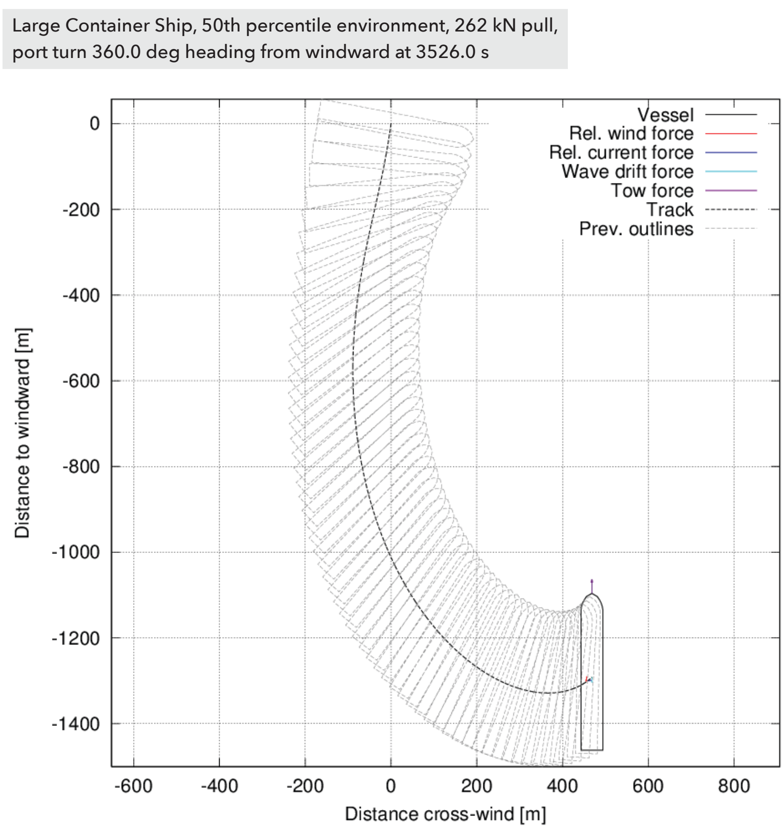

Figure 18. Large Container Ship trajectory with minimum feasible tow force, 50th percentile environment

Large Container Ship, 50th percentile environment, 262 kN pull, port turn

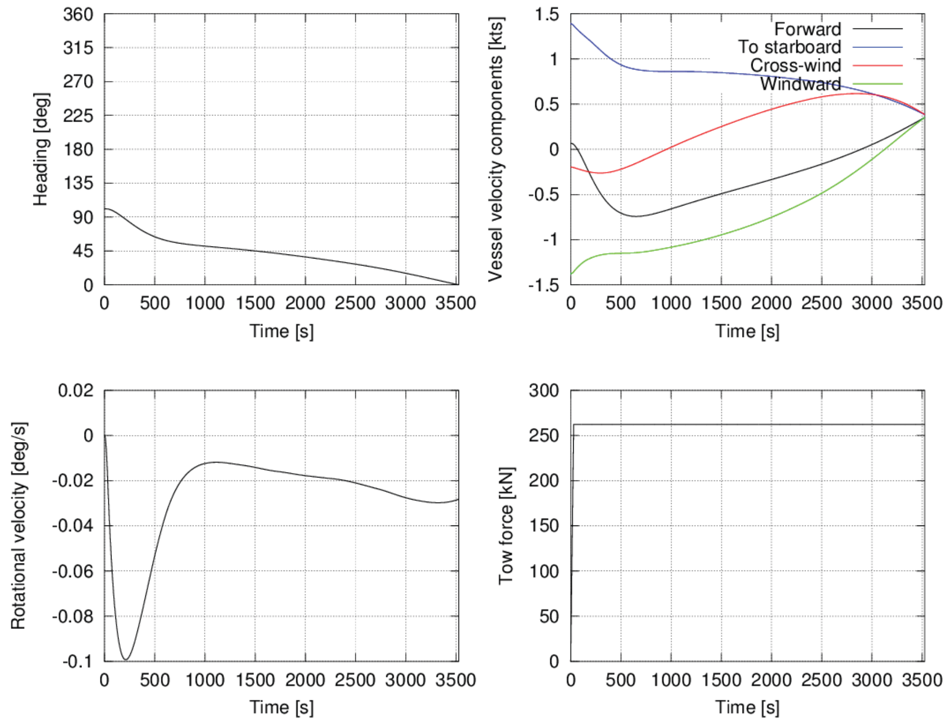

Figure 19. Large Container Ship time traces with minimum feasible tow force, 50th percentile environment

The different ships have different proportions and so different mechanisms govern the ability to effectively turn them into the weather, resulting in different performance. General observations on the observations for each ship are provided below. The tanker is a notable outlier, as its minimum feasible tow force is governed more by the need to absorb the ship's very high inertia; while environmental forces tend to dominate the other ships.

- *Large Container Ship*: turn to perpendicular achieved slightly after motion is arrested; trajectory curves to the right (bow).
- *Very Large Container Ship*: turn to perpendicular achieved slightly after motion is arrested; trajectory curves to the right (bow).
- *LNG Carrier*: turn to perpendicular and motion arrested at nearly the same time; trajectory curves to the right (bow). At higher tow forces turn to perpendicular is attained substantially before downwind motion is arrested.
- *Vehicle Carrier*: turn to perpendicular achieved slightly after motion is arrested; trajectory curves to the right (bow).
- *Passenger Ship*: turn to perpendicular achieved slightly after motion is arrested; trajectory curves to the right (bow). drift motion is near 2 nm in stronger environments.
- *Bulk Carrier*: turn to perpendicular achieved, and motion arrested at nearly the same time; trajectory curves to the right (bow). At higher tow forces turn to perpendicular is attained before downwind motion is arrested.
- *Aframax Tanker*: turn to perpendicular achieved much before downwind motion is arrested, indicating this is dominated by inertial effects rather than driving forces. Decaying heading oscillations occur, and trajectory deviation drift is to the left (astern). Dirft motion is relatively small.

While the primary means of assessing the influence of current on the required tow force is by means of the static analysis presented in Section 3.2.1, one set of sample turning simulations have been carried out including a 1 kn current acting collinear with the wind and seas. For the large container ship in the 50th percentile environment, Figure 20 shows the influence of tow force on the drift motion and time to turn to perpendicular and to arrest the downwind motion (considering speed over ground). Comparing this to Figure 17, it can clearly be seen that there is higher drift motion with a 1 kn current and a longer time to arrest the ship's downwind motion. However, the ship turns to perpendicular slightly faster with a current. This is because the initial drifting velocity of the ship is higher, such that the relative wind speed is reduced, and hence the wind forces and moments are reduced. The combined result of this is that the one-hour time limit to arrest the ship's downwind motion governs the limiting tow force with a 1 kn current; in the primary case without a current the limiting factor was the time to turn to perpendicular. The change in limiting tow force is very small: from 262 kN without a current to 265 kN with a current. However, by comparing Figure 17 and Figure 20 it can be seen that with a current a higher tow force is required to effect the turn within the same drift motion (ex. for 1000 m drift motion it is roughly 280 kN without a current vs. 350 kN with current).

Large Container Ship effect of tow force, 50th percentile environment

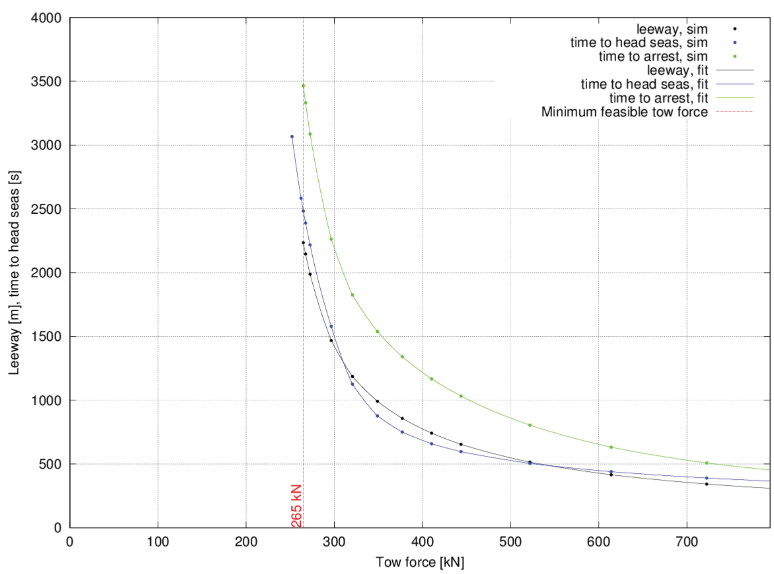

Figure 20. Large Container Ship effect of tow force, 50th percentile environment

3.2.3 Results Summary Figures

This section summarizes the analysis results developed as described in the sections above and presented in more detail in the appendices. The full set of ships is covered in Figure 21 to Figure 26. For each ship, towing force, turning force and holding steady force are presented for each of the metocean conditions considered. Beam seas forces are also shown but are used for information only. The largest of the turning, holding steady and towing forces is selected—this is almost always the turning force. Its value is then used to define the ETV bollard pull requirement and the approximate propulsion power, considering the estimated tug efficiencies taken from Figure 11.

The towing force from the ETV is produced by propulsors (propellers and other devices), driven in turn by the power of the propulsion machinery. The bollard pull (low or zero speed) towing force is a function of propulsor and power plant type, and relies on details of the ship and propulsor design. For the purposes of this study, a simple approximation has been used to relate the necessary towing force to vessel power. A similar approach, cited in NAS 1994, gives 75 break horsepower equals 1 tonne of bollard pull. This assumes that the vessel has nozzled propellers; open propellers will have a performance of 20-30% less than this. Converted into metric quantities and rounded (as there is a high level of variability):

Conversion Factor: 1 tonne of bollard pull is equal to 55 kW

This value is considered reasonable for smaller tugs but somewhat on the high side for larger vessels, so a more conservative value of 1 tonne for every 60 kW has been used to develop Figure 26 below.

The results show that the highest towing forces are required by the container ships, due to their very high windage. For similar reasons, the LNG Carrier and Cruise Ship are next highest, and the Aframax Tanker is lowest. The overall highest result, for Very Large Container Ship, requires an ETV capability of over 200 tonnes bollard pull. The Aframax Tanker in the same conditions requires around 90 tonnes.

The forces and, even more so, the towing requirements increase very considerably for the higher percentile cases. From the 85th to 95th percentiles, there is close to a 60% increase in the environmental forces, which becomes a more than 65% increase in ETV capacity when towing efficiencies are considered.

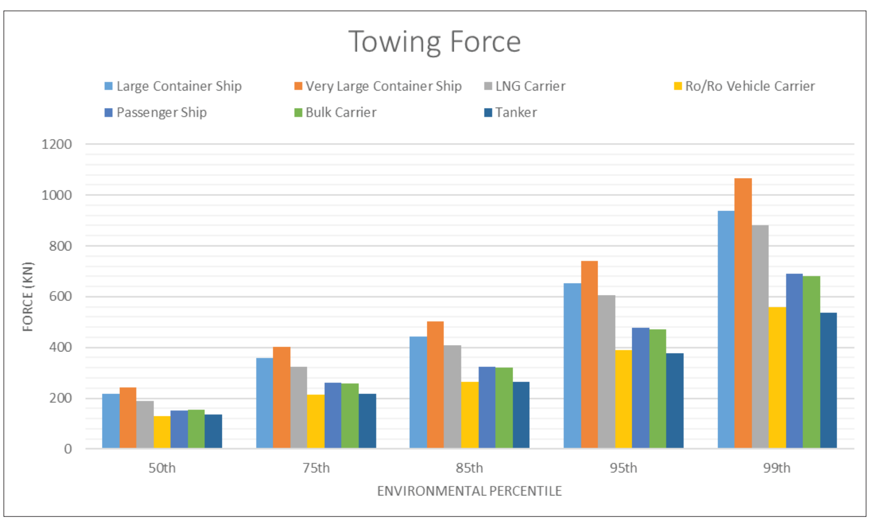

Figure 21. Towing force results

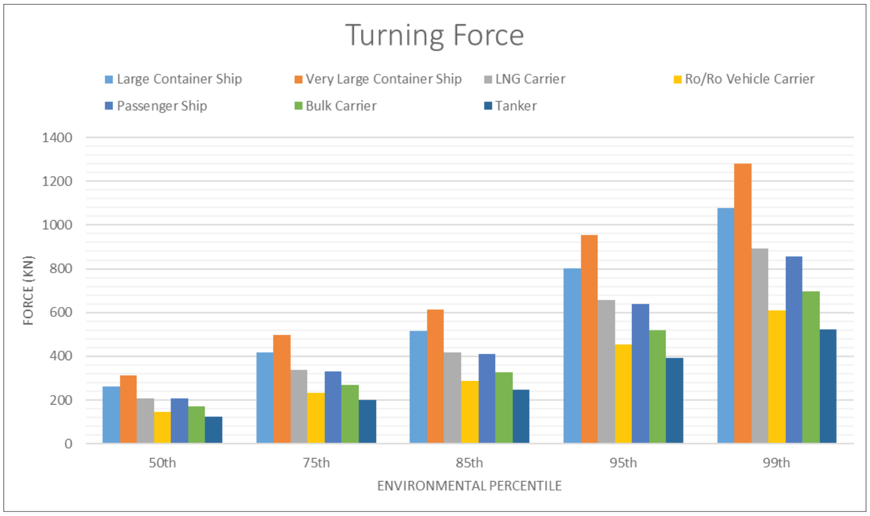

Figure 22. Turning force results

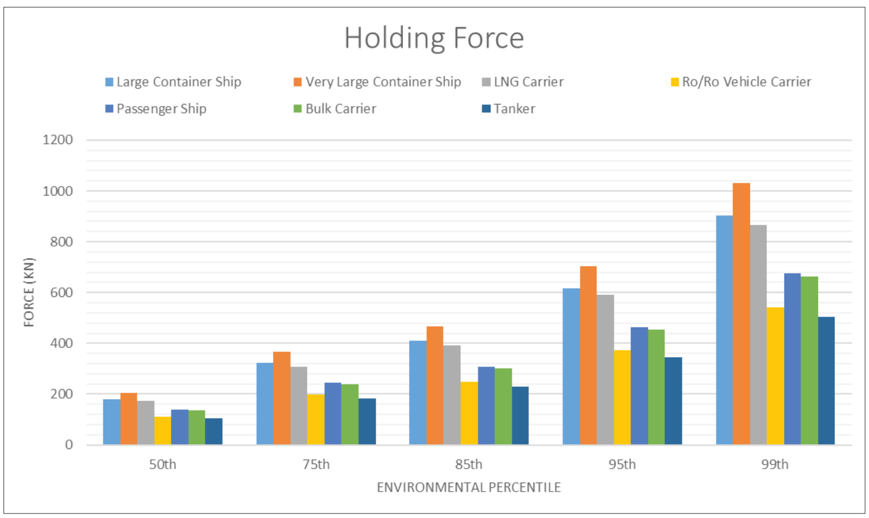

Figure 23. Holding force results

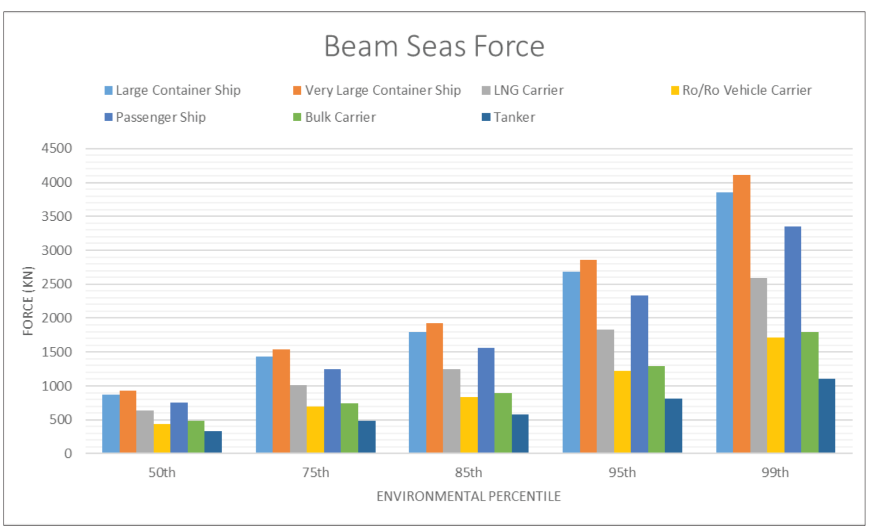

Figure 24. Beam seas force results

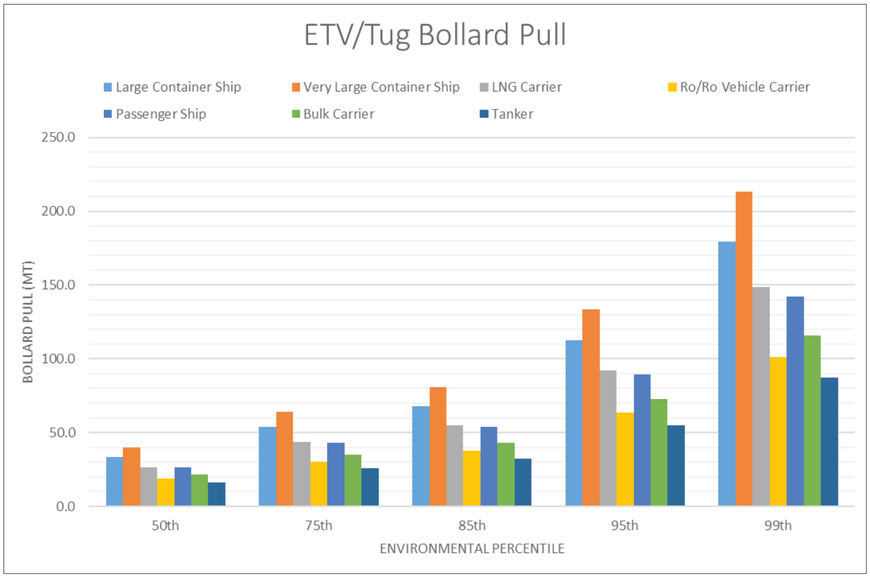

Figure 25. ETV/tug bollard pull results (repeated as Figure 1.)

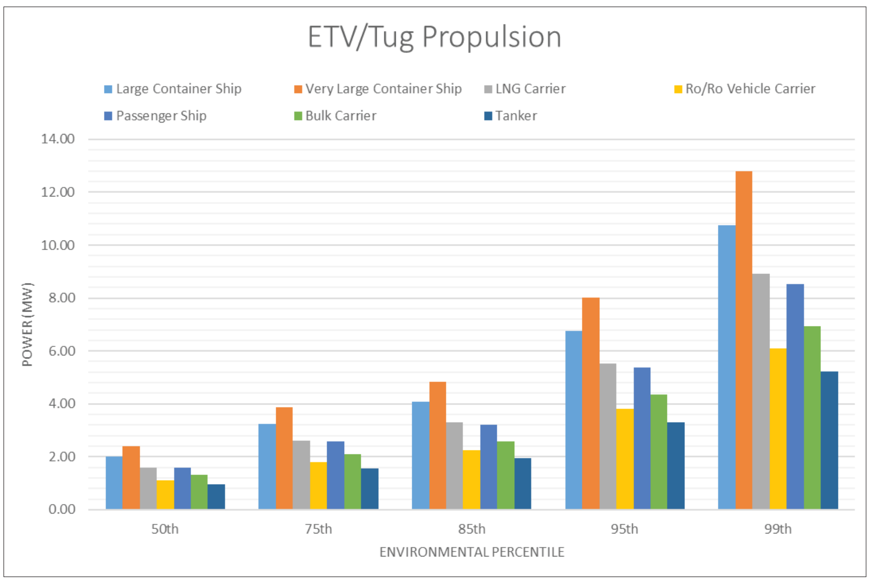

Figure 26. ETV/tug propulsion results

4.0 Tug and ETV Requirements

The ability of a tug or ETV to provide effective and safe towing operations is dependent not only on its bollard pull capacity, it is also affected by factors including the overall vessel characteristics, the equipment installed, and the training and experience of the crew. Some of these include:

- Ship size, including length (LOA and waterline), freeboard and stability
- Propulsion system (including propulsor type, redundancy, dynamic positioning (DP) capability)
- Free-running speed and speed loss in waves
- Minimum endurance and range; accounting for transit, towing and other operations
- Winch type and towing gear, considering both fore and aft capabilities and both equipment and layout
- Crew motion limits; using seasickness, motion-induced interruption and other metrics
- Crew certification and training

Each of these is discussed below in the context of Canadian Pacific coast towing scenarios, considering factors such as the sea areas to be covered and the potential availability of additional resources. The types of vessel operating parameters, discussed below, ought to be considered by government and industry as they seek new towing assets to meet the changing capability requirements presented by commercial ship traffic that transit and operate in Canadian coastal waters.

4.1 Ship Size

Many harbour and escort tugs are quite small but relatively very powerful vessels, which provide (for example) bollard pulls of around 80 tonnes on vessels as small as 30 m in length, as shown in Figure 27.

Figure 27. 30 m, 80 tonnes BP tug. [Image courtesy of Robert Allan.]

These types of tugs, however, have serious performance limitations in open ocean service, for which they were not designed. Their small size (length in particular) leads to high motions and accelerations in heavy seas. Low freeboard means that the working decks will be very wet, posing hazards to personnel. While small vessels may meet and exceed all relevant stability requirements, their small mass relative to the towed ship means that a towline can exert unsustainable capsize forces in the event of any operator error. The towing efficiency of smaller vessels in heavy weather will be low; their nominal bollard pull capability will be reduced considerably.

DNV guidance is that vessels below 40 m in length should not be considered for open ocean towing in harsh areas and seasons, which applies to most of the conditions encountered off the Pacific coast of Canada. The most recent newbuilds of deep sea towing and salvage tugs, shown in Figure 28, are 90 m vessels with a 300 tonne bollard pull and a wave-piercing “X-bow” claimed to reduce motions and towing loads. There are relatively few recent vessels designed specifically for deep sea towing and salvage. There is, however, a substantially larger population of offshore vessels designed for anchor handling and other operations with similar “towing” pull requirements, some of which are even larger and higher powered. The current Guinness world record bollard pull “tug” is the Far Samson, with 425 tonnes capacity. As can be seen from Figure 29, this vessel is not designed primarily for towing operations.

Figure 28. ALP Defender deep sea towing vessel. [Image courtesy of Ulstein.]

Figure 29. Far Samson, Guinness record bollard pull "tug". [Image courtesy of Ole K. Hammero, MarineTraffic.com.]

New vessels are quite different in appearance from the traditional salvage and deep ocean tugs, such as the ex-Smit Singapore shown in Figure 30 . However, they share important characteristics such as considerable length, central winch placement and high freeboard forward that are needed in the deep ocean towing role. Length and bow form are important for operability and for speed, especially in heavy weather. The central location of the winch helps with manoeuvrability during the towing operation. High freeboard reduces deck wetness. There are arguments for and against the "X-bow" hull form shown in Figure 28, which reduces pitch motions in some conditions but removes an effective forward working deck that can be very useful for picking up a tow in heavy seas.

Figure 30. Smit Singapore; "traditional" salvage tug. [Image courtesy of Mac Mackay, tugfaxblogspot.blogspot.com.]

4.2 Propulsion System

Tugs and other towing vessels have a very wide variety of propulsion systems, but there is an increasing tendency for larger vessels to use wholly or partially electric propulsion plant coupled with some form of azimuthing propulsor. Electric propulsion offers flexibility to locate the power plant within the ship, and to direct the power to whichever propulsor, thruster or large equipment item needs to use it. It is however more expensive than mechanical propulsion, and has lower peak overall efficiency, though this can be offset by better matching of loads to engine capacity. Electric propulsion systems can also ensure redundancy by splitting power generation between multiple units in segregated machinery spaces, so that a single failure or accident does not disable the ship.

Azimuthing propulsors help give the vessel manoeuvring and dynamic positioning (DP) capability. In longer vessels, good manoeuvrability and DP requires thrust at the bow as well as at the stern, which can be provided by tunnel thrusters or by (usually) retractable azimuthing units. Taking up a tow does not require true DP capability, but the same attributes are very useful in allowing the towing vessel to maintain station and adjust heading while line handling or recovering lifesaving equipment. Similarly, having good redundancy increases safety in all close quarters operations. There are standardized notations for levels of redundancy for DP (DP 1, 2 and 3 in increasing order). For more general redundancy Class societies have their own special notations, which are broadly similar to each other.

Figure 31. Azimuthing propulsor with nozzled propeller. [Image courtesy of Marine Propulsion Solutions.]

Propellers on shaft lines or on azimuthing units can be fixed or controllable pitch; open or ducted (nozzled), as shown in Figure 31. With electric drive, it is normal to use fixed pitch as shaft speed can be varied by motor speed. Mechanical drives have less speed flexibility and are therefore often coupled with controllable pitch propellers to allow thrust to be varied as required. Propellers can be optimized for speed or for low speed (bollard) thrust. Normally for towing vessels the optimization is for thrust, which will reduce maximum speeds somewhat. Nozzles can increase low speed thrust by up to 30% and are therefore fitted to most towing vessels. A good nozzle for thrust will increase high speed resistance, so designers and owners will make trade-offs depending on the vessel's mission profile.

4.3 Ship Speed

For most towing vessels, and certainly for harbour and escort tugs, high top speed is not a priority. They will be handling larger ships using reduced speeds in coastal waters and can often be pre-positioned for operations. Deep sea tows are also normally undertaken at modest speeds, and emergency towing equipment is sized for speeds of 6 kn or less. The only aspect of operations for which speed is important is transit to the scene of an incident.

The high power of most towing vessels does not translate into very high maximum speeds due to hull form considerations, and to the trade-offs between bollard thrust and open water performance discussed above. Generally, a longer vessel will go faster than a shorter one, but even the 90 m vessel shown in Figure 32 only claims a maximum speed of 19 kn. Most tugs, and high bollard offshore vessels have maximum speeds of 16 kn or below.

Maximum speeds will be reduced by speed loss in waves, which can be significant in severe weather conditions, as can be understood from Figure 32. This shows the French emergency response/towing vessel Abeille Bourbon, whose maximum speed of 20 kn in sea state 2 reduces to 16.5 kn in sea state 7 (Bourbon, 2018). Again, size, length and hull form are important. For any vessel, speed loss in different wave climates can be estimated by analysis or by model testing to help give an understanding of realistic transit times, and this should be factored into decisions such as where emergency vessels should be stationed and how many are needed to provide effective coverage.

Figure 32. Offshore vessel in waves. [Image courtesy of Bourbon.]

4.4 Endurance and Range

High power involves high fuel consumption. Most towing vessels, whether harbour or deep sea, do not use their full power for more than a small fraction of the time and have economical modes and speeds for transit. However, they have to have enough total fuel tankage for their full intended operations. At the high end, the vessel in Figure 28 declares an endurance sufficient for trans-Pacific towing. At the low end, many harbour tugs are "day boats" that will expect to return to port regularly for fuel and other stores.

For open ocean emergency towing, the endurance and range requirements need to incorporate transit to an incident at high speed, a high-power tow for the full duration of a storm system, and some margin for time required to set up the tow and for unexpected factors. This will translate into a substantial volume of fuel tankage (depending on the installed power). Most offshore type vessels will have sufficient volume and deadweight to allow for this, though a repurposed ship may need some modifications to adjust the balance between fuel and cargo capacities. Smaller tugs are unlikely to have sufficient endurance for any substantial offshore mission but may be able to provide first response until more capable back-up can arrive.

4.5 Winches and Towing Gear

A modern towing vessel will generally have a system including a towing winch, tow pins and shark jaws. Shark jaws, which grab and lock the tow line for operations such as anchor handling are less likely to be used in emergency response towing, as they cannot compensate for dynamic loadings in the same way as a self-tensioning or clutched winch. Both tow pins, which guide the tow line, and shark jaws are retractable into the deck when not in use (Figure 33).

Figure 33. Shark jaws and towing pins. [Image courtesy of Wikipedia.]

Large tow winches are often waterfall type, with several "cascading" drums to provide a combination of high capacity and rapid response (Figure 34). Traditionally, most large winches were hydraulic, but electric options are increasingly popular due to their lower maintenance effort and increasingly sophisticated controls. A number of suppliers offer towing winches of 300 tonnes plus safe working load. The towing winch capacity will normally be matched to the bollard pull capability of the vessel, though with allowance for dynamic overloads. Similarly, the foundations of the deck equipment and the breaking strength of towlines also need to account for dynamic effects. For open ocean towing, these factors of safety are generally required to be at least 2; i.e. a 100 tonne BP vessel should use 200 tonne BP foundations and towline (Tugs and Tows). Different class societies have somewhat different rules in this area. For example, DNVGL requires factors of safety between 2.2 and 3.0, declining with higher BP (DNVGL Veristar Marine Operations, 2015).

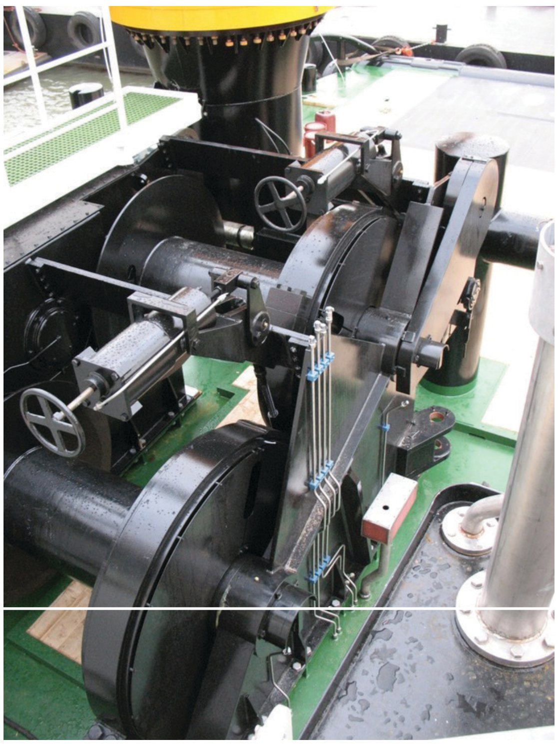

Figure 34. Waterfall winch. [Image courtesy Kraaijeveld Winches.]

Towing lines are generally steel wire rope (SWR) or synthetic fibre, with SWR preferred for the largest capacities. Both are subject to degradation in service, and it is important that they are inspected regularly and replaced at frequent intervals. Setting the length of a towing line is largely reliant on the operator's expertise. In heavier weather long lines are needed to absorb some of the dynamic effects in the towline catenary, and so the towing winch needs to be large enough to handle the lengths required. In addition to the main towing line, an emergency line should be deployed in parallel to allow for rapid recovery if the main line fails. This will be left slack until required. In some cases, it may be necessary to start a tow by passing a light messenger line, that can be captured and handled more easily by the crew of the vessel to be towed. Successively heavier lines can then be put in place with the eventual connection of the towline proper.

Towing arrangements and procedures also must take account of the capabilities of the ship under tow, as discussed in Section 2.3.2. A powerful towing vessel may be able to overload the ship's deck equipment and so brake or line tension settings on winches must be appropriate.

4.6 Crew Certification and Training

Although towing operations are specialized, challenging and potentially dangerous, currently there are no specific training or certification requirements for masters or crews of towing vessels in Canada, or in most other jurisdictions. Transport Canada relies on the general provisions of the personnel regulations that require all crew members to have appropriate competencies. Tug and towing companies, including those on the Pacific coast of Canada set their own experience requirements for personnel, and in many cases will provide training courses through maritime academies and other training services providers. These can be of varying levels of sophistication and intensity.

In Scandinavia increased attention to emergency towing resulted in the development of several emergency towing specific courses, such as the course by Force Technology in Denmark (Force Technology, 2018). This course consists of lectures, simulator exercises and debriefings using sophisticated replay tools. Simulators are available for a number of different towing vessel types and configurations.

4.7 Crew Limitations

An emergency towing operation will involve the crew of the ETV in mobilizing, transiting, establishing the tow, maintaining the tow, and turning over the rescued ship to a port or to another safe alternative. Several of these phases may involve significant levels of effort, stress, discomfort and risk. Ship motions will influence all of these and the level of fatigue experienced by the crew.

It is common practice to assess the influence of vessel motions in waves on a vessel's capability by means of task-based motions criteria. The vessel motions are calculated and compared to these criteria in the sea conditions, speeds, and headings relevant to each task. Table 9 shows suggested criteria for the tasks that may or will be involved in the emergency towing operation. In rows of Table 10 where more than one task is listed, the motions criteria associated with all tasks listed should be satisfied. In most cases, the criteria are drawn from naval practice, as this is an area in which navies have undertaken the bulk of the most useful research.

Table 9. Motions criteria by task

Task	Location	Motion	Criterion	Reference
General	Bridge, 1 m above deck	Motion Induced Interruption (MII)	≤ 1/min	STANAG 4154
		Root-mean-square (RMS) vertical acceleration	≤ 0.2 g	STANAG 4154
	Propeller, ¼ propeller diameter above shaft	Emergences	≤ 90/hr	STANAG 4154
	Keel, 15% aft of forward perpendicular	Slamming	≤ 20/hr	STANAG 4154
	Fwd. end of exposed deck (forecastle)	Deck wetness	≤ 30/hr	STANAG 4154
Aft deck work	Aft deck, 1 m above deck	MII	≤ 0.5/min	STANAG 4154
		RMS vertical acceleration	≤ 0.2 g	STANAG 4154
	Deck edge	Deck wetness	≤ 0.5/hr	STANAG 4154
	Deck edge, line handling	Relative vertical motion	TBD	
Helicopter launch/ recovery	N/A	RMS roll	≤ 2.5°	STANAG 4154
		RMS pitch	≤ 1.5°	STANAG 4154

Table 10. Relevant combinations of tasks, headings, and speeds

Phase of emergency tow operation	Tasks	Speeds	Headings	Basis
Transiting to site	General, aft deck work (preparation)	Cruise	Any	Free choice of heading is important to arrival on site. Barred heading ranges, if any, should be narrow.
Helicopter assistance	General, helicopter launch/ recovery	Zero to moderate, and cruise	Some headings near head seas	It may be practical to take on a preferred heading/ speed for short-duration helicopter launch/ recovery, and this may occur near the site or while the tow vessel is still transiting to the site.
Establishing the tow	General, aft deck work	Slow maneuvering, ahead and astern	Most; near head seas is critical	Assumes a preferred stern-to configuration on the upwind side of the vessel to be towed.
Towing	General, aft deck work	Slow to moderate	Most; near head seas is critical	Some barred headings may be acceptable, but when there is limited sea room pulling towards head seas is important for countering drift toward the lee shore.

The motions should typically be evaluated at the locations where the task would be carried out. For tasks carried out in a range of locations (such as the aft deck), the worst realistic location should be used. This would consider realistic crew stations in positions that are outboard or far from the vessel centre of gravity, areas where the bulwarks are removed or cut out, etc.

The term Motion-Induced Interruptions (MII) in Table 9 predicts the number of times per minute that a crew member's attention would be diverted from the task at hand in order to maintain or regain balance in a standing position. The calculation methodology is standardized and based on a simplified model in which the crew member, if treated as a simple rigid block, would either tip or slide due to the combined effects of roll, pitch, and accelerations in the vertical, lateral, and longitudinal directions. For towing operations including critical tasks carried out on deck, this is important to both crew safety and success of the tow.

Motion sickness is likely to be an important factor for towing operations in severe weather because the crew will not likely have time to habituate to the motions beforehand and may not have time to take mitigating measures such as applying a motion sickness patch. Unfortunately, the motion sickness of a crew of mariners that have been rapidly mobilized is not a particularly well-studied topic, so it is difficult to provide an exact criterion. NATO STANAG 4154 recommend either the use of the Motion Sickness Index (MSI) or a vertical acceleration criterion. The RMS (root-mean-square) vertical acceleration criterion is recommended here as MSI index has been found to predict excessively high results. Another alternative that may be considered is the Motion Sickness Dose Value, as defined in ISO 2631-1. The ISO standard shows how this may be calculated based on a frequency-weighted integration of the vertical acceleration spectrum and combined with the duration of exposure to determine the MSDV, then the associated percentage of crew affected by motion sickness is estimated as MSDV/3 for a general population of males and females not adapted to the motion environment. It may be less for a vessel's regular crew.

Relative vertical motion is noted as a "TBD" (to be determined) criterion at a location by the deck edge where line handling is carried out. This is recommended as a measure of the degree to which the relative motion between the waves and the vessel impede the ability to pass and retrieve messenger lines and larger tow lines. While the relative motion between the working deck and the towed ship may also be very important, this will vary from one towed ship to the next, so is much more difficult to include as a tow vessel requirement. Further work is required to quantify an appropriate criterion; this would ideally include field data.

While commercial helicopter criteria are available, naval criteria have been recommended here on the basis that a dedicated emergency tow vessel is likely to work with pilots and flight crew who are trained specifically for this type of operation in severe weather. If the vessel and crew are operated more like a commercial operation, it would be more appropriate to use commercial helicopter motions criteria, such as those recommended by the Helideck Certification Agency (see the Helideck Limitations List, Part C, as interpreted by CAA Paper 2008/03). This defines criteria for day and night operation based on the vessel configuration and helicopter size.

Table 10 recommends heading/speed ranges with consideration for when and how the tasks may be carried out. However, if the configuration of a particular tow vessel or its intended operation differ from the basis noted in the table, it would be appropriate to adjust the heading/speed ranges to suit the best means of operating the particular vessel.

In terms of tow vessel design/selection implications, these motion requirements will tend to require a vessel that is not small, with good freeboard, and with good rolling characteristics. To achieve adequate roll characteristics to allow safe operations on the aft towing deck (i.e. meet the MII criterion), the tow vessel is likely to require some form of roll stabilization, such as bilge keels or tank stabilizer. Caution is advised with regards to active stabilization via azimuthing thrust, as this may cause excessive yaw motions that interfere with operations. Vessel length will help to reduce pitch motions and their influence on most of the criteria specified. A long vessel may also allow a favourable helideck location.

4.8 Additional Considerations

An emergency towing vessel may have other attributes to assist with response to an incident or mitigation of its consequences. Having a helicopter landing deck, or at least a suitable winching area can help with casualty evacuation, with passing messenger lines, and with putting salvage personnel aboard a disabled ship to assist in rigging a towing line. Few vessels will be large enough or well-enough equipped to land a large Search and Rescue (SAR) helicopter in severe wind and waves, but they may still be able to work together with these to augment each other’s effectiveness.

The ETV itself may need to participate in recovering evacuees from the water, with lifesaving equipment such as boats and rafts, or from the disabled ship. This will be facilitated by having the same types of design features and equipment used in offshore standby vessels, including some level of medical treatment facilities and the ability to provide food and clothing to survivors. As noted, a roll stabilization system may also be highly desirable.

In extreme events, where an ETV cannot prevent a ship grounding, for example, due to lack of towing capacity on either or both vessels, it may become necessary to select the most suitable spot to ground, for example on a beach rather than on rocks. The ETV may be equipped to initiate spill response, by deploying booms and skimmers or using dispersants, depending on the location and conditions.

Depending on the size and design of the ETV, some of these factors may be relatively easy to incorporate rather than acting as major design and cost drivers.

5.0 Summary

This report presents the results of a set of analyses into the towing forces required to arrest, turn, and tow at slow speeds a set of large ships of different types. The contributions of wind, waves and current are accounted for at various probabilities of exceedance based on the specific metocean data from Canada's Pacific coast but are also applicable for the other regions with commercial shipping in Canada. Towing force requirements are related to towing vessel capacity, noting that the towing efficiency will be reduced in higher wind and sea state conditions.

For most ship types, the wind drag component dominates the forces acting on the ship, meaning that high windage ships such as loaded container ships and cruise ships represent greater challenges to ETVs than do tankers. However, these ships typically are advised to have minimum bollard strength requirements by classification societies for normal operation and not emergency towing, making it difficult to confidently assess if these vessels would be able to handle the worst-case scenario force requirements. Only tankers are required by SOLAS to be fitted with towing arrangements that will meet worst case requirements, and to have suitable emergency towing gear that can be deployed rapidly.

At the 50th percentile for wind and waves, towing forces (as measured in bollard pull) to hold position range from 16 to 40 tonnes for the seven ships. At the 99th percentile environmental conditions, these forces range from 90 to 210 tonnes for the Aframax Tanker and Very Large Container Ship, respectively.

The report presents a summary of various factors that may influence the effectiveness of tugs and other towing vessels in emergency situations, ranging from vessel size and power to crew competency. This information is intended to assist in setting the requirements for future emergency towing vessels and for emergency response capabilities in general.

6.0 References

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Appendix A

7.0 Appendix A.1: Beam Seas Forces

7.1 Total Forces

Beam Seas - Total Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-870	-1435	-1798	-2682	-3858
Very Large Container Ship	-933	-1535	-1921	-2862	-4114
LNG Carrier	-641	-1017	-1247	-1828	-2591
Vehicle Carrier	-442	-690	-838	-1218	-1715
Passenger Ship	-753	-1244	-1560	-2329	-3351
Bulk Carrier	-484	-742	-893	-1288	-1800
Aframax Tanker	-331	-488	-573	-807	-1106
LNG Carrier (Trimmed)	-621	-979	-1196	-1748	-2472

7.2 Wind Forces

Beam Seas - Wind Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-572	-1067	-1423	-2223	-3316
Very Large Container Ship	-607	-1133	-1511	-2360	-3521
LNG Carrier	-358	-669	-891	-1393	-2078
Vehicle Carrier	-229	-427	-570	-890	-1328
Passenger Ship	-498	-929	-1239	-1935	-2887
Bulk Carrier	-231	-432	-576	-900	-1342
Aframax Tanker	-127	-237	-315	-493	-735
LNG Carrier (Trimmed)	-338	-630	-840	-1313	-1959

Beam Seas – Wind Force as % of Total					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	66%	74%	79%	83%	86%
Very Large Container Ship	65%	74%	79%	82%	86%
LNG Carrier	56%	66%	71%	76%	80%
Vehicle Carrier	52%	62%	68%	73%	77%
Passenger Ship	66%	75%	79%	83%	86%
Bulk Carrier	48%	58%	65%	70%	75%
Aframax Tanker	38%	49%	55%	61%	66%
LNG Carrier (Trimmed)	54%	64%	70%	75%	79%

7.3 Wave Forces

Beam Seas – Wave Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-299	-368	-376	-459	-542
Very Large Container Ship	-326	-402	-411	-502	-592
LNG Carrier	-283	-348	-356	-435	-513
Vehicle Carrier	-213	-262	-268	-328	-387
Passenger Ship	-256	-315	-322	-393	-464
Bulk Carrier	-252	-311	-317	-388	-458
Aframax Tanker	-205	-252	-257	-315	-371
LNG Carrier (Trimmed)	-283	-348	-356	-435	-513

Beam Seas – Wave Force as % of Total					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	34%	26%	21%	17%	14%
Very Large Container Ship	35%	26%	21%	18%	14%
LNG Carrier	44%	34%	29%	24%	20%
Vehicle Carrier	48%	38%	32%	27%	23%
Passenger Ship	34%	25%	21%	17%	14%
Bulk Carrier	52%	42%	35%	30%	25%
Aframax Tanker	62%	52%	45%	39%	34%
LNG Carrier (Trimmed)	46%	36%	30%	25%	21%

8.0 Appendix A.2: Head Seas Forces

8.1 Total Forces

Head Seas – Total Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-181	-323	-409	-617	-903
Very Large Container Ship	-205	-367	-466	-704	-1031
LNG Carrier	-173	-309	-392	-592	-866
Vehicle Carrier	-112	-198	-248	-372	-543
Passenger Ship	-138	-245	-308	-463	-676
Bulk Carrier	-136	-240	-302	-454	-662
Aframax Tanker	-104	-184	-231	-346	-504
LNG Carrier (Trimmed)	-174	-311	-394	-596	-872

8.2 Wind Forces

Head Seas – Wind Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-88	-165	-220	-344	-513
Very Large Container Ship	-104	-195	-260	-406	-605
LNG Carrier	-86	-160	-213	-333	-497
Vehicle Carrier	-46	-85	-114	-177	-265
Passenger Ship	-59	-110	-147	-229	-342
Bulk Carrier	-57	-107	-143	-223	-333
Aframax Tanker	-41	-76	-102	-159	-237
LNG Carrier (Trimmed)	-87	-162	-216	-337	-503

Head Seas – Wind Force as % of Total					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	49%	51%	54%	56%	57%
Very Large Container Ship	51%	53%	56%	58%	59%
LNG Carrier	50%	52%	54%	56%	57%
Vehicle Carrier	41%	43%	46%	48%	49%
Passenger Ship	43%	45%	48%	49%	51%
Bulk Carrier	42%	45%	47%	49%	50%
Aframax Tanker	39%	41%	44%	46%	47%
LNG Carrier (Trimmed)	50%	52%	55%	57%	58%

8.3 Wave Forces

Head Seas – Wave Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-93	-158	-188	-273	-390
Very Large Container Ship	-101	-172	-206	-298	-426
LNG Carrier	-88	-149	-179	-259	-369
Vehicle Carrier	-66	-112	-134	-195	-278
Passenger Ship	-79	-135	-161	-234	-334
Bulk Carrier	-78	-133	-159	-231	-329
Aframax Tanker	-63	-108	-129	-187	-267
LNG Carrier (Trimmed)	-88	-149	-179	-259	-369

Head Seas – Wave Force as % of Total					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	51%	49%	46%	44%	43%
Very Large Container Ship	49%	47%	44%	42%	41%
LNG Carrier	51%	48%	46%	44%	43%
Vehicle Carrier	59%	57%	54%	52%	51%
Passenger Ship	57%	55%	52%	51%	49%
Bulk Carrier	57%	55%	53%	51%	50%
Aframax Tanker	61%	59%	56%	54%	53%
LNG Carrier (Trimmed)	51%	48%	45%	43%	42%

9.0 Appendix A.3: Towing Condition Forces

9.1 Total Forces

Head Seas w/ Current – Total Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-216	-358	-444	-652	-938
Very Large Container Ship	-241	-402	-501	-739	-1067
LNG Carrier	-189	-325	-407	-607	-882
Vehicle Carrier	-129	-215	-265	-389	-560
Passenger Ship	-153	-260	-323	-478	-691
Bulk Carrier	-154	-258	-320	-472	-680
Aframax Tanker	-137	-217	-263	-378	-537
LNG Carrier (Trimmed)	-189	-325	-409	-610	-886

9.2 Wind Forces

Head Seas w/ Current – Wind Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-88	-165	-220	-344	-513
Very Large Container Ship	-104	-195	-260	-406	-605
LNG Carrier	-86	-160	-213	-333	-497
Vehicle Carrier	-46	-85	-114	-177	-265
Passenger Ship	-59	-110	-147	-229	-342
Bulk Carrier	-57	-107	-143	-223	-333
Aframax Tanker	-41	-76	-102	-159	-237
LNG Carrier (Trimmed)	-87	-162	-216	-337	-503

Head Seas w/ Current – Wind Force as % of Total					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	41%	46%	50%	53%	55%
Very Large Container Ship	43%	49%	52%	55%	57%
LNG Carrier	46%	49%	52%	55%	56%
Vehicle Carrier	36%	40%	43%	46%	47%
Passenger Ship	39%	42%	46%	48%	49%
Bulk Carrier	37%	41%	45%	47%	49%
Aframax Tanker	30%	35%	39%	42%	44%
LNG Carrier (Trimmed)	46%	50%	53%	55%	57%

9.3 Wave Forces

Head Seas w/ Current – Wave Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-93	-158	-188	-273	-390
Very Large Container Ship	-101	-172	-206	-298	-426
LNG Carrier	-88	-149	-179	-259	-369
Vehicle Carrier	-66	-112	-134	-195	-278
Passenger Ship	-79	-135	-161	-234	-334
Bulk Carrier	-78	-133	-159	-231	-329
Aframax Tanker	-63	-108	-129	-187	-267
LNG Carrier (Trimmed)	-88	-149	-179	-259	-369

Head Seas w/ Current – Wave Force as % of Total					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	43%	44%	42%	42%	42%
Very Large Container Ship	42%	43%	41%	40%	40%
LNG Carrier	47%	46%	44%	43%	42%
Vehicle Carrier	51%	52%	51%	50%	50%
Passenger Ship	52%	52%	50%	49%	48%
Bulk Carrier	51%	52%	50%	49%	48%
Aframax Tanker	46%	50%	49%	49%	50%
LNG Carrier (Trimmed)	47%	46%	44%	42%	42%

9.4 Current Forces

Head Seas w/ Current – Current Force (kN)					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	-35	-35	-35	-35	-35
Very Large Container Ship	-36	-36	-36	-36	-36
LNG Carrier	-16	-16	-16	-16	-16
Vehicle Carrier	-17	-17	-17	-17	-17
Passenger Ship	-15	-15	-15	-15	-15
Bulk Carrier	-18	-18	-18	-18	-18
Aframax Tanker	-33	-33	-33	-33	-33
LNG Carrier (Trimmed)	-14	-14	-14	-14	-14

Head Seas w/ Current – Current Force as % of Total					
Environmental Condition Percentile	**50**	**75**	**85**	**95**	**99**
Large Container Ship	16%	10%	8%	5%	4%
Very Large Container Ship	15%	9%	7%	5%	3%
LNG Carrier	8%	5%	4%	3%	2%
Vehicle Carrier	13%	8%	6%	4%	3%
Passenger Ship	10%	6%	5%	3%	2%
Bulk Carrier	12%	7%	6%	4%	3%
Aframax Tanker	24%	15%	13%	9%	6%
LNG Carrier (Trimmed)	7%	4%	3%	2%	2%

10.0 Appendix A.4: Results By Vessel

10.1 Large Container Ship

Vessel 1 – Large Container Ship								
MET-OCEAN Conditions	Wind (kn)	Beam Seas Force (kN)	Towing Force (kN)	Turning Force (kN)	Holding Steady Force (kN)	Estimated Tug Efficiency (%)	ETV/TUG Bollard Pull (tonnes)	ETV/TUG Propulsion (MW)
50th Percentile	7.1	870	216	262	181	79.9	33.5	2.01
75th Percentile	9.7	1435	358	419	323	78.9	54.1	3.25
85th Percentile	11.2	1798	444	517	409	77.6	68.0	4.08
95th Percentile	14	2682	652	802	617	72.8	112.4	6.74
99th Percentile	17.1	3858	938	1078	903	61.3	179.3	10.76

10.2 Very Large Container Ship

Vessel 2 – Very Large Container Ship								
MET-OCEAN Conditions	Wind (kn)	Beam Seas Force (kN)	Towing Force (kN)	Turning Force (kN)	Holding Steady Force (kN)	Estimated Tug Efficiency (%)	ETV/TUG Bollard Pull (tonnes)	ETV/TUG Propulsion (MW)
50th Percentile	7.1	933	241	312	205	79.9	39.8	2.39
75th Percentile	9.7	1535	402	498	367	78.9	64.3	3.86
85th Percentile	11.2	1921	501	614	466	77.6	80.7	4.84
95th Percentile	14	2862	739	953	704	72.8	133.5	8.01
99th Percentile	17.1	4114	1067	1281	1031	61.3	213.1	12.79

10.3 LNG Carrier

Vessel 3 – LNG Carrier								
MET-OCEAN Conditions	Wind (kn)	Beam Seas Force (kN)	Towing Force (kN)	Turning Force (kN)	Holding Steady Force (kN)	Estimated Tug Efficiency (%)	ETV/TUG Bollard Pull (tonnes)	ETV/TUG Propulsion (MW)
50th Percentile	7.1	641	189	206	173	79.9	26.3	1.58
75th Percentile	9.7	1017	325	338	309	78.9	43.6	2.62
85th Percentile	11.2	1247	407	417	392	77.6	54.8	3.29
95th Percentile	14	1828	607	658	592	72.8	92.2	5.53
99th Percentile	17.1	2591	882	892	866	61.3	148.4	8.90

10.4 Vehicle Carrier

Vessel 4 – Vehicle Carrier								
MET-OCEAN Conditions	Wind (kn)	Beam Seas Force (kN)	Towing Force (kN)	Turning Force (kN)	Holding Steady Force (kN)	Estimated Tug Efficiency (%)	ETV/TUG Bollard Pull (tonnes)	ETV/TUG Propulsion (MW)
50th Percentile	7.1	442	129	146	112	79.9	18.7	1.12
75th Percentile	9.7	690	215	234	198	78.9	30.2	1.81
85th Percentile	11.2	838	265	287	248	77.6	37.7	2.26
95th Percentile	14	1218	389	453	372	72.8	63.5	3.81
99th Percentile	17.1	1715	560	609	543	61.3	101.4	6.08

10.5 Passenger Ship

Vessel 5 – Passenger Ship								
MET-OCEAN Conditions	Wind (kn)	Beam Seas Force (kN)	Towing Force (kN)	Turning Force (kN)	Holding Steady Force (kN)	Estimated Tug Efficiency (%)	ETV/TUG Bollard Pull (tonnes)	ETV/TUG Propulsion (MW)
50th Percentile	7.1	753	153	207	138	79.9	26.5	1.59
75th Percentile	9.7	1244	260	332	245	78.9	43.0	2.58
85th Percentile	11.2	1560	323	409	308	77.6	53.8	3.23
95th Percentile	14	2329	478	638	463	72.8	89.3	5.36
99th Percentile	17.1	3351	691	855	676	61.3	142.2	8.53

10.6 Bulk Carrier

Vessel 6 – Bulk Carrier								
MET-OCEAN Conditions	Wind (kn)	Beam Seas Force (kN)	Towing Force (kN)	Turning Force (kN)	Holding Steady Force (kN)	Estimated Tug Efficiency (%)	ETV/TUG Bollard Pull (tonnes)	ETV/TUG Propulsion (MW)
50th Percentile	7.1	484	154	170	136	79.9	21.8	1.31
75th Percentile	9.7	742	258	270	240	78.9	34.8	2.09
85th Percentile	11.2	893	320	327	302	77.6	43.0	2.58
95th Percentile	14	1288	472	520	454	72.8	72.8	4.37
99th Percentile	17.1	1800	680	695	662	61.3	115.7	6.94

10.7 Aframax Tanker

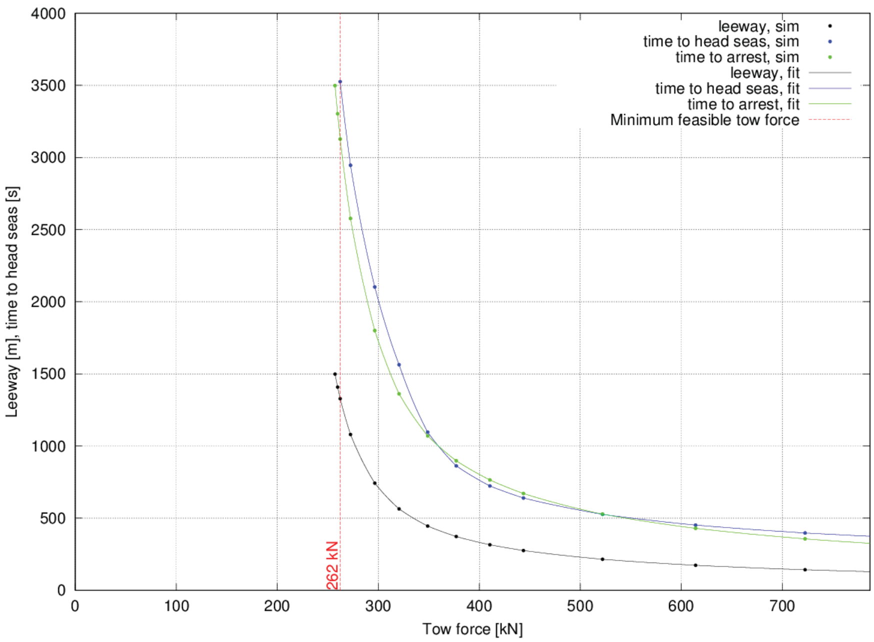
Vessel 7 – Aframax Tanker								
MET-OCEAN Conditions	Wind (kn)	Beam Seas Force (kN)	Towing Force (kN)	Turning Force (kN)	Holding Steady Force (kN)	Estimated Tug Efficiency (%)	ETV/TUG Bollard Pull (tonnes)	ETV/TUG Propulsion (MW)
50th Percentile	7.1	331	137	126	104	79.9	16.1	0.97
75th Percentile	9.7	488	217	200	184	78.9	25.8	1.55
85th Percentile	11.2	573	263	246	231	77.6	32.4	1.94
95th Percentile	14	807	378	391	346	72.8	54.8	3.29
99th Percentile	17.1	1106	537	523	504	61.3	87.1	5.22

Appendix B

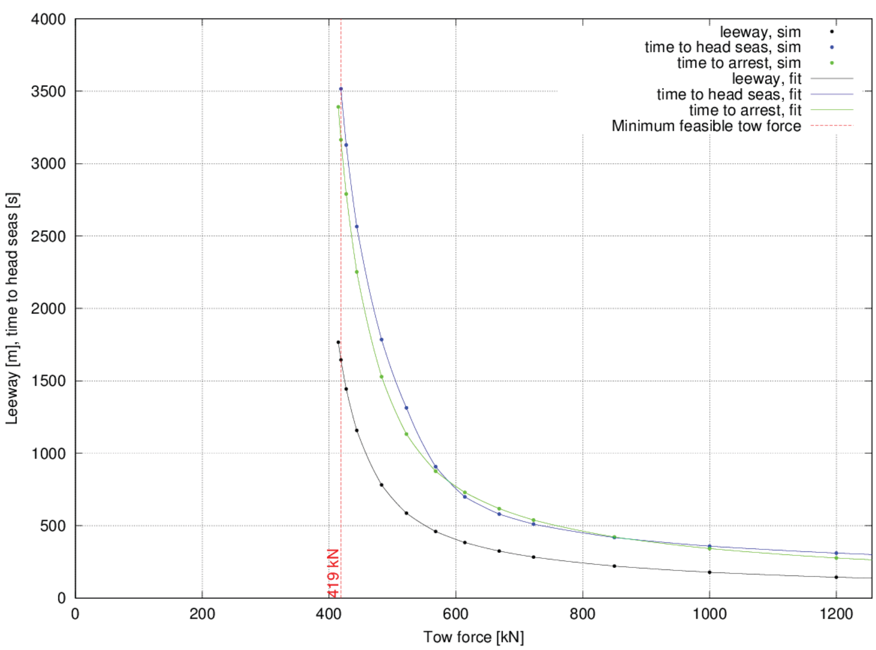
11.0 Appendix B.1: Large Container Ship Simulation Results

11.1 Effect of Tow Force

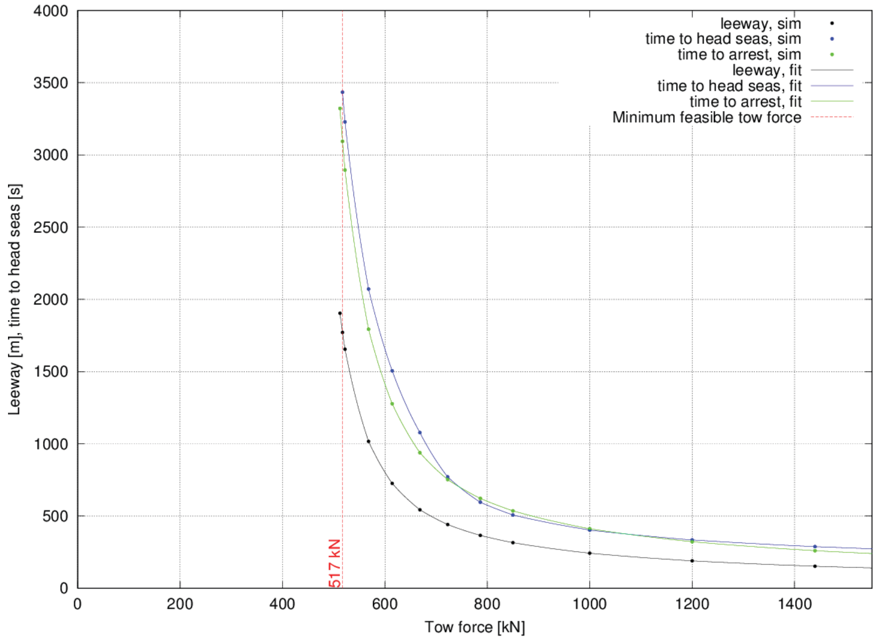
Large Container Ship effect of tow force, 50th percentile environment



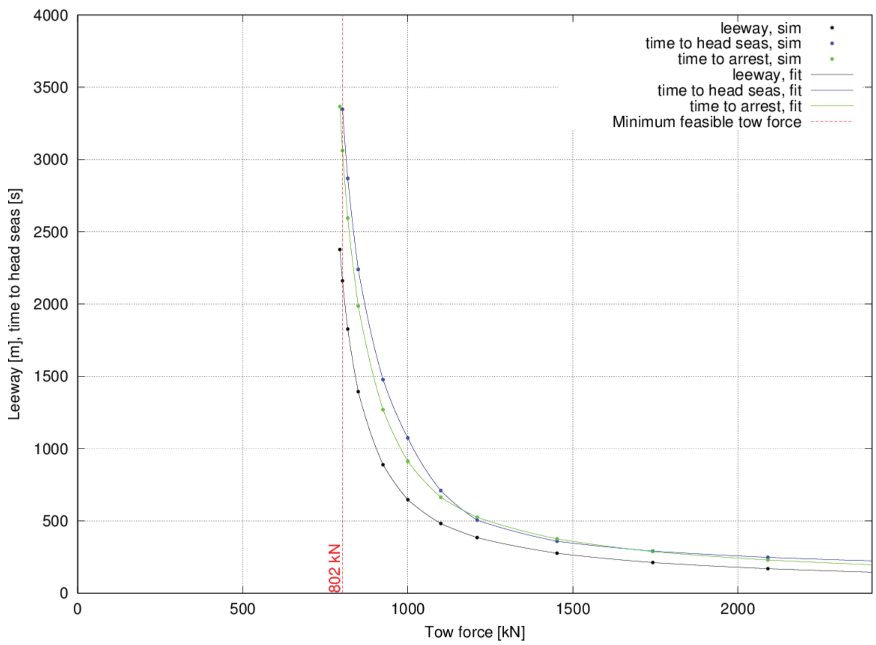
Large Container Ship effect of tow force, 75th percentile environment



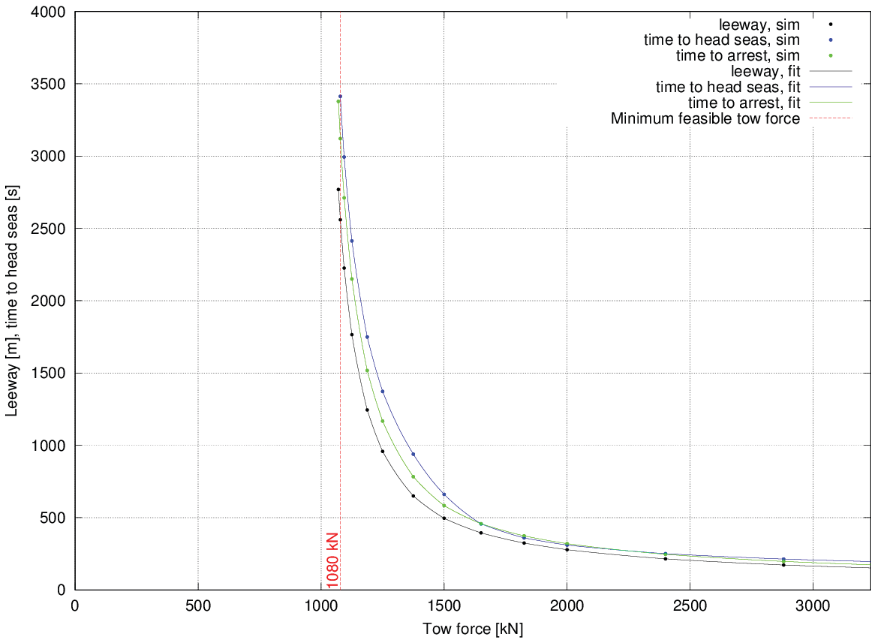
Large Container Ship effect of tow force, 85th percentile environment



Large Container Ship effect of tow force, 95th percentile environment

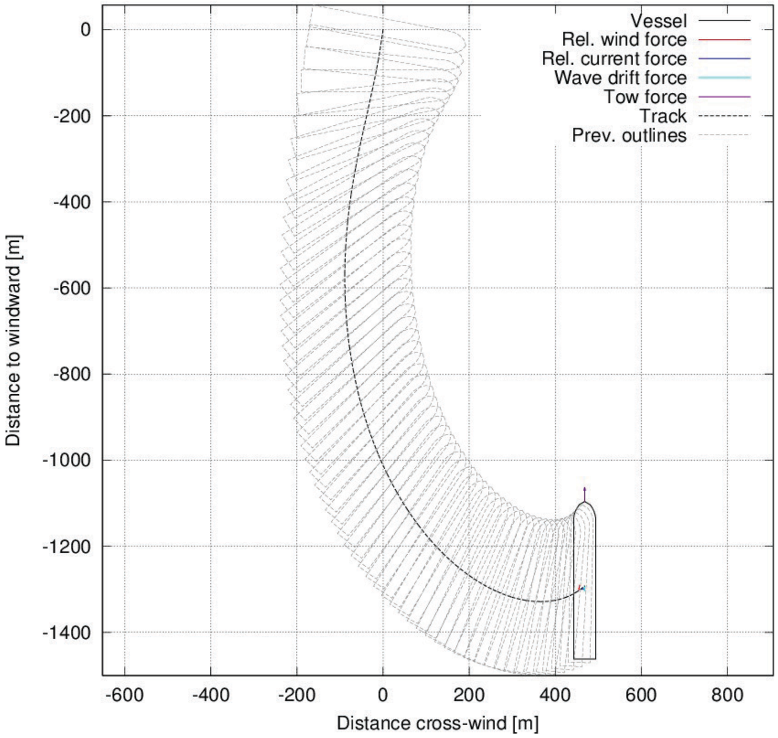


Large Container Ship effect of tow force, 99th percentile environment

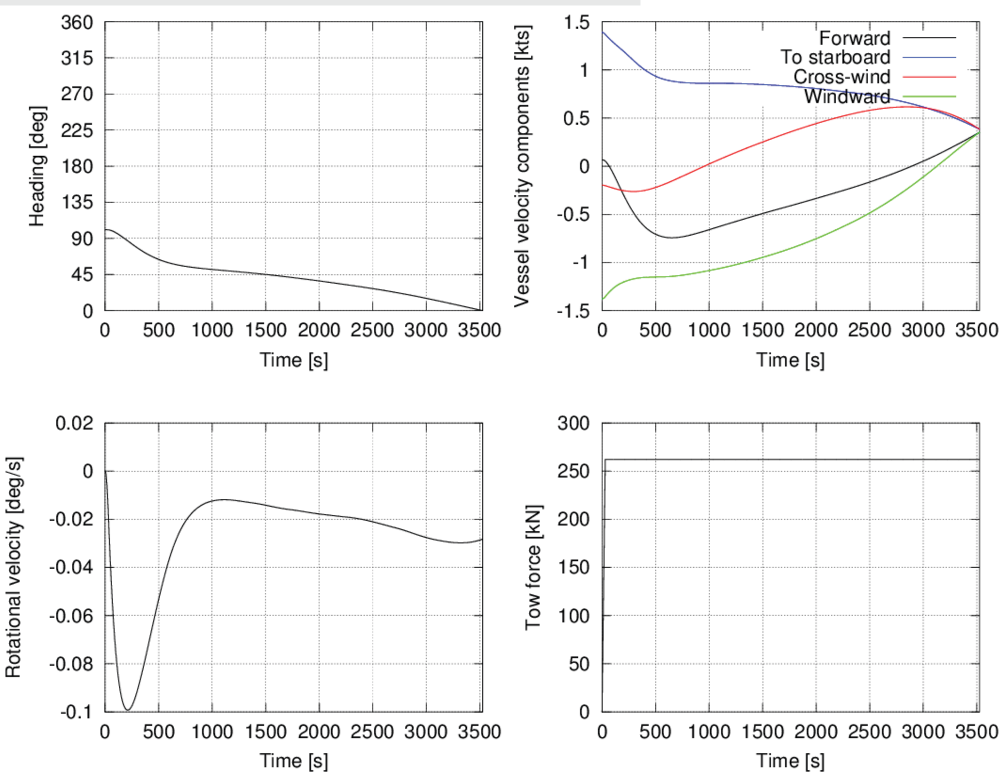


11.2 Simulations at Minimum Feasible Tow Force

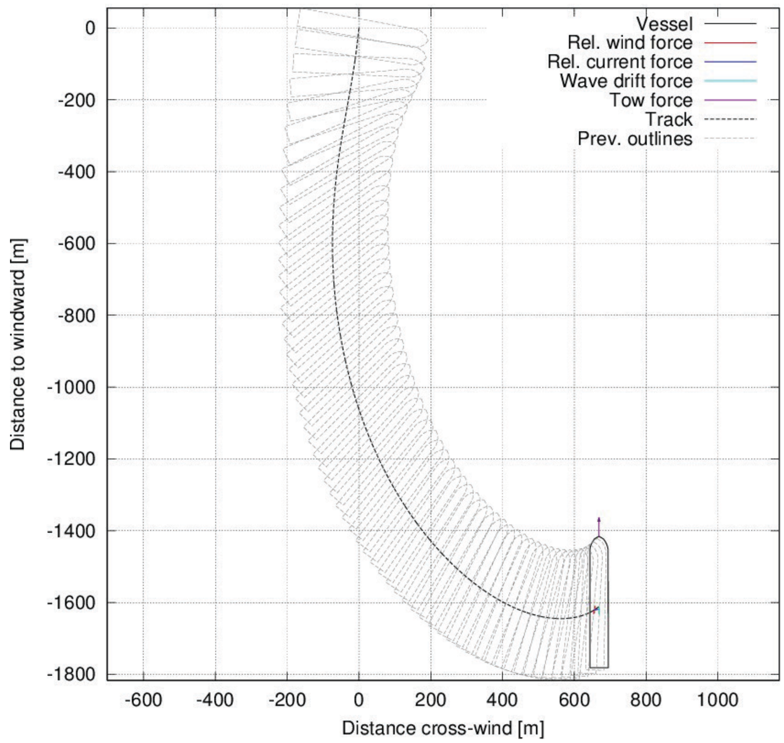
Large Container Ship, 50th percentile environment, 262 kN pull, port turn 360.0 deg heading from windward at 3526.0 s



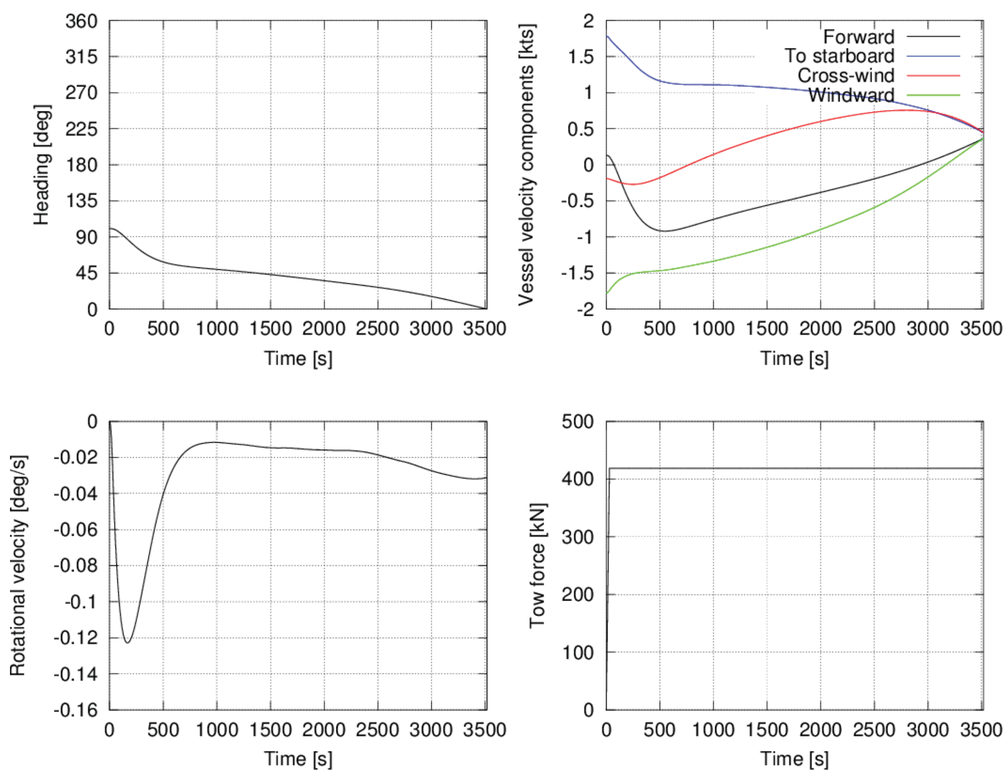
Large Container Ship, 50th percentile environment, 262 kN pull, port turn



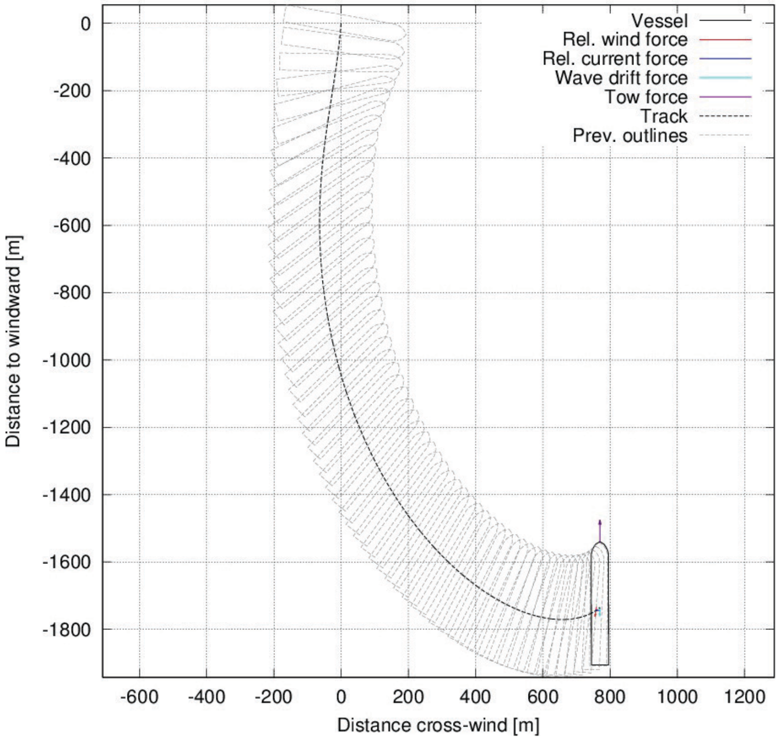
Large Container Ship, 75th percentile environment, 419 kN pull, port turn 360.0 deg heading from windward at 3517.0 s



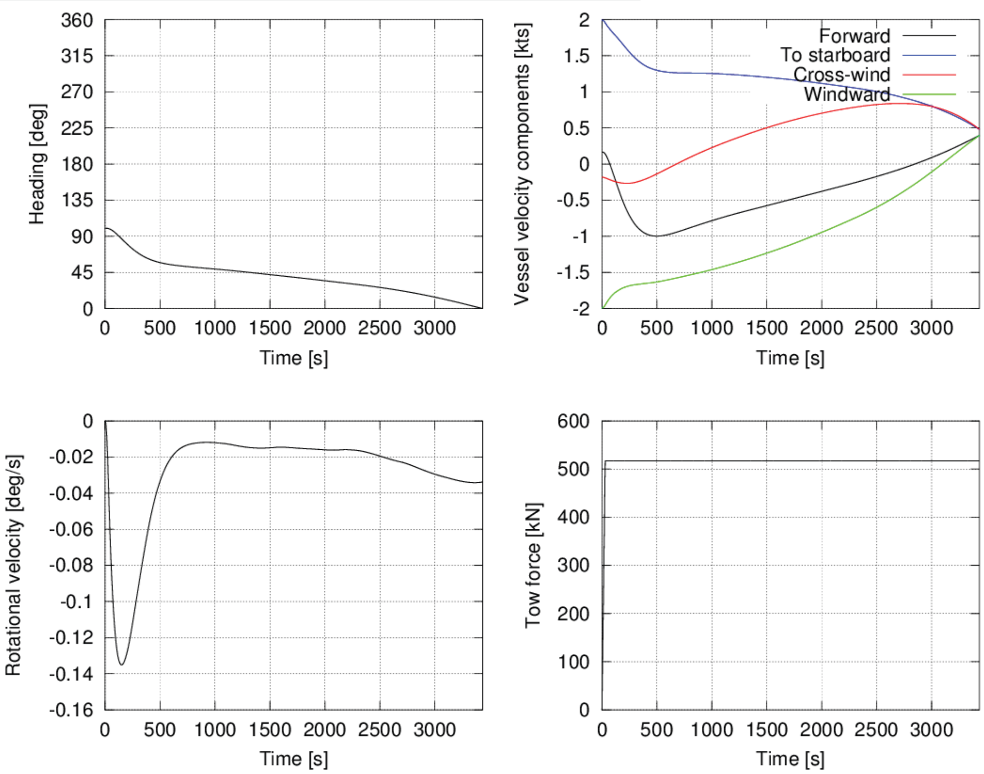
Large Container Ship, 75th percentile environment, 419 kN pull, port turn



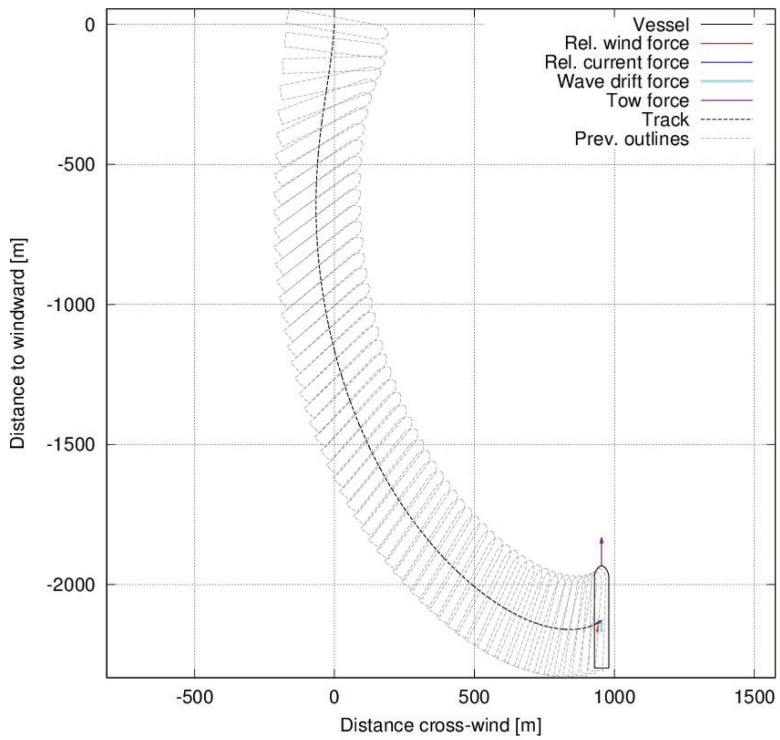
Large Container Ship, 85th percentile environment, 517 kN pull, port turn 360.0 deg heading from windward at 3435.0 s



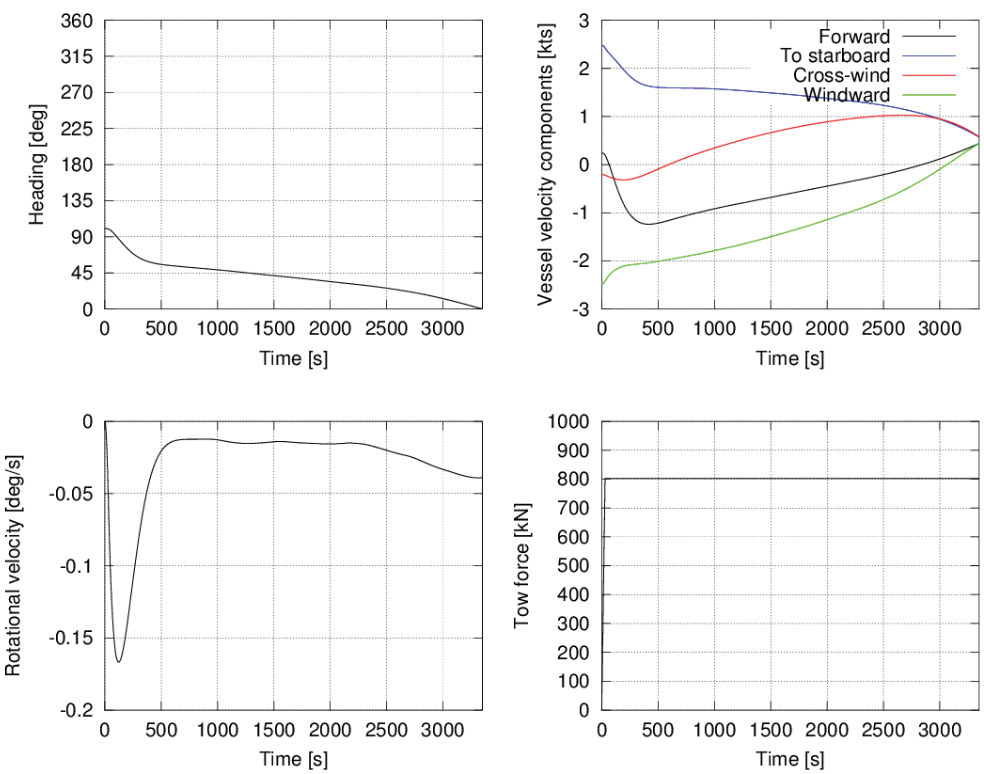
Large Container Ship, 85th percentile environment, 517 kN pull, port turn



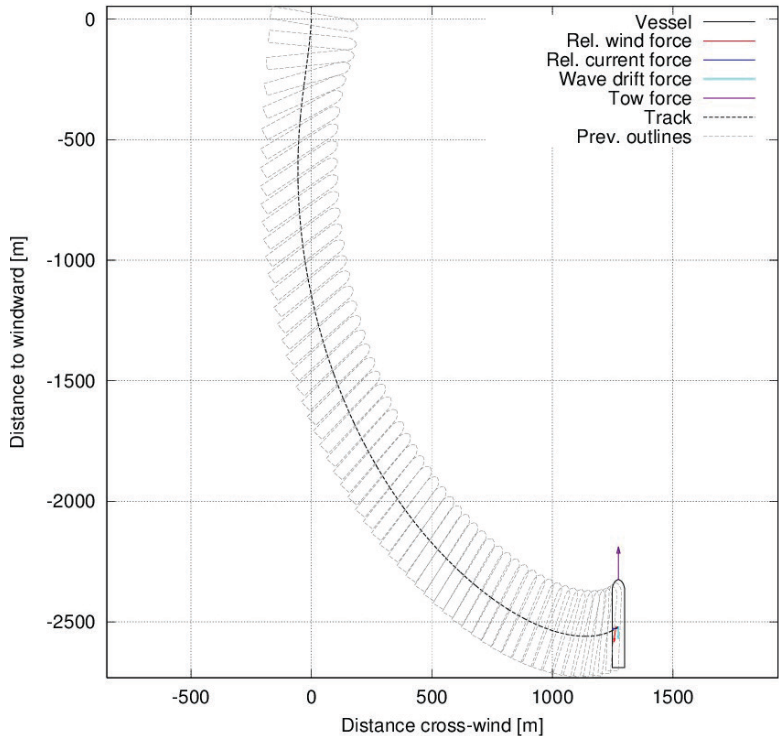
Large Container Ship, 95th percentile environment, 802 kN pull, port turn 360.0 deg heading from windward at 3349.0 s



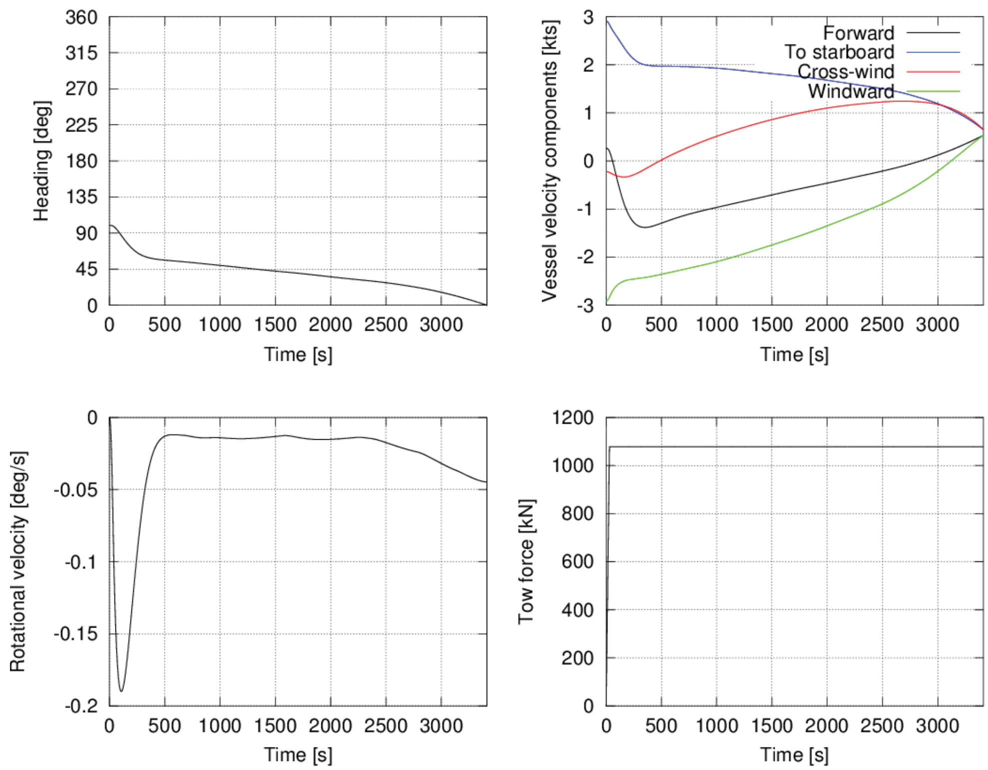
Large Container Ship, 95th percentile environment, 802 kN pull, port turn



Large Container Ship, 99th percentile environment, 1078 kN pull, port turn 360.0 deg heading from windward at 34130.0 s



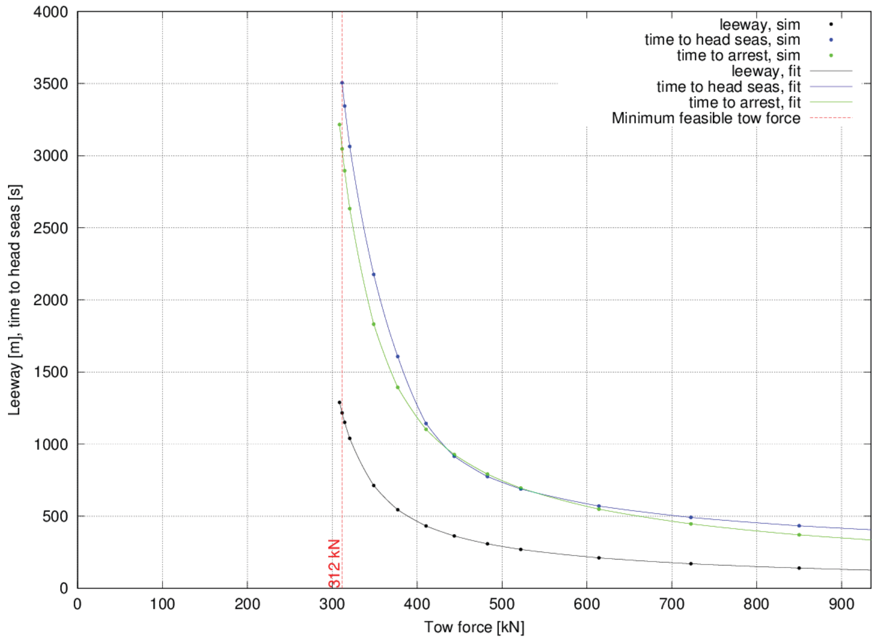
Large Container Ship, 99th percentile environment, 1078 kN pull, port turn



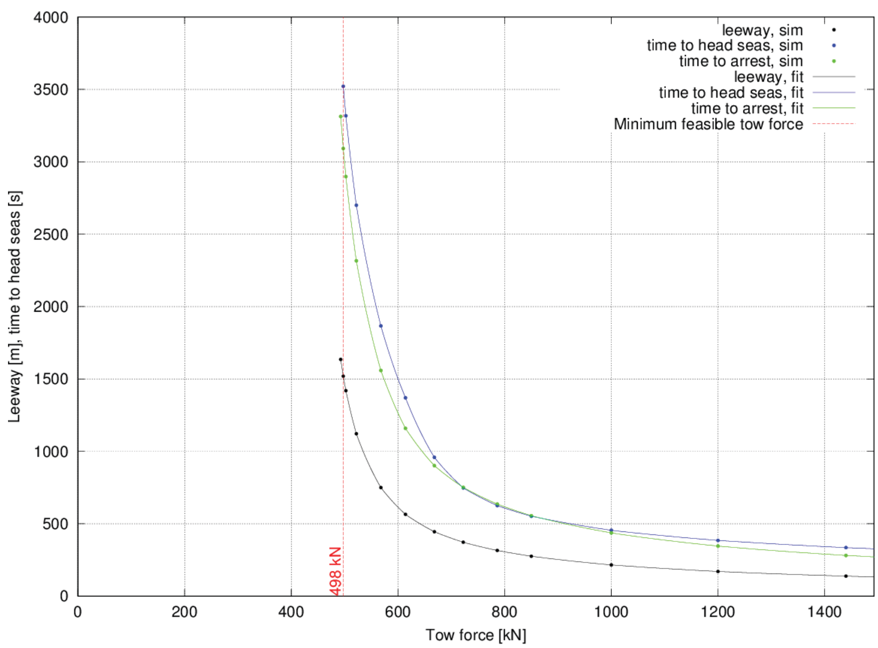
12.0 Appendix B.2: Very Large Container Ship Simulation Results

12.1 Effect of Tow Force

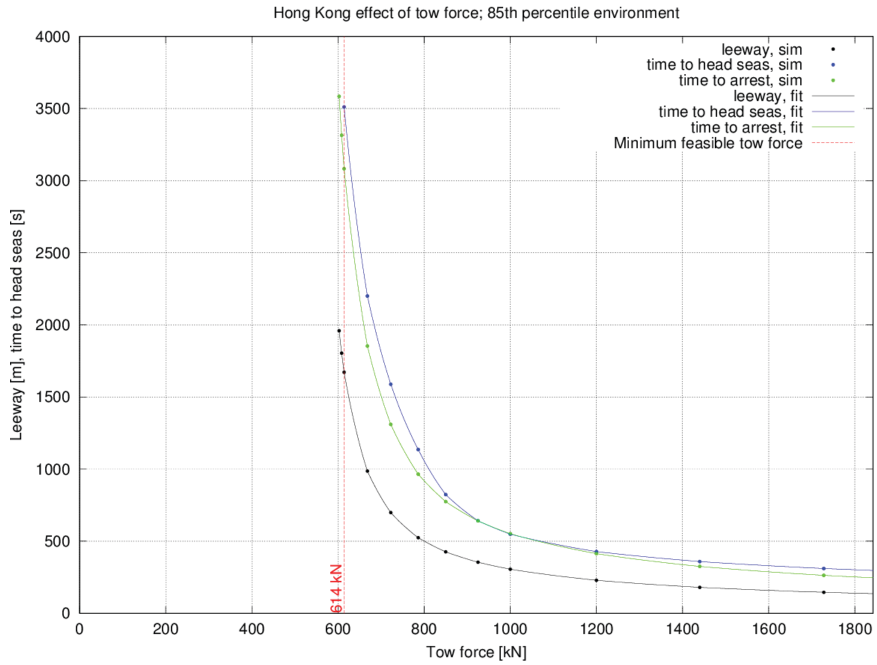
Very Large Container Ship effect of tow force; 50th percentile environment



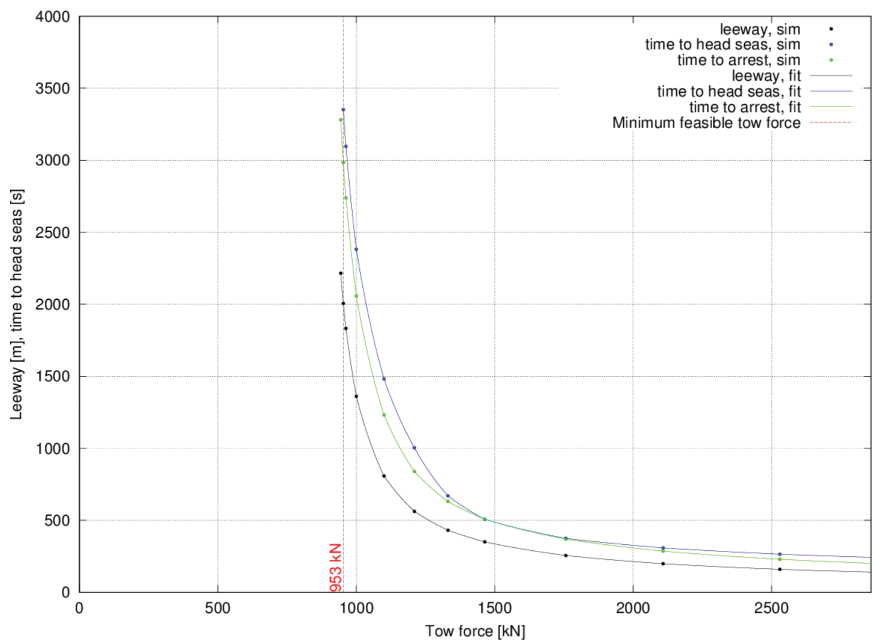
Very Large Container Ship effect of tow force; 75th percentile environment



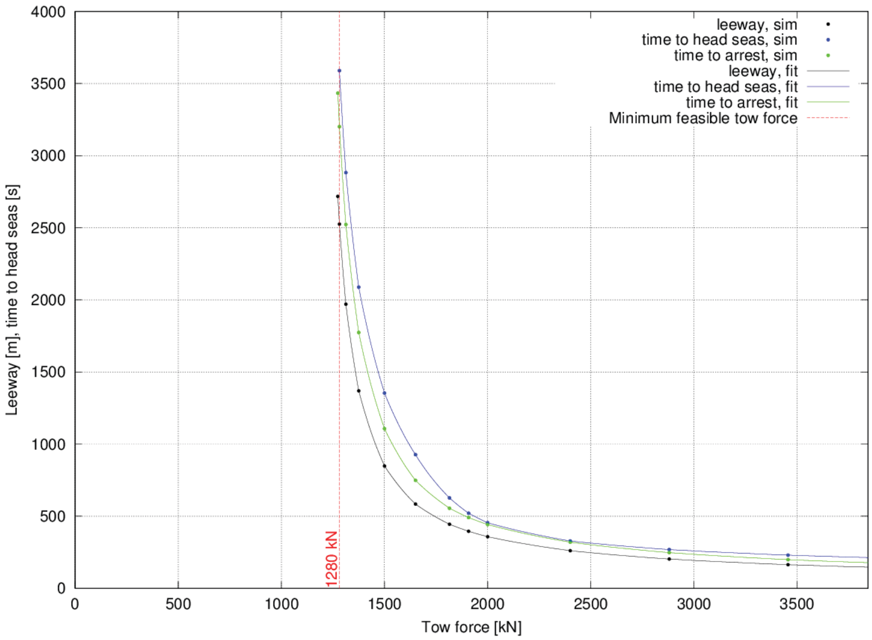
Very Large Container Ship effect of tow force; 85th percentile environment



Very Large Container Ship effect of tow force; 95th percentile environment

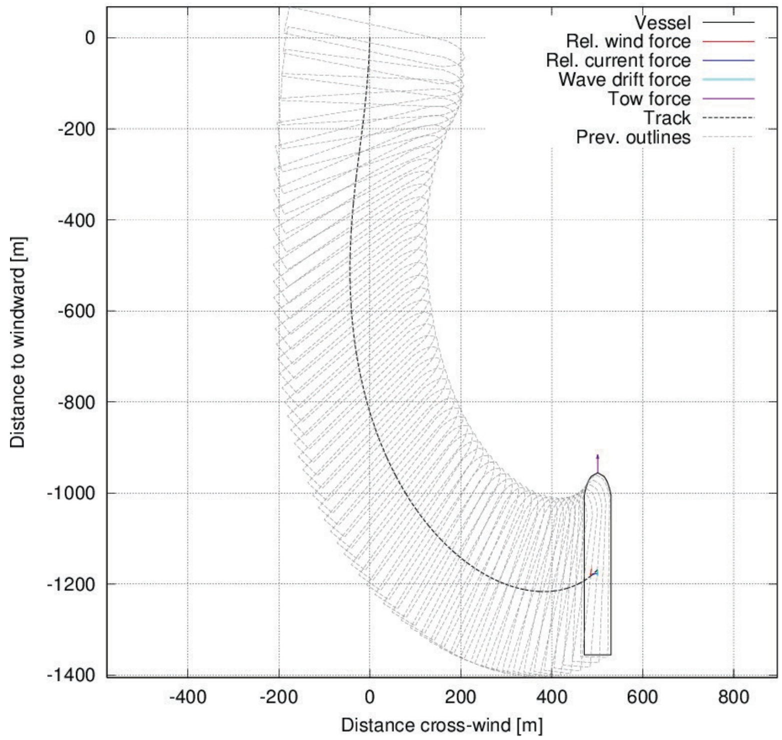


Very Large Container Ship effect of tow force; 99th percentile environment

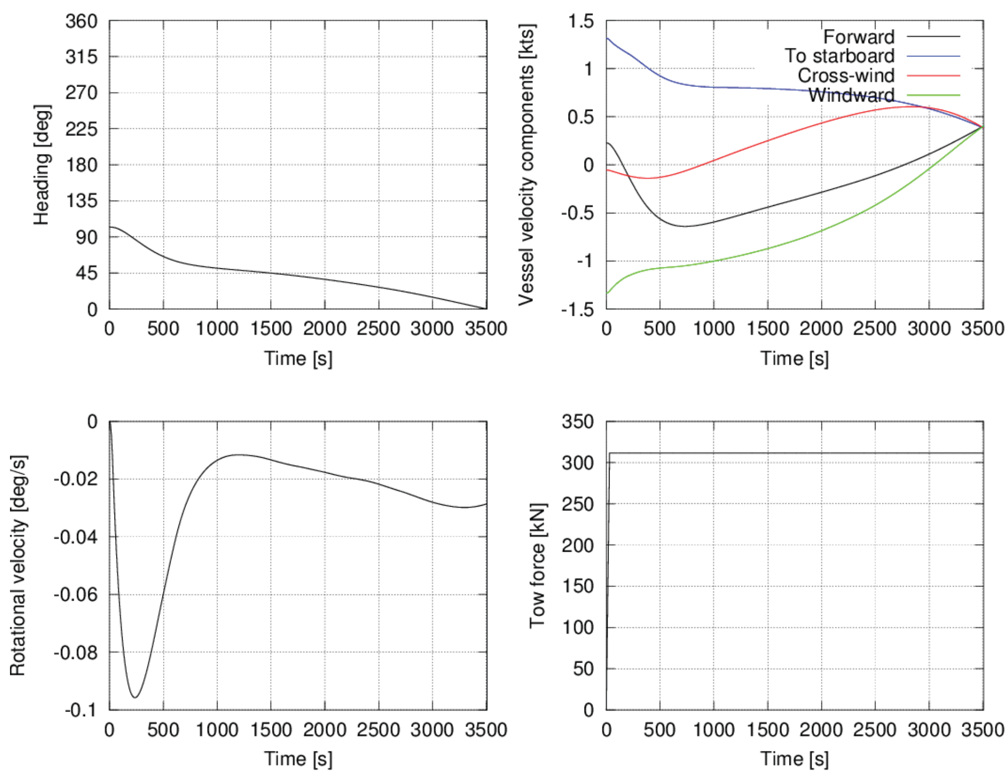


12.2 Simulations at Minimum Feasible Tow Force

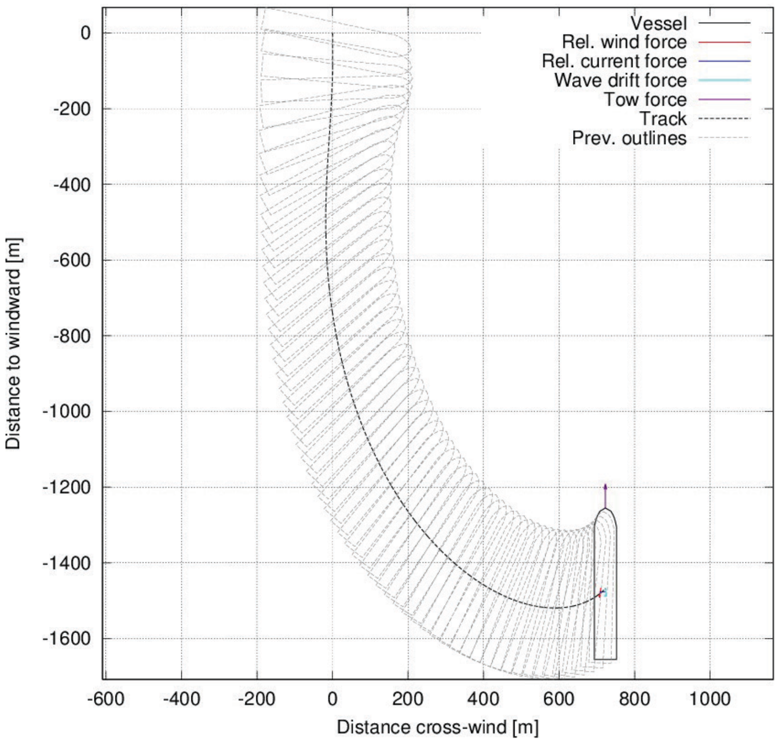
Very Large Container Ship, 50th percentile environment, 312 kN pull, port turn 360.0 deg heading from windward at 3506.0 s



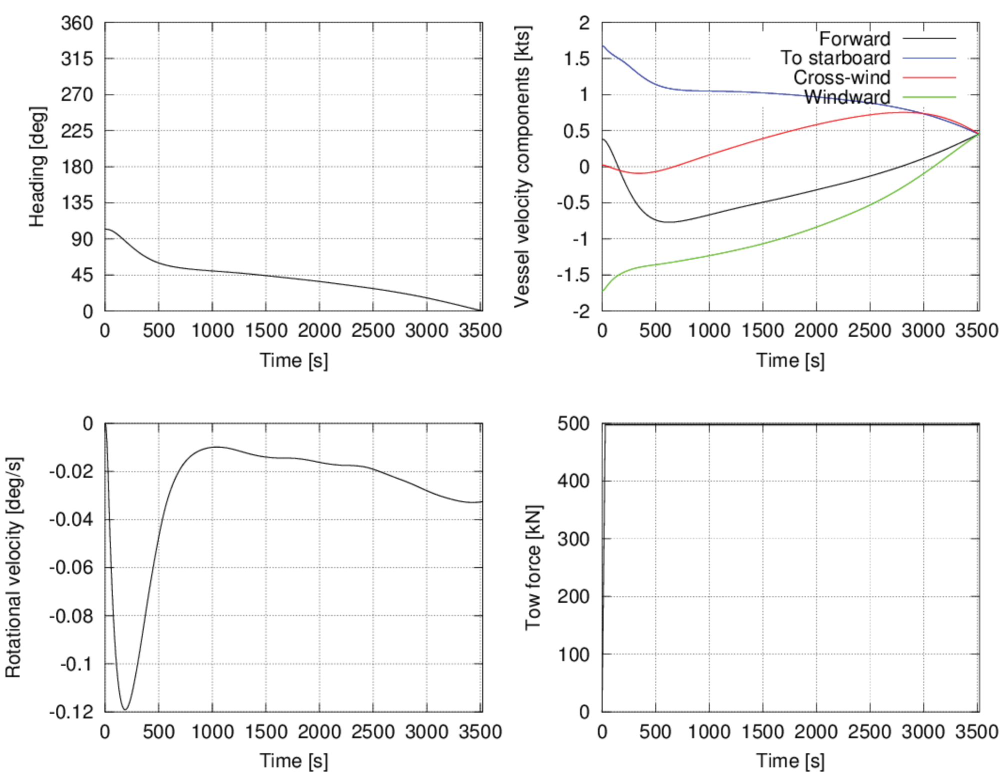
Very Large Container Ship, 50th percentile environment, 312 kN pull, port turn



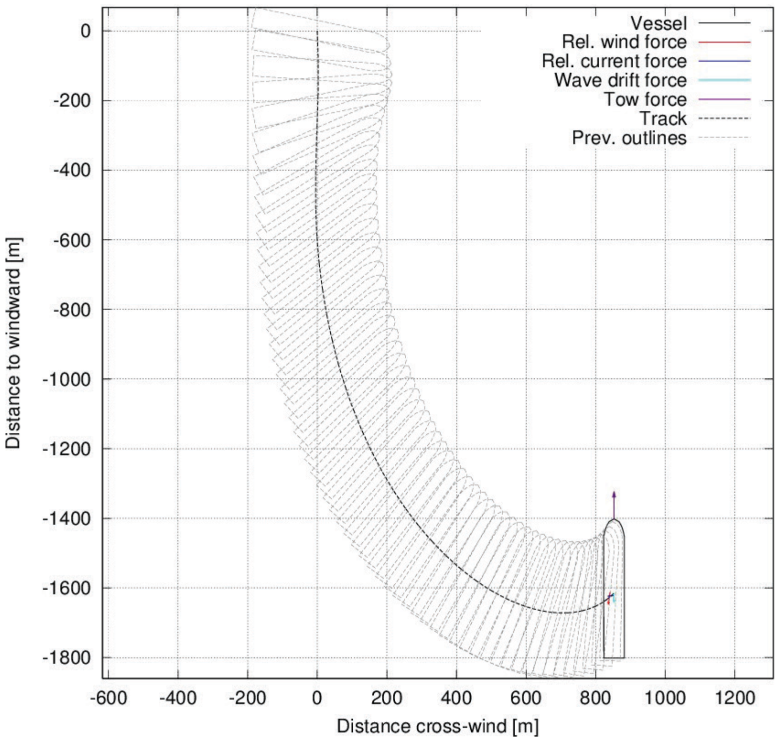
Very Large Container Ship, 75th percentile environment, 498 kN pull, port turn 360.0 deg heading from windward at 3522.0 s



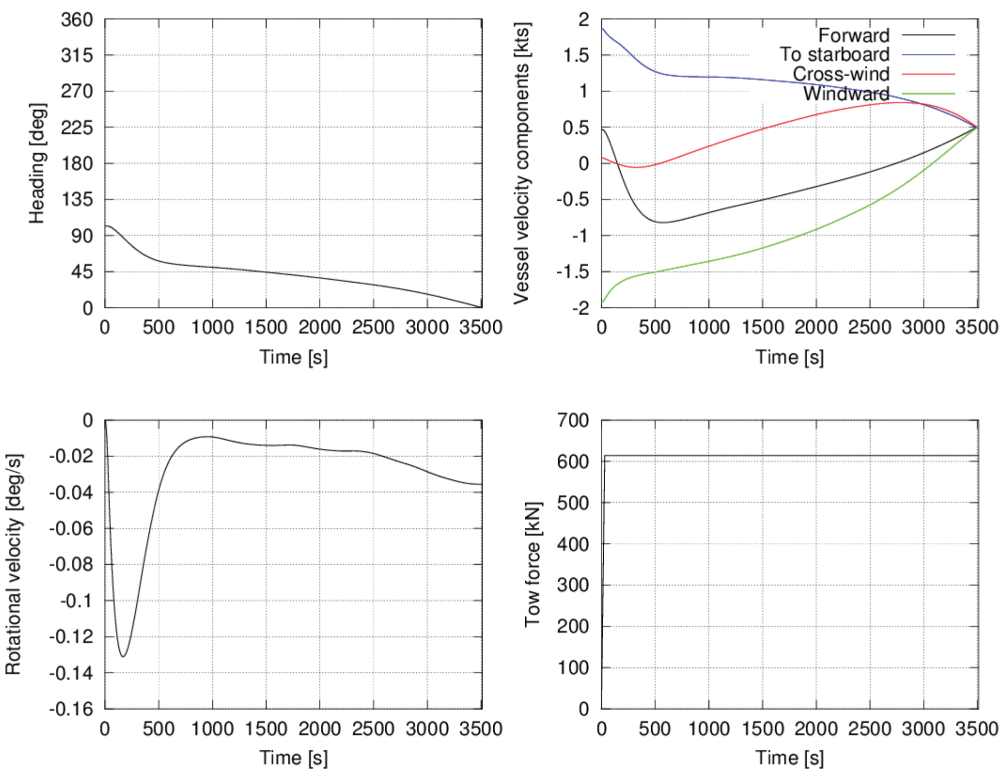
Very Large Container Ship, 75th percentile environment, 498 kN pull, port turn



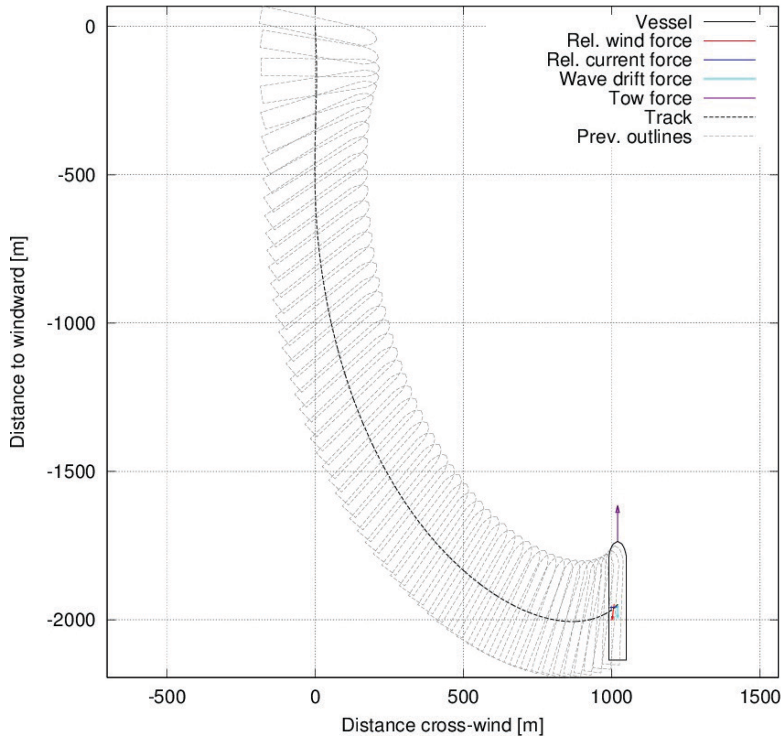
Very Large Container Ship, 85th percentile environment, 614 kN pull, port turn 360.0 deg heading from windward at 3511.0 s



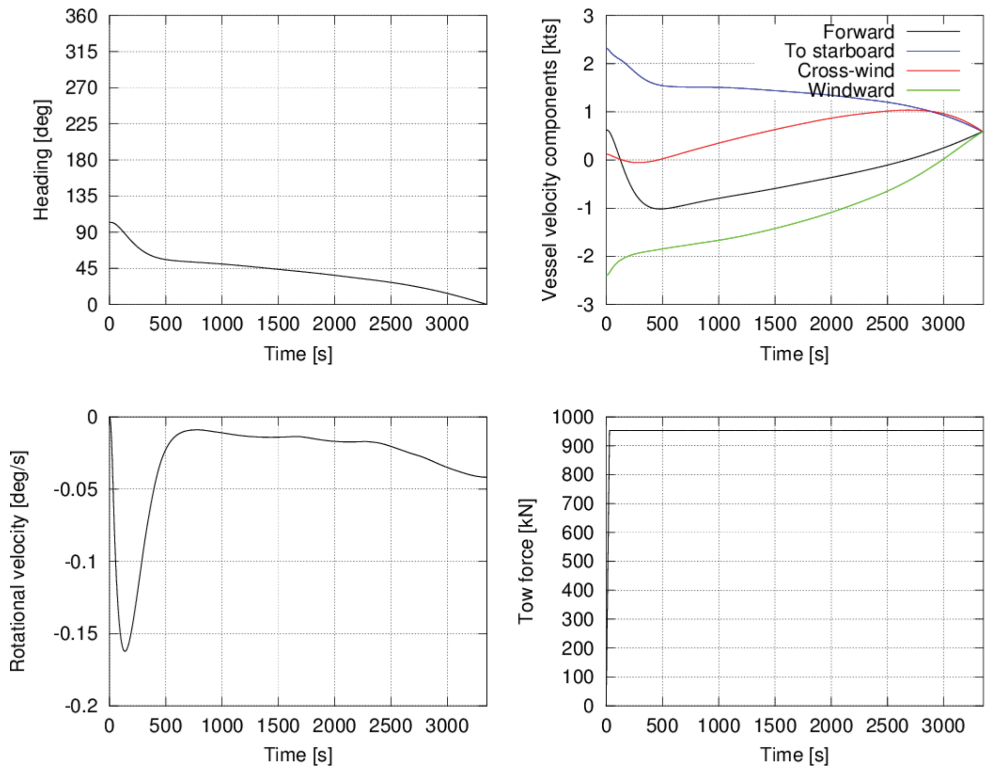
Very Large Container Ship, 85th percentile environment, 614 kN pull, port turn



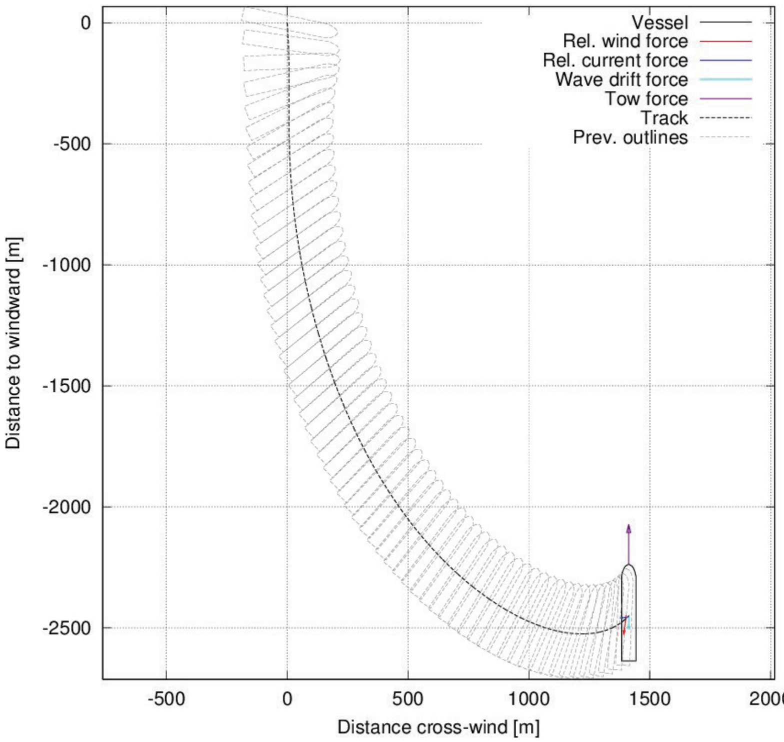
Very Large Container Ship, 95th percentile environment, 953 kN pull, port turn 360.0 deg heading from windward at 3552.0 s



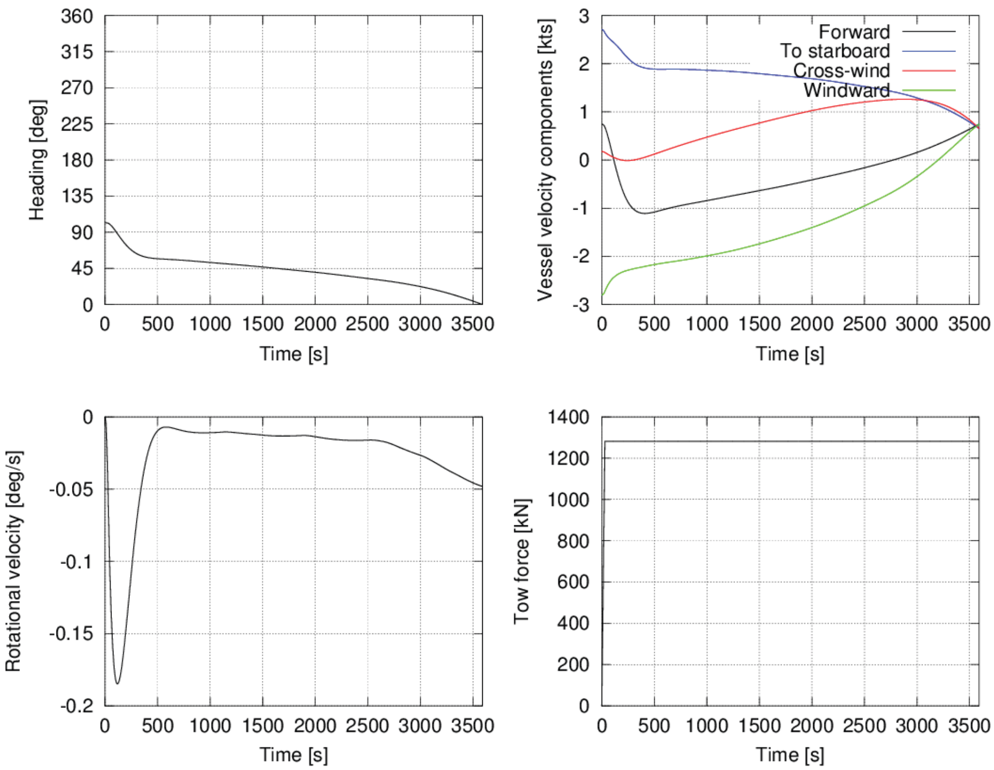
Very Large Container Ship, 95th percentile environment, 953 kN pull, port turn



Very Large Container Ship, 99th percentile environment, 1281 kN pull, port turn 360.0 deg heading from windward at 3590.0 s



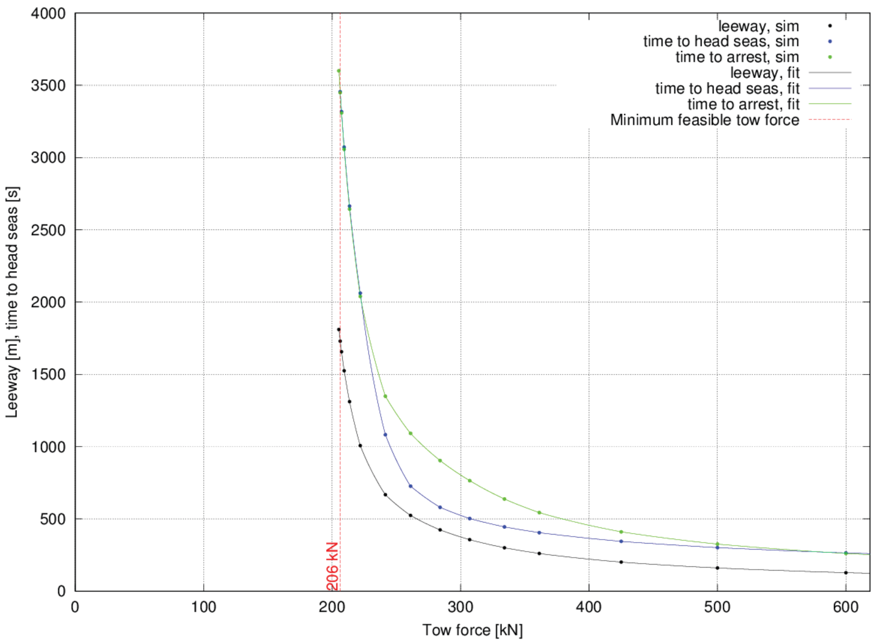
Very Large Container Ship, 99th percentile environment, 1281 kN pull, port turn



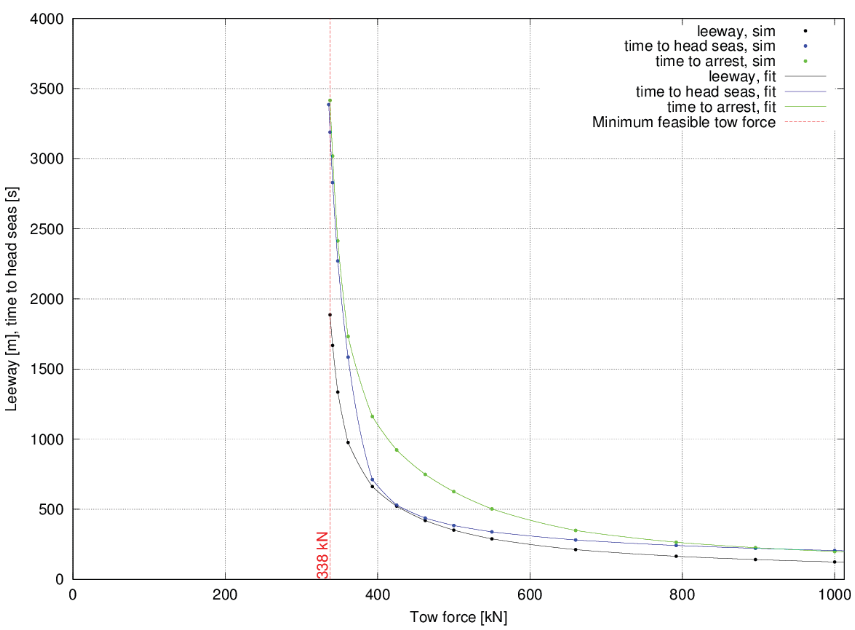
13.0 Appendix B.3: LNG Carrier Simulation Results

13.1 Effect of Tow Force

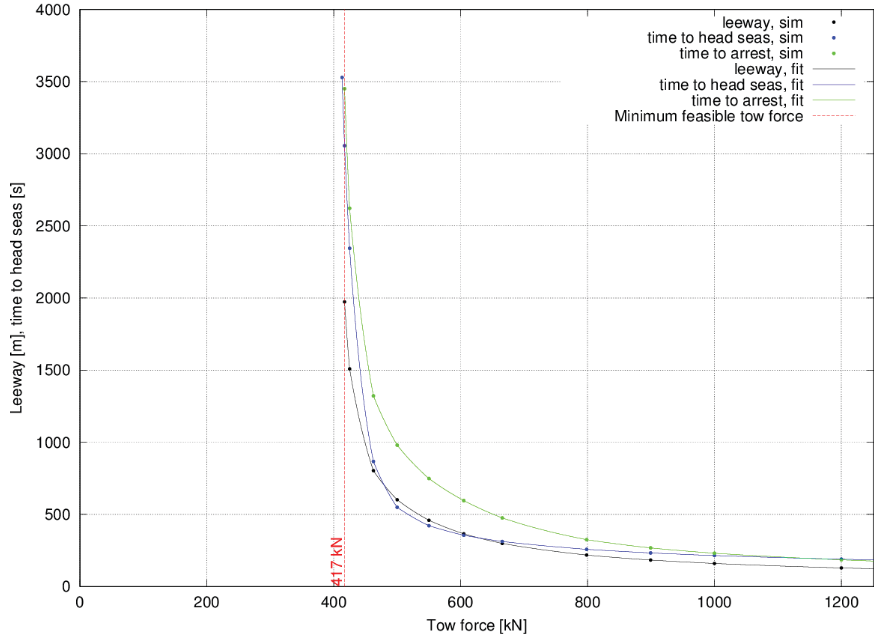
LNG Carrier effect of tow force; 50th percentile environment



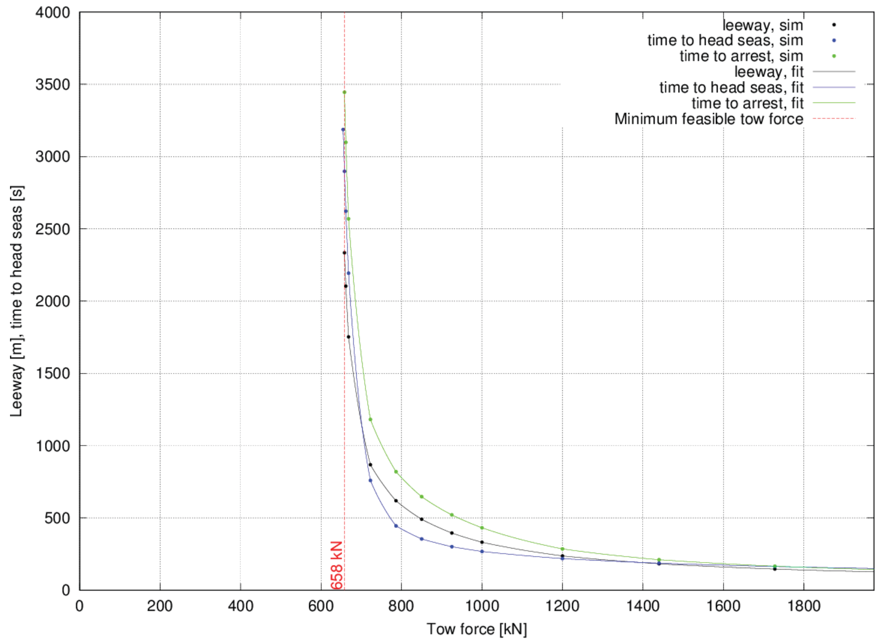
LNG Carrier effect of tow force; 75th percentile environment



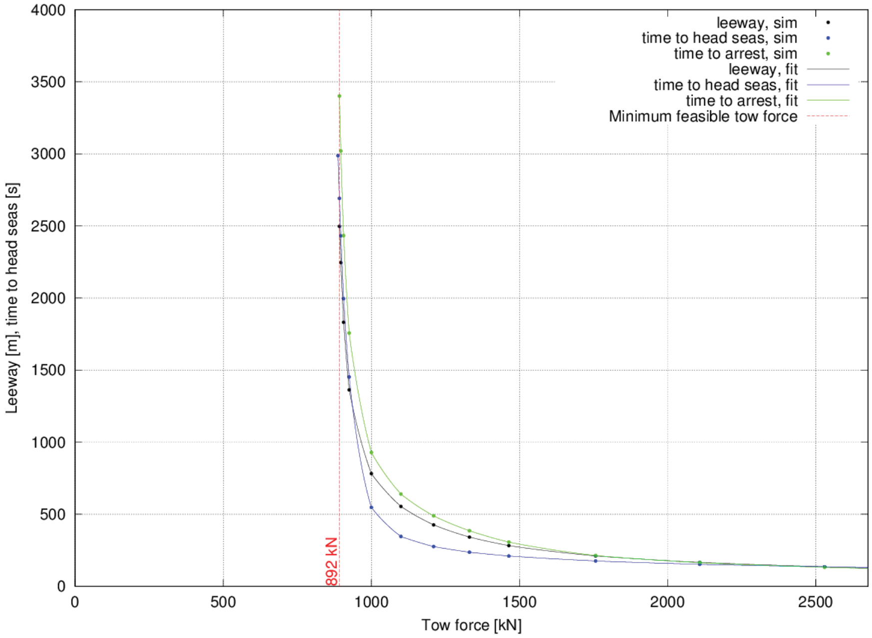
LNG Carrier effect of tow force; 85th percentile environment



LNG Carrier effect of tow force; 95th percentile environment

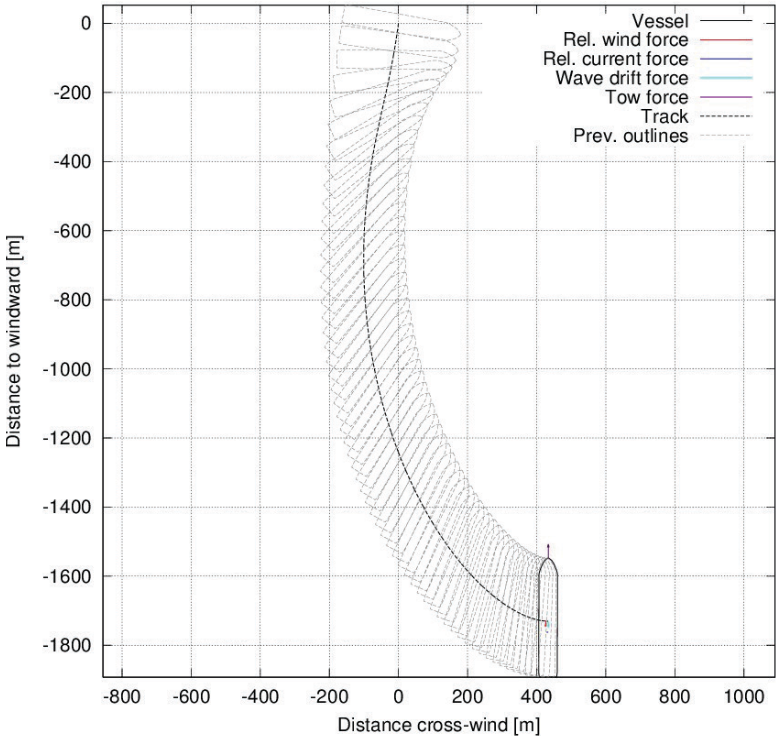


LNG Carrier effect of tow force; 99th percentile environment

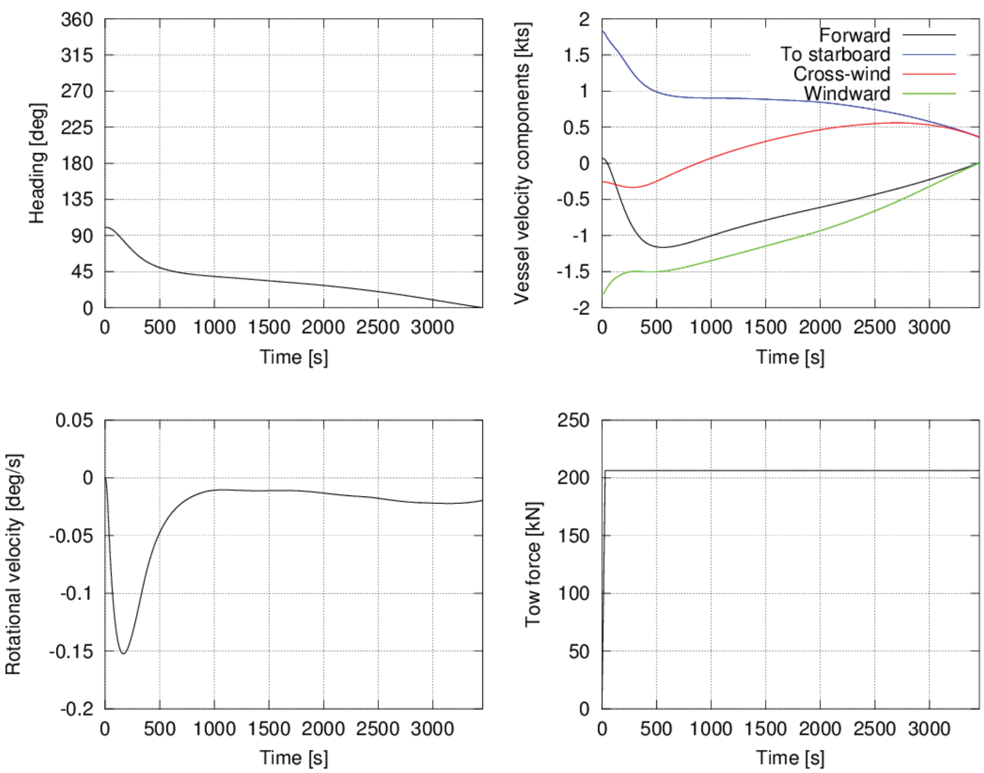


13.2 Simulations at Minimum Feasible Tow Force

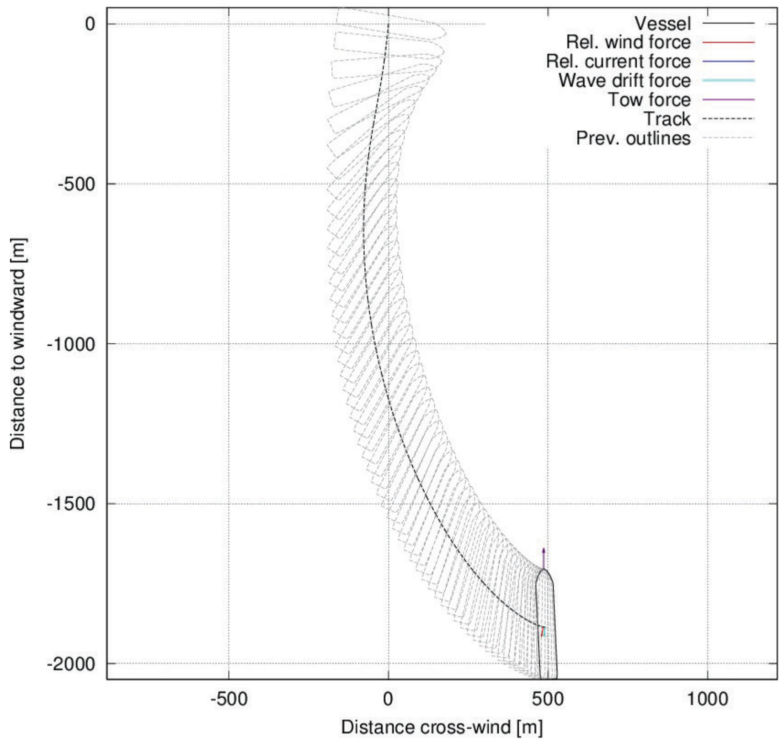
LNG Carrier, 50th percentile environment, 206 kN pull, port turn 0.1 deg heading from windward at 3448.0 s



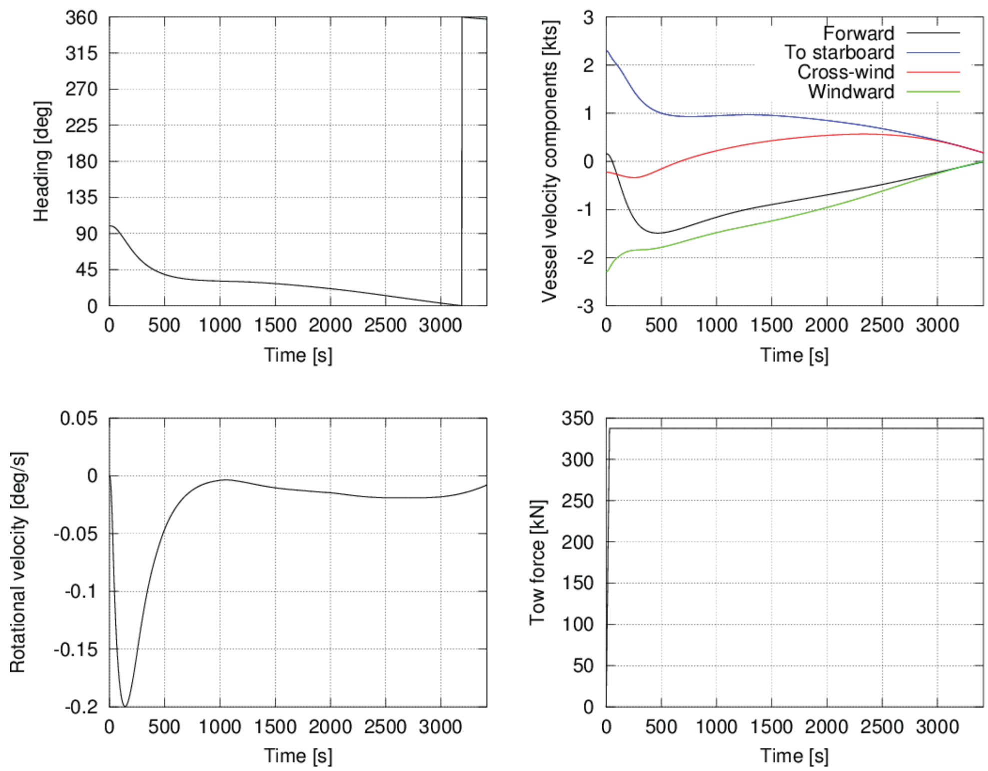
LNG Carrier, 50th percentile environment, 206 kN pull, port turn



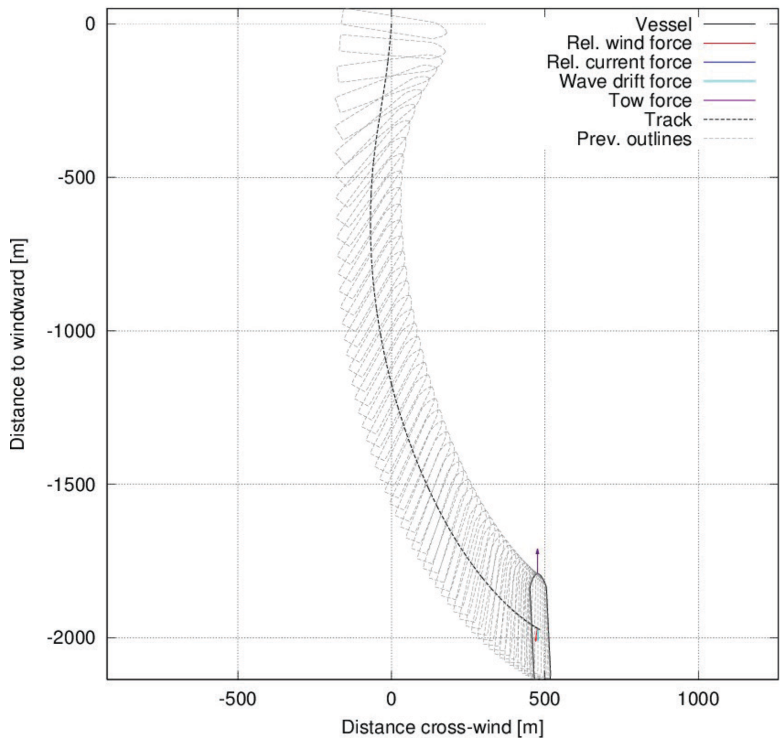
LNG Carrier, 75th percentile environment, 338 kN pull,
port turn 357.3 deg heading from windward at 3416.0 s



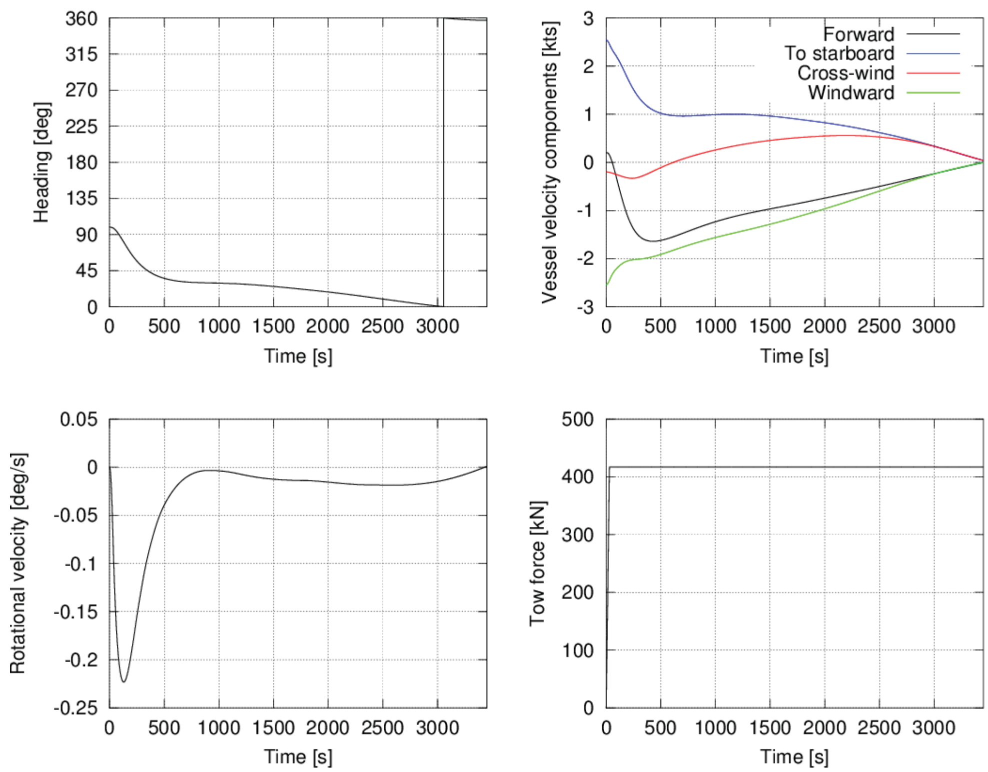
LNG Carrier, 75th percentile environment, 338 kN pull, port turn



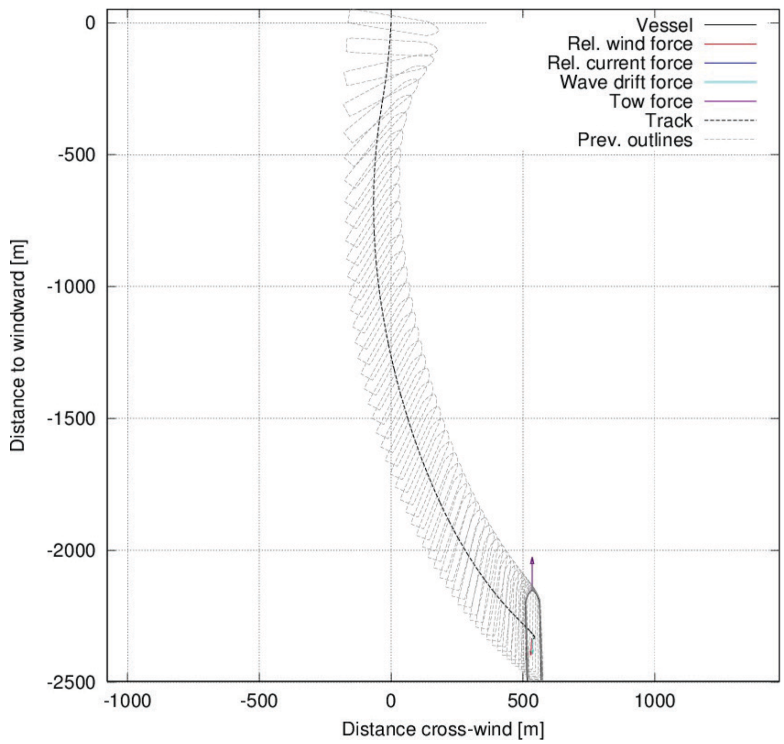
LNG Carrier, 85th percentile environment, 417 kN pull, port turn 357.2 deg heading from windward at 3451.0 s



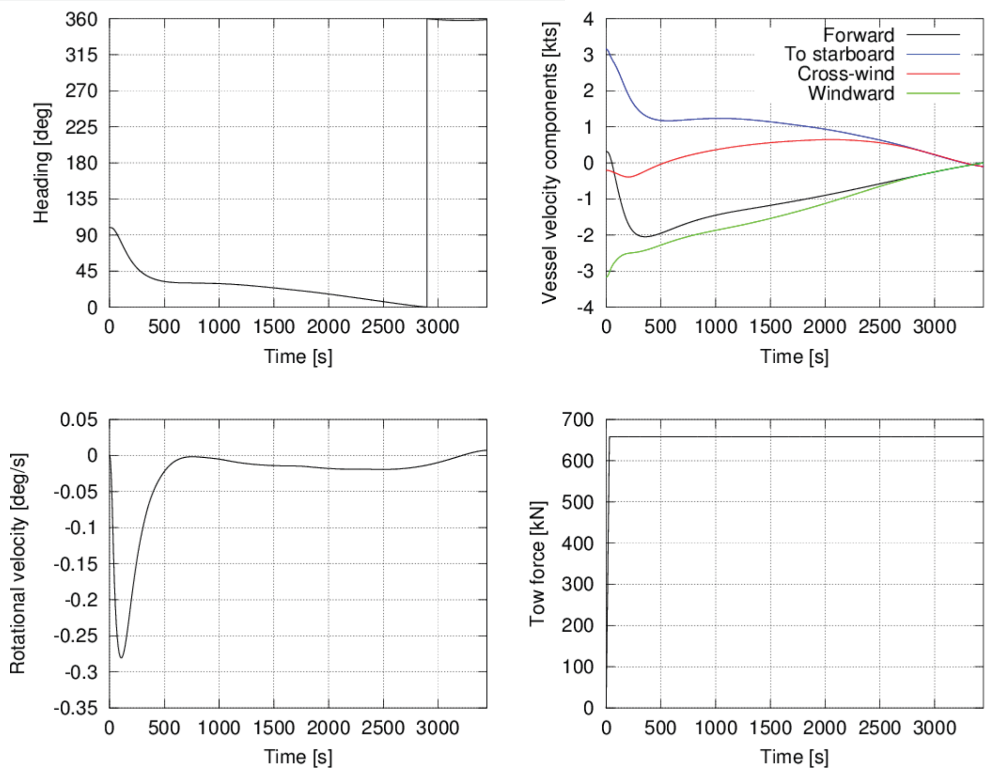
LNG Carrier, 85th percentile environment, 417 kN pull, port turn



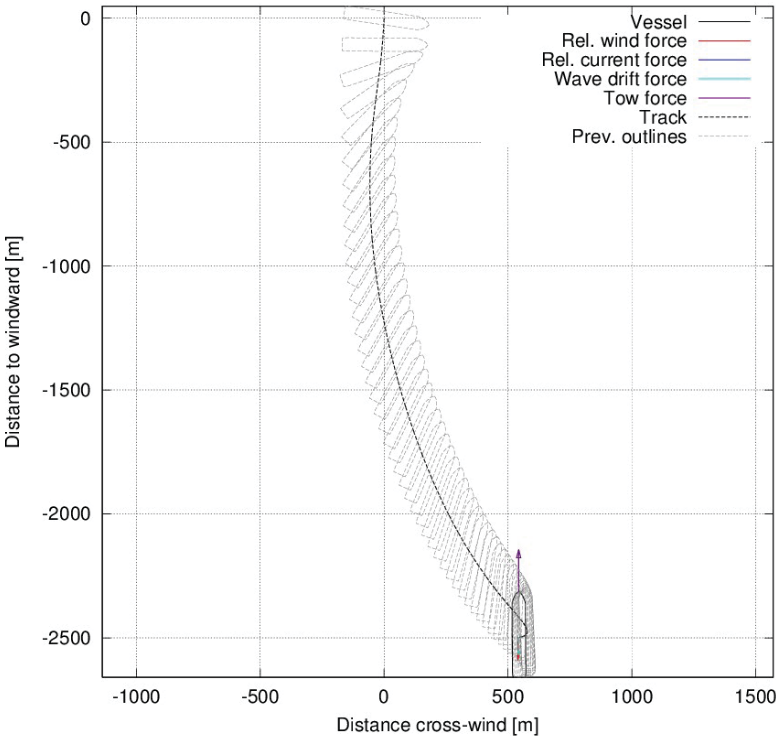
LNG Carrier, 95th percentile environment, 658 kN pull, port turn 358.7 deg heading from windward at 3445.0 s



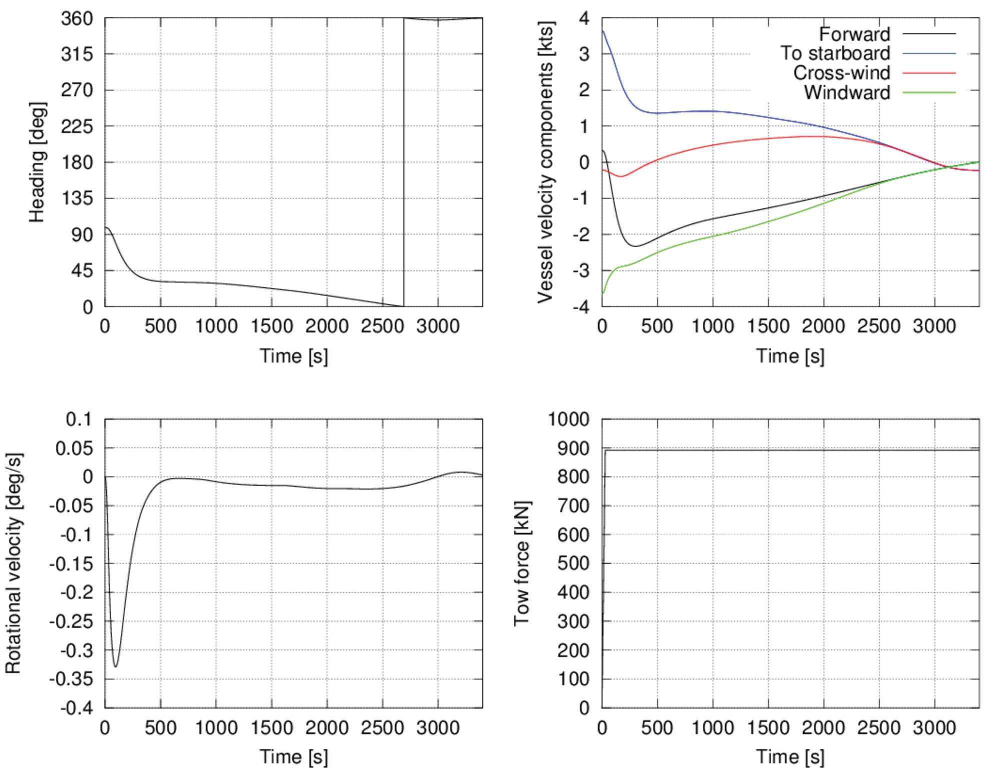
LNG Carrier, 95th percentile environment, 658 kN pull, port turn



LNG Carrier, 99th percentile environment, 892 kN pull, port turn 359.6 deg heading from windward at 3401.0 s



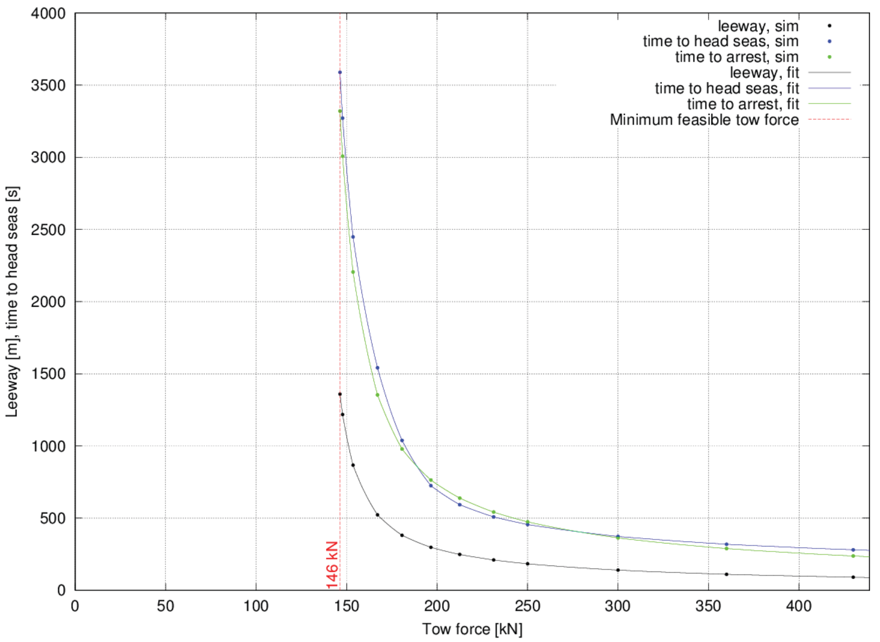
LNG Carrier, 99th percentile environment, 892 kN pull, port turn



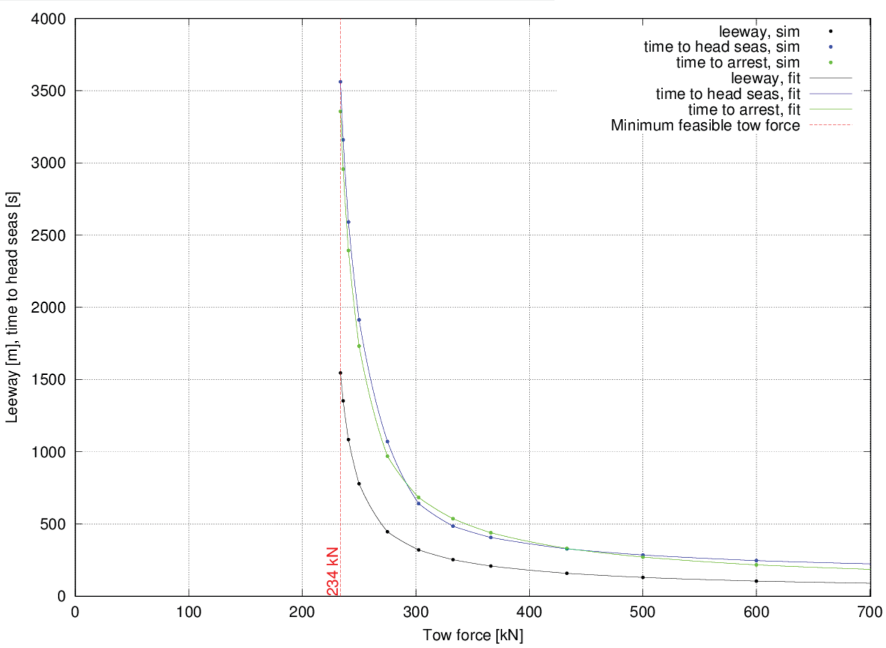
14.0 Appendix B.4: Vehicle Carrier Simulation Results

14.1 Effect of Tow Force

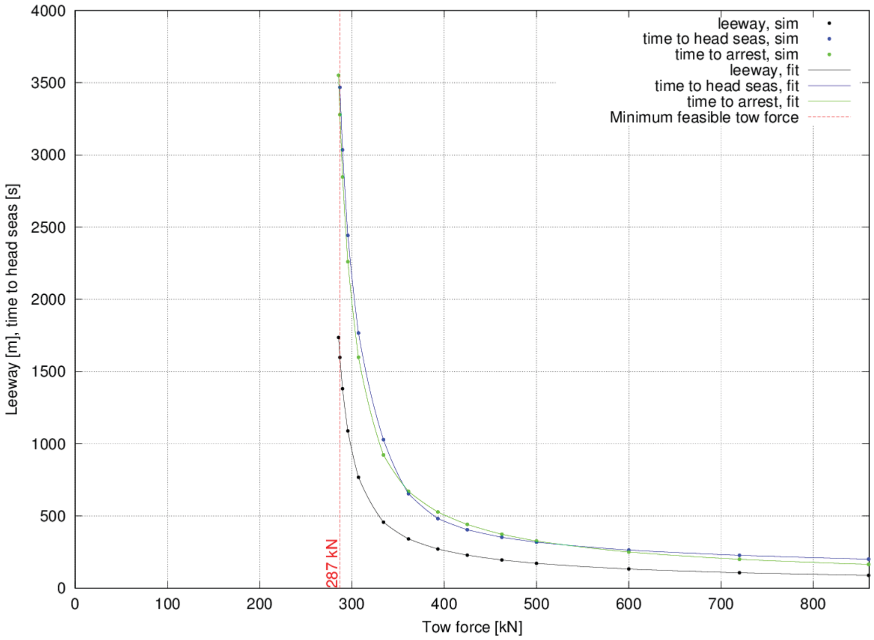
Vehicle Carrier effect of tow force; 50th percentile environment



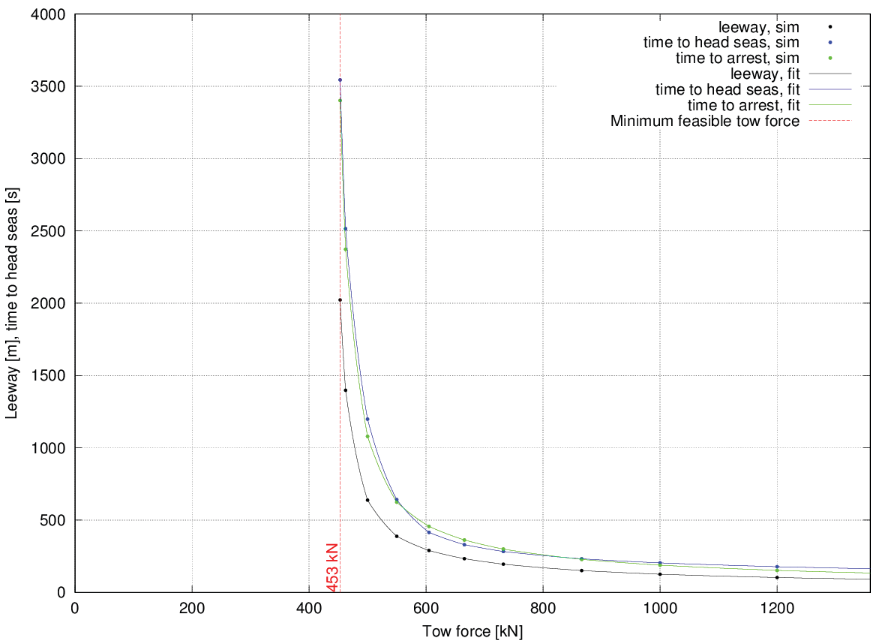
Vehicle Carrier effect of tow force; 75th percentile environment



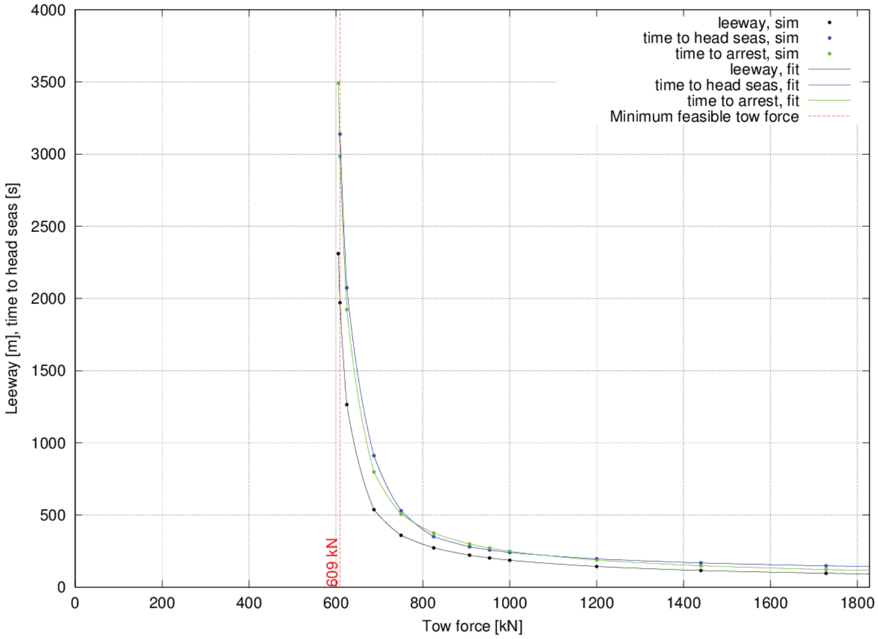
Vehicle Carrier effect of tow force; 85th percentile environment



Vehicle Carrier effect of tow force; 95th percentile environment

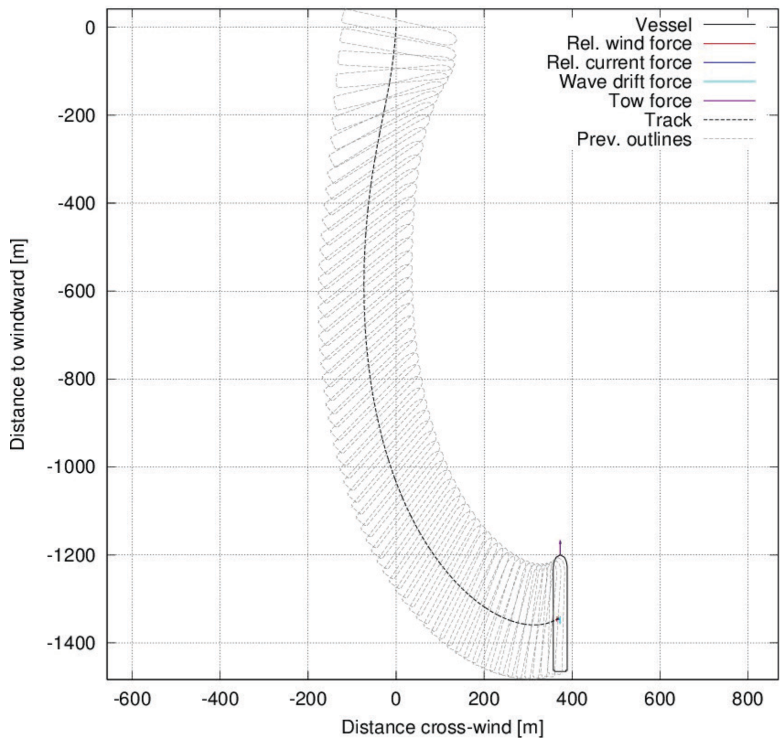


Vehicle Carrier effect of tow force; 99th percentile environment

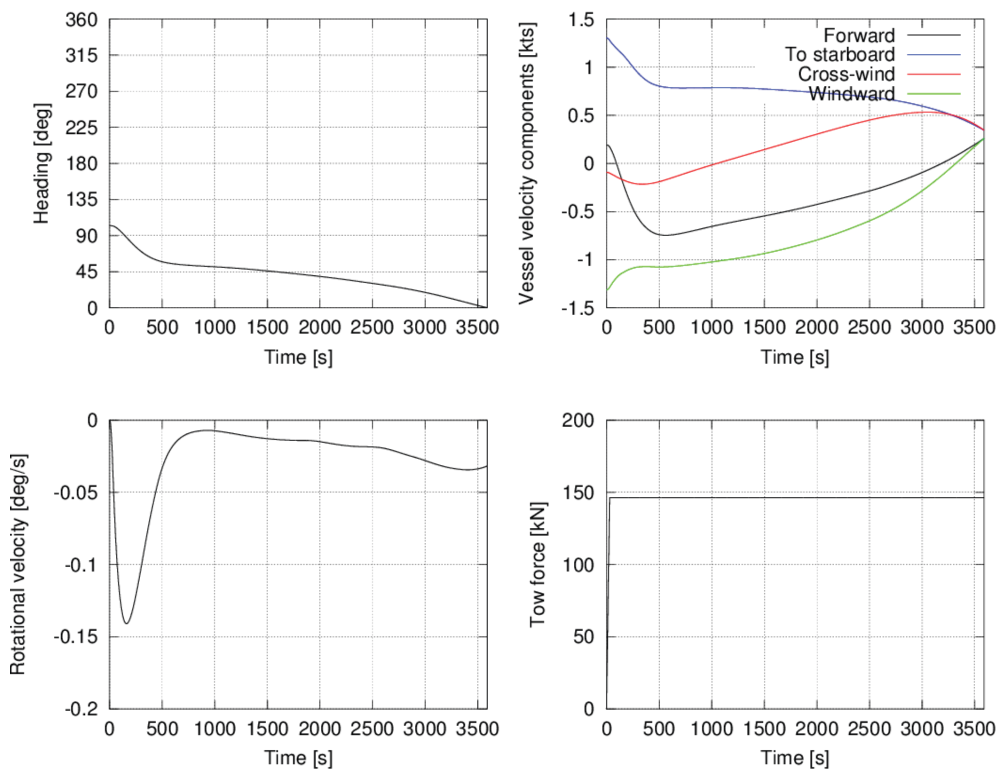


14.2 Simulations at Minimum Feasible Tow Force

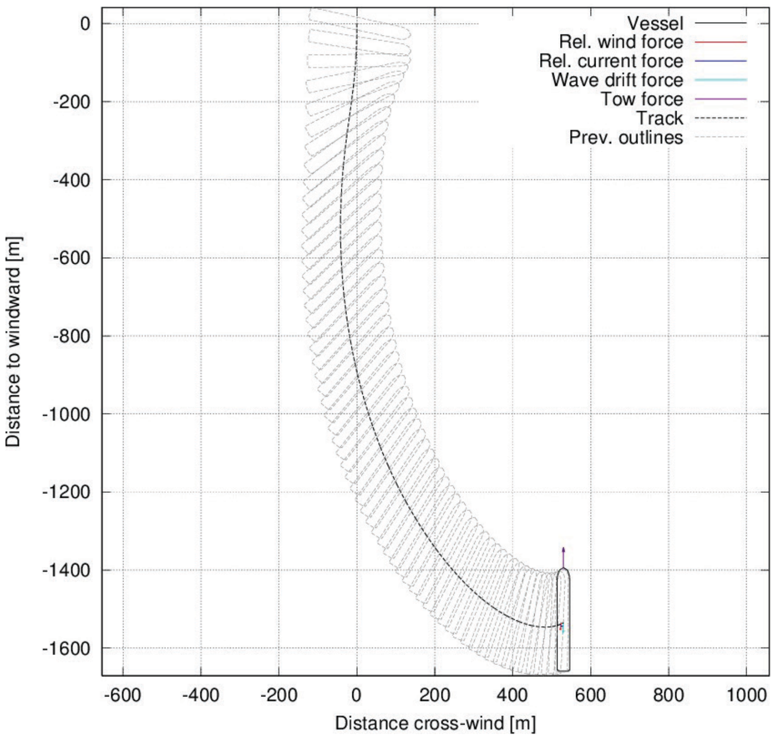
Vehicle Carrier, 50th percentile environment, 146 kN pull, port turn 360.0 deg heading from windward at 3589.0 s



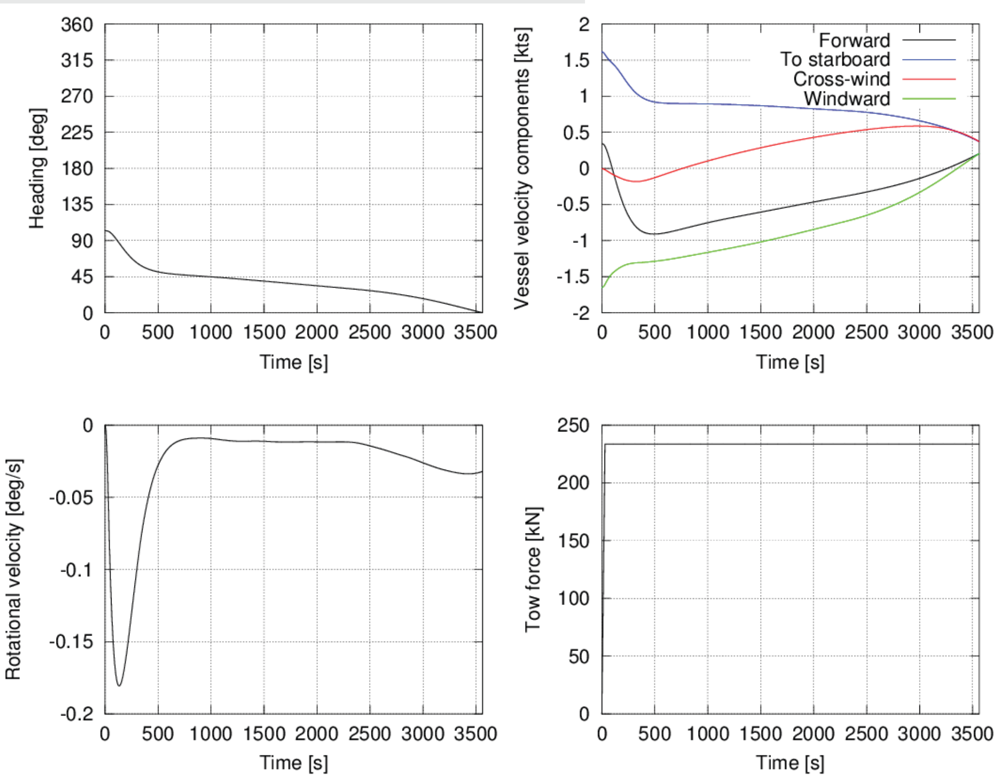
Vehicle Carrier, 50th percentile environment, 146 kN pull, port turn



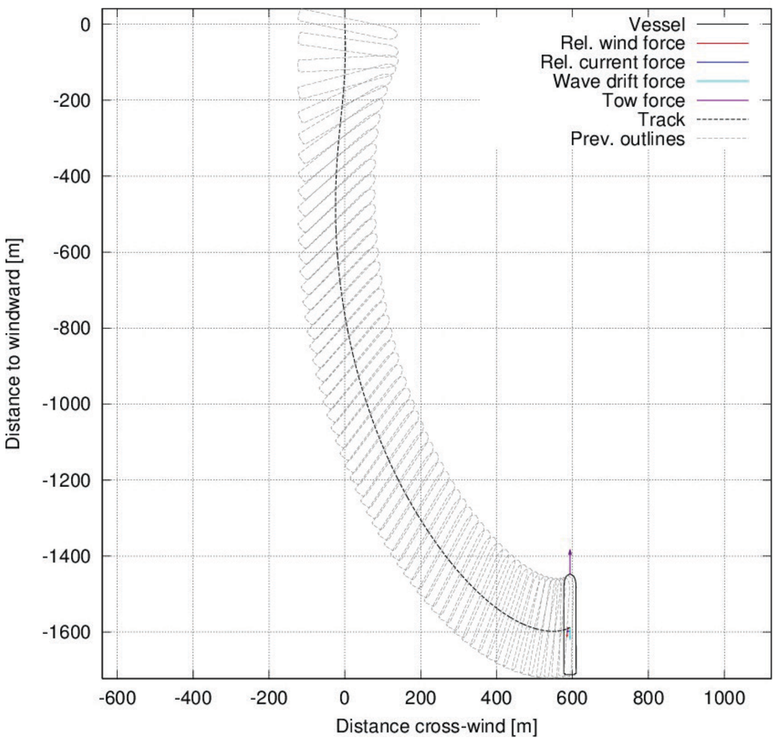
Vehicle Carrier, 75th percentile environment, 234 kN pull, port turn 360.0 deg heading from windward at 3562.0 s



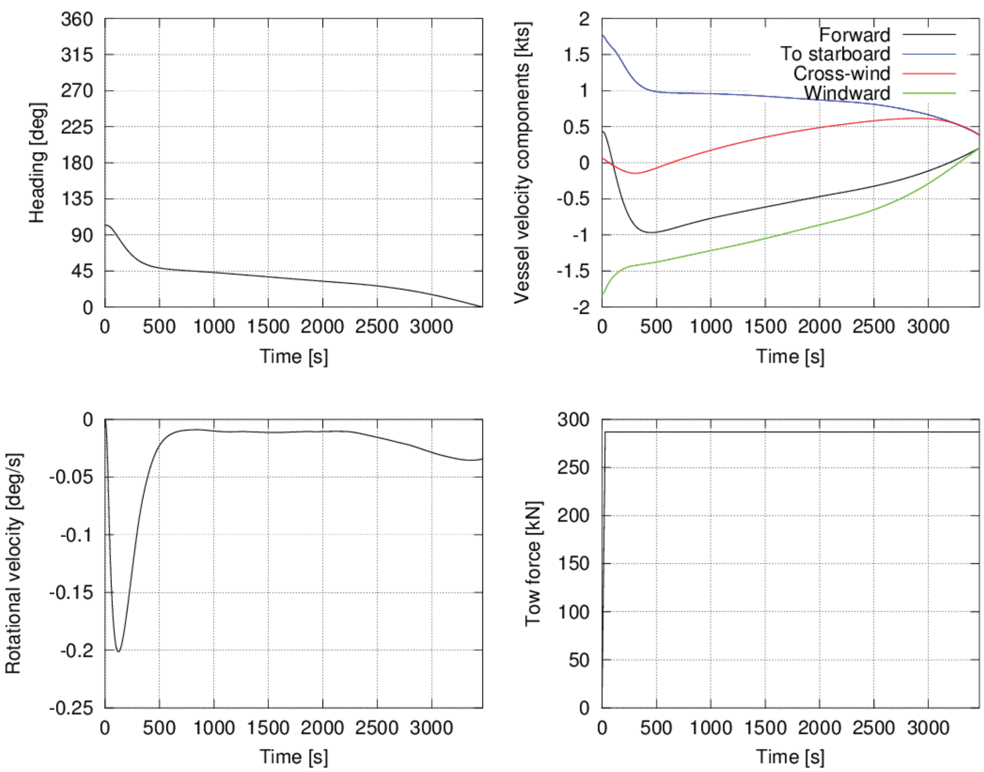
Vehicle Carrier, 75th percentile environment, 234 kN pull, port turn



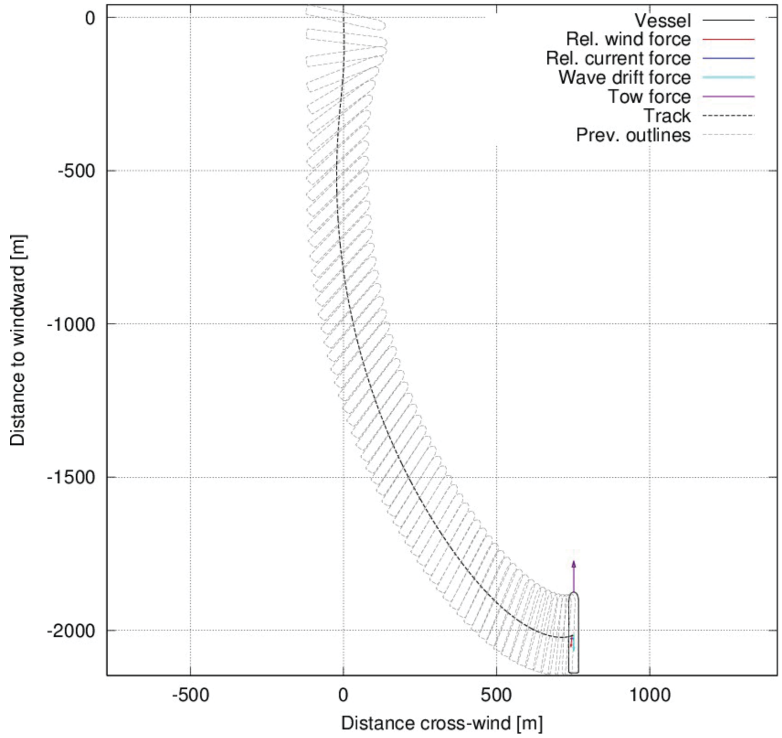
Vehicle Carrier, 85th percentile environment, 287 kN pull, port turn 360.0 deg heading from windward at 3468.0 s



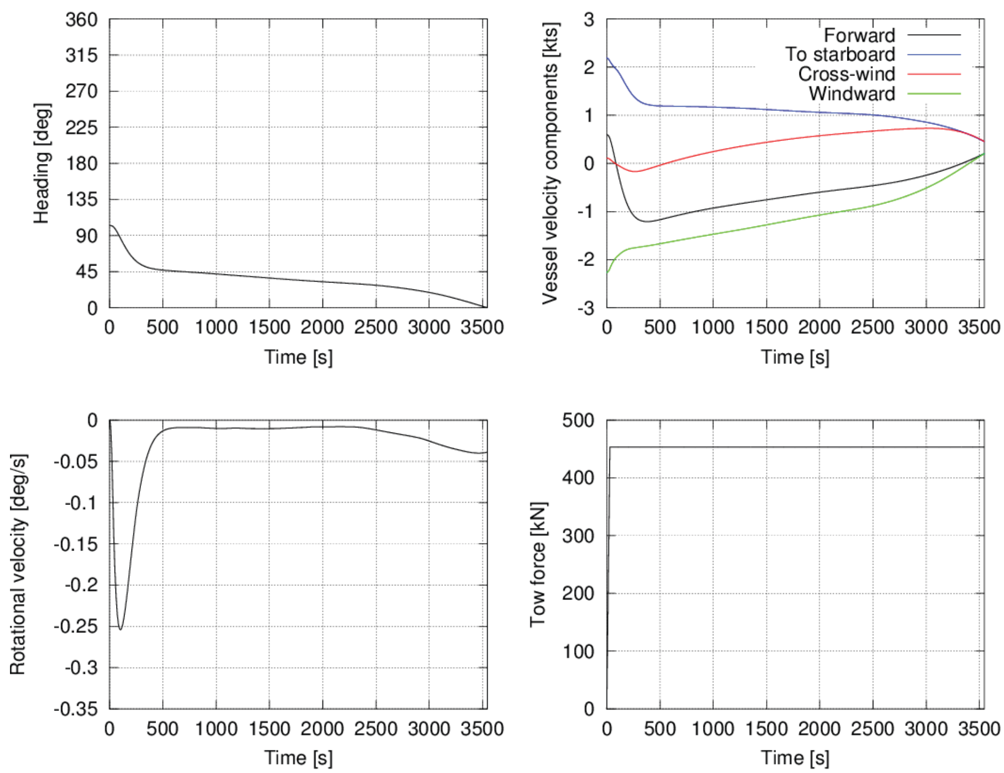
Vehicle Carrier, 85th percentile environment, 287 kN pull, port turn



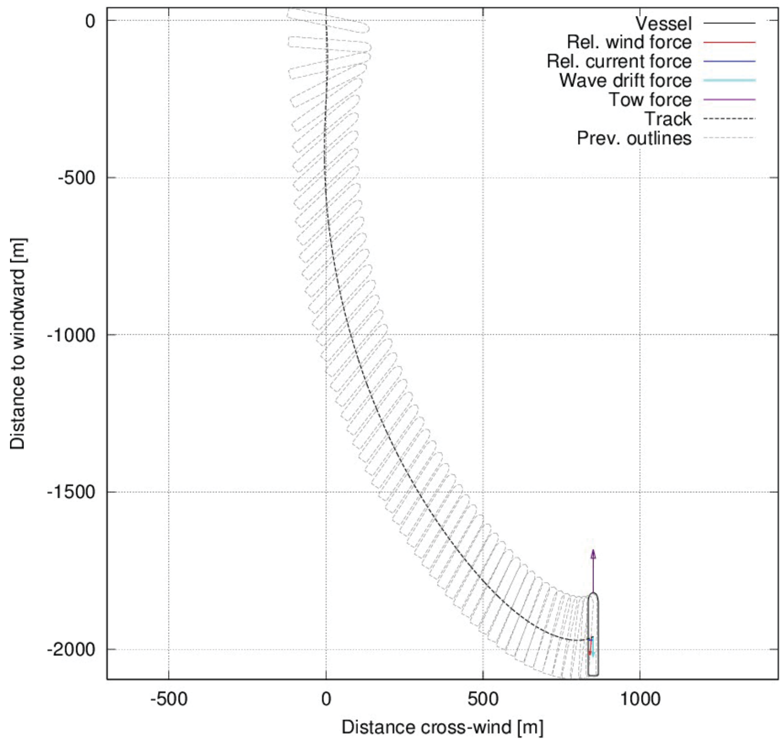
Vehicle Carrier, 95th percentile environment, 453 kN pull, port turn 360.0 deg heading from windward at 3545.0 s



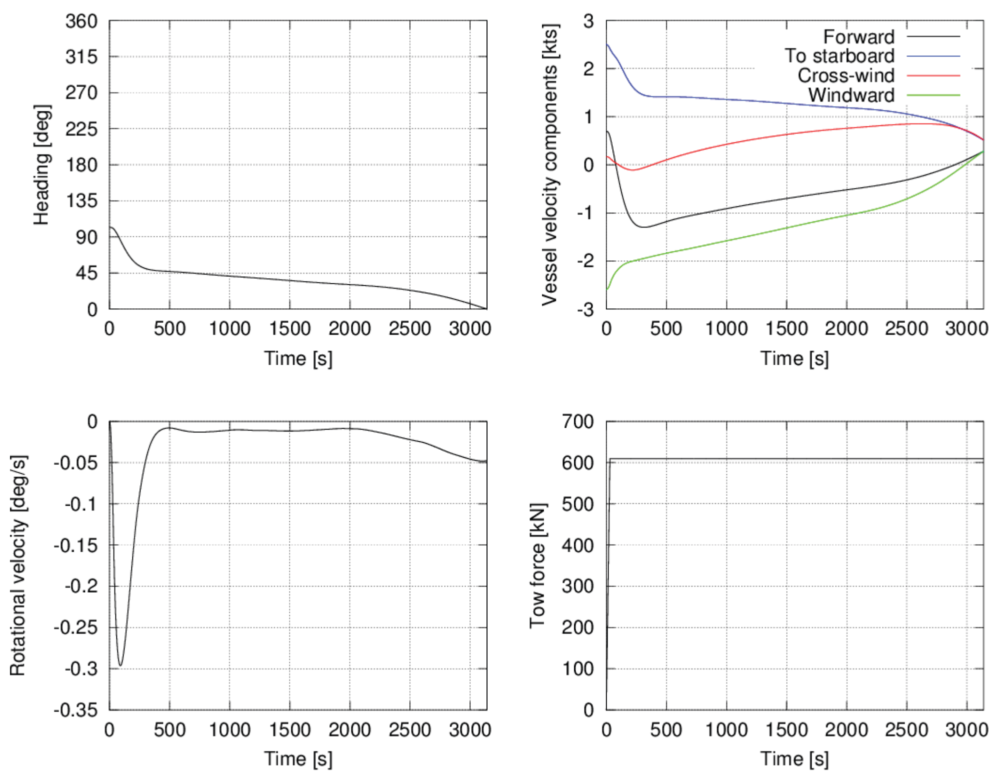
Vehicle Carrier, 95th percentile environment, 453 kN pull, port turn



Vehicle Carrier, 99th percentile environment, 609 kN pull, port turn 360.0 deg heading from windward at 3139.0 s



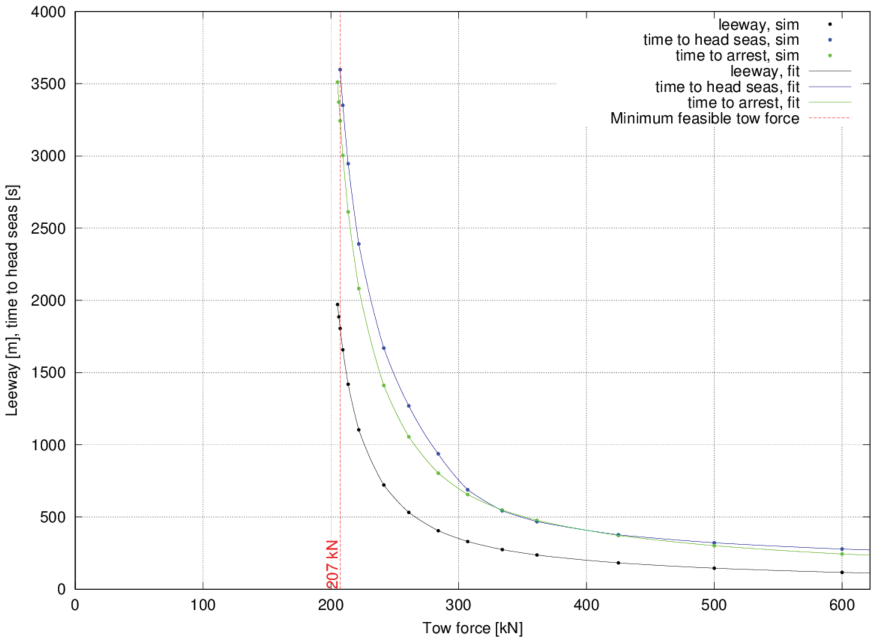
Vehicle Carrier, 99th percentile environment, 609 kN pull, port turn



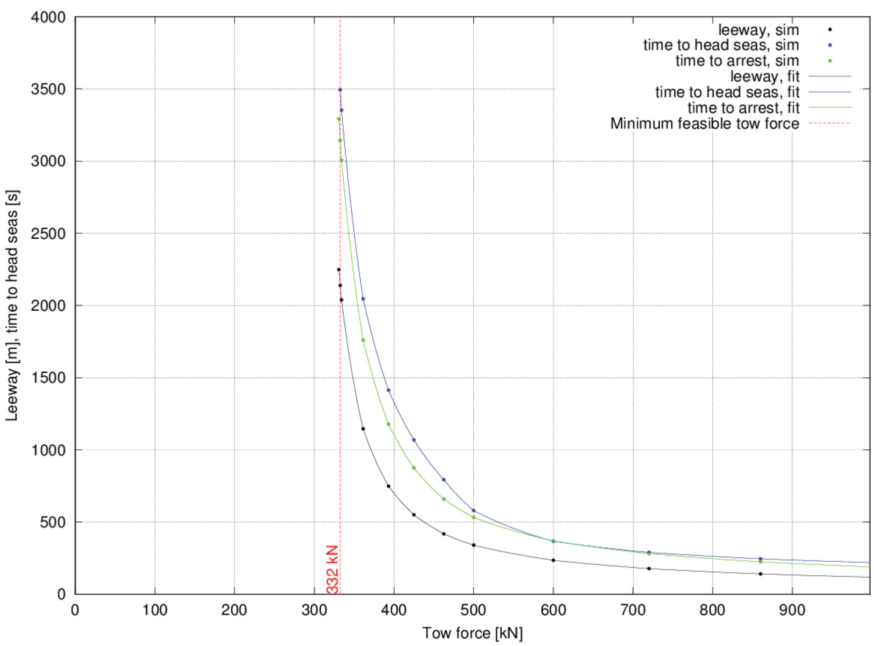
15.0 Appendix B.5: Passenger Ship Simulation Results

15.1 Effect of Tow Force

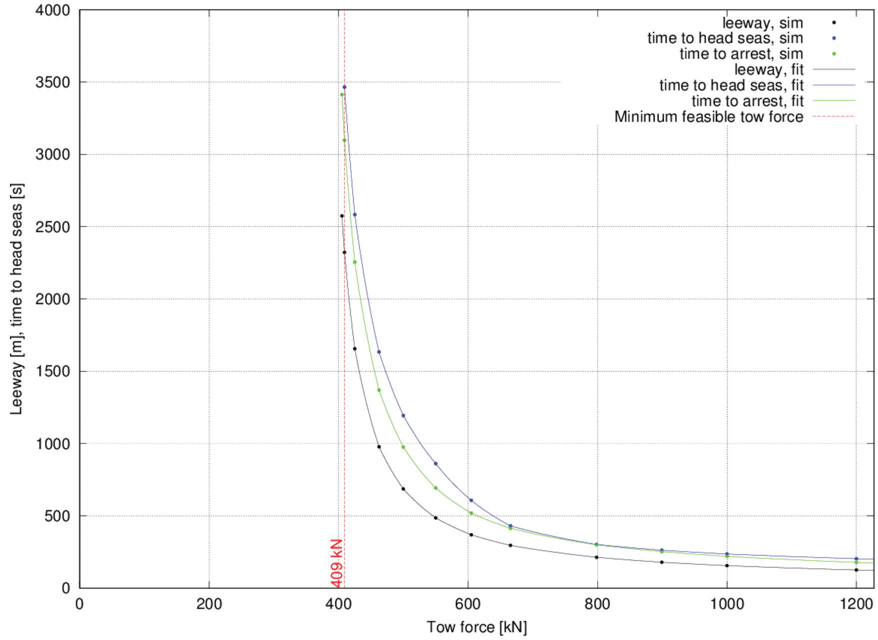
Passenger Ship effect of tow force; 50th percentile environment



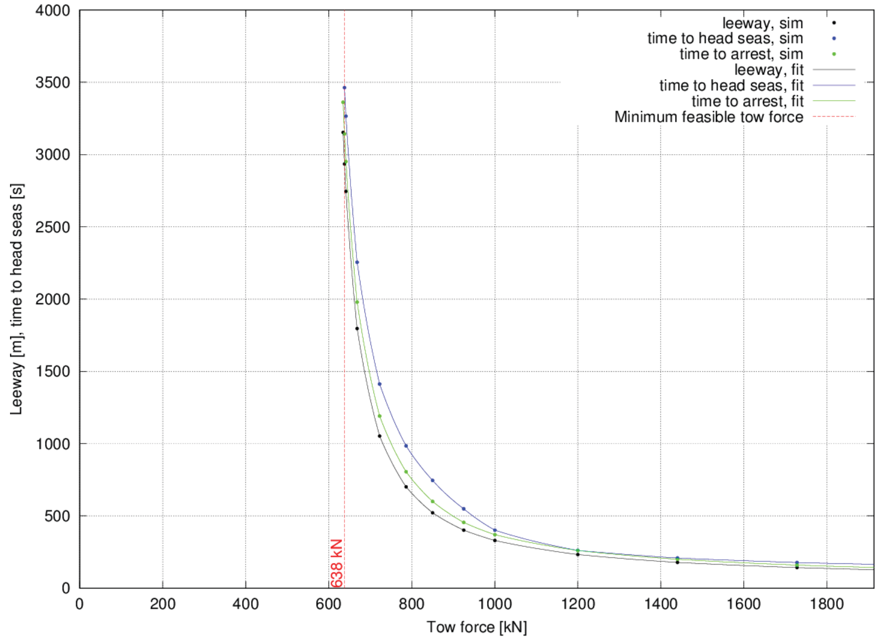
Passenger Ship effect of tow force; 75th percentile environment



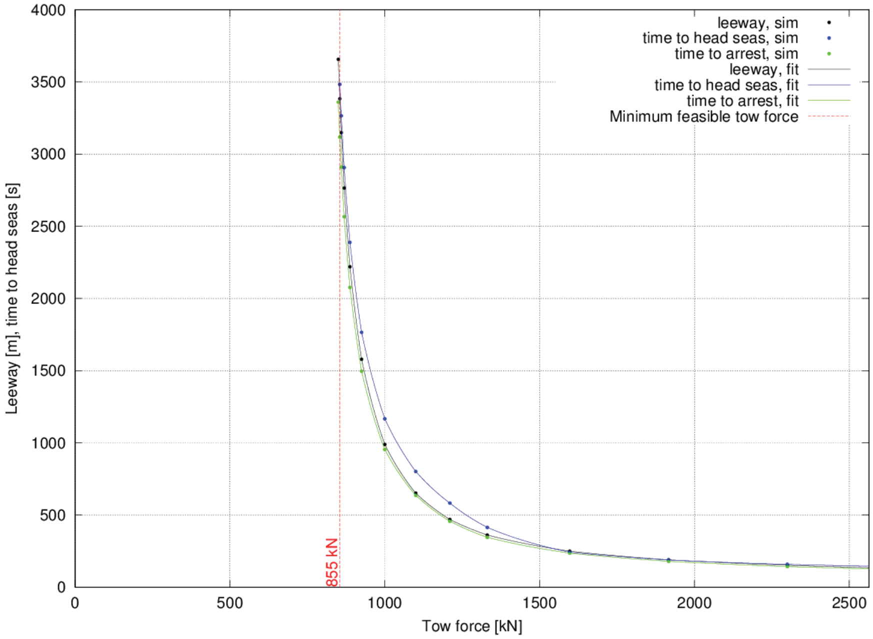
Passenger Ship effect of tow force; 85th percentile environment



Passenger Ship effect of tow force; 95th percentile environment

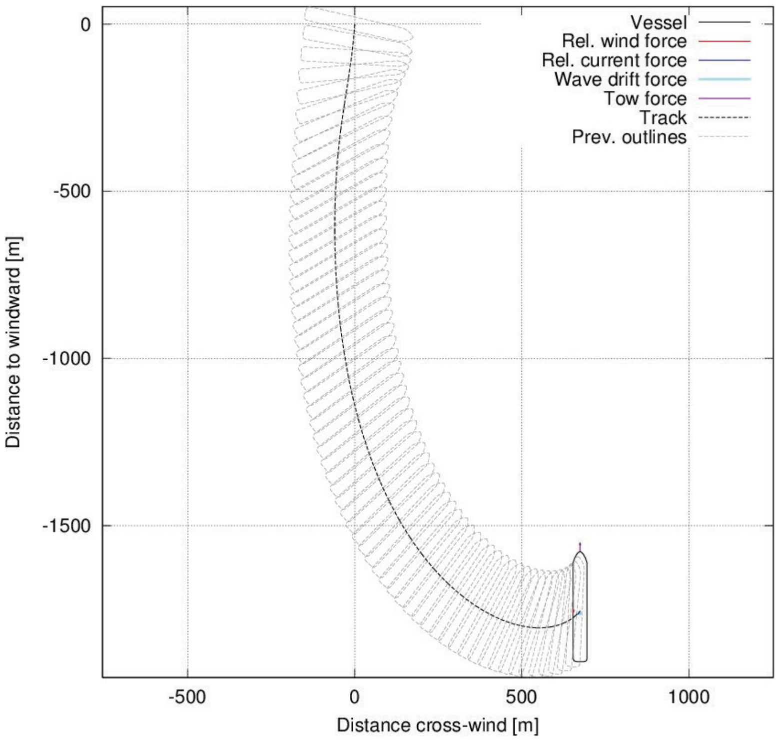


Passenger Ship effect of tow force; 99th percentile environment

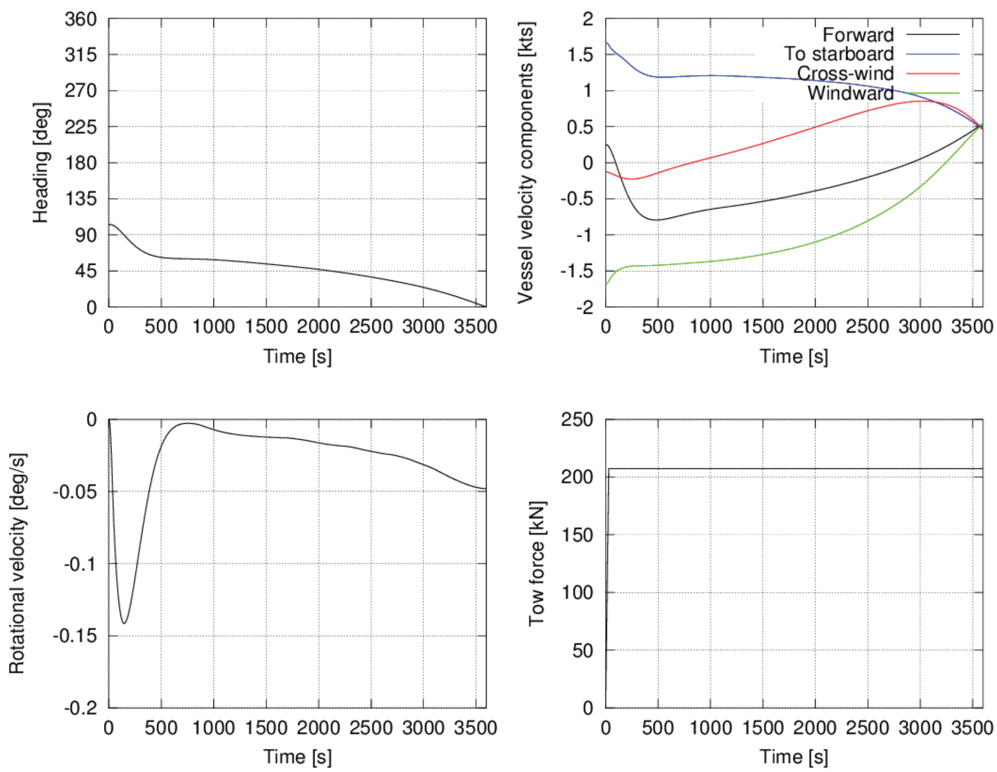


15.2 Simulations at Minimum Feasible Tow Force

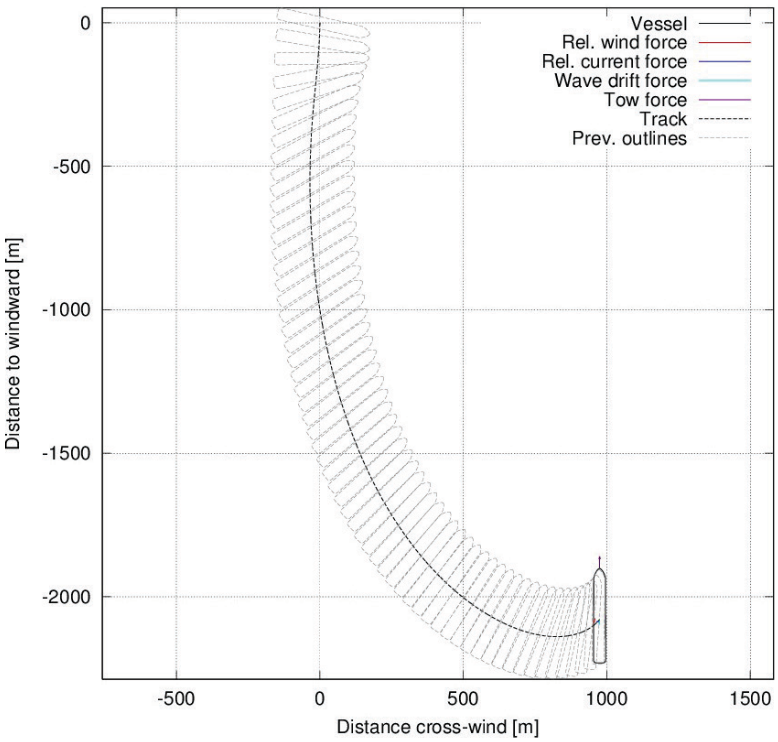
Passenger Ship, 50th percentile environment, 207 kN pull, port turn 360.0 deg heading from windward at 3598.0 s



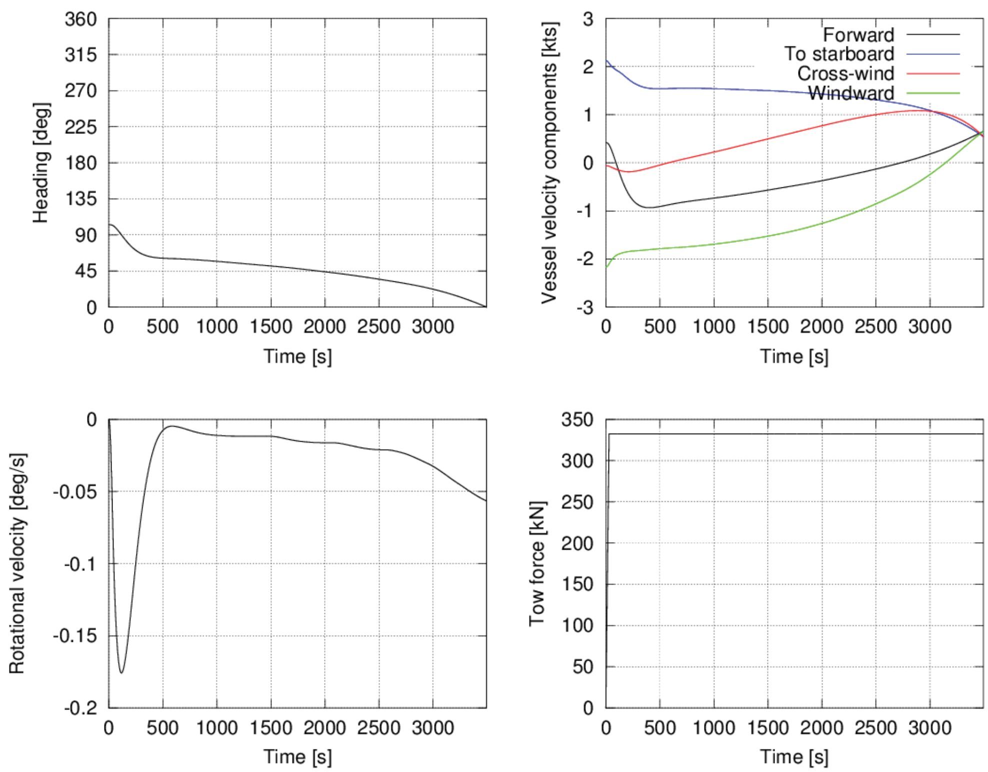
Passenger Ship, 50th percentile environment, 207 kN pull, port turn



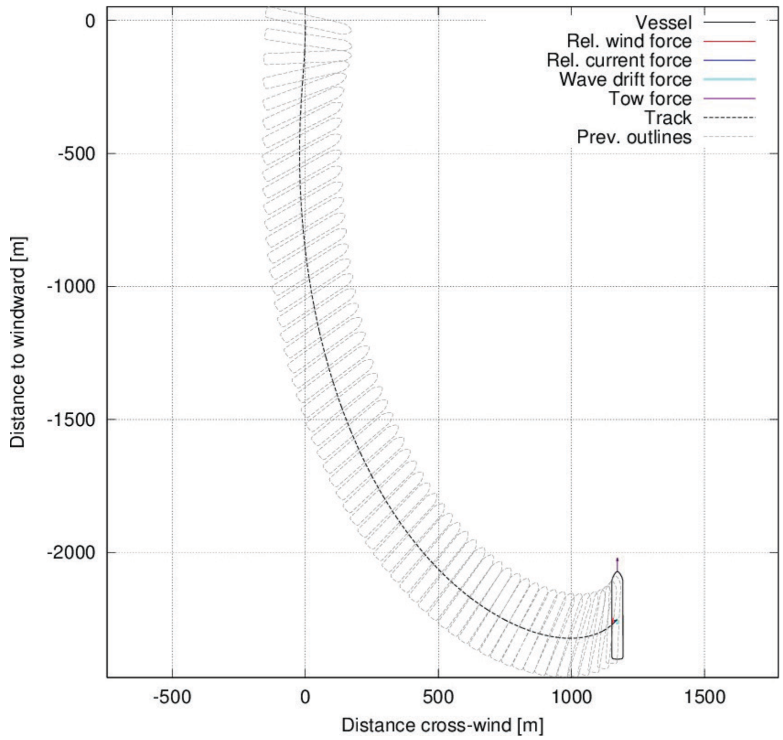
Passenger Ship, 75th percentile environment, 332 kN pull, port turn 360.0 deg heading from windward at 3494.0 s



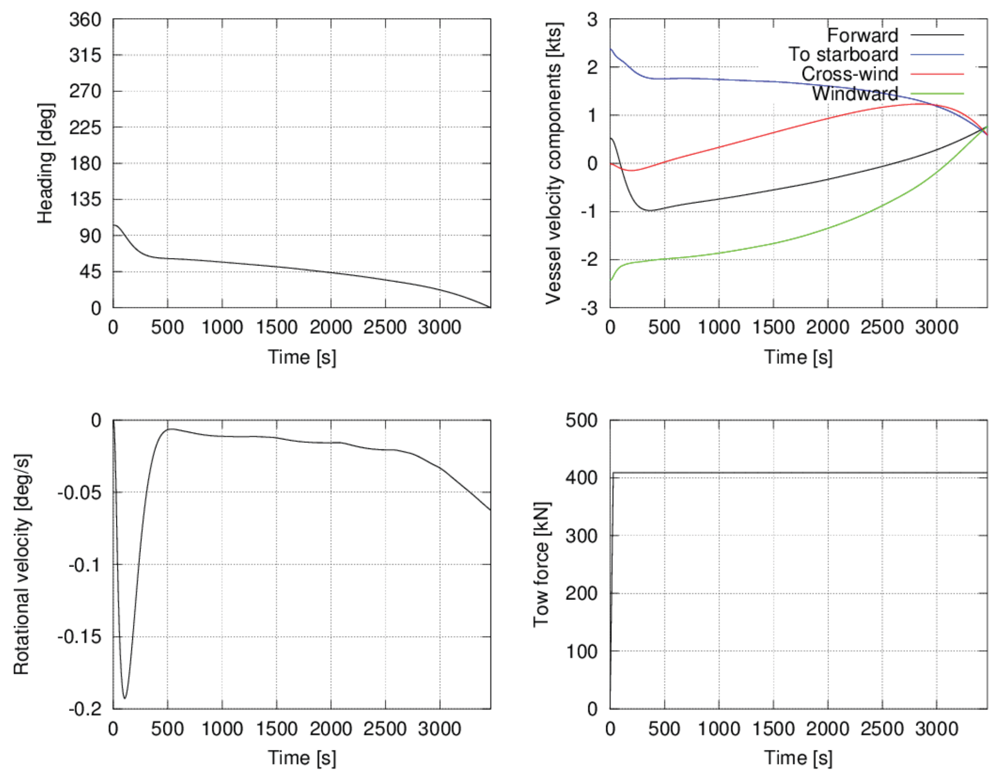
Passenger Ship, 75th percentile environment, 332 kN pull, port turn



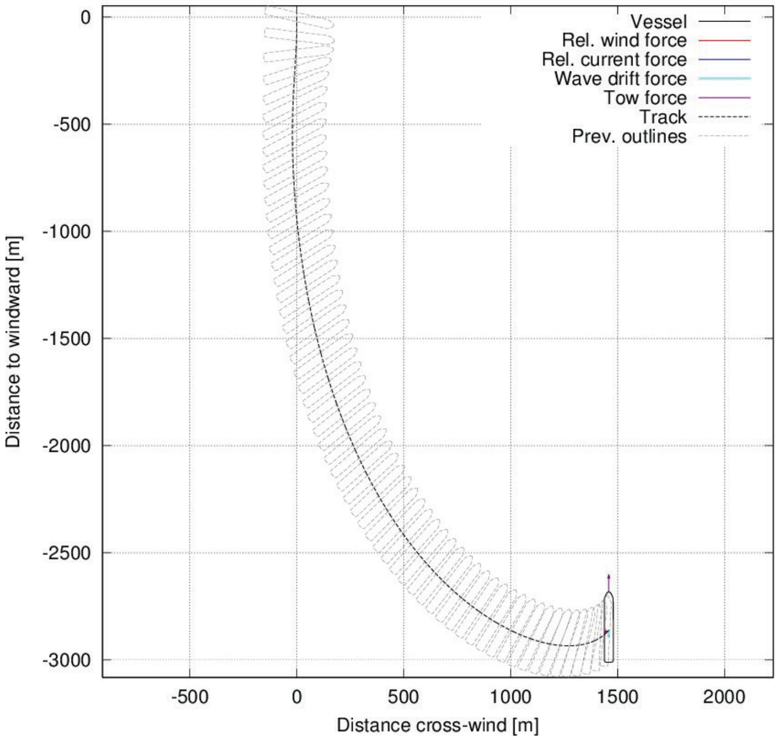
Passenger Ship, 85th percentile environment, 409 kN pull, port turn 360.0 deg heading from windward at 3465.0 s



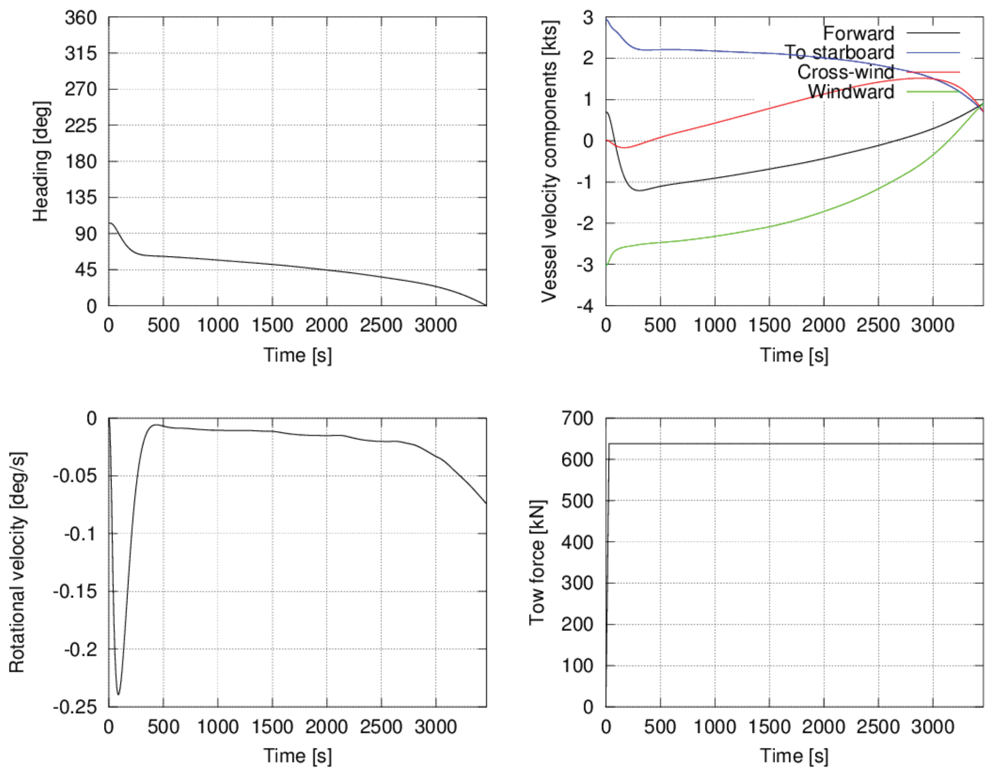
Passenger Ship, 85th percentile environment, 409 kN pull, port turn



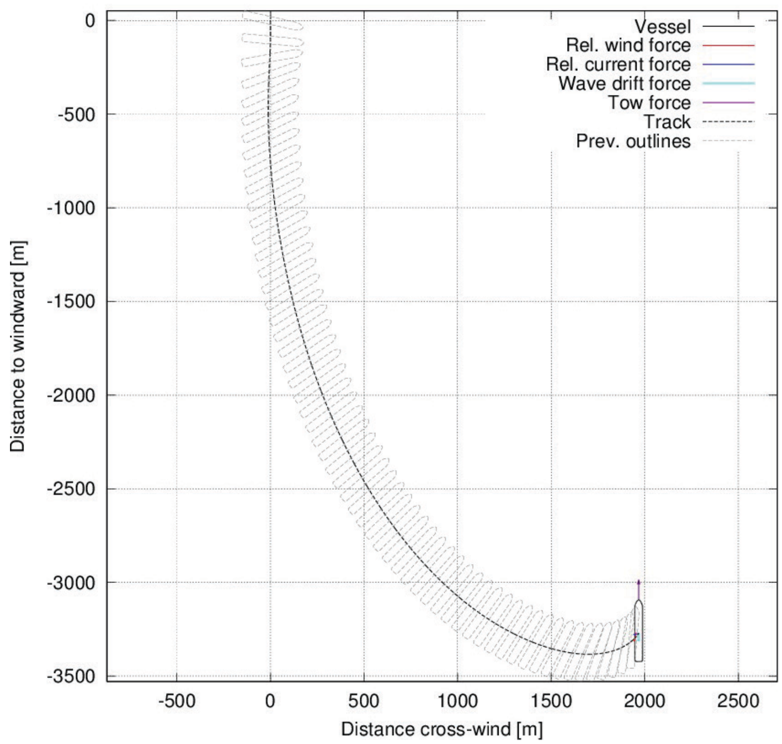
Passenger Ship, 95th percentile environment, 638 kN pull, port turn 360.0 deg heading from windward at 3463.0 s



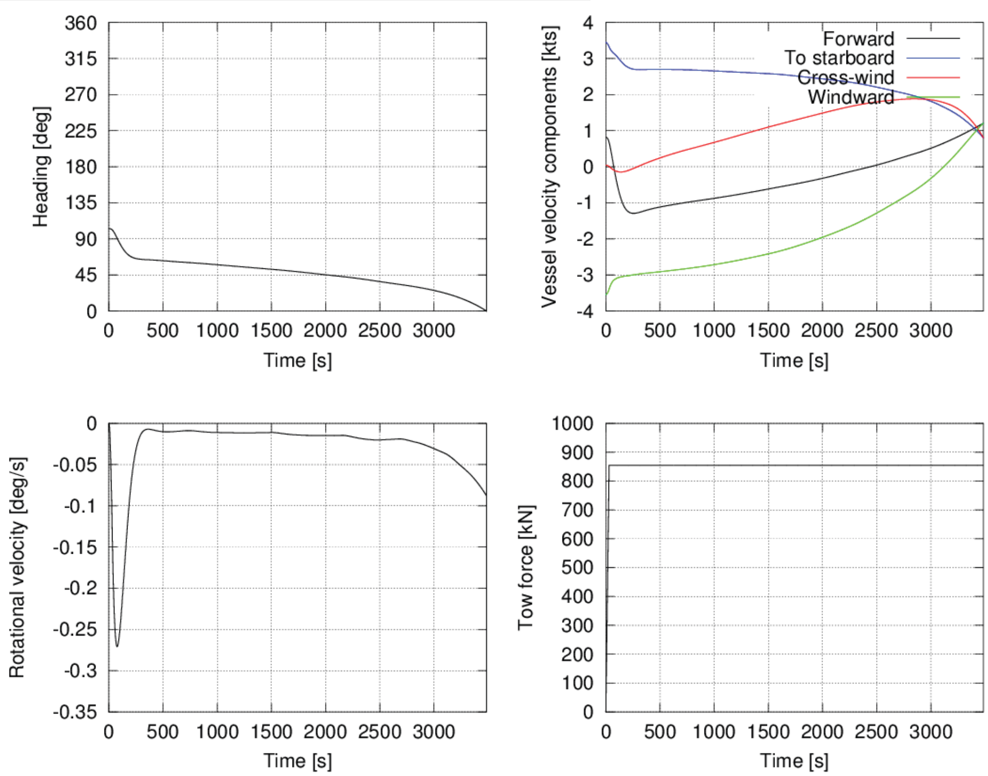
Passenger Ship, 95th percentile environment, 638 kN pull, port turn



Passenger Ship, 99th percentile environment, 855 kN pull, port turn 359.9 deg heading from windward at 3484.0 s



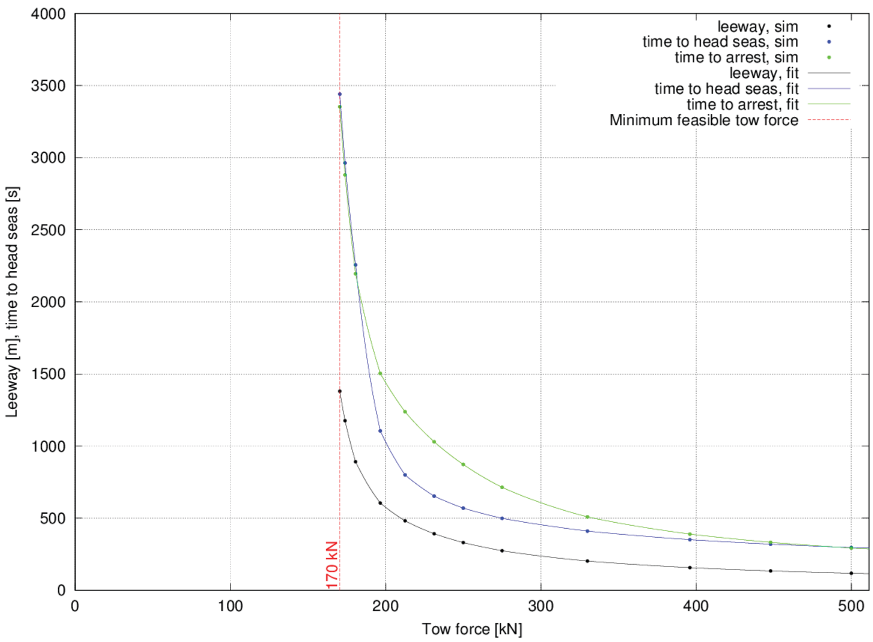
Passenger Ship, 99th percentile environment, 855 kN pull, port turn



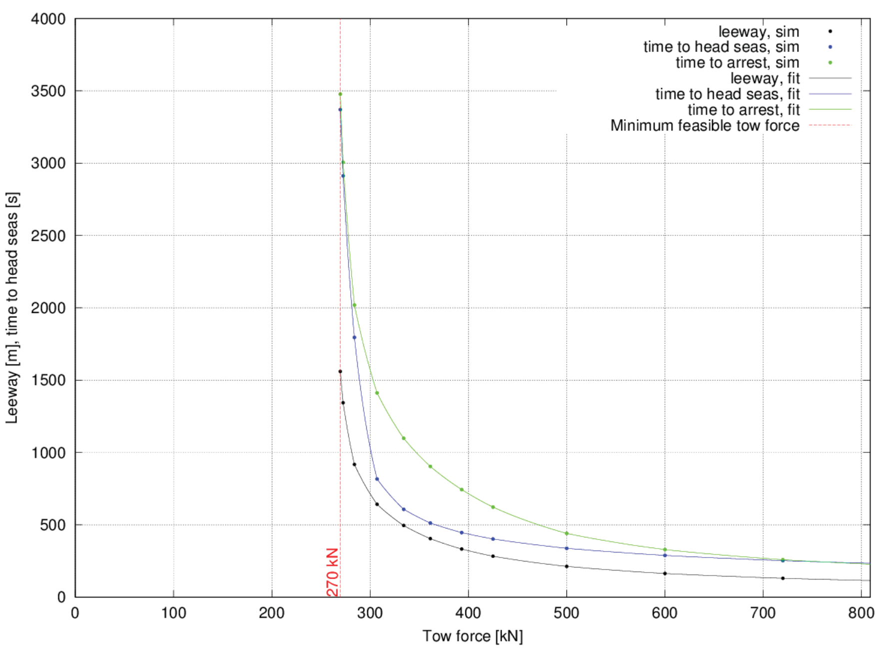
16.0 Appendix B.6: Bulk Carrier Simulation Results

16.1 Effect of Tow Force

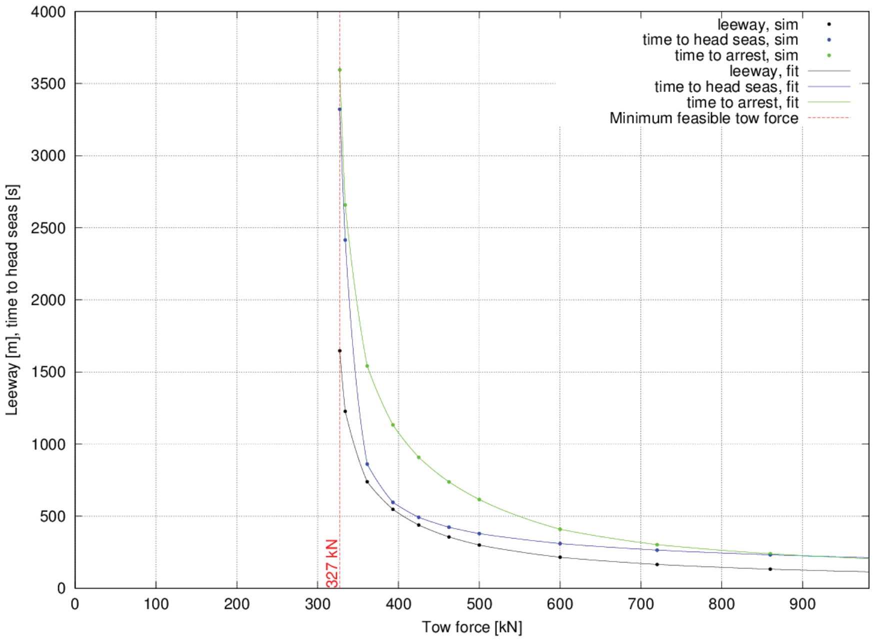
Bulk Carrier effect of tow force; 50th percentile environment



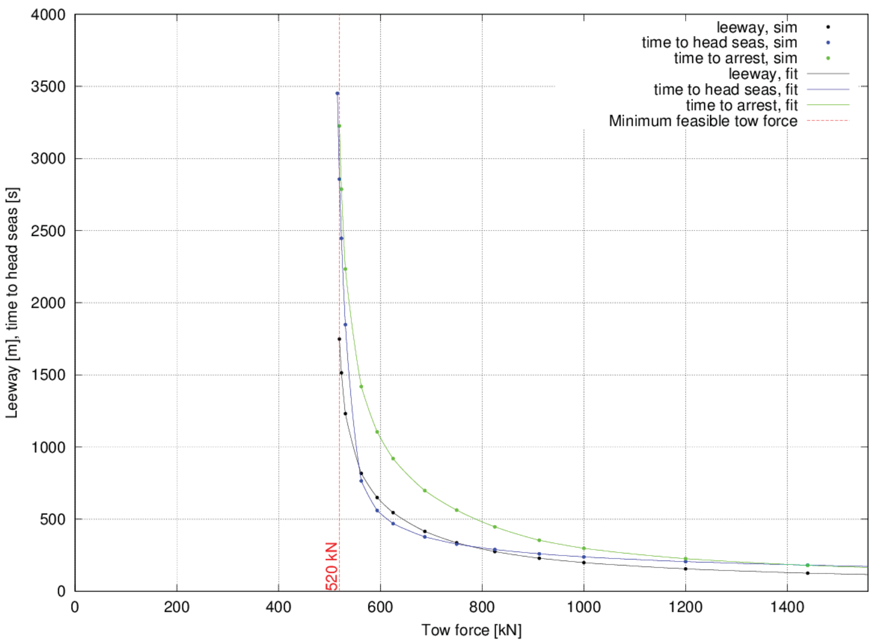
Bulk Carrier effect of tow force; 50th percentile environment



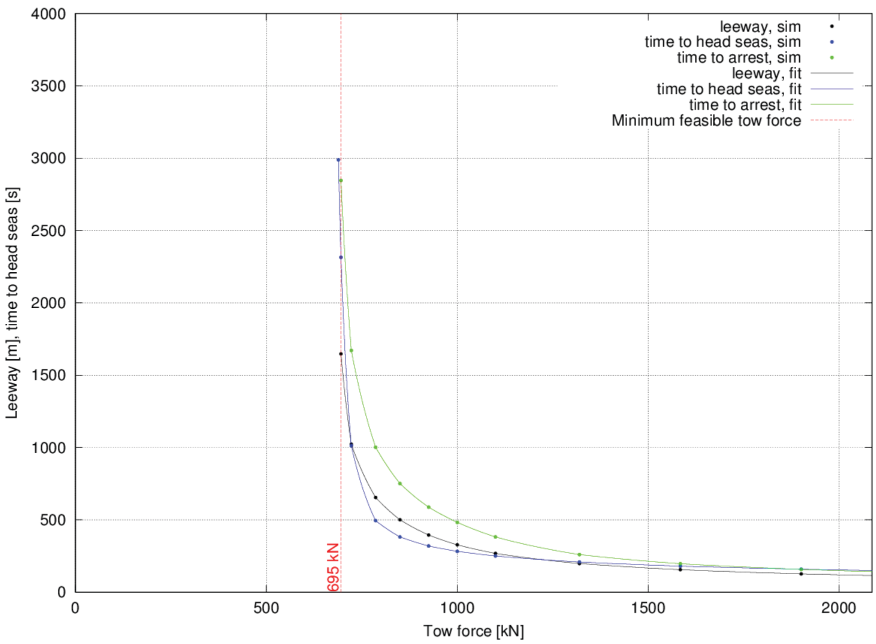
Bulk Carrier effect of tow force; 85th percentile environment



Bulk Carrier effect of tow force; 95th percentile environment

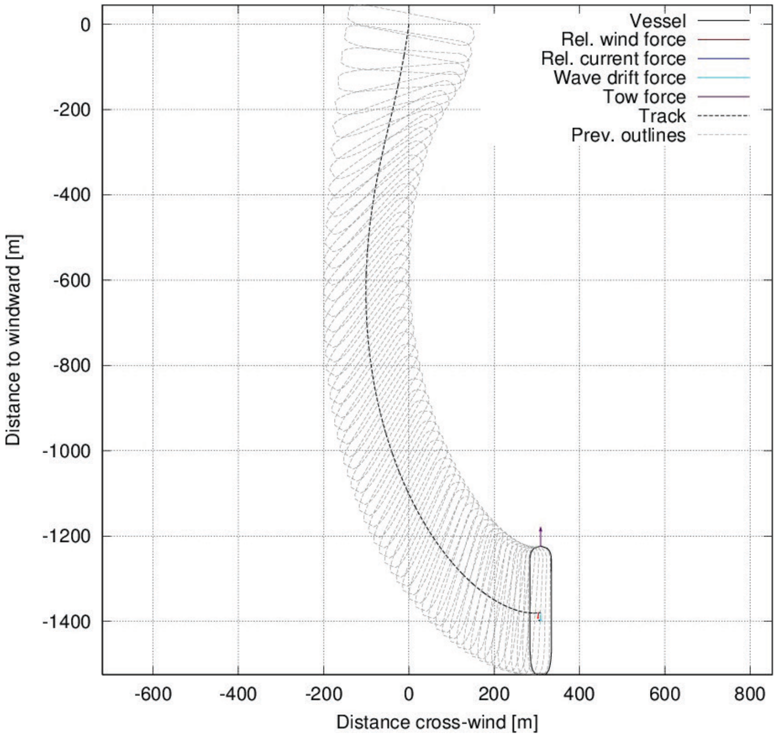


Bulk Carrier effect of tow force; 99th percentile environment

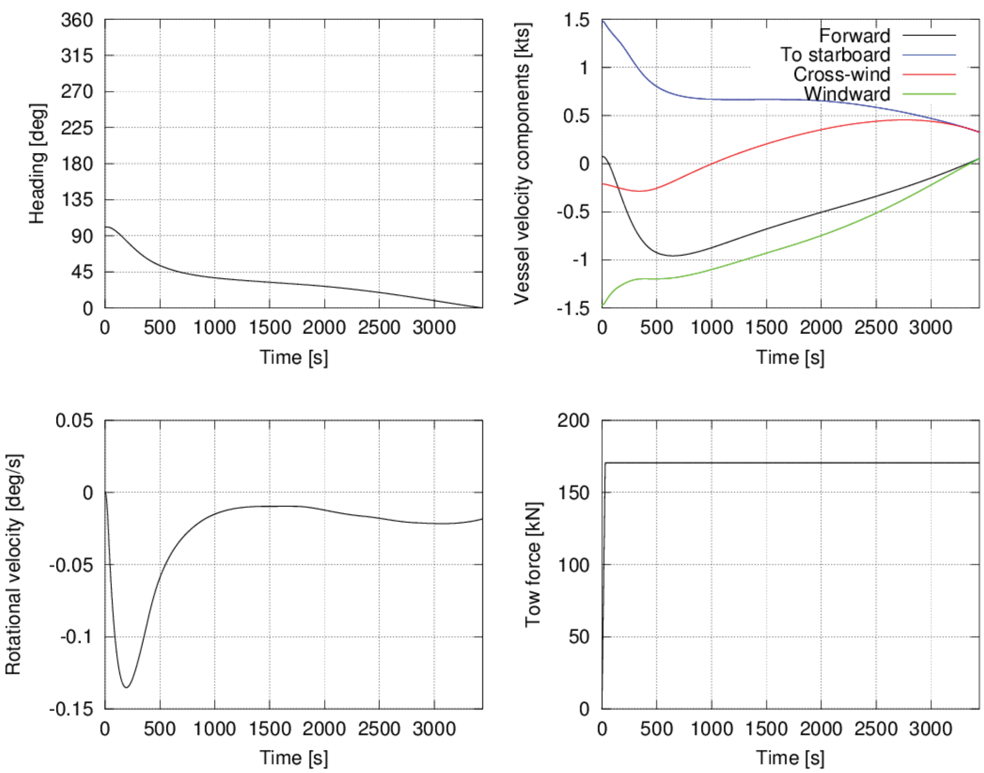


16.2 Simulations at Minimum Feasible Tow Force

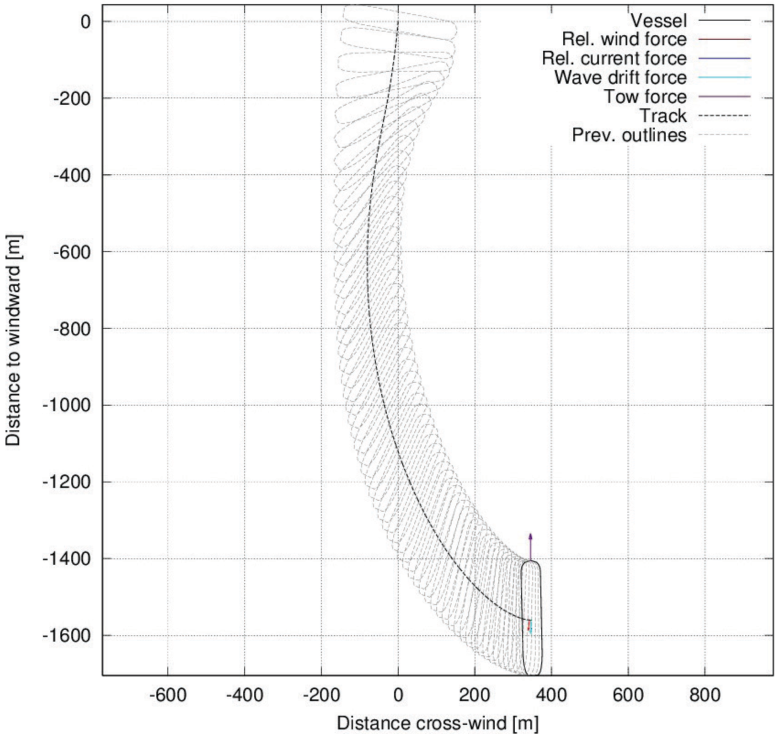
Bulk Carrier, 50th percentile environment, 170 kN pull, port turn 360.0 deg heading from windward at 3441.0 s



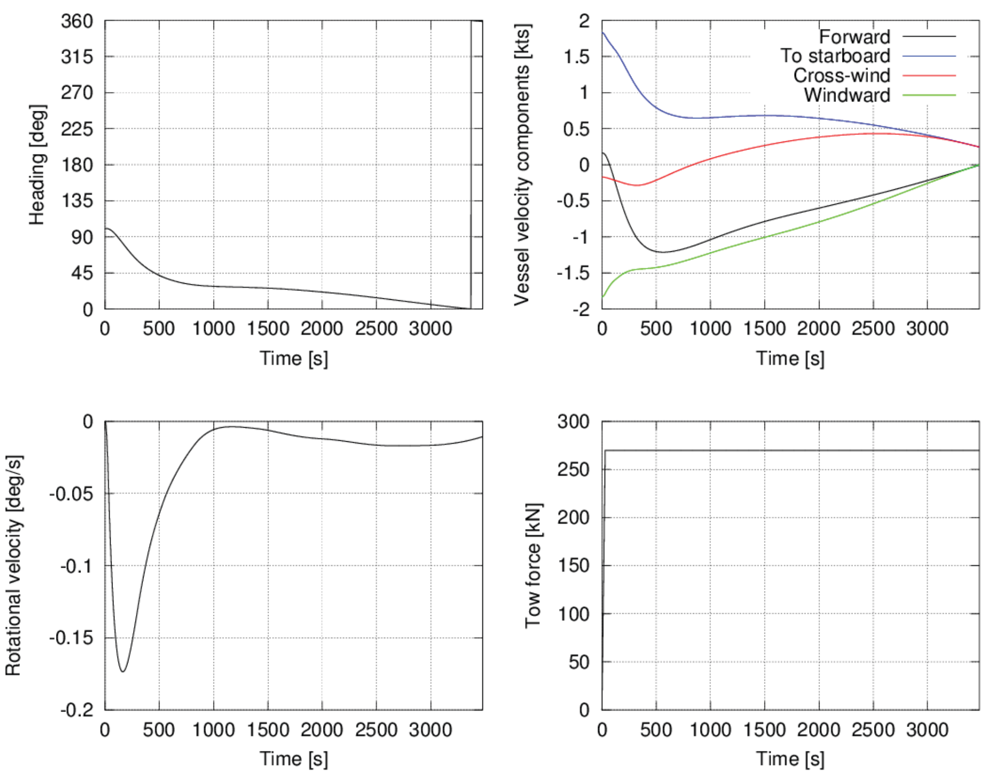
Bulk Carrier, 50th percentile environment, 170 kN pull, port turn



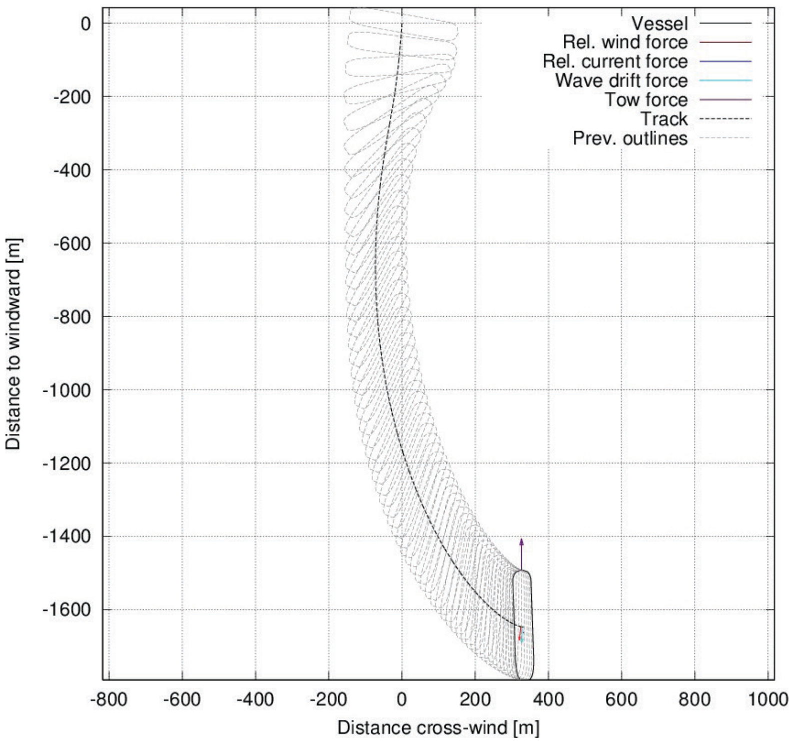
Bulk Carrier, 75th percentile environment, 270 kN pull,
port turn 358.7 deg heading from windward at 3477.0 s



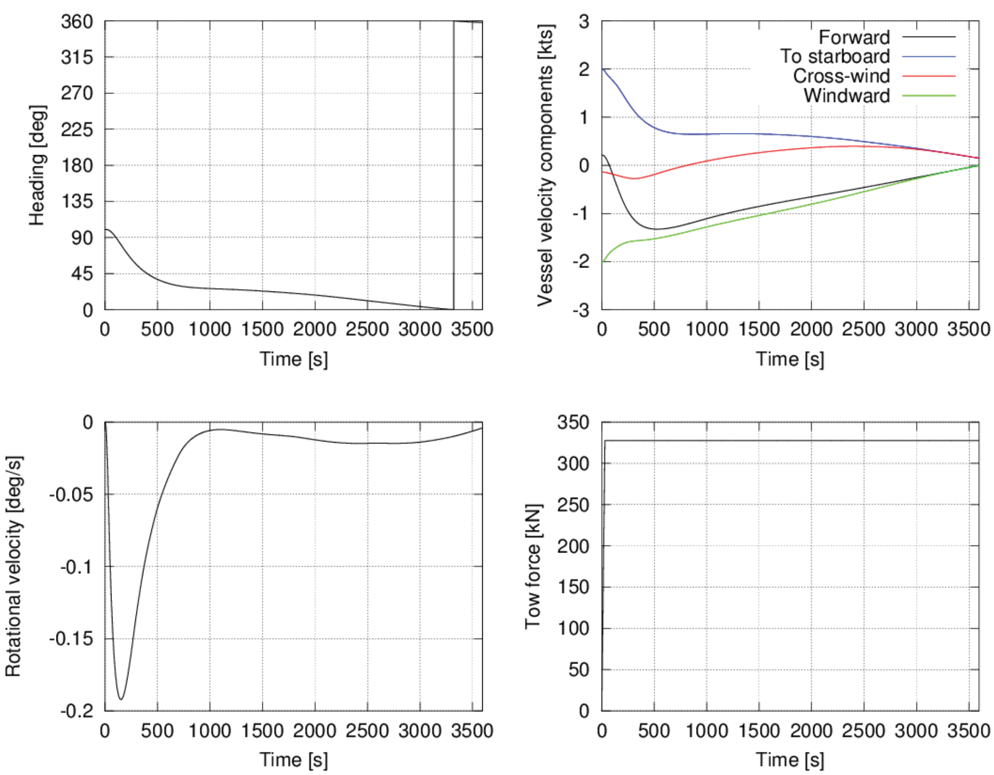
Bulk Carrier, 75th percentile environment, 270 kN pull, port turn



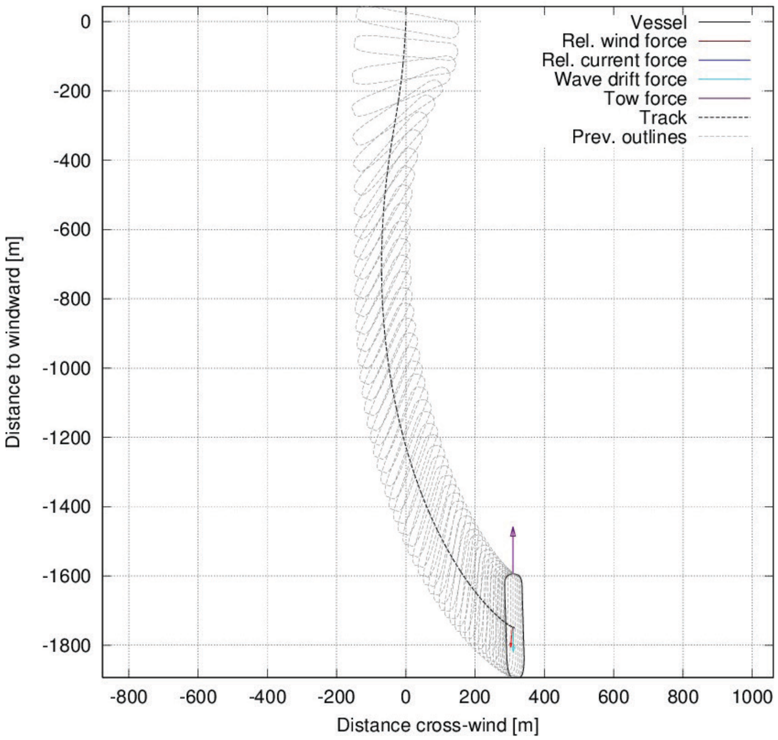
Bulk Carrier, 85th percentile environment, 327 kN pull,
port turn 358.1 deg heading from windward at 3595.0 s



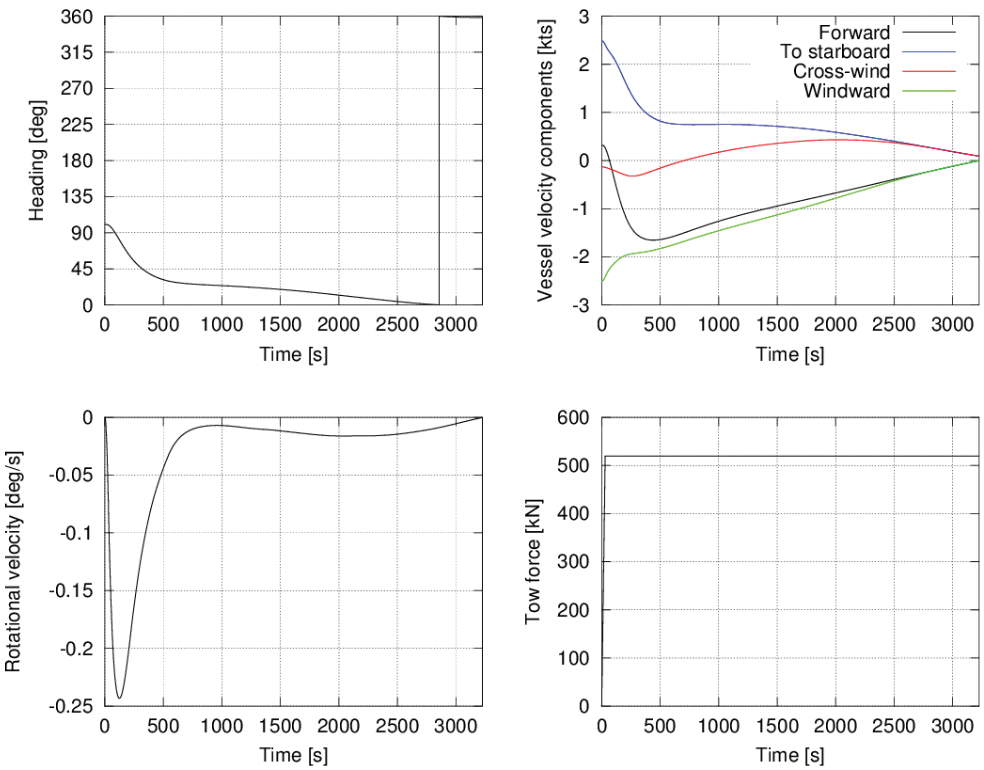
Bulk Carrier, 85th percentile environment, 327 kN pull, port turn



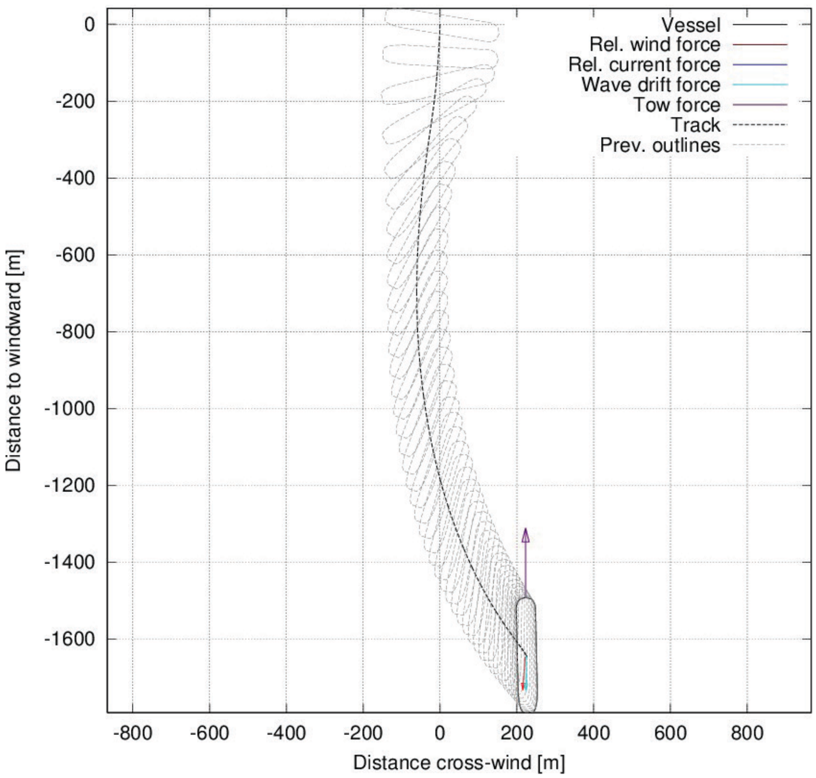
Bulk Carrier, 95th percentile environment, 520 kN pull,
port turn 358.3 deg heading from windward at 3226.0 s



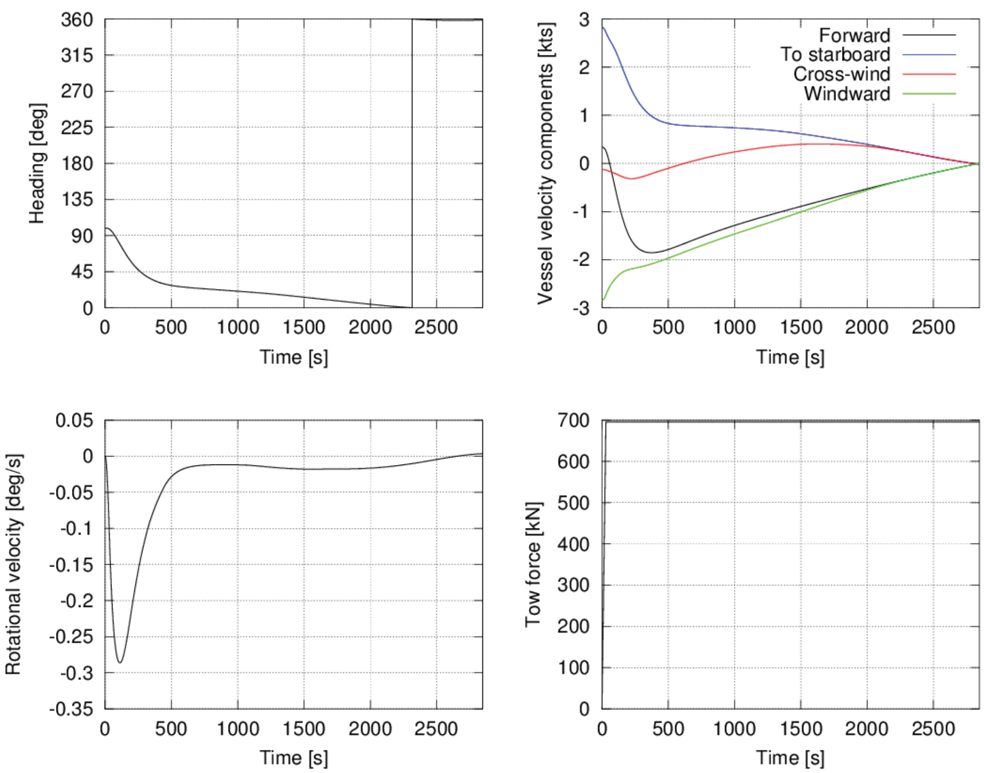
Bulk Carrier, 95th percentile environment, 520 kN pull, port turn



Bulk Carrier, 99th percentile environment, 695 kN pull, port turn 358.7 deg heading from windward at 2846.0 s



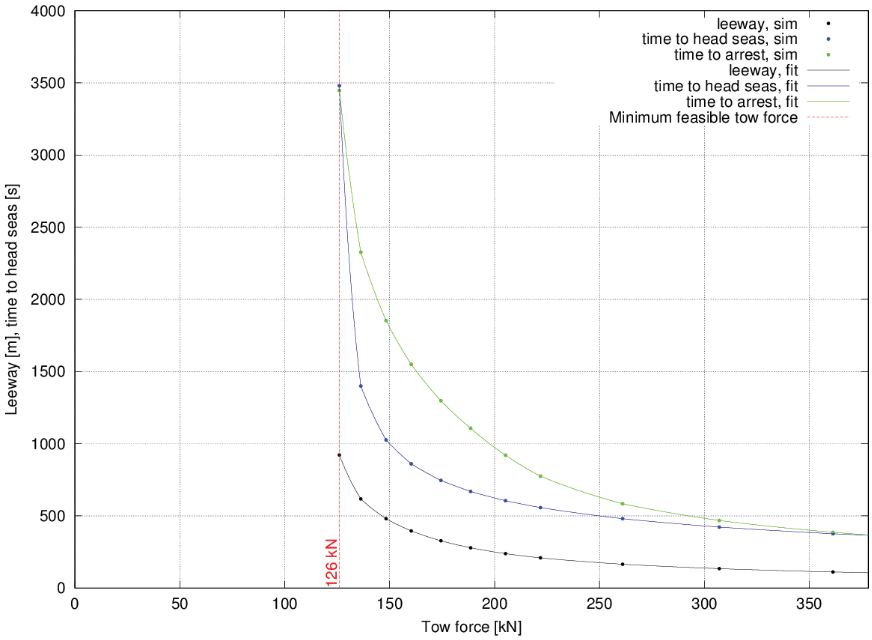
Bulk Carrier, 99th percentile environment, 695 kN pull, port turn



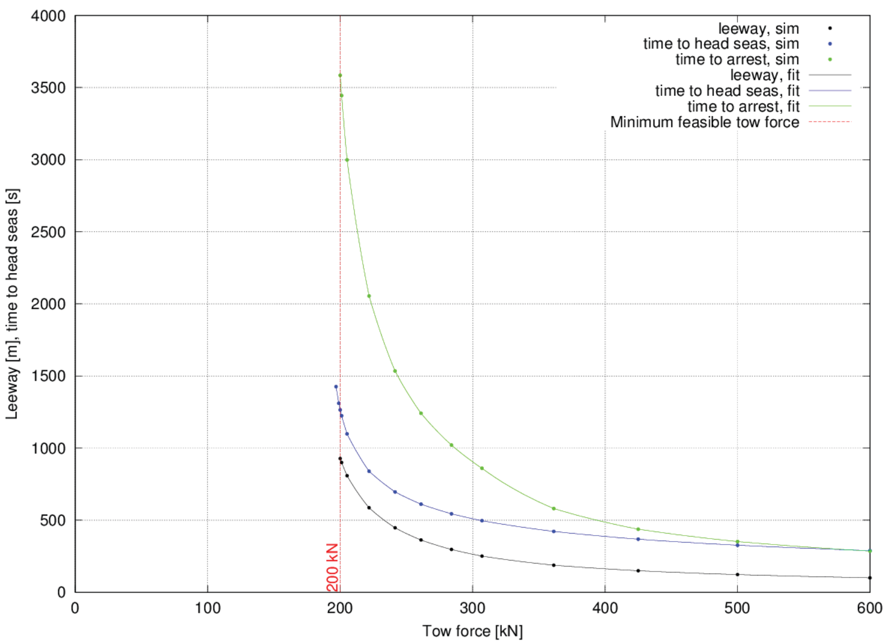
17.0 Appendix B.7: Aframax Tanker Simulation Results

17.1 Effect of Tow Force

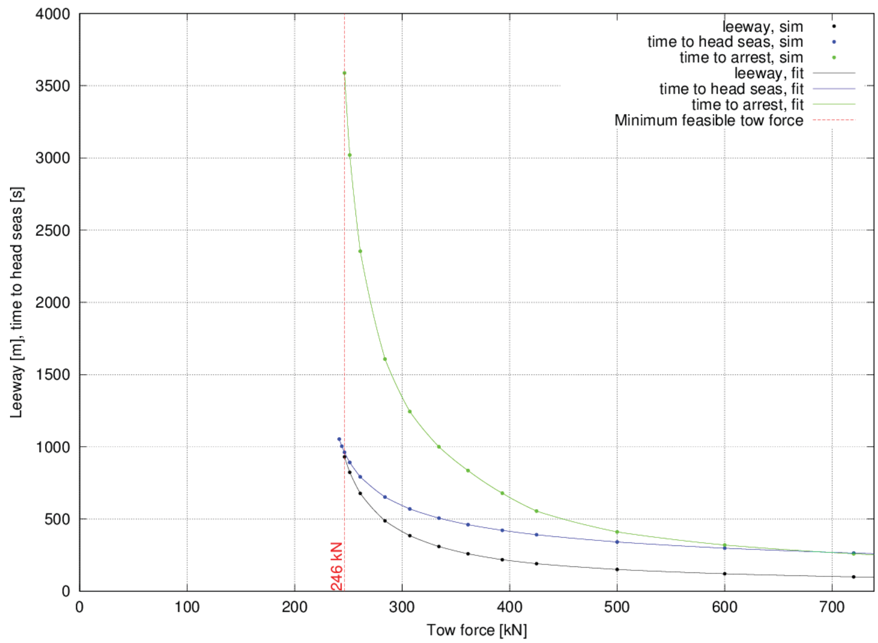
Aframax Tanker effect of tow force; 50th percentile environment



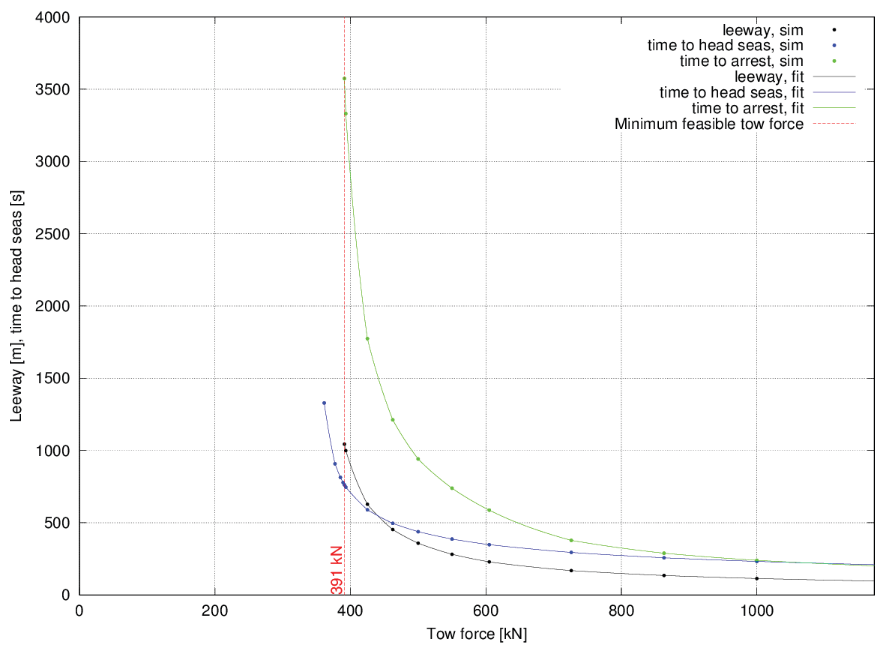
Aframax Tanker effect of tow force; 75th percentile environment



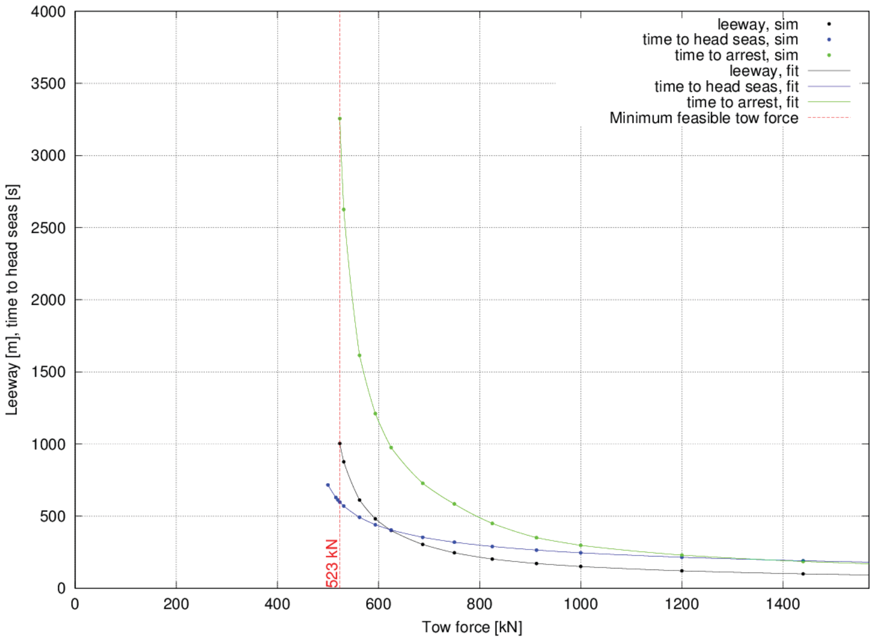
Aframax Tanker effect of tow force; 85th percentile environment



Aframax Tanker effect of tow force; 95th percentile environment

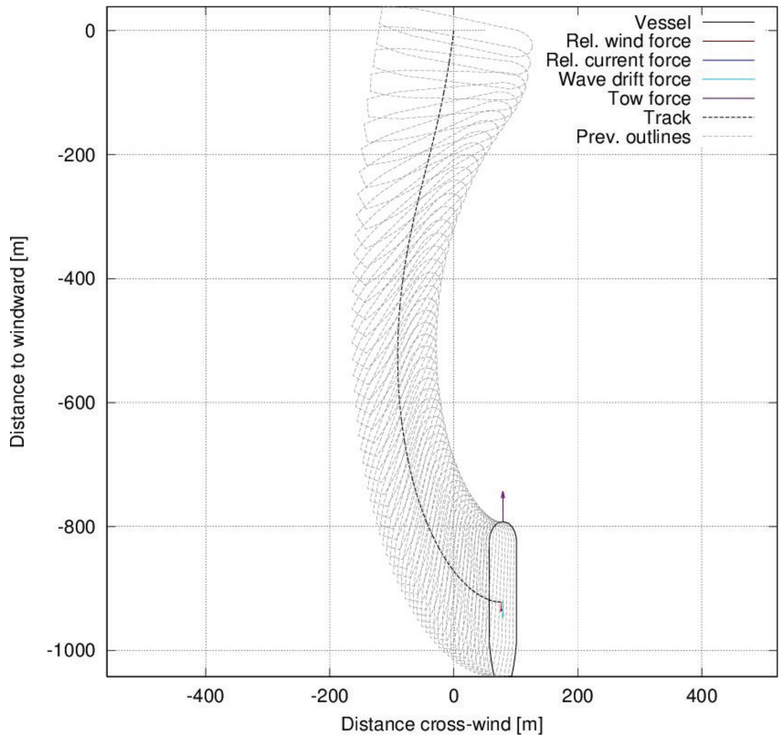


Aframax Tanker effect of tow force; 99th percentile environment

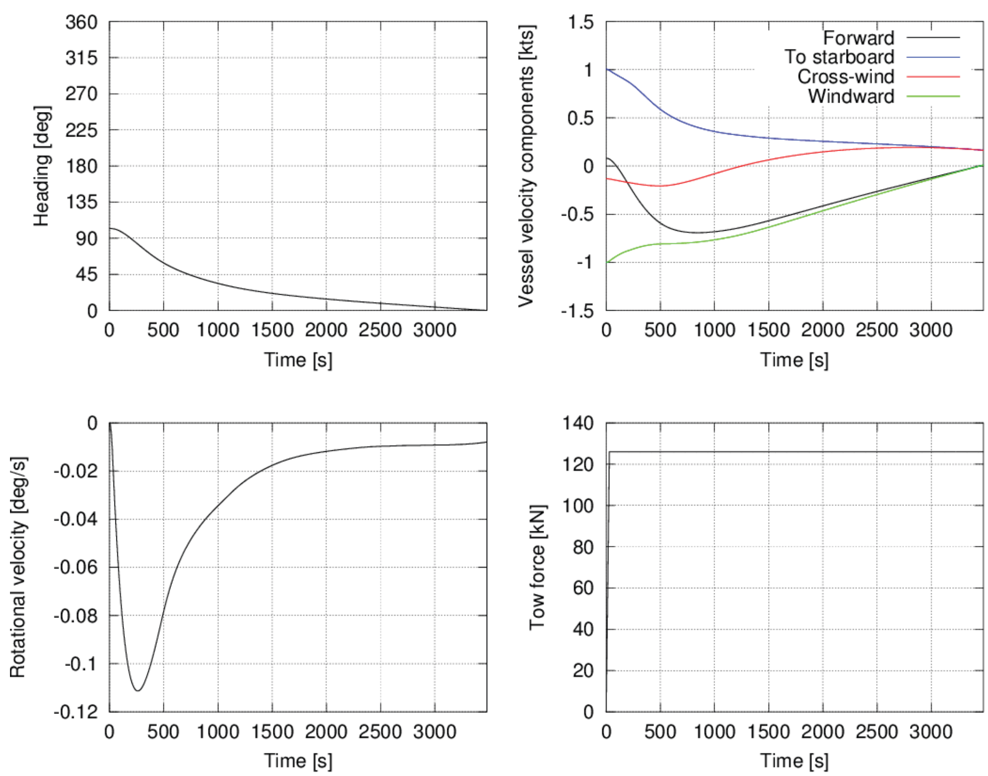


17.2 Simulations at Minimum Feasible Tow Force

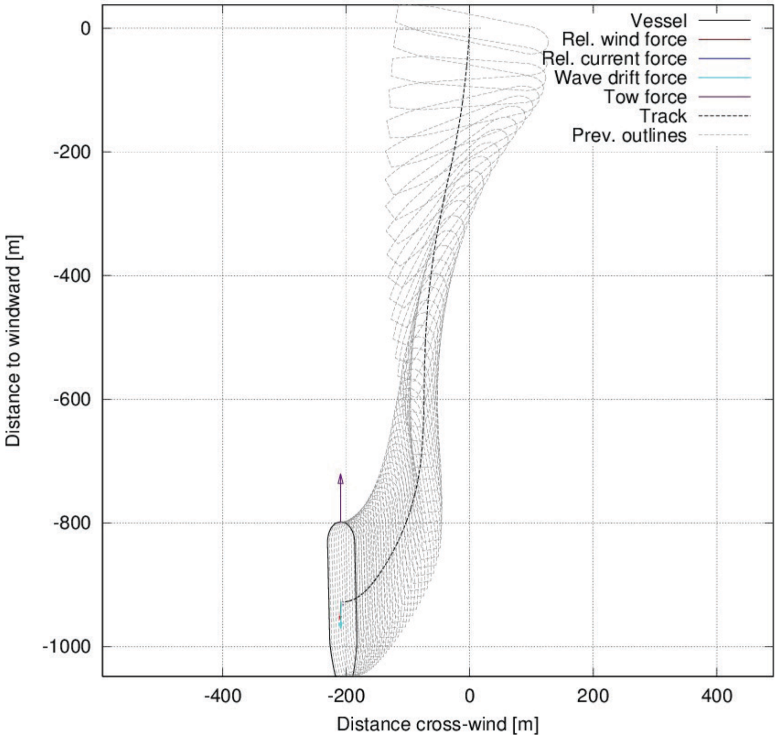
Aframax Tanker, 50th percentile environment, 126 kN pull,
port turn 360.0 deg heading from windward at 3480.0 s



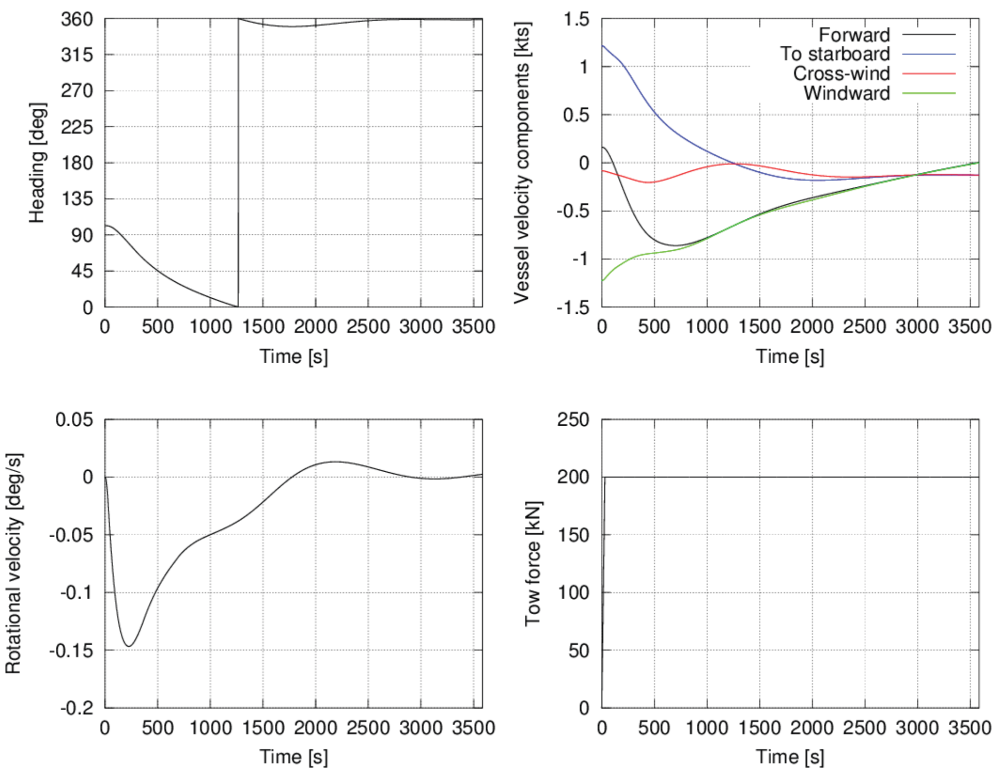
Aframax Tanker, 50th percentile environment, 126 kN pull, port turn



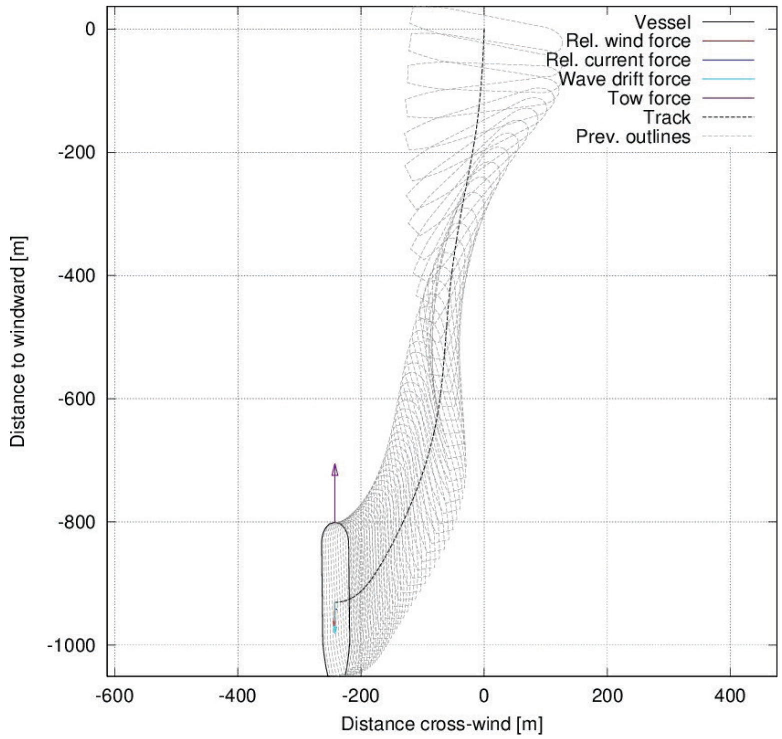
Aframax Tanker, 75th percentile environment, 200 kN pull, port turn 358.7 deg heading from windward at 3585.0 s



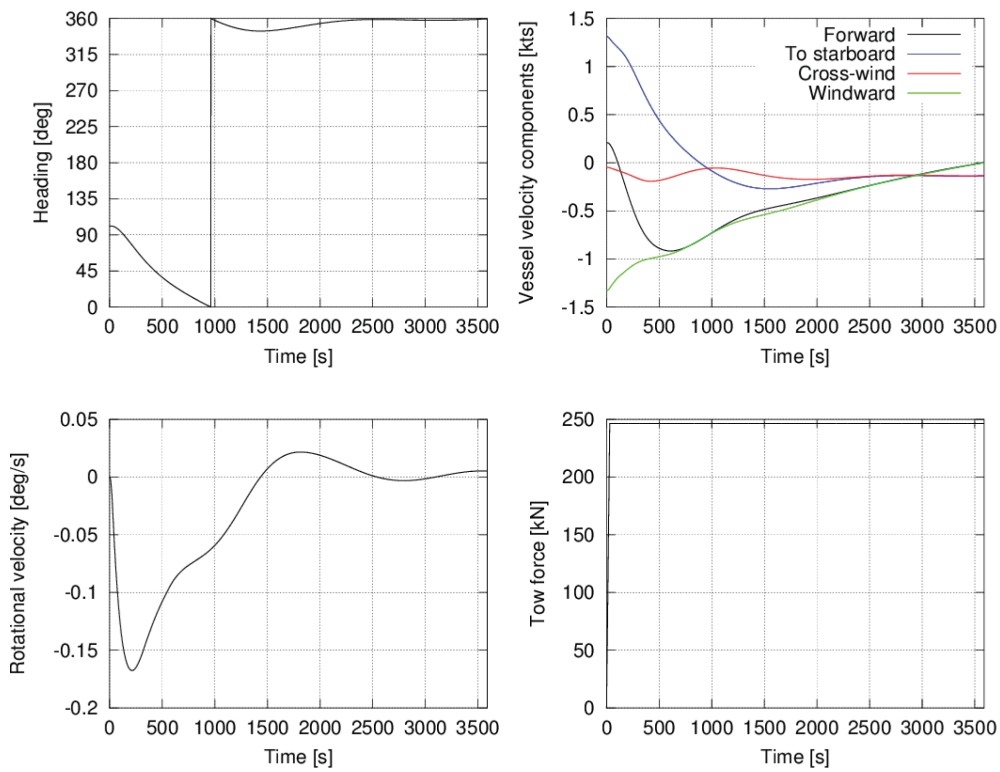
Aframax Tanker, 75th percentile environment, 200 kN pull, port turn



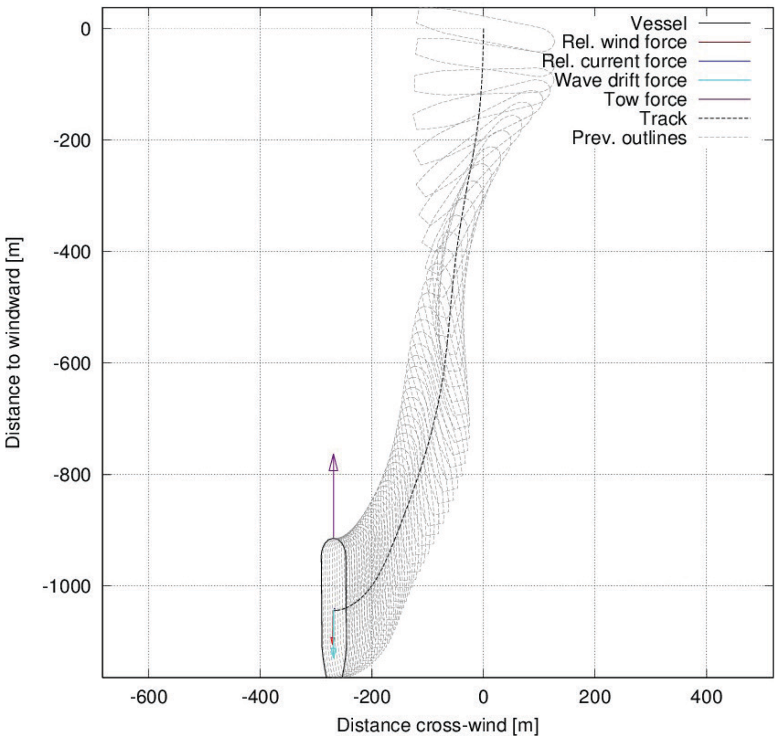
Aframax Tanker, 85th percentile environment, 246 kN pull, port turn 359.4 deg heading from windward at 3588.0 s



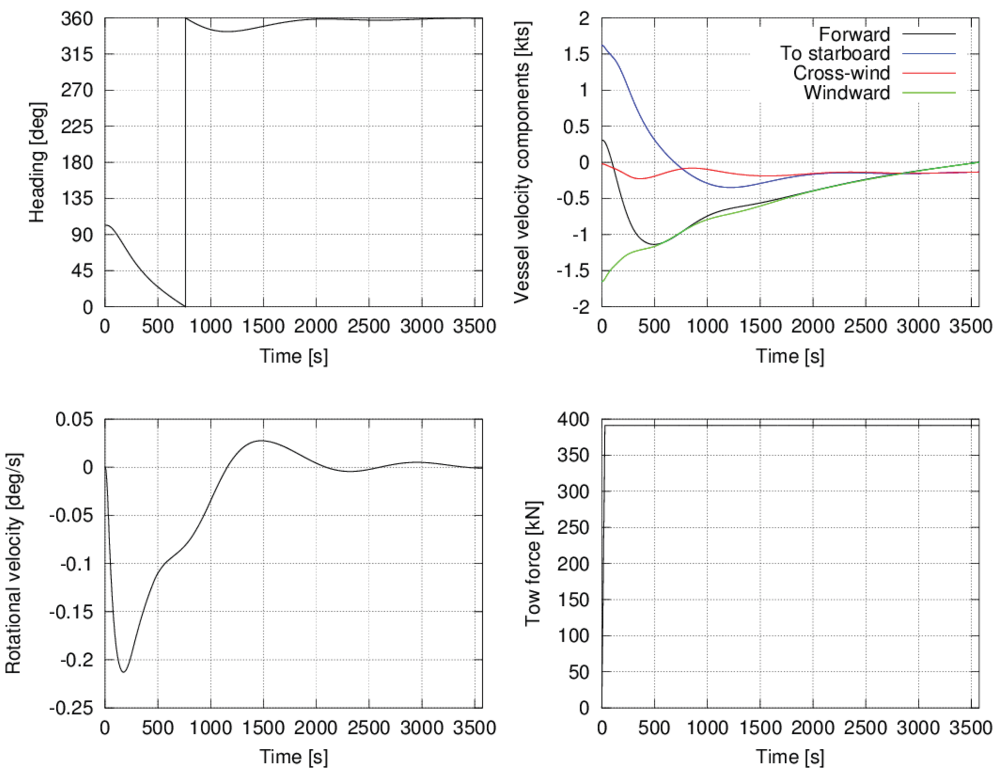
Aframax Tanker, 85th percentile environment, 246 kN pull, port turn



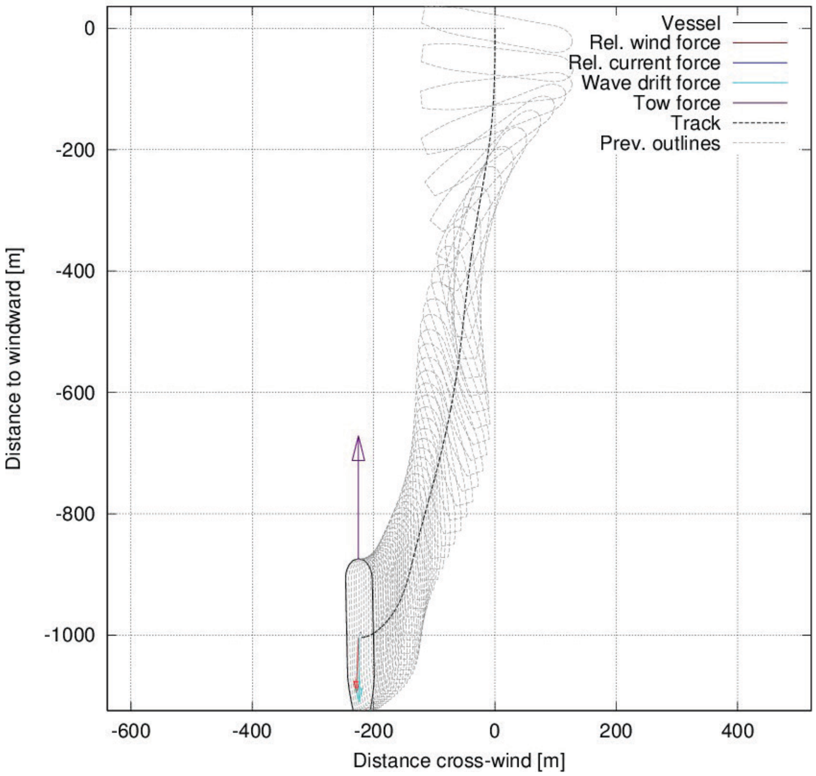
Aframax Tanker, 95th percentile environment, 391 kN pull, port turn 359.6 deg heading from windward at 3574.0 s



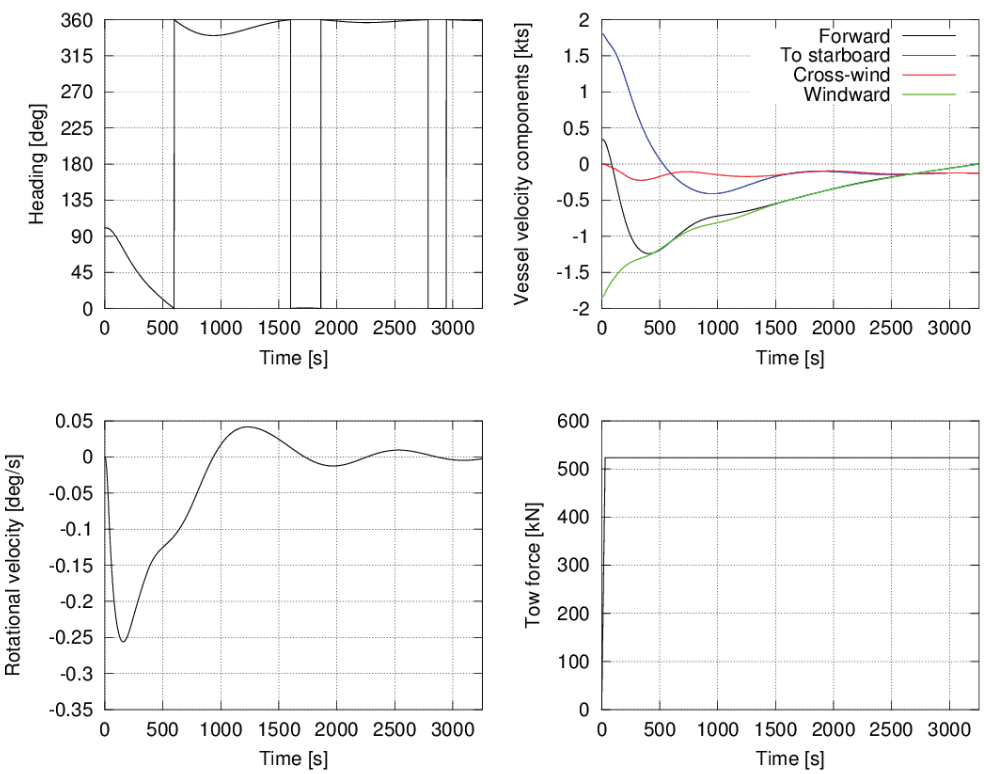
Aframax Tanker, 95th percentile environment, 391 kN pull, port turn



Aframax Tanker, 99th percentile environment, 523 kN pull, port turn 358.8 deg heading from windward at 3256.0 s



Aframax Tanker, 99th percentile environment, 523 kN pull, port turn



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