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DRAFT: Towing Capability Study for Single Tug Barge Tows

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Prepared for: Vancouver Fraser Port Authority

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Engineering

Conseil national de recherches
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Génie océanique, côtier et
fluvial

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Executive Summary

The enclosed report prepared by the National Research Council of Canada's Ocean, Coastal and River Engineering Research Centre (NRC-OCRE) is delivered to the Vancouver Fraser Port Authority (VFPA) as a deliverable of their contracted single tow tug and barge evaluation study.

This report contains a summary of all knowledge acquired by NRC-OCRE to-date that constitutes the basis of the background material of this work. This background includes a review of published regulations, standards, guidelines and practices that pertain to tugboat towing in Canada. It includes a summary of a subset of relevant tugboat towing incidents that have been investigated by the Transportation Safety Board of Canada. The state of the academic literature in numerical simulation is presented, along with investigation into a commonly used empirical formulation for tug boat powering. Effort undertaken between VFPA and NRC-OCRE to gather information from industry stakeholders is discussed.

Standard resistance and propulsion calculations were performed for a range of barges and tugboats. This was used to develop a minimum powering formula. This formula is compared to the commonly used standard formula, and their suitability for the VFPA regions is discussed.

A numerical simulation framework was developed for this work to gain insight on girding and the impact of towpull margin overhead. These results are presented and discussed. While insightful, their absolute accuracy is unknown due to the uncertainty of the coefficients used in the literature.

A summary of findings and concluding remarks is presented in the final section of this report. It includes recommendations regarding the implementation of minimum powering guidelines, as well as the continued development of aspects of this work. An important recommendation is presented regarding tugboat stability and the need for special attention to be given to this problem.

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1 Introduction

The Vancouver Fraser Port Authority (VFPA) has contracted the National Research Council of Canada's Ocean, Coastal and River Engineering Research Centre (OCRE) to perform the following study on single tow tug and barge powering.

VFPA has observed incidents involving tug and barge towing operations over many years, and has identified potential risks related to inadequate towing power. These include higher risk of navigational incidents (collisions or impediment of navigation for other marine users) as well as allisions with critical port infrastructure (including road and rail bridges). VFPA would like to evaluate and establish guidelines for tug capability to help mitigate barge towing risks, and have requested that OCRE assist them in developing these criteria.

Transport Canada, as part of TP11960: Standards for the Construction, Inspection, and Operation of Barges Carrying Oil or Dangerous Chemicals in Bulk, provides a simple semi-empirical equation for minimum bollard pull requirements of tug boats performing single-tow operations with barges. This has been identified by VFPA as both a desirable method of determining a requirement based upon barge particulars, as well as a point of investigation for this study.

The main objective of this work is to deliver to VFPA an investigation into existing methodologies and their applicability to barge towing operations in the Port of Vancouver and Fraser River, and/or a simplified formula or look-up table which can take barge particulars as input and provide estimated tug powering requirements as output.

This report summarizes the work performed to-date. It presents a background review, a parametric powering study, a manoeuvring investigation, a discussion on applicability and limitations of the work, and recommendations for further investigation.

2 Background

Upfront effort was taken to survey the state-of-the-art in regulations, industry best practices, and tug powering and simulation work. It was also desired to investigate known tug and barge incidents as well as the environmental conditions relevant to the area.

NRC's Intelligence and Analytics, Library and Information Management Services group produced an intelligence report in November 2020 to support aspects of this review. Specifically, they looked to address:

- **The state of the existing research literature:** Research literature databases were searched for any available publications relating to tugboats towing barges, as well as other marine vessels. This literature was scanned for relevancy and studied for existing practices.
- **The state of existing regulations:** A search was performed to determine available relevant federal government regulations or government department standards and guidance documents. The search was limited to the act of towing and excluded regulations used in tugboat construction. Additionally, the search was limited to Canada and the United States.
- **Industry Organizations:** A search was conducted for standards and standard practices for tugboat towing by released by marine industry organizations (such as ASTM, ISO, etc.)

Sections 2.1 through 2.5 comprise a summary of this effort. The remaining sections in this background review are specific to VFPA's request and include a review of an empirical formula, an industry survey of tug and barge operators in the Fraser River region, and a summary of points of interest within the region.

2.1 Regulations, standards and guidelines

2.1.1 Canada

NRC was unable to find any Canadian federal regulations listed in the *Canada Shipping Act, 2001*[1] that pertain specifically to tugboats towing barges or other marine vessels. There are, however, regulations relating to the construction, operation an safety of tugs and barges. These are referenced in Transport Canada guidelines and standards.

Two departmental standards and guidelines were found under *Transport Canada. TP 15180E: Guidelines for the Construction, Inspection, Certification and Operation of Tugs <24 Metres in Length*[2] does not provide any guidance on sizing tugs for tows. This is specifically acknowledged in Section 1.5.3, “There are no internationally recognized guidelines governing the relationships between the size and power of a tug and the size or type of its tow."

TP 11960E: Standards for the Construction, Inspection, and Operation of Barges Carrying Oil or Dangerous Chemicals in Bulk[3] offers similar guidance as the guidelines in *TP 15180E* but with specific attention given to the nature of sensitive tows. Appendix A, Section 1.3 provides an empirical formula (later discussed in depth) for estimating the required bollard pull for any tow vessel for “any type of tow".

2.1.2 United States

The United States Federal regulations on “Towing Vessels" can be found in *Title 46, Chapter 1, Subchapter M*[4] Parts 136-144. Section 140.801 (“Towing Gear") states the “owner, managing operator, master or officer in charge of a navigational watch of a towing vessel must ensure” that the towing components and materials are adequate for the boat’s horsepower and size of the intended tow. However, no formulae are provided to make these calculations."

U.S. Coast Guard’s *Towing Vessel National Center of Expertise*[5] provides guidance and documentation on how to adhere to Federal regulations (such as *Subchapter M* above) as well as best practices. A search of their website produced no specific recommendations for towing vessel powering, other than that found in the regulations.

2.2 Standards and Standard Practices

2.2.1 IMO

IMO has provided two circulars for towing. *Guidelines for Safe Ocean Towing (MSC.1/Circ.884)*[6] states in section 9.4:

> The continuous bollard pull of the towing vessel(s) involved should be sufficient to maintain station keeping of the tow in the following environmental conditions, acting in the same direction:
>
> - Wind: 20 m/s
> - Significant wave height: 5 m
> - Current: 0.5 m/s

This guideline provides a greater level of specificity regarding the definition of sufficient powering. By specifying station-keeping within this worst-case environmental condition as the powering requirement, the required propulsive force becomes equal to the towing vessel’s bollard pull. Additionally, since both the towing and towed vessels are stationary, wind force, current force, and second-order wave drift become the only forces required for calculation.

This guideline is best-suited for towing operations in open ocean conditions as the suggested maximum current is low while maximum wind and significant wave heights are high. Additionally, this guideline lacks specificity in how these forces should be evaluated.

IMO’s second towing-related Circular, *Guidance on Shipboard Towing and Mooring Equipment (MSC.1 / Circ.1175)*[7], pertains mainly to towline arrangements and specification and offers no guidance for towing vessel powering.

2.2.2 DNV GL

DNV GL provides a service specification for towing vessels, *Nobel Denton marine services - certification for towing vessel approvability (DNVGL-SE-0122)*[8]. This specification requires no quantitative assessment of adequate towing vessel power. It does provide requirements for towing vessel stability and seakeeping in Section 6, and in section 6.4.1 states, “Vessels in all categories shall be of such a design to allow them to operate safely and effectively in their designated areas."

2.3 Other Documents and Publications of Relevance

2.3.1 Transport Canada Canada/US comparative study

In October 1997, Transport Canada issued *Comparative Study into Canadian and United States Regulations on Small Passenger Vessels and Towboats - Summaries and Response by Marine Safety*[9]. This study was commissioned in response to industry criticisms of Canadian regulations on small passenger vessels and towboats. Criticism largely centered on the perception that Canada's regulations were much more stringent than those in the US and that they were too costly, especially for smaller vessels.

The study concluded that the number of serious towing incidents at this time in the US was significantly higher than in Canada (and approximately 60% of incidents were directly attributable to human error). It concludes, in part, "The major differences between Canada and US regulations for towboats relate to manning, stability and loadline,[sic] inspection and lifesaving equipment."

Of note, no factors pertaining to powering appear in the conclusions or recommendations for either country. The US has since implemented more stringent regulations (as previously discussed).

2.3.2 The Safety of Tugboats in BC

In December 2015, Robert G. Allan published the article *The Safety of Tugboats in BC*[10] in the *Western Mariner* magazine. A conclusion from a Robert Allan Ltd. study in 2004 into US/Canada tugboat safety regulations is presented, stating "The information indicates that the implementation of quite stringent regulations in 1970 has had no measurable effect on the safety of towing vessels on this coast." He presents an analysis of the six tugboats lost in 2015 and notes that four of them fall under the 10 Gross Registered Tonnage (GRT) limit and the other two fall under the 15 GRT limit[1]. He also notes that all six tugboats have reported rule depths lower than should be expected for their size (evidence of false floors being used to reduce the internal depth of the ship), and that they all have very low freeboard.

Allan notes that vessels built prior to 1972 are exempt from Canadian hull construction regulations, within which is a requirement that, "no ship shall be used for towing until its stability characteristics have been approved by the Board [of Steamship Inspection]". As four of the tugboats lost in 2015 were built after 1972, and as they had visually low freeboards, he argues it is likely that their stability characteristics had changed since their original certification as equipment was added to the boats over time (there is no Canadian requirement for stability reassessment). He recommends that GRT not be used for tug class regulations as stability is a key factor in towing safety, and that work be done to produce stability requirements based on tow loads.

2.3.3 Shipowners' Club

The *Shipowners' Club* is a mutual insurance organization. It produced the loss prevention booklet *Tugs and Tows – A Practical Safety and Operational Guide*[11] in an effort to address the safety issues raised from claims (where over half of the reported incidents were attributed to "human error"). Of note, this booklet references the empirical formula for bollard required bollard pull as presented in Transport Canada's *TP 11960*. It also notes that a tug should have sufficient stability so as to withstand capsizing when girded with

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[1] All self-propelled non-passenger vessels over 15 GRT are subject to Transport Canada hull inspection criteria.

the maximum towline load force, and that it should be equipped with an appropriate emergency release mechanism for this scenario.

2.4 TSB investigations

There have been numerous incidents with tugboats in Canada which required investigation by the Transportation Safety Board of Canada. A selection of these incidents within the last two decades are presented here, along with tugboat particulars and select TSB conclusions.

2.4.1 M09W0141

From Marine Investigation Report M09W0141[12]:

> On 19 July 2009, the tug *North Arm Venture* was towing the barge *North Arm Express*, loaded with fuel and deck cargo, from Toba Inlet to Sechelt Inlet. The tug girded and capsized at approximately 1250 Pacific Daylight Time while making a turn to port at the entrance to Sechelt Rapids. The four crew members on board were rescued, with two suffering minor injuries.

North Am Venture is a 12.80 m tug with a gross tonnage of 35.46 and an installed engine capacity of 640 horsepower (477 kW). *North Arm Express* is a 52.43 m barge with a gross tonnage of 786 and cargo of “5 empty cement carriers, 3 trucks, 370 156 litres of diesel fuel and gasoline in bulk". The incident occurred just prior to slack low tide (with an ebb current around 1-2 knots) with light winds. The tug was unable to effect the barge, and the barge overtook to the tow, leading to girding and capsizing. The master chose not to use the emergency release.

TSB findings were:

- The transit through Sechelt Rapids began prior to slack tide and, as a result, the barge came under the influence of the ebb tide, causing it to shear to starboard.
- The attempt to regain control of the barge was unsuccessful due to an insufficient reserve of power on the tug.
- The North Arm Venture capsized when the shortened towline pivoted athwartships; its force, then acting transversely, rapidly overcame the tug’s righting ability.
- The absence of procedures or guidelines on girding left the master without important information to aid in his decision-making.

2.4.2 M11W0091

From Marine Investigation Report M11W0091[13]:

> On 28 June 2011 at 0410 Pacific Daylight Time, while under tow of the tug *F.W. Wright*, the loaded gravel barge *Empire 40* struck the Queensborough Railway Bridge in the Fraser River, British Columbia. The bridge centre swing span and protection pier sustained extensive damage. This resulted in the bridge being inoperable for a period of 2 months after the striking, causing

> major disruptions to railway and river traffic. No one was injured and there was no pollution as a result of this occurrence.

F.W. Wright is 12.59 m tug with a gross tonnage of 8.7 and an installed engine capacity of 880 horsepower (656 kW). *Empire 40* is a 61.57 m barge with a gross tonnage of 1174 and had a cargo of "3600 tons paving aggregate". The incident occurred in a freshet of approximately 4 knots (uncertain due to reliance on current monitoring at New Westminster) and low winds. At time of reporting, this was the fifth allision with the Queensborough Railway Bridge within the 10 years prior.

TSB findings were:

- The master had been awake for approximately 22 hours and was likely experiencing feelings of fatigue when he handed over the con to the mate prior to a critical stage in the passage.
- The master did not take advantage of the opportunity to rest and sleep after the mate joined the tug and fell asleep at a critical stage in the passage.
- The mate had limited experience transiting the Queensborough Railway Bridge, and, after having confirmed his approach to the bridge prior to Shoal Point, attempted the transit on his own without seeking assistance from the master.
- The setting of the barge to the north by the high freshet was underestimated during the approach, and resulted in the barge striking the bridge.
- An approximate 1-knot difference in the speed of the current at the time of the transit was likely not a factor in this occurrence.

2.4.3 M15P0037

From Marine Investigation Report M15P0037[14]:

> On 18 March 2015, at approximately 1541 Pacific Daylight Time, the tug *Syringa* took on water and sank about 40 metres north of Merry Island, off Sechelt, British Columbia. The tug had been towing the loaded barge *Matcon 1*, which was released shortly before the sinking. The 2 crew members swam ashore and were later evacuated by the Canadian Coast Guard; no injuries were reported. A small quantity of diesel fuel was released from the tug after it sank, and the adrift barge was recovered by another tug.

Syringa was a 10.85 m tug with a gross tonnage of 14.57 and an installed engine capacity of 335 horsepower (250 kW). *Matcon 1* is a 32.19 m barge with a gross tonnage of 160 and had a cargo of "Construction equipment (an excavator, loader, trucks, and trailers), a tank of diesel fuel, and explosives". The incident occurred in 17 knot winds ad a 1m swell.

TSB findings were, in part:

- The Syringa sank because it was not maintained sufficiently to prevent water ingress during the voyage, and inadequate subdivision of the hull compartments allowed progressive downflooding to occur.
- If vessel operators do not have a process for managing safety, there is an increased risk that hazards will go unidentified or unaddressed.

- If Canadian tugs less than 15 gross tons are not subject to adequate regulatory oversight, there is an increased risk that shortcomings in vessel management will go unresolved and tugs will not be operated safely.
- The Syringa had undergone modifications under the previous owners, but these modifications had not been reported to Transport Canada and the vessel had not been assessed for stability.
- Without procedures, familiarization and training, the crew were unaware of any problems with their equipment, thus depriving them of its use during an emergency.

This was one of the tugboat incidents analysed by Robert G. Allan in his *Western Mariner* article (previously discussed). The TSB findings regarding inspection requirements (or lack thereof) for vessels under 15 GRT and modifications support his analysis regarding stability.

2.4.4 M16P0062

From Marine Investigation Report M16P0062[15]:

> On 02 March 2016, at 1730 Pacific Standard Time, the tug *H.M. Scout* departed Victoria, British Columbia, en route to Bamberton, British Columbia, with the barges *HM Tacoma* and *HM Blue Horizon* in tandem tow. During the passage, the tug encountered severe weather, the tow line between the barges parted, and the *HM Blue Horizon* grounded near Clover Point, British Columbia. During the recovery attempt, a piece of the parted tow line fouled the tug's propeller, partially disabling the tug. The *HM Tacoma* subsequently grounded near Finlayson Point, British Columbia, and the disabled tug released the tow line and returned to Victoria. There were no injuries, but some of the scrap construction material from the *HM Blue Horizon* was lost overboard.

H.M. Scout was a 12.01 m tug with a gross tonnage of 13.88 and an installed engine capacity of 520 horsepower (387.8 kW). *HM Tacoma* and *HM Blue Horizon* are 45.56 m and 53.34 m barges with gross tonnages of 532.39 and 818.82 and were carrying “Lifting equipment and construction equipment" and “Scrap construction materials and piles from a dock", respectively. The incident occurred in high winds of 40 knots (gusting to 47).

Findings were, in part:

- The master and owner, operating without procedures or a systematic assessment of the risks, unintentionally made decisions that contributed to the barges going aground.
- The overall adequacy of the towing arrangement had not been assessed in the context of the voyage conditions and an inadequate towing arrangement was used.
- The tug and tow encountered the forecasted gale-force winds and rough sea conditions, and the combined forces of these movements caused the ropes between the barges to part; the HM Blue Horizon drifted free and went aground.
- There was no contingency plan to guide the crew, so they made ad hoc decisions and placed themselves at risk in the attempt to recover the HM Blue Horizon.

- If TC does not provide easily understandable standards and guidance to assist towing vessel owners and operators to ensure the adequacy of their towing arrangement and the condition of their towing equipment, including the selection of tow ropes, there is an increased risk of the towing equipment failing, resulting in the loss of tow.
- In the absence of safe manning requirements presented in a simple, clear, and practicable format for end users, especially those who operate vessels that are not routinely inspected, there is a risk that vessels will proceed to sea with an inadequate number of crew on board.
- If tugs with a gross tonnage of less than 15 are not subject to adequate regulatory oversight to ensure compliance with regulations, there is a risk that shortcomings in operations will go unresolved.

While not part of the findings summary, this particular incident report does make explicit mention of the bollard pull of *H.M. Scout*. It notes that, if the engine were new, the bollard pull would be approximately 5.2 tonnes. Given that it was built in 1961, and in applying DNV GL estimation methods of a 1% reduction in power every year after 10 years of life, TSB estimates a realistic bollard pull of 2.86 tonnes.

2.4.5 M18P0230

From Marine Investigation Report M18P0230[16]:

> On 13 August 2018, the tug *George H Ledcor* was towing the loaded gravel barge *Evco 55*, with the assist tug *Westview Chinook* pushing to an unloading facility on Mitchell Island in the north arm of the Fraser River, British Columbia (BC). At approximately 2210, the *George H Ledcor* girded and capsized after being overtaken by the barge. The 4 crew members on board were rescued from the tug's overturned hull by the nearby yarding tug *River Rebel* and the assist tug *Westview Chinook*. One crew member sustained a serious injury to his hand. The assist tug then towed the overturned tug and barge to a nearby tie-up, where a pollution boom was deployed around the tug. An unknown quantity of diesel fuel was released as a result of the occurrence.

George H Ledcor is a 19.29 m tug with a gross tonnage of 81.41 and an installed engine capacity of 760 horsepower (567 kW). *Westview Chinook* is a 13.47 m tug with a gross tonnage of 52.50 and an installed engine capacity of 940 horsepower (701 kW). *Evco 55* is a 78.03 m barge with a gross tonnage of 2275.33 and was carrying “4621 tonnes of gravel". The incident occurred in light winds and at high river depth with tide at the end of a flood.

TSB findings were, in part:

- The *George H Ledcor* attempted to pull the *Evco 55* to port, but the tug was unable to change the direction of the loaded barge, due in part to the assist tug pushing on the stern.
- As the barge began to overtake the *George H Ledcor*, the towline, which was not secured by hold-down gear, began to exert a broadside force on the tug, placing the tug in a girded position.
- The master applied full starboard rudder and full throttle; however, given the forces acting on the vessel's stability, such as thrust from the propellers, flow of river against the hull, and increasing force from the towline, this action increased the tug's heel.

- As the tug's heel progressed, and given the shortened towline, the master did not have sufficient time to initiate corrective action.
- As the tug's deck edge and bulwarks submerged, they created a dragging force, and the tug heeled further to starboard; the crew attempted to abort the tow, but they were unsuccessful and the tug rapidly capsized.

The report makes explicit mention of the bollard pull of the *George H Ledcor*, but stops short of mentioning anything about its suitability for the tow. Of note, prior to the assitance of *Westview Chinook*, the tug and barge were making approximately 5 knots of way at 80% throttle. When *Westview Chinook* joined, it was used primarily as an additional push, allowing the tow to achieve 6 knots of way.

2.4.6 M19P0246

From Marine Investigation Report M19P0246[17]:

> The *Sheena M* was a twin-screw steel-hulled tug of 9.99 gross tonnage (GT) that was built in 1981 and owned by Active Marine Towing Ltd, which was also the authorized representative. It was powered by 2 diesel engines of 447 kW total power and had a towing winch located aft on the centreline. The *Sheena M* was normally used to tow log booms; it had also towed 500-series Seaspan barges on numerous occasions. The tug was crewed by a master and a deckhand. The *Seaspan 566* is a non-propelled unmanned steel barge of 883 GT with a cargo capacity of 2500 short tons. On the occurrence voyage, the barge was loaded with 2159 short tons of wood chips and had a draft of 2.25 m, an aft trim of approximately 20 cm, and a starboard list of approximately 3 cm.

The incident occurred in light winds, calm sea state, and flooding tide. The vessel was making 2 knots of way when girding began. The master initiated a port turn and the barge did not respond to the course alteration. Girding began and the tug heeled to starboard. The master slowed the tug speed, allowing the tug to right itself. Shortly after, the tug heeled starboard again. Water entered the wheelhouse through a starboard-side door (secured open with a hook). The tug then capsized.

The report makes no mention of the bollard pull capacity of the *Sheena M* with respect to its tow. Its findings center on the lack of inspection regulations for vessels under 15 GRT, the finding that the vessel had no stability booklet onboard (or in a previous random inspection), and that the master was not of the appropriate certification level for the tug.

2.4.7 Other incidents of note

In TSB's Marine Investigation Report M18P0230, Appendix B notes a history of related tug and barge incident reports and summarize the occurrence. These are presented here for interest, with previously decsribed incidents removed.

- M91W1035 – On 20 June 1991, the tug Seaspan Rustler girded and capsized while attempting to regain control of its tow in the Fraser River, BC. The TSB issued Recommendation M93-15 in response to this occurrence.

- M94W0039 – On 18 June 1994, the tug Savage Warrior girded and capsized while towing a loaded barge near the entrance to Campbell River, BC, resulting in 1 fatality.
- M95W0006 – On 12 February 1995, the tug Kaien Pride girded and capsized while towing a barge in strong winds and moderate seas in Cornwall Inlet, BC. The master is presumed to have drowned.
- M95L0010 – On 01 May 1995, the service vessel Vézina No. 1, which was being used as a tug, girded and capsized while manoeuvring another vessel in the Port of Quebec, QC. A lack of watertight integrity and the fact that the tug was not equipped with an abort mechanism contributed to the accident. There was 1 fatality.
- M95W0205 – On 16 November 1995, the tug Duke Point was towing a log boom upriver when it girded and capsized as it was manoeuvring around a deadhead near Campbell River, BC.
- M98W0220 – On 07 October 1998, the tug Evco Crest girded, took on water, and nearly capsized while towing a loaded gravel barge in Vancouver Harbour, BC.
- M99W0119 – On 19 July 1999, the tug Compass Rebel girded and capsized due to the river current while towing a log boom in the north arm of the Fraser River, BC.
- M00L0040 – On 09 May 2000, the tug Ocean Jupiter girded and nearly capsized while assisting with the departure manoeuvre of a deep-sea vessel at the Port of Montreal, QC.
- M00L0061 – On 23 June 2000, the tug 10D34138 girded and capsized while landing a barge at Lac des Deux Montagnes, QC.
- M03L0137 – On 09 November 2003, the tug Ocean Hercule girded and nearly capsized while towing a barge at Trois-Rivières, QC.
- M04W0045 – On 14 March 2004, the tug Samantha J girded and capsized while assisting with the manoeuvring of a log barge in Ladysmith Harbour, BC.
- M04W0235 – On 06 November 2004, the tug Manson girded, capsized, and sank while attempting to recover its second tow, which had broken loose at Texada Island, BC. There were 2 fatalities.
- M05W0038 – On 20 March 2005, the tug Aqua Queen girded and capsized while pulling anchors off a float in Toquart Bay, BC.
- M05W0199 – On 15 October 2005, the tug Samantha J girded and sank while towing a barge in Northumberland Channel, BC.
- M07L0175 – On 07 September 2007, the tug Boatman No. 5 girded and capsized while coming alongside with a barge in Koksoak River, Quebec.
- M07W0012 – On 21 January 2007, the tug Jacques Cartier girded and listed heavily to starboard while towing a loaded barge in Vancouver Harbour, BC.
- M07W0072 – On 06 June 2007, the tug Glenshiel girded, capsized, and rapidly sank while towing a barge in Nakwakto Rapids, Seymour Inlet, BC.

- M07W0104 – On 27 July 2007, the tug Butler girded and capsized while towing logs near the Queensborough rail bridge in the north arm of the Fraser River, BC.
- M07W0129 – On 19 September 2007, the tug D & E No. 1 girded and capsized while towing a sports fishing lodge barge at Queen Charlotte Islands, BC.
- M08W0103 – On 09 June 2008, the tug Sea Cap III girded and capsized while manoeuvring a barge in Derby Reach, Fraser River, BC.
- M08W0137 – On 02 July 2008, the tug Cricket No. 1 girded and nearly capsized while manoeuvring a barge in the Taku River, BC.
- M09C0063 – On 19 November 2009, the tug Connie E girded and capsized while towing a barge with another tug in the Trent Severn Waterway near Trenton, ON.
- M09W0039 – On 07 March 2009, the tug Island Provider 1 girded and capsized while towing 2 barges in Sunderland Channel, BC.
- M10W0006 – On 28 January 2010, the tug Iris G girded and sank while towing a barge downstream in the Fraser River, BC.
- M11W0171 – On 05 October 2011, the tug Warnoc girded and capsized while tending a log barge in Cleo Bay, BC.
- M12W0023 – On 14 February 2010, the tug Sea Imp XV girded and capsized while towing a barge in the Fraser River near Mission, BC.
- M12W0153 – On 28 June 2012, the tug Sea Cap VII girded and capsized while shifting a barge near the Pattullo Bridge in the Fraser River, BC.
- M13W0198 – On 04 August 2013, the tug Maren J girded and nearly capsized while assisting in barge-towing operations in Northumberland Channel, BC.
- M14P0265 – On 06 October 2014, the tug Samantha J girded and sank while moving a barge in Northumberland, BC.
- M15P0107 – On 24 May 2015, the tug Fraser Warrior girded and nearly capsized while towing a barge, when the jog steering control malfunctioned in Prince Rupert Harbour, BC.
- M15P0152 – On 19 June 2015, the tug Hodder Ranger girded and capsized while pulling anchors off a barge near Port Mellon, BC.
- M15C0108 – On 22 June 2015, the tug LCM131 girded and capsized while manoeuvring a tow wire attached to a barge on the St. Lawrence Seaway near Cornwall, ON.
- M15P0298 – On 11 September 2015, the tug Ocean Gordon girded and capsized while towing a barge in Vancouver Harbour, BC.
- M16A0415 – On 05 December 2016, the service vessel C25510PE girded and capsized while assisting a tug with a cable operation near Borden, PEI.

- M16P0243 – On 13 July 2016, the tug Charles H. Gates VI was attempting to land a fuel barge when the tug girded and was struck by the barge in Vancouver Harbour, BC.
- M18P0063 – On 27 February 2018, the tug Seaspan Raven girded and nearly capsized while assisting a container ship in Vancouver Harbour, BC.

It is clear from these reports (and their abundance) that girding represents the primary loss potential scenario of tug towing on Canadian waters.

The majority of these investigations cite human error and/or failure (or unsuitability) of equipment as the main factor in the event. A large number of the reports discuss the suitability of the vessel's stability in context of the tow, but rarely explicitly state stability as a primary finding. A small number of the reports discuss the suitability of the vessel's installed power in context of the tow, and none reviewed state available power or thrust as a primary finding. While stability and powering are rarely present in finding summaries, they may be factored as a component in "human error" around operating procedures.

Also of note, most of the West-coast river incidents have occurred in relatively calm wind and "sea state" conditions, and many occurred while attempting to transit difficult river sections at slack tide conditions.

2.5 State of the Literature

Research literature was scanned for any tug and barge-related academic work from the 1980s forward. This excluded first-principles formulations (discussed in subsequent sections of this report), and is intended to serve as a check for existing bodies of work in tug and barge powering and manoeuvring simulation. Some of these and their methods and findings are presented here.

Bernitsas and Chung (1990)[18] present a model for simulation of towing or mooring of a body with two towing lines. A three-dimensional manoeuvring model is formulated in a standard way, along with cable dynamics modelled using catenary and strain modeling. Four specific tows are evaluated using coefficients gathered from a previous study.

Sisong and Genyu (1996)[19] present a model for a single towing tug and tow scenario with a manouevring model (using Clarke and Inoue empirically-determined coefficients), zero extension catenary model for the tow line, along with the addition of wind and Froude-Krylov wave forces. They use an autopilot-driven tug for towing vessel motions. They compare the tow in various conditions in simulation to a model tank test. The behaviours diverge slightly due to unknown confidence in the manouevering coefficients and the scale modeling of the towline.

MacSween (2011)[20] attempts to use field measurements of GPS and INS to produce lumped dynamic models for simulation. They conclude that better measurements of towline length and end-point motion would be required as uncertainty creates large differences

Fitriadhy el al. (2013)[21] present a model for assessing course stability of stable and unstable towed ships in wind. A lumped mass model is used for towline modeling. A non-linear formulation for manouevring is implemented, then linearized (with good agreement) to incorporate the effects of wind. Coefficients are obtained from model scale testing experiments and used in simulation. Fitriadhy and Hironori (2016)[22] later extend this work to assess turning ability of various tug and barge configurations.

Sun et al. (2018)[23] present a hydrodynamic model of a towed bridle system (tug-tow-barge) using a six degree-of-freedom manouevering model and finite difference model for the bridle. Good comparison between simulation and experimentation is shown.

Moctar et al. (2019)[24] present a wide range of RANS computational work performed in StarCCM+. Several vessels and barges were simulated to determine lateral and longitudinal drag coefficients (both hydrodynamic and aerodynamic). They show good agreement with more general methods.

Raman-Nair et al. (2014)[25] present the basis for a single body three degree-of-freedom manouevring model with wind and current. This work was performed at OCRE and is adapted with knowledge of the aforementioned studies to the cable-coupled tug and barge model presented in this work.

2.6 Empirical Bollard Pull Estimation

Transport Canada's TP 11960E[3] provides the following semi-empirical formula for estimating required tug powering as a function of barge particulars:

$$BP = \left(\frac{\Delta^{2/3} V^3}{120 \times 60} + 0.06 B \times D_1 \right) \times K \tag{1}$$

where:

BP: required bollard pull (tons)
Δ: displacement of towed vessel (tons)
V: tow speed (knots)
B: breadth of towed vessel (metres)
D_1: depth of the exposed transverse section of the towed vessel (metres)
K: a factor that reflects potential weather and sea conditions

It is suggested that for tows of 6 knots, an examination of Canadian coastal towing practices shows a good safety record with a K value between 0.5 and 2.0 (from protected water conditions to exposed coastal tows).

The standard mentions that this formula is “widely used", but provides no reference for its origins or its choice of fixed parameters. Effort was undertaken to determine its origin. The Shipowners' Club towing guide[11] explicitly cites TP 11960E (1995) for this formula. However, they have altered the upper bound value of the K parameter to 3.0 for exposed coastal tows. Clydeport (Scotland) also references the Canadian standard in their towing regulations and port Towage Notification Form[26]. A bollard pull calculation document produced by the now-defunct Association of Hanseatic Marine Underwriters[27] presents several uncited empirical formulas for bollard pull calculation. This equation is presented there in a modified format (with 7200 in the denominator instead of 120×60) and a K ranging from 3.0 to 8.0.

A direct sourcing of its origin could not be found at this time. However, the first term of the formula takes the form:

$$P = \frac{\Delta^{2/3} V^3}{A_c}$$

which is known as Admiralty's Law[28]. This is an empirical equation commonly used to estimate total horsepower of ship-shaped vessels of varying Froude numbers, where the Admiralty Coefficient A_c is typically a number ranging from 350 to 600 depending on the ship length and maximum speed. It is likely, then, that the originator chose a value of 120 for barges. This formula was created circa 1840[29], and originated from early practice of estimating power requirements for new ships by observing the horsepower-per-ton numbers of existing steam ships. This formula is particularly useful if ships of moderate speed have hull and engine characteristics that are similar.

A common rule-of-thumb for estimating bollard pull from engine horsepower is to assume one ton of pull for every 100 horsepower. Since many tugboat thrusters are ducted, the pull can be expected to be higher. This is likely the origin of the divisor of 60 - a term to convert horsepower to tons of bollard pull.

While the Admiralty's Law calculation accounts for the drag through water, the second part of the equation accounts for the longitudinal wind resistance of the above-water portion of the vessel. This is typically formulated as a cross-flow drag in the form of:

$$R_{\text{wind}} = \frac{1}{2}\rho A C_d V^2$$

Assuming that a similar approach was taken here, the value of 0.06 in Equation 1 accounts for the lumped effect of everything other than the cross-sectional area (calculating with a single wind speed and drag coefficient).

The K multiplier likely takes into account safety factors as well as average forces present from higher sea states.

As this is the only available quantitative guidance given to Canadian operators for tow vessel capacity for a given tow, and since it has been recommended for adoption beyond the scope of TP 11960E, it is used throughout this report as a basis for comparison.

2.7 Industry Survey

2.7.1 Particulars of tugs and barges in the VFPA region

In December of 2020, a survey document was prepared between NRC-OCRE and VFPA. VFPA made an open call to towing operators and other relevant parties to discuss the current state of practice in the industry and to gather technical information for OCRE as part of its powering and simulation work. Specifically, OCRE looked for any information pertaining to:

1. Tugboat fleet particulars, including
    - Length at WL
    - Beam at WL
    - Draught
    - Displacement
    - Propulsion arrangement (including number and types of propellers, whether they are ducted, are they fixed with rudders or aimuthing, etc.)
    - Installed power
    - Bollard pull
    - Free-running speed
    - Any photos/drawings/supporting external information

  - Any existing guidelines for choosing a tug for a given load

2. Towline particulars, including
    - Bridle configurations
    - Towpoint placement
    - Use of winches / emergency release
    - Tow line type (e.g., what kind of cable, material, strength rating, etc.)
    - Tow length(s), and how that would be selected / varied.
3. Barge particulars, includeing
    - Length
    - Beam
    - Draught
    - Displacement (light and loaded)
    - Skeg arrangements (if any)
    - Windage (typical and extreme)
    - Any other relevant information

2.7.2 Interviews

In February 2021, VFPA and OCRE conducted interviews with respondents of VFPA's open call, including Seaspan Marine, North Arm Transportation, Ledcor Marine Services, Harken Towing, and Capilano Maritime Design Ltd. These respondents provided much of the above information on their entire fleets and designs. In many cases, respondents provided technical drawings and other advice to OCRE staff. This process provided invaluable input into the work performed.

In the interest of privacy, details of these interviews will not be reproduced here. However, engaging discussion and commentary was provided throughout the process, and some of those points (particularly those that emerged often) are presented here for interest.

- Most (if not all) tugboat operators in the region have decades of experience with their tows and the river. Practical knowledge transfer occurs at all levels, especially amongst older, well-established operators.

- Most tugboat operators do not follow a formal process for determining which tugboat is required for a given barge load. Many operators own their own barges, or work regular seasonal contracts with barge-owning companies. Operators and masters in this position are typically inherently aware of which tug and barge combinations are admissible.

- Some operators have expressed concern over some smaller, older tugboats operating in the area. Many feel that the stability of some of these tugs is inherently low (having low freeboard and rounded hulls). Some have also expressed concern over the recent additions of high-powered engines to some of these boats as they attempt to increase their bollard pull capability, and that they may be inadvertently worsening any stability problems by adding weight and increasing the potential horizontal tow pull force. One participant indicated that many “modern" tugboats are designed to maintain stability at their maximum tow pull force when girded at ninety degrees to the tow.

- Some operators have expressed concern over existing Transport Canada regulations (including manning and inspection requirements for different sized vessels), and that these may be compromising safety of operations of small tugboat operators.
- Some participants have expressed concern over this work itself and how it may impact their operations.

2.8 Hydrographical Points of Interest

Bridge Name	Location	Lat	Long
First Narrows Bridge, Lions Gate Bridge	Port of Vancouver	49°18’55"N	123°08’19"W
Iron Workers Memorial Bridge	Port of Vancouver	49°17’42"N	123°01’34"W
Second Narrows Rail Bridge	Port of Vancouver	49°17’41"N	123°01’28"W
No. 2 Road Bridge	Middle Arm FR	49°10’35"N	123°09’23"W
Dinsmore Bridge	Middle Arm FR	49°10’43"N	123°08’55"W
Moray Bridge	Middle Arm FR	49°11’30"N	123°08’13"W
Sea Island Connector	Middle Arm FR	49°11’32"N	123°08’20"W
Canada Line Bridge	Middle Arm FR	49°11’44"N	123°08’06"W
Westham Island Bridge	South Arm FR	49°04’49"N	123°07’43"W
Arthur Lang Bridge	North Arm FR	49°11’57"N	123°08’09"W
Oak Street bridge	North Arm FR	49°11’59"N	123°07’31"W
Canada Line Bridge	North Arm FR	49°12’10"N	123°07’04"W
Knight Street Bridge	North Span	49°12’29"N	123°04’38"W
Knight Street Bridge	South Span	49°12’07"N	123°04’39"W
CN Rail Bridge	North Arm FR	49°10’58"N	122°59’16"W
Queensborough Road Bridge	North Arm FR	49°11’46"N	122°56’48"W
Queensborough Rail Bridge	North Arm FR	49°11’50"N	122°55’23"W
Fraser River Bridge	Annacis Channel FR	49°10’28"N	122°57’28"W
Annacis Channel Bridge	Annacis Channel FR	49°10’33"N	122°57’19"W
Annacis Island Swing Bridge	Annacis Channel FR	46°11’09"N	122°55’55"W
Alex Fraser Bridge	South Arm FR	49°09’35"N	122°56’34"W
Sky Bridge	Fraser River	49°12’19"N	122°53’46"W
Patullo Bridge	Fraser River	49°12’26"N	122°53’38"W
New Westminster Rail Bridge	Fraser River	49°12’32"N	122°53’79"W
Port Mann Bridge	Fraser River	49°13’11"N	122°48’46"W
Pitt River Rail Bridge	Pitt River	49°14’42"N	122°44’01"W
Pitt River Road Bridge	Pitt River	49°14’52"N	122°49’45"W
Golden Ears Bridge	Fraser River	49°11’46"N	122°39’56"W

Table 1: Summary of bridges in Fraser River / Port of Vancouver region

Many of the tug and barge towing incidents which have occurred in the VFPA region have involved allisions with or near bridges. Damage to bridge infrastructure in this region have the potential disrupt major rail and road passages and thus poses concern to the port authority and other stakeholders. OCRE has compiled in Table 1 a listing of 28 bridges of interest (some of which may have been removed since their compilation). VFPA has provided nine locations of concern. These are presented in bold type in the table.

These points of interest provide information regarding the spatial constraints in which tug and barge manoeuvres are performed.

In April 2021, VFPA provided hydrographical current data to OCRE on these points of interest. This data includes the maximum predicted river currents for various prediction zones in both peak flooding and ebbing conditions. These are presented in Table 2. Bold type denotes locations corresponding to those of concern listed above.

Arm	Location Name	Bridges	Flood	Ebb
South Arm				
	Sand Heads		3.1	8.6
	Sand Heads Reach		4.8	11.3
	Steveston Bend		5.2	11.0
	Steveston Cut		3.3	7.0
	Fraser Wharves		1.8	3.7
	Tilbury		2.0	4.0
	St Mungo	Alex Fraser Hwy	1.6	3.2
	Fraser Surrey Docks		1.8	3.5
	New West	Skybridge. Pattullo Hwy. New West Rail	3.1	5.8
	Annacis Channel	Annacis Swing Bridge	1.2	2.4
Main Arm				
	Port Mann	Port Mann	3.3	5.9
	Port Coquitlam		3.2	2.7
	Parsons Channel	Golden Ears Hwy Bridge	1.1	3.6
	Port Hammond	Golden Ears Hwy Bridge	2.0	6.2
	Albion Ferry		1.7	5.1
	Mission	Mission Hwy. Mission Rail	0.9	5.1
	Chilliwack		-2.6	5.2
North Arm				
	Point Grey		1.8	3.8
	Wood Island		2.4	5.4
	Dinsmore	Canada Line	1.8	2.9
	Oak Street	Oak Streeet. Knight Street. Canada Line	1.9	3.5
	Mitichel Channel		1.2	2.4
	Big Bend	CN Rail Bridge	3.2	5.4
	Queensborough	Queensborough Rail Bridge	1.9	4.4
Pitt River				
	Pitt River		1.4	1.0
	Fenton Slough	Pitt River Hwy. Pitt River Rail	1.8	1.4
Burrard Inlet				
	First Narrows	Lions Gate Hwy Bridge	5.9	5.9
	Second Narrows	Ironworkers Hwy. Second Narrows CN Rail	4.8	6.6

Table 2: Maximum flood and ebb current predictions in regions of interest

3 Powering Estimation

Powering requirements are typically assessed at a range of steady-state speeds over the operational envelope of a vessel. Total hull resistance is found as[2]

$$R_{\text{Total}} = R_{\text{Hydrodynamic}} + R_{\text{Aerodynamic}} + R_{\text{Wave}}$$

or the summation of hydrodynamic hull resistance, wind resistance and wave resistance (wave-making and wave-induced forces).

To achieve any given speed, the vessel must produce a net propulsive force equal to its total resistance at that speed.

Utilizing the fleet listings of each operator that participated in VFPA's open call, a list of tugs and barges was compiled along with their particulars provided in the survey. Tug resistance and propulsion as well as barge tow resistance was estimated using these particulars and naval architectural tools.

Tug and barge combinations are assessed together to determine powering overheads at given towspeeds. A specific example is given as a case study to demonstrate the methodology applied.

Finally, effort is made to reduce these specific estimations into a more general set of formulas. The results of these are compared against the empirical formula presented in TP 11960E[3] and Equation 1.

3.1 Case Study: Towing a Chip Barge

3.1.1 Seaspan 550

Figure 1: Seaspan 550 Chip Barge, obtained from MarineTraffic.com

The Seaspan 550 is one of the larger chip barges in use in Seaspan's fleet. It is representative of typical barge hull forms that are neither wholly ship-shaped or box-shaped.

Particulars of this barge are presented in Table 3.

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[2] A simplified representation is presented here.

Parameter	Value
LWL	64.62 m
Beam	15.85 m
Draught	3.29 m
Air Draught	10.5 m
C_b	0.850123(est)
Displacement	2371 tons

Table 3: Particulars of the Seaspan 550 chip barge (laden)

Resistance is calculated using HydroComp Inc.'s NavCad[30] software. This software is widely used within industry and has shown good agreement with first-principles work performed at OCRE and within the research community. The methodology used is based on ITTC-78 (CT), calculating residuary and viscous resistance. Figure 2 illustrates the additional parameters of interest over general ship particulars required for resistance estimation of a rectangular barge. These typically have a raked bow entrance (although they may not) and a stern run. NavCad provides a special prediction tool for these barge shapes which corrects for bow separation and pressure drag, as well as stern drag. This methodology is based on a regression of over 20 box barge model tests with different bow and stern configurations, and has been shown to produce results more accurate than standard Holtrop estimation methods[3]. Figures 3 and 4 show typical input and calculation procedure using this tool.

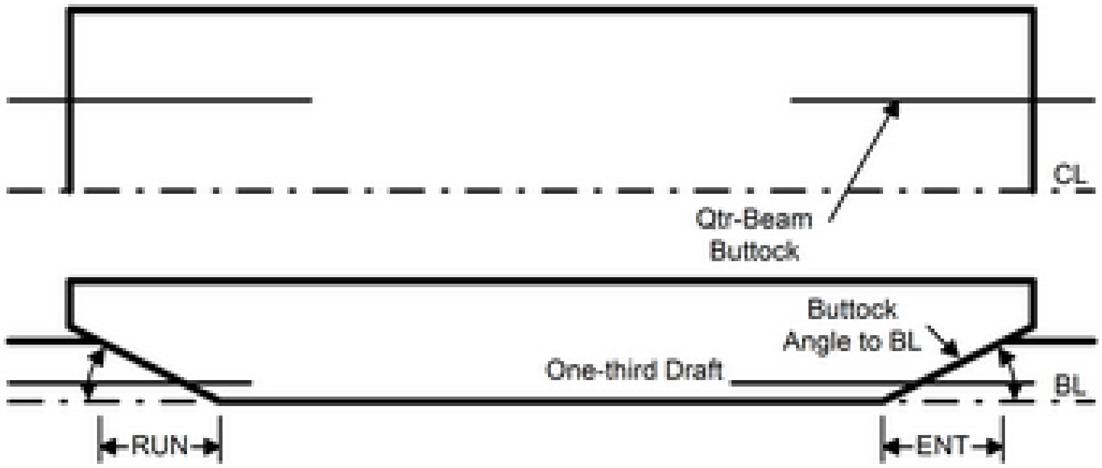

Figure 2: Additional parameters of significance for rectangular barge shape resistance prediction

Wind is evaluated separately. Combinations of Taylor, Blendermann and Fujiwara wind estimations were evaluated, all producing similar results. A 10% margin is applied for hull drag, and 5% appendage drag is assumed. A Schlichting model is applied for shallow water/channel effect corrections.

Figure 5 shows the calculated resistance of this barge example, along with the results of a cross-flow

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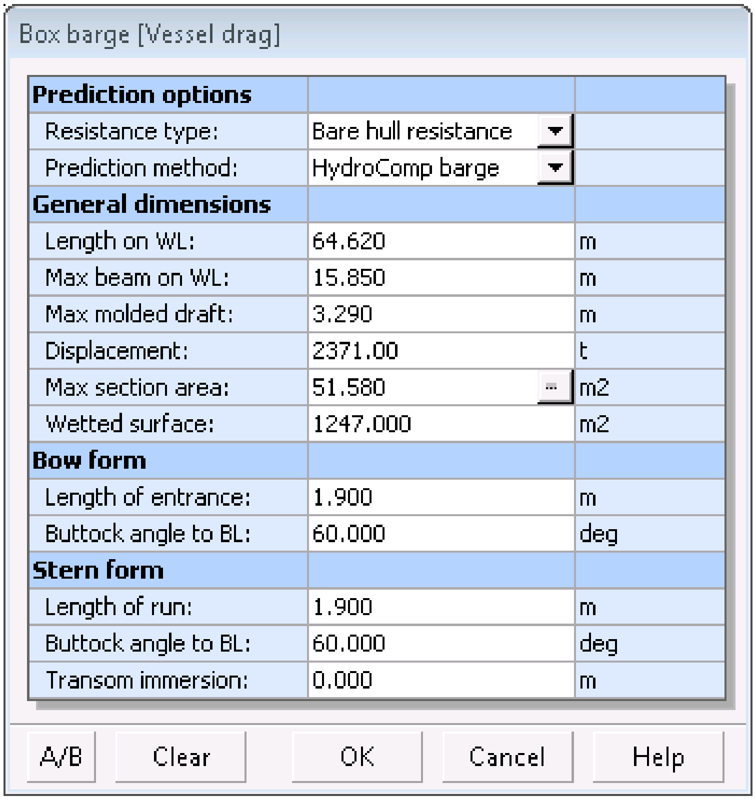
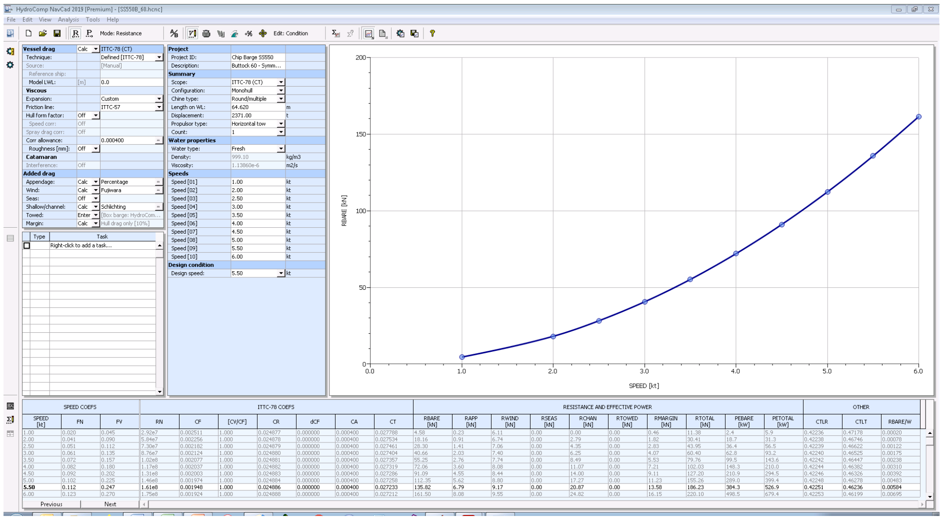
[3] Holtrop estimation still holds best for ship-type barges.



Prediction options		
Resistance type:	Bare hull resistance	
Prediction method:	HydroComp barge	
General dimensions		
Length on WL:	64.620	m
Max beam on WL:	15.850	m
Max molded draft:	3.290	m
Displacement:	2371.00	t
Max section area:	51.580	m2
Wetted surface:	1247.000	m2
Bow form		
Length of entrance:	1.900	m
Buttock angle to BL:	60.000	deg
Stern form		
Length of run:	1.900	m
Buttock angle to BL:	60.000	deg
Transom immersion:	0.000	m

Figure 3: Entering parameters for HydroComp barge special predictions



Vessel drag	Calc	ITTC-78 (CT)
Technique:		Defined [ITTC-78]
Source:		[Manual]
Reference ship:		
Model LWL:	[m]	0.0
Viscous		
Expansion:		Custom
Friction line:		ITTC-57
Hull form factor:	Off	
Speed corr:	Off	
Spray drag corr:	Off	
Corr allowance:		0.000400
Roughness [mm]:	Off	
Catamaran		
Interference:	Off	
Added drag		
Appendage:	Calc	Percentage
Wind:	Calc	Fujiwara
Seas:	Off	
Shallow/channel:	Calc	Schlichting
Towed:	Enter	[Box barge: HydroCom…
Margin:	Calc	Hull drag only [10%]

	Type	Task
☐		Right-click to add a task…

Project		
Project ID:	Chip Barge SS550	
Description:	Buttock 60 - Symm…	
Summary		
Scope:	ITTC-78 (CT)	
Configuration:	Monohull	
Chine type:	Round/multiple	
Length on WL:	64.620	m
Displacement:	2371.00	t
Propulsor type:	Horizontal tow	
Count:	1	
Water properties		
Water type:	Fresh	
Density:	999.10	kg/m3
Viscosity:	1.13860e-6	m2/s
Speeds		
Speed [01]	1.00	kt
Speed [02]	2.00	kt
Speed [03]	2.50	kt
Speed [04]	3.00	kt
Speed [05]	3.50	kt
Speed [06]	4.00	kt
Speed [07]	4.50	kt
Speed [08]	5.00	kt
Speed [09]	5.50	kt
Speed [10]	6.00	kt
Design condition		
Design speed:	5.50	kt

SPEED COEFS			ITTC-78 COEFS						
SPEED [kt]	FN	FV	RN	CF	[CV/CF]	CR	dCF	CA	CT
1.00	0.020	0.045	2.92e7	0.002511	1.000	0.024877	0.000000	0.000400	0.027788
2.00	0.041	0.090	5.84e7	0.002256	1.000	0.024878	0.000000	0.000400	0.027534
2.50	0.051	0.112	7.30e7	0.002182	1.000	0.024879	0.000000	0.000400	0.027461
3.00	0.061	0.135	8.76e7	0.002124	1.000	0.024880	0.000000	0.000400	0.027404
3.50	0.072	0.157	1.02e8	0.002077	1.000	0.024881	0.000000	0.000400	0.027357
4.00	0.082	0.180	1.17e8	0.002037	1.000	0.024882	0.000000	0.000400	0.027319
4.50	0.092	0.202	1.31e8	0.002003	1.000	0.024883	0.000000	0.000400	0.027286
5.00	0.102	0.225	1.46e8	0.001974	1.000	0.024884	0.000000	0.000400	0.027258
5.50	0.112	0.247	1.61e8	0.001948	1.000	0.024886	0.000000	0.000400	0.027233
6.00	0.123	0.270	1.75e8	0.001924	1.000	0.024888	0.000000	0.000400	0.027212

	RESISTANCE AND EFFECTIVE POWER										OTHER		
SPEED [kt]	RBARE [kN]	RAPP [kN]	RWIND [kN]	RSEAS [kN]	RCHAN [kN]	RTOWED [kN]	RMARGIN [kN]	RTOTAL [kN]	PEBARE [kW]	PETOTAL [kW]	CTLR	CTLT	RBARE/W
1.00	4.58	0.23	6.11	0.00	0.00	0.00	0.46	11.38	2.4	5.9	0.42236	0.47178	0.00020
2.00	18.16	0.91	6.74	0.00	2.79	0.00	1.82	30.41	18.7	31.3	0.42238	0.46746	0.00078
2.50	28.30	1.41	7.06	0.00	4.35	0.00	2.83	43.95	36.4	56.5	0.42239	0.46622	0.00122
3.00	40.66	2.03	7.40	0.00	6.25	0.00	4.07	60.40	62.8	93.2	0.42240	0.46525	0.00175
3.50	55.25	2.76	7.74	0.00	8.49	0.00	5.53	79.76	99.5	143.6	0.42242	0.46447	0.00238
4.00	72.06	3.60	8.08	0.00	11.07	0.00	7.21	102.03	148.3	210.0	0.42244	0.46382	0.00310
4.50	91.09	4.55	8.44	0.00	14.00	0.00	9.11	127.20	210.9	294.5	0.42246	0.46326	0.00392
5.00	112.35	5.62	8.80	0.00	17.27	0.00	11.23	155.26	289.0	399.4	0.42248	0.46278	0.00483
5.50	135.82	6.79	9.17	0.00	20.87	0.00	13.58	186.23	384.3	526.9	0.42251	0.46236	0.00584
6.00	161.50	8.08	9.55	0.00	24.82	0.00	16.15	220.10	498.5	679.4	0.42253	0.46199	0.00695

Figure 4: Typical NavCad resistance estimation window

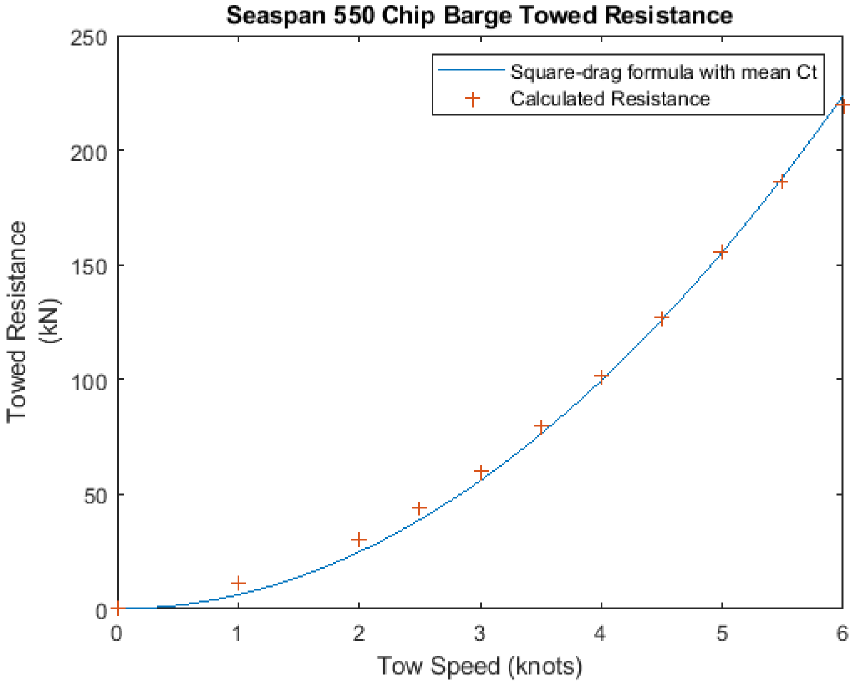


Figure 5: Calculated towed resistance and square-drag formula

drag model produced by calculating an average total drag coefficient C_t from the calculated resistance. This simple parameter model lumps the multiple drag sources together and shows good agreement with the results.

3.1.2 Seaspan tugboats

Three tugboats encompassing a range of Seaspan's fleet are chosen here for interest: *Cates 20*, *Raider* (Figure 6), and *Royal*. Simulation particulars for each are listed in Tables 4 though 6. Some propulsion parameters are estimated from best available knowledge.

Parameter	Value
LWL	12.273 m
Beam	4.719 m
Draught	0.946 m
Displacement	31.00 tons
Propulsor Count	2
Blade Count	4
Prop Diameter	1117.5 mm
P/D	1.25
Engine Power	261.0 kW (350 horsepower)

Table 4: Particulars and simulation parameters of *Cates 20*

Figure 6: Seaspan Raider, obtained from MarineTraffic.com

Parameter	Value
LWL	32.231 m
Beam	10.420 m
Draught	3.187 m
Displacement	573.18 tons
Propulsor Count	2
Blade Count	4
Prop Diameter	2400 mm
P/D	0.9248
Engine Power	1342.3 kW (1800 horsepower)

Table 5: Particulars and simulation parameters of *Raider*

Parameter	Value
LWL	39.021 m
Beam	11.740 m
Draught	3.485 m
Displacement	861.06 tons
Propulsor Count	2
Blade Count	4
Prop Diameter	3048 mm
P/D	1.049
Engine Power	2311.7 kW (3100 horsepower)

Table 6: Particulars and simulation parameters of *Royal*

Details of resistance and propulsion prediction can be seen in the NavCad output summary files for these three tugboats in Appendix A.

3.1.3 Overhead power analysis

Combining the tug and barge resistance numbers allows us to make predictions about the available overhead towpull at any given towing speed. Required propulsive force to meet resistance at a given speed is used with the propulsion modeling to determine the remaining propulsive force. This is important to quantify as it determines the envelope of propulsion available to helm for manouevering the barge. If little overhead is available, manouevers (such as course changes in a girding scenario) will be slow. Figure 7 shows the available towpull from Cates 20 as a function of forward speed with the loaded Seaspan 550 attached. From the propulsion calculations performed (available in Appendix A), Cates 20 has a bollard pull of around 87 kN. While theoretically this combination could make approximately 3 knots of way, there would be very little overhead.

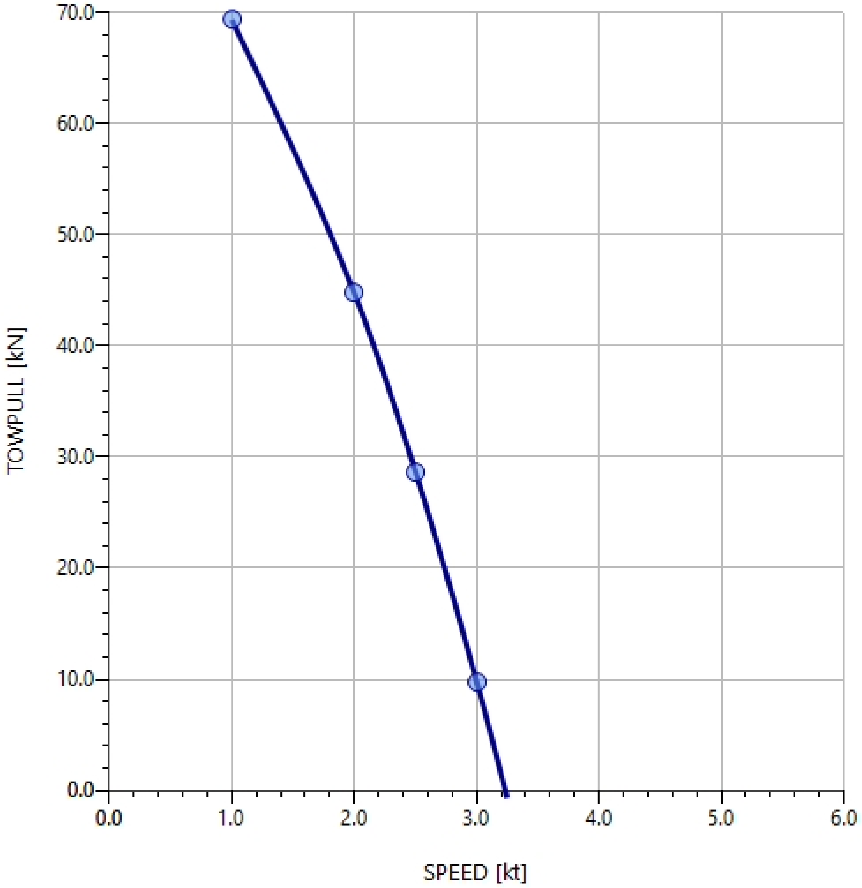


Figure 7: Propulsion overhead availability as a function of forward speed (Cates 20)

Figure 8 shows the available towpull from Raider as a function of forward speed with the loaded Seaspan 550 attached. From the propulsion calculations performed (available in Appendix A), Raider has a bollard pull of around 465 kN. It can be seen here that at 3 knots of way, Raider has over 35 tons of towpull margin. Even at 6 knots there are approximately 10 tons of margin available. It is clear that Raider would be much more capable of manouevering the loaded barge compared against Cates 20.

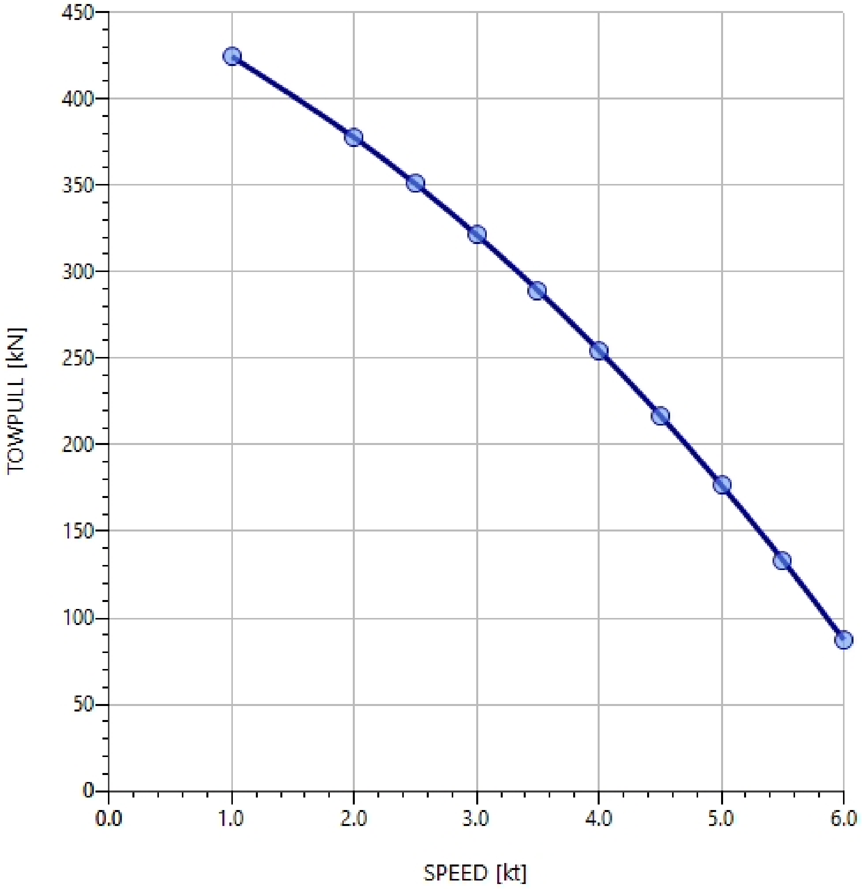


Figure 8: Propulsion overhead availability as a function of forward speed (Raider

Figure 9 shows the available towpull from Royal as a function of forward speed with the loaded Seaspan 550 attached. From the propulsion calculations performed (available in Appendix A), Raider has a bollard pull of around 910 kN. At 6 knots of way, Royal would have over 45 tons of margin.

This methodology can easily be evaluated for a large number of tug and barge combinations. Towpull overhead numbers can be used in numerical simulation as applied thrust limits for course change manouevers. Examples of this are shown later in the report.

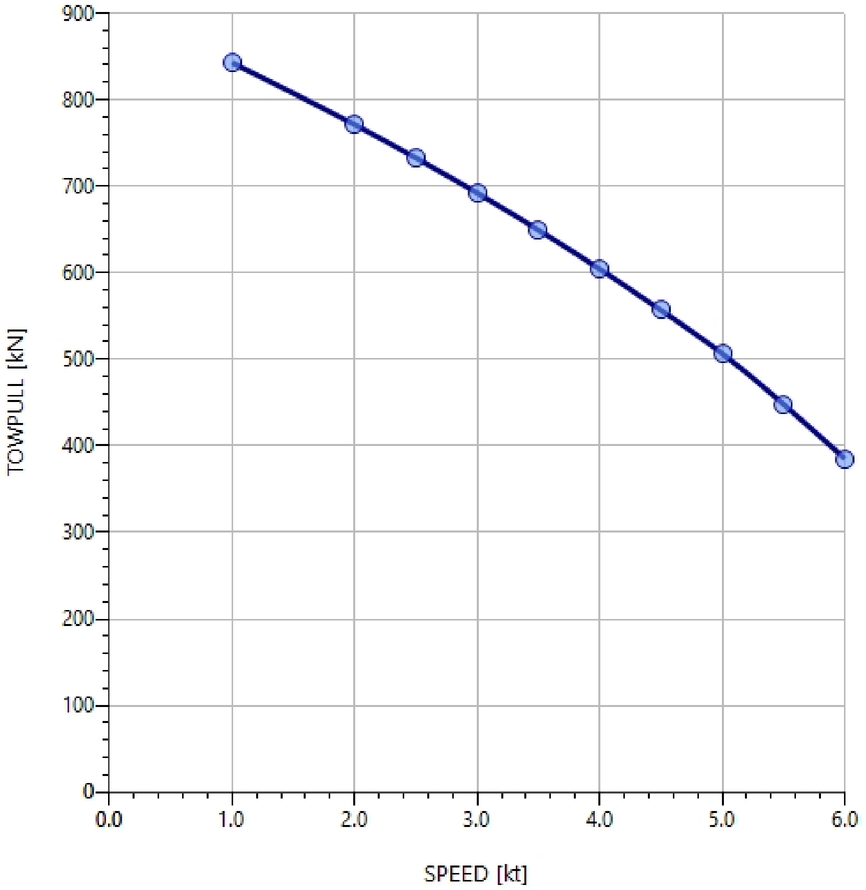


Figure 9: Propulsion overhead availability as a function of forward speed (Royal)

3.2 Generalizing the resistance prediction

Upon analysis of several barge forms, the following formulation was created:

$$R_{\text{Barge}} = R_{\text{Bare}} + R_{\text{App}} + R_{\text{Chan}} + R_{\text{Wind}} \tag{2}$$

where R_{Bare} is the bare hull barge resistance in Newtons (N). This resistance, as a function of forward speed, can be approximated by:

$$R_{\text{Bare}} = \frac{1}{2}\rho_{\text{w}}(B_{\text{hull}} \times T_{\text{hull}})C_{hull}v^2 \tag{3}$$

where ρ_{w} is the density of water in kg/m^3 (assumed to be 999.10 in fresh water), B is the maximum beam below the waterline in meters, T is the draught in meters, C_{hull} is the hull drag coefficient, and v is the speed of water over the hull in m/s. The drag coefficient C_{hull} is evaluated for each forward speed (using Computational Fluid Dynamics, physical scale model testing, or in this case, validated numerical tools such as NavCad). During this investigation, it was determined that these values do not change significantly for barges as speed increases, indicating that this is a suitable formulation. Values for C_{hull} are provided in Table 7.

R_{App} is the added hull appendage resistance, assumed to be 5% of hull drag ($R_{\text{App}} = 0.05 \times R_{\text{Bare}}$). R_{Chan} is a shallow water / channel drag correction factor. This was evaluated in NavCad using Schlichting correction factors, and was found to be approximately 10% of hull drag at a $10m$ water depth ($R_{\text{Chan}} = 0.10 \times R_{\text{Bare}}$)).

R_{Wind} is the wind resistance of the transverse area of the hull and superstructure (and exposed cargo) above the waterline and is given by:

$$R_{\text{Wind}} = \frac{1}{2}\rho_{\text{a}}(B_{\text{sup}} \times T_{\text{sup}})C_{sup}v^2 \tag{4}$$

where ρ_{a} is the density of air in kg/m^3 (assumed to be 1.225), B is the maximum beam above the waterline in meters, T_{sup} is the height of the exposed hull and superstructure above the waterline in meters, C_{sup} is the wind drag coefficient, and v is the speed of air over the superstructure in m/s. A typical value for C_{sup} is approximately 0.95.

Typical resistance calculations for powering estimation purposes would also include added wave resistance and design margin components. Given the relatively low sea states of the VFPA region, and thus relatively low contribution to added resistance, these are neglected here. Typical design margins would include an additional 10% to bare hull resistance. However, given the addition of appendage and shallow water corrections, this component is also neglected.

With these simplifications, the barge resistance formula in fresh water can be simplified to:

$$R_{\text{Barge}} = 574.5(B_{\text{hull}} \times T_{\text{hull}})C_{hull}v_{\text{water}}^2 + 0.6125(B_{\text{sup}} \times T_{\text{sup}})C_{sup}v_{\text{wind}}^2 \tag{5}$$

Equation 5 can be converted to tons by multiplying the result by $0.000102\frac{t}{N}$.

3.2.1 Calculation of drag coefficients

Three generic barge shapes are considered here: ship-shaped, standard, and box-shaped. Ranges of hull drag coefficients for these barges are given in Table 7.

Barge Type	**Drag Coefficient** (m/s)	**Drag Coefficient** (knots)
Ship-shaped	0.10-0.35	0.0265-0.0926
Standard	0.25-0.98	0.0662-0.2594
Box-shaped	1.0	0.2646

Table 7: Ranges of hull drag coefficients

Ship-shaped barges have the lowest hull drag. Typical drag coefficient values observed in simulation fall around 0.16 for typical ship-shape barge hull forms with no transom immersion, and up to 0.35 or higher for full transom immersion.

Standard barges are the typical barges observed in the Fraser River region. Typical drag coefficient values observed in simulation fall around 0.45. A major factor contributing to varying drag coefficient values is the buttock angle of the barge, shown in Figure 10. Here, a standard barge shape was altered in buttock angle only, and drag coefficients were averaged for each change in configuration.

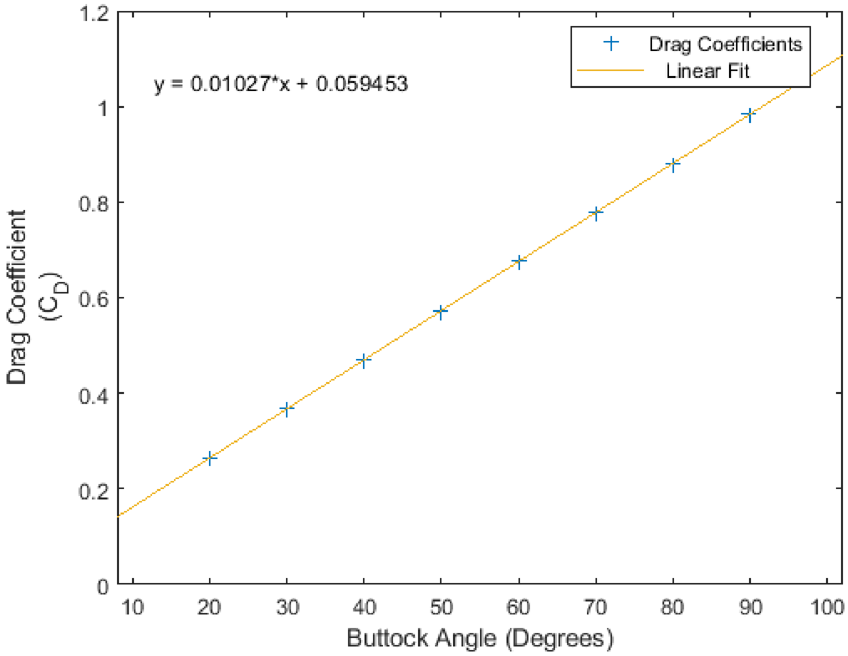


Figure 10: Effect of buttock angle on drag parameters

This shows good agreement with a linear trend, and is given as Equation 6[4] as a function of buttock angle θ_b.

$$C_{\text{standard hull}} = 0.0103 \times \theta_\text{b} + 0.0595 \tag{6}$$

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[4] The suitability of this equation for all barge shapes is unknown, but given here as an example. A value of 0.45 was observed as typical.

Box-shape barges have a coefficient of 1.0, and can be used as an “upper limit" for minimum powering when determining the minimum powering requirements for unknown hull forms.

Equation 5 can be used with current and wind speed given in either m/s (as has been presented thus far) or in knots. If knots are the desired input unit, the drag coefficients in m/s must be converted by dividing by the square of the conversion factor of knots to meters-per-second, or approximately 3.7786. For example, converting a C_{hull} of 0.48 to knots would result in a drag coefficient of 0.12, and converting a C_{sup} of 0.95 to knots would result in a drag coefficient of 0.251.

The Seaspan 550 barge is revisited here for illustration of Equation 5. Figure 11 shows the calculated resistance of the barge at various forward speeds, denoted by ‘+’ symbols as before (with no additional 10% margin added). Equation 5 is plotted in red using the “typical" drag coefficients stated above for superstructure wind drag and a value of 0.68 for hull drag based on a $60°$ buttock angle (assuming zero environmental current and wind speed).

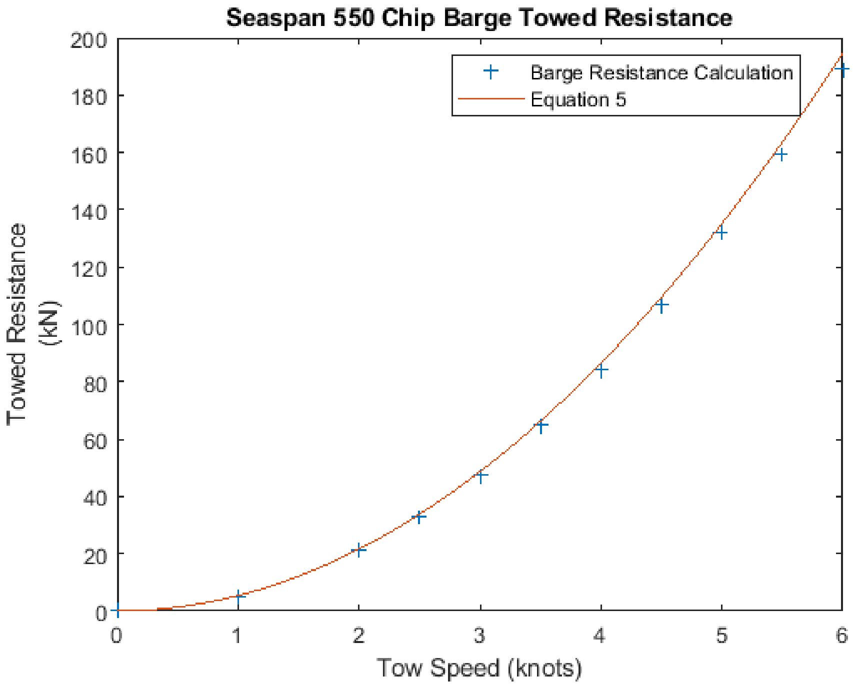

Figure 11: Calculated towed resistance compared with Equation 5

3.2.2 Minimum required bollard pull

It is recommended here that any tug and barge combination be capable of performing station-keeping against the worst-case current and wind predictions (assuming they are acting in the same direction) along their planned route. This constitutes a minimum powering requirement in that:

- it is assumed that the tug and barge are able to be aligned with the worst-case environmental condition so as to minimize the incident drag force,
- it is assumed that the helm is able to act in advance to anticipate and correct for changes in momentum

of the tug and its tow (in a given river current profile) to avoid a girding scenario, and,

- is is assumed that, in station-keeping, the bollard pull of the tug is the maximum available propulsive force to counter the environment.

Thus, *the minimum bollard pull requirement for a given barge can be found by calculating the station-keeping resistance of Equation 5 in the worst-case prediction of encountered current and wind speeds*. It is recommended that an additional 10% margin be added to this to compensate for the environmental drag experienced by the tug. If bollard pull certifications are not available, an accepted method of estimation should be used to calculate the bollard pull force from engine power[5].

As Equation 1 is given in terms of required bollard pull as a function of forward speed in knots, Equation 5 is re-stated here to match equivalent units (with an additional 10% margin to account for tug resistance):

$$BP = 1.122 \times 10^{-4} \left(574.5(B_{\text{hull}} \times T_{\text{hull}})C_{hull}V_{\text{water}}^2 + 0.6125(B_{\text{sup}} \times T_{\text{sup}})C_{sup}V_{\text{wind}}^2\right) \tag{7}$$

where:

BP: required bollard pull (tons)
B_{hull}: max breadth of towed vessel hull (metres)
T_{hull}: max draught of towed vessel hull (metres)
C_{hull}: hull drag coefficient (0.18 typical, see discussion)
V_{water}: maximum encountered current speed (knots)
B_{sup}: max breadth of towed vessel superstructure (metres)
T_{sup}: max height of towed vessel hull (metres)
C_{sup}: superstructure drag coefficient (0.251 typical, see discussion)
V_{wind}: Maximum encountered wind speed (knots)

This minimum bollard pull requirement is not suitable for scenarios when loss of controlled tow has occurred.

3.3 Suitability for minimum power estimation

A selection of twenty barges and their minimum bollard pull requirements as calculated by the simplified drag method previously shown is presented here. The parameters of these barges were used to estimate a range of typical barge L/B, L/T, block coefficients and relative superstructure windages.

Figures 12 through 17 illustrate the bollard pull predictions from the empirical formula presented in TP 11960E (and in Equation 1) in the shaded region. The lower bound of the shaded region is set by $K = 0.5$, while the upper bound is set by $K = 1.5$ ($K = 1.0$ illustrated by the dashed line). Values of above-water area are selected by the mean of L/B and D_1/B values in recorded in the compilation of survey data.

Minimum bollard pull calculations for individual barge cases as calculated by the simplified formula are denoted by $+$ symbols. It can be seen that for speeds under 3 knots, the empirical formula tends to overestimate the minimum power requirements. However, as tow speeds increase, the empirical formula tends to bound the actual calculations well. Of note, however, is that as the Admiralty's Law component of

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[5] A common estimation method, previously discussed, is to assume 1 ton of bollard pull per 100 horsepower, with a 1% reduction in power per year from original rating after 10 years. For ducted propellers, this number can be has high as 1.2 to 1.4 tons per 100 horsepower.

the empirical formula becomes more dominant over the wind component, the range of power uncertainty goes up (as illustrated by the growing range in Figure 17).

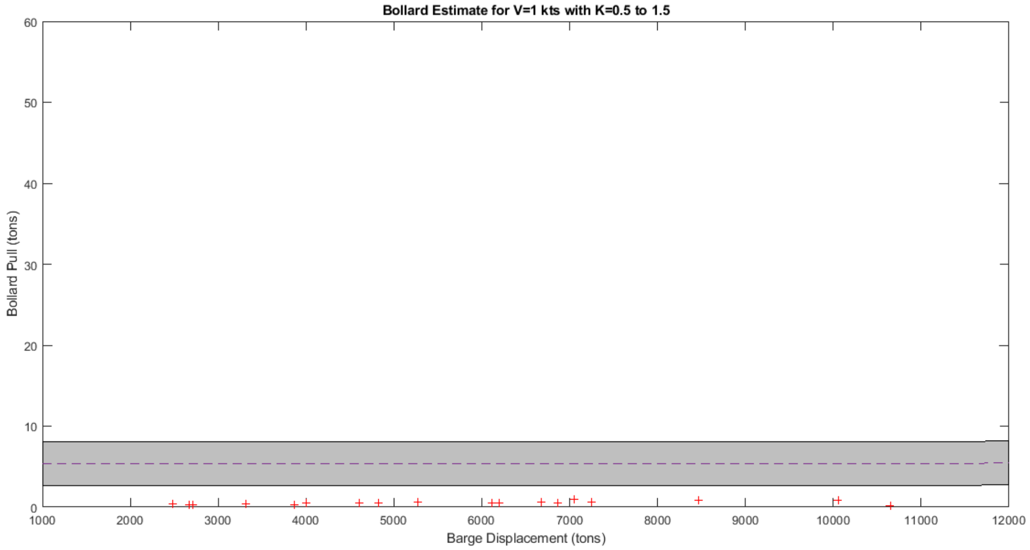

Figure 12: Bollard pull requirement calculation, $V = 1.0$ knots

TP 11960E states that the safety record for $V = 6$ knots is good in Canada. Figure 17 indicates that this is would likely be true, as a value $K = 1.5$ encompasses most of the barges calculated.

Assuming 1.4 tons of bollard pull per 100 horsepower, Figures 18 and 19 show the horsepower requirements for $V = 4.0$ knots and $V = 6.0$ knots, respectively.

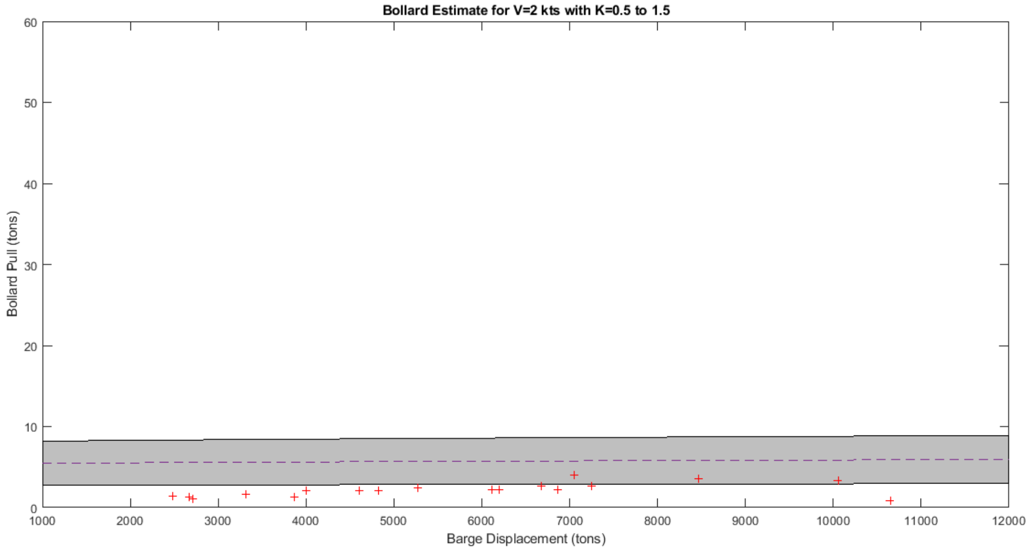

Figure 13: Bollard pull requirement calculation, $V = 2.0$ knots

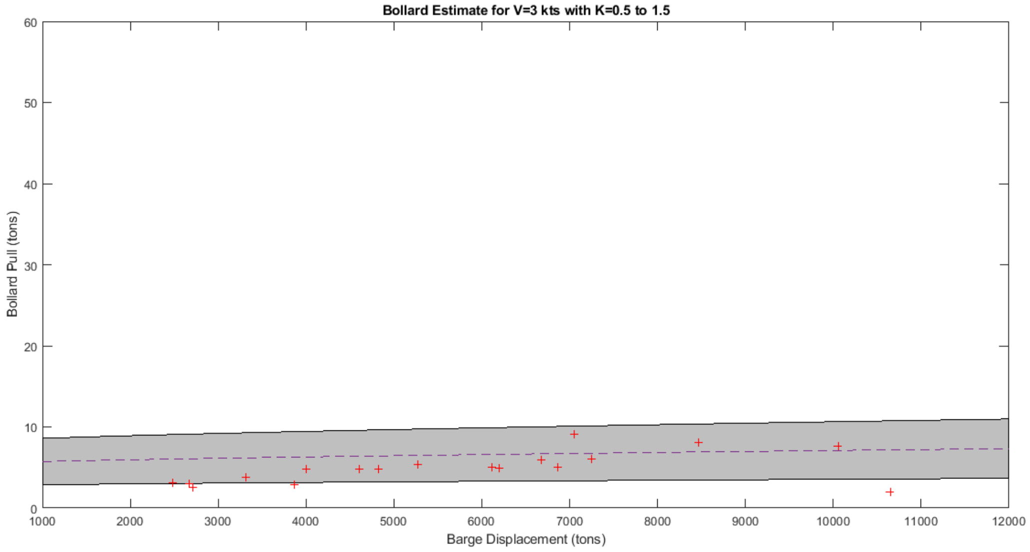

Figure 14: Bollard pull requirement calculation, $V = 3.0$ knots

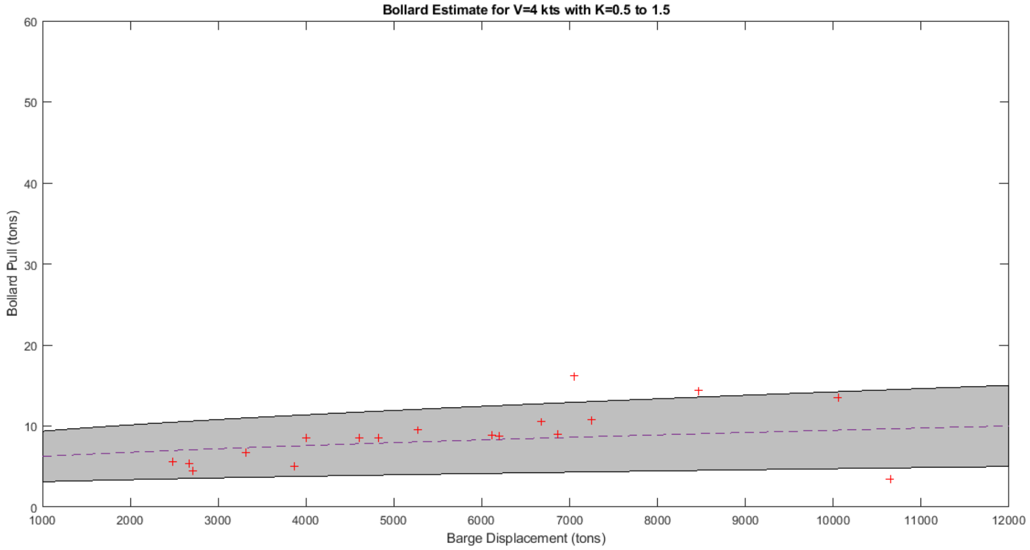

Figure 15: Bollard pull requirement calculation, $V = 4.0$ knots

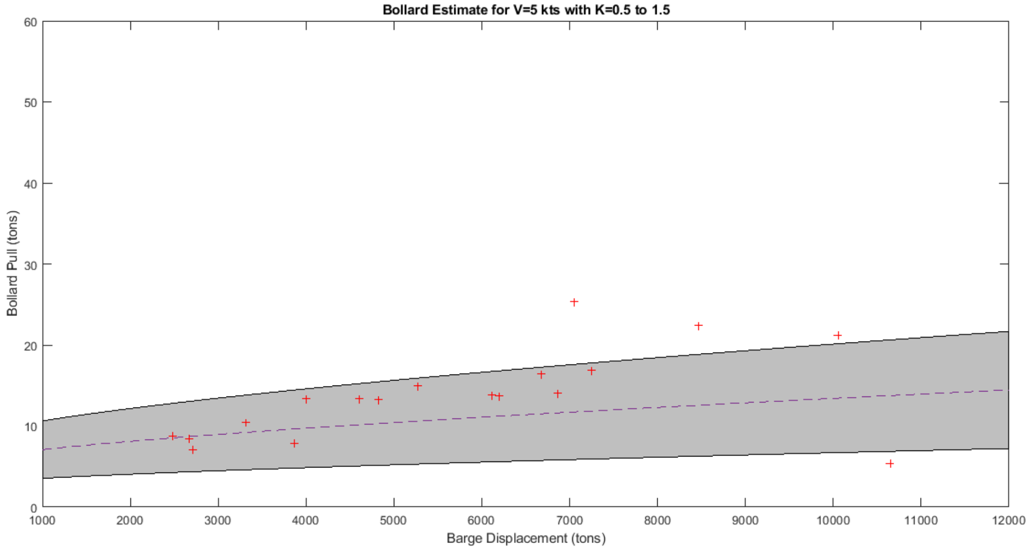

Figure 16: Bollard pull requirement calculation, $V = 5.0$ knots

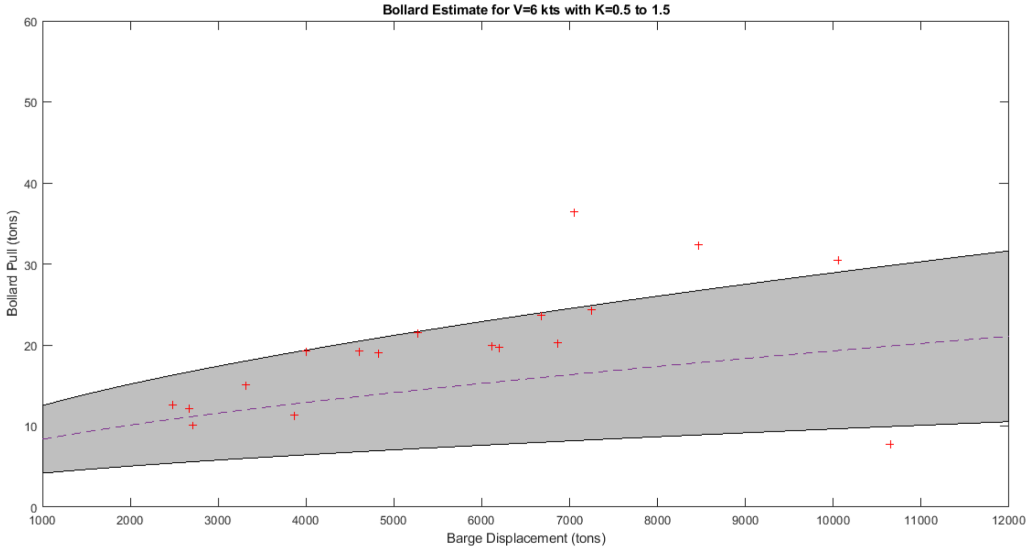

Figure 17: Bollard pull requirement calculation, $V = 6.0$ knots

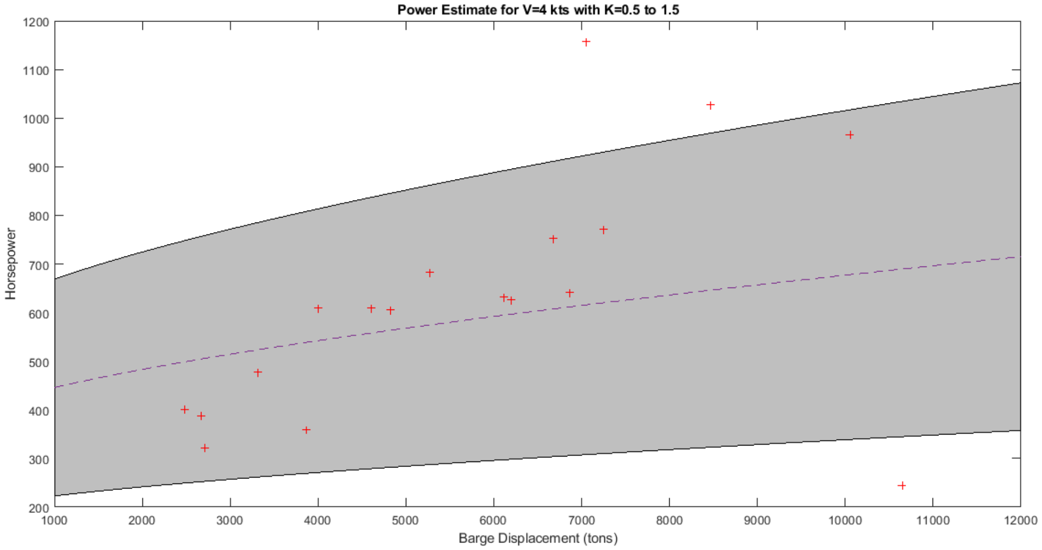

Figure 18: Horsepower requirement estimate, $V = 4.0$ knots

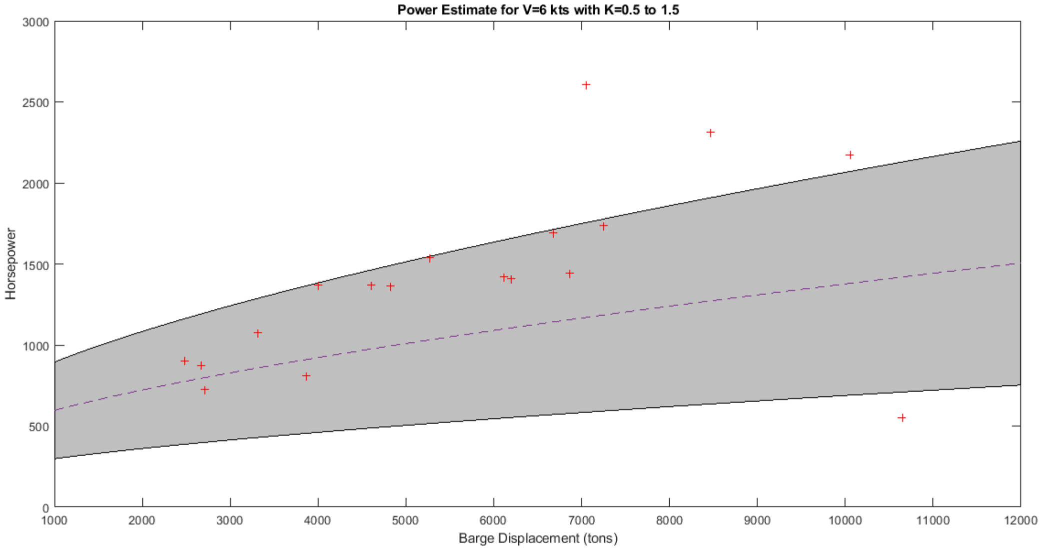

Figure 19: Horsepower requirement estimate, $V = 6.0$ knots

4 Numerical Simulation

The powering estimation work presented up to this section constitutes the basis for theoretical minimum powering, that is, the minimum power or propulsive force required to make way or stationkeep against an environmental force. This method of estimation accounts for a tug and barge combination in steady-state transit and does not account for the transient dynamics of tug and barge motions which occur during a powering changes, course changes, and changing relative environmental conditions. In girding scenarios, a tug is unable to effect a change in course of a barge underway with its given momentum in a timely manner. Assuming the stability of the towing vessel is able to withstand the force of the towpull, the amount of overhead propulsive force available during a course change will determine the rate at which the barge's course can be altered.

A numerical simulation based on existing methodologies in the literature and past OCRE simulation development has been developed in an attempt to address this unknown. In the following sections, the mathematical formulation of a three degree-of-freedom MATLAB tug and barge towing model is presented. Three simulation scenarios are presented for consideration. Acceleration time to various forward speeds from rest at full throttle is estimated. This provides insight into how quickly a speed through water change can occur along a single axis. 90 degree course changes under autopilot heading control are evaluated, where maximum throttle is applied at course change. This provides insight into the possibility of girding at various levels of overhead propulsion. Finally, a simulation in a point of interest is given.

4.1 System Definition

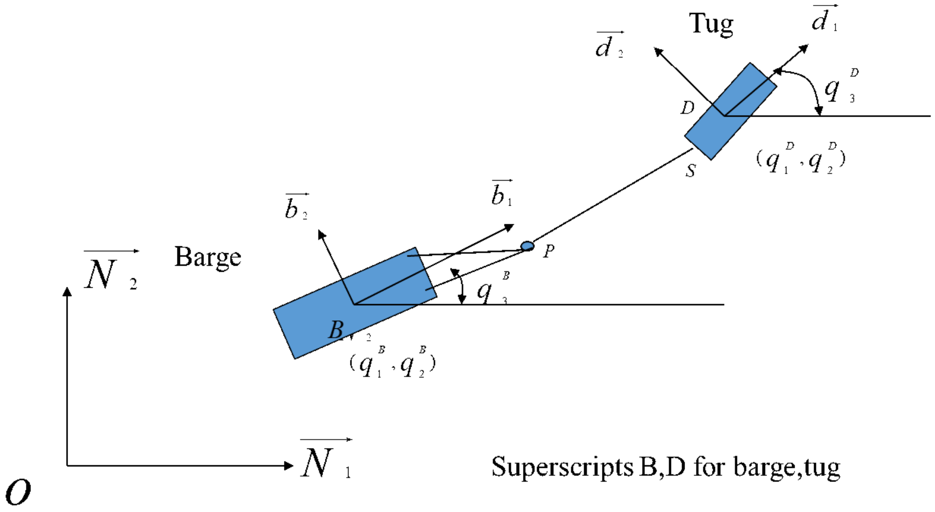

Figure 20: System Definition

The system configuration is shown in Figure 20. The inertial frame N has origin O and unit vectors $\vec{N}_1, \vec{N}_2$. The barge B has a body-fixed frame with origin at its centre of mass B and unit vectors $\vec{b}_1, \vec{b}_2$. Similarly, the tug D has a body-fixed frame with origin at its centre of mass D and unit vectors $\vec{d}_1, \vec{d}_2$. The tow line is connected to the tug at S and to the barge by a bridle at P. The bridle is assumed to be massless and inextensible. The inertial coordinates of the barge are denoted by $\left(q_1^B, q_2^B\right)$ and the angle between its longitudinal axis $\vec{b}_1$ and the $\vec{N}_1$ axis is denoted by q_3^B. The corresponding quantities for the tug are denoted by $q_r^D,\ (r = 1,2,3)$. The surge,sway and yaw velocities for the barge and tug are denoted by u_r^B and u_r^D $(r = 1,2,3)$ respectively. Time derivatives are denoted by overdots. Standard kinematic analysis yields the relations

$$\begin{pmatrix} \dot{q}_1^B \\ \dot{q}_2^B \\ \dot{q}_3^B \end{pmatrix} = \begin{pmatrix} \cos q_3^B & -\sin q_3^B & 0 \\ \sin q_3^B & \cos q_3^B & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u_1^B \\ u_2^B \\ u_3^B \end{pmatrix} \tag{8}$$

The acceleration $\vec{a}^B$ of the barge and its angular acceleration $\vec{\alpha}^B$ sre given by

$$\begin{aligned} \vec{a}^B &= \dot{u}_1 \vec{b}_1 + \dot{u}_2 \vec{b}_2 + \left(u_1^B u_3^B\right) \vec{b}_2 - \left(u_2^B u_3^B\right) \vec{b}_1 \\ \vec{\alpha}^B &= \dot{u}_3 \vec{b}_3 \text{ where } \vec{b}_3 = \vec{b}_1 \times \vec{b}_2 \end{aligned}$$

Similar relations hold for the tug. We will formulate the equations of motion using Kane's formalism. For this purpose we define the generalised coordinates of the barge and tug as q_r^B, q_r^D respectively with generalised speeds u_r^B and u_r^D $(r = 1,2,3)$. The partial velocities of a given point on a body are defined as the vector coefficients of the generalised speeds in the expression for the velocity of the point, and are written by inspection. Partial angular velocities of a body are similarly defined as the vector coefficients of the yaw angular velocities. Generalised forces are then defined as the dot product of forces and moments with the appropriate partial velocities.

4.2 Forces on Barge and Tug

The forces on the system are *summarised* as follows, where superscripts B and D refer to the barge and tug respectively.

4.2.1 *Inertia Forces*

The generalised forces on the barge due to inertia and first-order (linear) maneuvering resistance in calm water take the form

$$\left\{G^B\right\} = -\left[M^B\right]\left\{\dot{u}^B\right\} + \left\{\phi^B\right\}$$

where $\left\{\dot{u}^B\right\}$ is the vector of generalised speeds for the barge and

$$\left[M^B\right] = \begin{pmatrix} m^B - X_{\dot{u}}^B & 0 & 0 \\ 0 & m^B - Y_{\dot{v}}^B & -Y_{\dot{r}}^B \\ 0 & -N_{\dot{v}}^B & I^B - N_{\dot{r}}^B \end{pmatrix}$$

$$\{\phi^B\} = \begin{pmatrix} m^B u_2^B u_3^B + \left(u_1^B - u_0^B\right) X_u^B \\ -m^B u_1^B u_3^B + u_2^B Y_v^B + u_3^B Y_r^B \\ u_2^B N_v^B + u_3^B N_r^B \end{pmatrix}$$

In these equations, m^B is the mass of the barge, I^B is the moment of inertia of the barge about the yaw axis, and we have used the standard notation for linear maneuvering coefficients in which subscripts u, v and r refer to surge, sway and yaw respectively. Identical relations hold for the tug, with superscript D instead of B.

4.2.2 *Current and Wind Forces*

It is assumed that the current and wind velocities are known in the inertial N frame. These velocities are then transformed to the body-fixed frames for the barge and tug and the relative velocities computed as functions of the instantaneous surge and sway velocities of each vessel. The drag forces due to current and wind are then calculated in the usual way using drag coefficients and projected areas. The points of application of the current and wind forces are taken as the centroids of the projected areas exposed to these loads. As an example, the drag force on the barge due to current takes the form

$$F_r^{C/B} = \left\{ \begin{array}{c} \gamma_r^{C/B} \\ p_1^{C/B} \gamma_2^{C/B} - p_2^{C/B} \gamma_1^{C/B} \end{array} \right.$$

where superscript C/B refers to current force on barge B and

$$\gamma_i^{C/B} = \frac{1}{2} \rho_w \left| \overrightarrow{v}^{CR/B} \right| (AC_D)_i^{C/B} \left(v_i^{C/B} - u_i^B \right) \qquad , \ (i = 1, 2)$$

Here, $\overrightarrow{v}^{CR/B}$ is the velocity of the current relative to the barge in the B frame and it $i-$th component is $\left(v_i^{C/B} - u_i^B\right)$. The quantity $(AC_D)_i^{C/B}$ is the product of drag coefficient and projected area for current flow in direction i (B frame) and ρ_w is water density. The point of application of the drag force has coordinates $\left(p_1^{C/B}, p_2^{C/B}\right)$ in the B frame. *The force due to wind takes the same form. The formulations for current and wind forces on the tug D are identical.*

4.2.3 *Tow Line Forces*

Referring to Figure 21, the tow line PS is attached to the tug at S and to a bridle point P which is attached to the barge. The points P and S are specified relative to the barge and tug body-fixed frames respectively. We denote the B frame coordinates of P by (p_1, p_2) and the D frame coordinates of S by(s_1, s_2). The instantaneous length of the tow line L^{Tow} is found from the *inertial* coordinates of P, S. if the unstretched length of the tow line is L_0^{Tow} the line extension is defined as

$$s^{\text{Tow}} = \frac{1}{2} \left\{ \left(L^{\text{Tow}} - L_0^{\text{Tow}} \right) + \left| L^{\text{Tow}} - L_0^{\text{Tow}} \right| \right\}$$

which is identically zero if the line goes slack $\left(L^{\text{Tow}} < L_0^{\text{Tow}}\right)$. In this way, snap loads can be simulated. The generalised forces due to tow line tension on the barge B and tug D are found as

$$F_r^{\text{Tow}/B} = k^{\text{Tow}} s^{\text{Tow}} \begin{cases} e_1^{\text{Tow}} \cos q_3^B + e_2^{\text{Tow}} \sin q_3^B & (r=1) \\ -e_1^{\text{Tow}} \sin q_3^B + e_2^{\text{Tow}} \cos q_3^B & (r=2) \\ e_1^{\text{Tow}} \left(-p_1 \sin q_3^B - p_2 \cos q_3^B\right) & \\ +e_2^{\text{Tow}} \left(p_1 \cos q_3^B - p_2 \sin q_3^B\right) & (r=3) \end{cases}$$

$$F_r^{\text{Tow}/D} = -k^{\text{Tow}} s^{\text{Tow}} \begin{cases} e_1^{\text{Tow}} \cos q_3^D + e_2^{\text{Tow}} \sin q_3^D & (r=1) \\ -e_1^{\text{Tow}} \sin q_3^D + e_2^{\text{Tow}} \cos q_3^D & (r=2) \\ e_1^{\text{Tow}} \left(-s_1 \sin q_3^D - s_2 \cos q_3^D\right) & \\ +e_2^{\text{Tow}} \left(s_1 \cos q_3^D - s_2 \sin q_3^D\right) & (r=3) \end{cases}$$

In these equations, $e_1^{\text{Tow}}, e_2^{\text{Tow}}$ are the inertial components of the unit vector along $\overrightarrow{PS}$ and k^{Tow} is the line stiffness.

4.2.4 *Tug Propulsion and Trajectory Control*

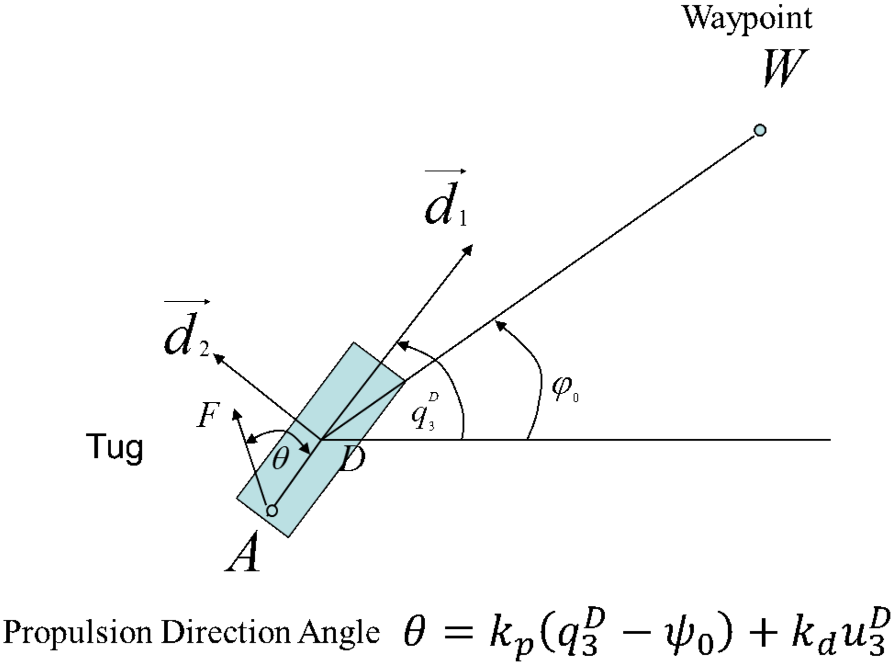

Figure 21: Tug Trajectory Control

The propulsive force on the tug is F applied at a point A on the longitudinal axis $\overrightarrow{d}_1$ at angle θ to this axis as shown in Figure 21. The intention is to steer the tug toward waypoint W whose inertial coordinates are (w_1, w_2). The angle θ is designed according to the PD control law

$$\theta = k_p \left(q_3^D - \psi_0\right) + k_d u_3^D \tag{9}$$

where k_p and k_d are proportional and derivative control parameters respectively, and ψ_0 is the angle between vectors $\overrightarrow{DW}$ and $\overrightarrow{N}_1$ (Figure 21). One method of choosing the control parameters is to consider a simple yaw equation of motion under the action of moment $\overrightarrow{M} = (aF\sin\theta)\,\overrightarrow{d}_3$ where a is defined by $\overrightarrow{DA} = a\,\overrightarrow{d}_1 \quad (a<0)$. If the orientation angle between the tug longitudinal axis $\overrightarrow{d}_1$ and vector $\overrightarrow{N}_1$ is denoted by ψ, the yaw equation of motion takes the form

$$\ddot{\psi} + 2\zeta\omega_n\dot{\psi} + \omega_n^2\psi = g(t)$$

where

$$\omega_n^2 = \frac{|a|Fk_p}{\widetilde{m}_{33}^D} \quad 2\zeta\omega_n = \frac{|a|Fk_d}{\widetilde{m}_{33}^D} \tag{10}$$

By analogy with a mass-spring-damper system, the parameters ω_n and ζ are interpreted as natural frequency and damping ratio respectively. The 2% settling time is given approximately by

$$t_s \approx \frac{4}{\zeta\omega_n}$$

so that if the parameters t_s and ζ are chosen, we can find the control parameters k_p and k_d from (10). With θ given by (9) we find the generalised force due to propulsion as

$$F_r^{\text{prop}} = F\begin{cases} \cos\theta & (r=1) \\ \sin\theta & (r=2) \\ a\sin\theta & (r=3) \end{cases}$$

4.3 Equations of Motion

We define the generalised coordinates of the coupled barge and tug system as

$$q_r = q_r^B \;\; ; \; q_{3+r} = q_r^D \quad (r = 1,2,3) \tag{11}$$

Similarly, we define the generalised speeds as

$$u_r = u_r^B \;\; ; \; u_{3+r} = u_r^D \quad (r = 1,2,3) \tag{12}$$

We define the 6×1 vectors $\{q\}$ and $\{u\}$ to be the vectors consisting of the generalised coordinates and generalised speeds respectively. The generalised inertia and active forces for the system are assembled following this notation. For example, the generalised inertia and linear maneuvering forces on the system are defined as

$$G_r = G_r^B \;\; ; \; G_{3+r} = G_r^D \quad (r = 1,2,3)$$

The same convention is used to assemble the generalised forces due to current,wind,tow line and propulsion and the sum is denoted by the 6×1 vector $\{F\}$. It is necessary to write the inertia and linear maneuvering forces in the form

$$\{G\} = -[M]\left\{\dot{u}\right\} + \{\phi\}$$

where $[M]$ is the 6×6 *block* diagonal matrix

$$[M] = \text{diag}\left(\left[M^B\right], \left[M^D\right]\right)$$

and

$$\{\phi\} = \begin{pmatrix} \{\phi^B\} \\ \{\phi^D\} \end{pmatrix}$$

The equations of motion are [31] are

$$\{G\} + \{F\} = \{0\}$$

from which we find

$$\left\{\dot{u}\right\} = [M]^{-1}\left(\{F\} + \{\phi\}\right) \tag{13}$$

Define the 12×1 vector $\{z\}$ as

$$\{z\} = \begin{pmatrix} \{q\} \\ \{u\} \end{pmatrix}$$

Using the kinematic relations of the form (8) for both barge and tug, and equation (13) we write $\left\{\dot{z}\right\}$ in the form

$$\left\{\dot{z}\right\} = f\left(t, \{z\}\right)$$

which is solved by a standard Runge-Kutta routine in MATLAB.

4.4 Example Simulation

An example simulation was conducted with the following parameters.

	Barge	*Tug*
Length (m)	75	30
Beam (m)	20	11
Draft (m)	10	6
Mass (kg)	9.23×10^6	1.01×10^6
Yaw Moment of Inertia $\left(kg.m^2\right)$	1.76×10^{10}	3.15×10^8
$-X_{\dot{u}}(kg)$	9.23×10^5	1.01×10^5
$-Y_{\dot{v}}\ (kg)$	9.23×10^6	1.01×10^6
$-N_{\dot{r}}(kg.m^2)$	6.93×10^9	1.11×10^8

The current velocity is $2m/\sec$ due North (direction $\overrightarrow{N}_2$). The drag coefficient for current is assumed to be 1.2 for both axial and transverse flow. A propulsive force of $F = 5 \times 10^7\ N$ is applied at the stern of the tug at angle θ given by equation (9). The control parameters in this equation are $k_p = 0.74$ (dimensionless) and $k_d = 0.91\,\sec$. Waypoint coordinates in metres are $(600, 800)$, $(3000, 100)$ and $(6000, 2000)$. The tow line has unstretched length $100\ m$ and stiffness $2.43 \times 10^6 N/m$. The trajectories are shown in Figure 22.

4.5 Time to accelerate

The following effort revisits the Seaspan tugs *Cates 20*, *Raider*, and *Royal* towing the Seaspan 550 barge. Calculation is performed to determine the time to achieve various forward speeds against various opposing currents with this single tow configuration. Towpull overheads from powering estimation are used. This gives

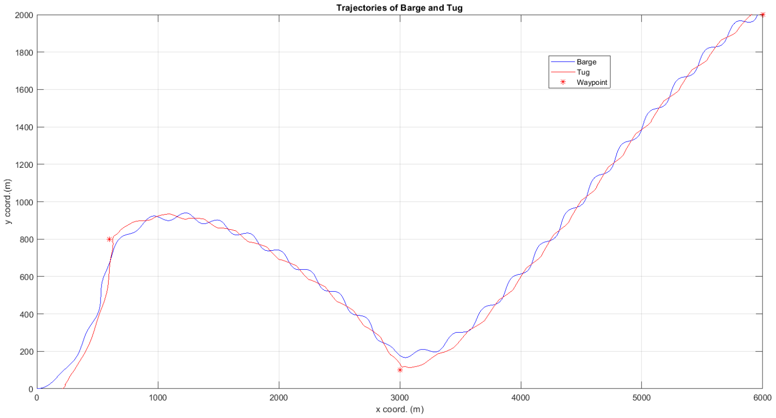

Figure 22: Trajectories

insight into reaction times to overcome various current speeds.

4.5.1 Examples

Table 8 gives the time in seconds for *Royal* to achieve various forward speeds V with a range of opposing currents.

	$V = 1.0$	$V = 2.0$	$V = 3.0$	$V = 4.0$	$V = 5.0$	$V = 6.0$
Current (knots)						
0.00	2.55	5.13	7.80	10.59	13.58	16.85
1.00	2.58	5.25	8.04	11.03	14.30	18.00
2.00	2.66	5.46	8.45	11.72	15.41	19.76
3.00	2.79	5.78	9.06	12.75	17.10	22.56
4.00	2.99	6.26	9.96	14.30	19.76	27.44

Table 8: Seaspan Royal/Seaspan 550 acceleration times in seconds against various currents

Table 9 gives the time in seconds for *Raider* to achieve various forward speeds V with a range of opposing currents.

	$V = 1.0$	$V = 2.0$	$V = 3.0$	$V = 4.0$	$V = 5.0$	$V = 6.0$
Current (knots)						
0.00	5.11	10.37	15.97	22.19	29.46	38.70
1.00	5.26	10.87	17.08	24.35	33.59	47.35
2.00	5.61	11.82	19.09	28.33	42.09	77.42
3.00	6.21	13.48	22.72	36.49	71.82	DNF
4.00	7.27	16.51	30.27	65.60	DNF	DNF

Table 9: Seaspan Raider/Seaspan 550 acceleration times in seconds against various currents

Table 10 gives the time in seconds for *Cates 20* to achieve various forward speeds V with a range of opposing currents.

Current (knots)	$V = 1.0$	$V = 2.0$	$V = 3.0$	$V = 4.0$	$V = 5.0$	$V = 6.0$
0.00	31.82	71.17	150.08	DNF	DNF	DNF
1.00	39.35	118.26	DNF	DNF	DNF	DNF
2.00	78.91	DNF	DNF	DNF	DNF	DNF
3.00	DNF	DNF	DNF	DNF	DNF	DNF
4.00	DNF	DNF	DNF	DNF	DNF	DNF

Table 10: Seaspan Cates 20/Seaspan 550 acceleration times in seconds against various currents

4.5.2 Direct formula

Effort was performed to formulate a direct calculation of time to accelerate. This work is presented here.

Consider a bluff body, mass m, added mass m_a being towed by a force F against a current of speed v_c. If the speed of the body at time t is $v(t)$ the drag force on it is $F_D = \frac{1}{2}\rho A C_D (v + v_c)^2$, where A is the projected area normal to the direction of motion, C_D is the associated drag coefficient and ρ is the fluid density. The equation of motion is

$$F - \frac{1}{2}\rho A C_D (v + v_c)^2 = m' \frac{dv}{dt} \tag{14}$$

where $m' = m + m_a$. Let

$$w = v(t) + v_c \tag{15}$$

Then noting that $\frac{dw}{dt} = \frac{dv}{dt}$ we write (14) as

$$\frac{dw}{dt} = b\left(c^2 - w^2\right) \tag{16}$$

where

$$b = \frac{\rho A C_D}{2m'} \quad \text{and} \quad c^2 = \frac{2F}{\rho A C_D} \tag{17}$$

The initial condition is

$$v(0) = 0 \implies w(0) = v_c \tag{18}$$

The solution of (16) subject to initial condition (18) is

$$\frac{1}{2c} \ln\left|\frac{w + c}{w - c}\right| - \frac{1}{2c} \ln\left|\frac{v_c + c}{v_c - c}\right| = bt \tag{19}$$

We now assume that

$$w < c \text{ for all } t$$

which implies that $w(0) < c$ i.e. $v_c < c$. Then (19) becomes

$$\frac{1}{\beta} \ln\left\{\frac{a(c + w)}{c - w}\right\} = t \tag{20}$$

where

$$\beta = 2bc = \frac{\sqrt{2\rho A C_D F}}{m'} \quad \text{and} \quad a = \frac{c - v_c}{c + v_c}$$

This gives

$$w(t) = \frac{c\left(1 - ae^{-\beta t}\right)}{1 + ae^{-\beta t}} \tag{21}$$

From (21) we deduce that as $t \to \infty$, $w \to c$. Note that from (16) we find that when $w = c$, $\frac{dw}{dt} = 0$ (zero acceleration).

From (15) we have

$$v(t) = \frac{c\left(1 - ae^{-\beta t}\right)}{1 + ae^{-\beta t}} - v_c \tag{22}$$

The terminal velocity is thus

$$v(\infty) = c - v_c \tag{23}$$

Let the time required to reach speed v^* be t^*, i.e. $v(t^*) = v^*$. Then $w(t^*) = v^* + v_c$ and from (20) we have

$$t^* = \frac{1}{\beta} \ln \left\{ \frac{a(c + w^*)}{c - w^*} \right\} \tag{24}$$

where

$$\begin{aligned} w^* &= v^* + v_c \\ c &= \sqrt{\frac{2F}{\rho A C_D}} \\ a &= \frac{c - v_c}{c + v_c} \\ \beta &= \frac{\sqrt{2\rho A C_D F}}{m'} \end{aligned}$$

4.6 90 degree turns

To investigate time required to overcome a girding scenario, 90 degree course changes of the barge were assessed for time. The previous three tug examples are used here, with their relative powering overhead, to assess time required to execute the heading change. These are summarized in Table 11 for an initial towing speed of 2 knots and zero current.

Tow vessel	Time (s)
Cates 20	90.53
Raider	36.74
Royal	25.98

Table 11: Summary of times to complete a 90 degree heading change

Effort was performed to formulate a direct approximation of time to achieve a 90 degree course change. This work is presented here.

4.6.1 Nomoto Model (First Order)

The yaw equation of motion is , in the usual notation,

$$\left(I_{Cz} - N_{\dot{r}}\right)\dot{r} + \left(m_0 x_G - N_{\dot{v}}\right)\dot{v} \ = \ N_v v + \left(N_r - m_0 x_G u_0\right) r + N(t) \tag{25}$$

where $N(t)$ is an applied moment and $r = \frac{d\psi}{dt}$. Assume fore/aft symmetry such that $x_G \cong 0,\ N_{\dot{v}} \cong 0,\ N_v \cong 0$. Equation (25) then reduces to

$$\left(I_{Cz} - N_{\dot{r}}\right)\dot{r} - N_r r = N(t)$$

The quantity $\left(-N_{\dot{r}}\right)$ is large and positive and is the added yaw moment of inertia (units: $kg.m^2$). The quantity $(-N_r)$ is a yaw damping coefficient (units: $N.m.\sec/rad$) and is large and positive. Dividing by $(-N_r)$ gives

$$T\dot{r} + r = \gamma(t) \tag{26}$$

where

$$T \ = \ \frac{I_{Cz} - N_{\dot{r}}}{-N_r} \quad \text{(units: } \sec\text{)} \tag{27}$$

$$\gamma \ = \ -\frac{N}{N_r} \ \left(\text{units: } \sec^{-1}\right) \tag{28}$$

This is the first order Nomoto model with a general applied moment.

4.6.2 Nomoto Model with Rudder

In the case where the applied moment N is due to a rudder with angle $\delta(t)$ and moment coefficient N_δ we write

$$N = N_\delta \delta \tag{29}$$

and equation (28) becomes

$$\gamma = K\delta(t) \tag{30}$$

where

$$K = -\frac{N_\delta}{N_r} \tag{31}$$

Equation (26) then becomes

$$T\dot{r} + r = K\delta(t) \tag{32}$$

which is the Nomoto model with rudder.

4.6.3 Solution for Constant Applied Moment

If $N = N_0 =$ constant applied moment, equation (26) becomes

$$T\dot{r} + r = \gamma_0 \tag{33}$$

where

$$\gamma_0 = -\frac{N_0}{N_r} \tag{34}$$

For initial condition $r(0) = r_0$, the solution of (33) is

$$r(t) = \gamma_0 + (r_0 - \gamma_0)\, e^{-\left(\frac{t}{T}\right)} \tag{35}$$

Putting $r = \frac{d\psi}{dt}$ we solve (35) with initial condition $\psi(0) = \psi_0$ to get

$$\psi(t) = \psi_0 + \gamma_0 t + T(r_0 - \gamma_0)\left(1 - e^{-\left(\frac{t}{T}\right)}\right) \tag{36}$$

Let the time taken for ψ to increase from ψ_0 to $\psi_0 + \alpha$ be t_α where α is a specified angle in radians,i.e. $\psi(t_\alpha) = \psi_0 + \alpha$. Then we have from (36)

$$\alpha = \gamma_0 t_a + T(r_0 - \gamma_0)\left(1 - e^{-\left(\frac{t_\alpha}{T}\right)}\right)$$

This can be written

$$\beta + ae^{-\beta} = b \tag{37}$$

where

$$\beta = \frac{t_\alpha}{T} \;\; ; \;\; a = 1 - \frac{r_0}{\gamma_0} \;\; ; \; b = \frac{\alpha}{\gamma_0 T} + a$$

Equation (37) is solved for β and we obtain the required time $t_\alpha = T\beta$.

4.6.4 Approximate Solution of (37) for small β when $r_0 = 0$

If $r_0 = 0,\ a = 1$ and $b = \frac{\alpha}{\gamma_0 T} + 1$. For small β, $e^{-\beta} \cong 1 - \beta + \frac{1}{2}\beta^2$. In this case equation (37) reduces to

$$\beta^2 \cong \frac{2\alpha}{\gamma_0 T} \tag{38}$$

If $\gamma_0 T$ is large then β will be small. This gives the approximate value of t_α as

$$t_\alpha \cong \sqrt{\frac{2\alpha T}{\gamma_0}} \tag{39}$$

Using (27) and (34) this gives

$$t_\alpha \cong \sqrt{\frac{2\alpha\left(I_{Cz} - N_{\dot{r}}\right)}{N_0}} \tag{40}$$

This shows that for zero initial yaw rate r_0 and small β (large $\gamma_0 T$), the value of t_α is inversely proportional to the square root of the applied moment N_0.

4.7 Points of interest

It was originally desired to simulate trajectory following for tug and barge combinations along the various points of interest within the VFPA region (Table 2). The framework for this effort is complete, and is comprised of a Matlab implementation of the dynamic equations of motions and parameters presented to this point. Unfortunately, detailed manoeuvring simulation within the context of the points of interest has not been performed as NRC-OCRE has been unable to obtain accurate hydrodynamic derivatives for the tugs and barges assessed. At this time, it is reasonable to assume that additional CFD effort would be required to obtain coefficients accurate enough to draw conclusions from.

The way-point following autopilot integrated with this simulation was intended to serve as the method of assessing barge motions under transit. Unfortunately, it is currently only capable of accepting a constant propulsive force. It has been determined that any system which attempts to assess tug and barge manoeuvring in channels will require a propulsion control as well. This is beyond the scope of this project but of interest for future development work.

Table 2 presents maximum currents forecast at various locations for the tidal extremes. Information like this can be utilized along with Equations 5 and 7 to calculate minimum bollard pull as defined.

4.8 Simulation findings and limitations

A tug and barge simulation framework similar to those found in the academic literature has been implemented. With improved certainty in coefficients and with an improved propulsion strategy, this can likely be expanded to assess barge motions with increased accuracy. This could be useful both in augmenting the definition of minimum powering, as well providing further modeling accuracy to other training simulator environments.

Acceleration time calculations can be useful for assessing a particular tug's responsiveness to overcome various currents.

The finding that barge course change time is proportional to the square-root of applied tow force is also useful. Practically, this means that increasing the available towpull force will have a significant effect on girding response only up to some point, after which more towpull presents little additional advantage. This must be assessed on a per-barge basis.

It is important to note that while these findings provide some insight into the overhead propulsion requirements needed to avoid girding scenarios, the absolute accuracy of these simulations is unknown. The manouevering derivative coefficients used in this simulation are estimated from statistically-derived means and not from PMM model testing or CFD calculation, and as such, their accuracy is unknown. Moreover, the propulsion modeling in this simulation is relatively simplified in nature. Inputs for propulsion are provided from previous NavCad calculations and does not include a complete treatment of thruster dynamics.

5 Findings and Concluding Remarks

5.1 Calculation of Minimum Power

The empirical formula for bollard pull presented in TP 11960E has been evaluated. It is shown that it has a tendency to overestimate required bollard at low towing speeds, but creates reasonable estimates of bollard pull at higher speeds. As shown by the effect of varying K parameters, however, it is clear that it is better used as a rough calculation tool rather than an absolute. A formula has been presented which shows promise for a more accurate calculation of minimum bollard pull. Coefficients are presented which encompass the general range of barges observed in the VFPA region. This makes the formulation amenable to spreadsheet-style implementations for use by operators.

When defining a “minimum powering" guideline for controlled waterways, implementing adherence to a single simplified formula may be difficult. It may be possible to define one sufficient for a narrowed or known set of criteria, but its validity in unforeseen criteria will be uncertain.

IMO[6] and others have based minimum powering criteria on vessel capability in various environmental conditions to simplify this problem. For example, one potential minimum capability requirement for river tows could be written similar to:

> Any tugboat transiting the region with tow must meet the minimum bollard pull requirement (presented in Equation 7) to perform station-keeping against the worst-case current and wind forecast along their route for their given transit time.

NRC-OCRE recommends that adequate power be calculated based upon Equations 5 and 7 and their surrounding discussion outlined in this report.

5.2 Simulation

While minimum powering has been addressed to some degree through steady-state resistance and propulsion analysis, it does not sufficiently address the dynamic requirements of powering overhead. This is especially true when determining the scenarios in which girding can occur.

The simulation effort performed herein has shown promise for assessing these requirements. One notable result from simulation is that a seemingly good towing strategy seems to be to tow at as low a speed as is admissible, allowing for the maximum level of propulsion overhead to be available for course changes. Not only does this give the helm the most controllability over the tow, but it also limits the amount of inertia which has to be overcome in a girding scenario. This effort has not made any attempt to address a “minimum" safe transit speed.

At outset of the project, it was desired to create a simulation framework of a high enough fidelity to assess these dynamic requirements automatically through methods of optimization in specific environmental scenarios (specifically, along the multiple transit points of interest). This has not been possible at present as two major limitations have been observed:

- Accurate coefficients for maneouvering simulation must be produced from PMM model testing and/or CFD work. It is recommended that work be done to extract coefficients for a wide range of tug and barge shapes to improve upon the general empirical coefficients available that are based on large, fast ship shapes. This would increase the confidence in simulation, particularly with respect to transient motions.

- Optimization of an ideal throttle and helm trajectory for a given environmental condition (i.e., the set of actions that produces a minimum deviation in a planned trajectory) is a difficult problem, and one which is not addressed in a satisfactory way with a course-keeping autopilot. To OCRE's knowledge, this problem has yet to be solved. It would, however, give a new "minimum powering" floor which includes the dynamics of different environmental scenarios and constraints of motions to avoid collisions. OCRE looks to continue this work where possible.

5.3 Tugboat Stability

From the review of the multiple TSB reports at the outset of this work, it is evident that tugboat stability is a major outstanding issue in the regulations and standards which should be addressed. Stability is the primary concern for capsizing during girding. Multiple industry stakeholders have highlighted this, not only publicly, but also in consultation with VFPA and OCRE in this work.

There are many instances in TSB reports that indicate capsizing or loss of tow events when the towing vessel had a bollard pull which was seemingly adequate based on available knowledge. While power is undoubtedly an important factor in avoiding girding scenarios, stability plays an important role in being capable of applying that power to prevent or reverse girding and loss of tow.

It is recommended that a comprehensive study be performed on tugboat stability, particularly on those operating under the 15 GRT limit to address:

- Maximum lateral towpull possible for a given hull and freeboard, and,
- Benefit of the installation of sponsons, blisters, bilge keels, etc. to increase roll stability.

Also of interest is the feasibility of the design concept of ensuring a vessel maintains enough stability to withstand capsizing with a towpull equal to the maximum tow propulsive force.

5.4 Current monitoring and prediction

Through both review of past TSB incident reports as well as this work, it has been determined that a robust river current monitoring and prediction system could benefit planned transits in the area by providing increased accuracy of local current profiles at major infrastructural points of interest. To NRC-OCRE's knowledge at this time, current forecasts are produced by monitoring river levels at various locations within the area, and numerical tools predict current based upon those levels. A high-level concept for such a system is presented here for interest.

To aid in the production of valid, real time inputs into calculation of minimum powering for transit, it is suggested that a network of real-time environmental sensors be implemented. This system could include the infrastructure to provide the sensors, communications and distribution software to provide real-time updates on current, wind, visibility and any other critical environmental conditions at the critical bridge transit points and their approaches. The system would include basic weather stations, current meters and visibility range sensors at bridge transit points and the upstream and downstream approaches.

The sensors would be connected into a communications system that would, in real-time, relay the data to a processing server. The data would be processed and packaged and made available via a web based interface. Users would access the data via a computer app from the internet, via cell data on a personal device, phone or tablet, etc.

Sensors would be placed at transit points but also upstream on the various water courses feeding the Fraser and the Fraser itself. The positions would be selected to supply warning of any significant change to the current in any of the streams. The Processing centre could then send out updates via push message to registered users.

Such a system could also serve to provide the fidelity of environmental data required to support vessels of increasing levels of autonomy and self-supported decision-making. As unmanned, remote controlled and autonomous vessels begin to enter controlled waterways, such infrastructure may be critical. NRC-OCRE recommends opening discussion with Transport Canada and authorities such as the VFPA to explore such development.

5.5 Acknowledgements

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A Example NavCad Tugboat Resistance and Propulsion Output

Resistance

16 Mar 2021 08:24 PM
HydroComp NavCad 2020 [Premium]

Project ID **VFPA Tug Prediction**
Description **SS Cates20**
File name **SSCates20.hcnc**

Analysis parameters

Vessel drag		**ITTC-78 (CT)**
Technique:	**[Calc]**	**Prediction**
Prediction:		**Holtrop**
Reference ship:		
Model LWL:		
Expansion:		**Custom**
Friction line:		**ITTC-57**
Hull form factor:	**[Off]**	
Speed corr:		
Spray drag corr:	**[Off]**	
Corr allowance:		**0.000800**
Roughness [mm]:	**[Off]**	

Added drag		
Appendage:	**[Calc]**	**Fung (Simple FPP)**
Wind:	**[Calc]**	**Fujiwara**
Seas:	**[Off]**	
Shallow/channel:	**[Calc]**	**Schlichting**
Towed:	**[Off]**	
Margin:	**[Calc]**	**Hull drag only [10%]**
Water properties		
Water type:		**Salt**
Density:		**1026.00 kg/m3**
Viscosity:		**1.18920e-6 m2/s**

Prediction method check [Holtrop]

Parameters	FN [design]	CP	LWL/BWL	BWL/T	Lambda
Value	**0.42**	**0.65**	**2.60***	**4.99***	**0.87**
Range	**0.06··0.44**	**0.55··0.85**	**3.90··14.90**	**2.10··4.00**	**0.01··0.88**

Prediction results

	SPEED COEFS		ITTC-78 COEFS						
SPEED [kt]	FN	FV	RN	CF	[CV/CF]	CR	dCF	CA	CT
0.01 !	**0.000**	**0.001**	**5.31e4**	**0.010100**	**1.000**	**0.004701**	**0.000000**	**0.000800**	**0.015601**
2.00	**0.094**	**0.186**	**1.06e7**	**0.002969**	**1.000**	**0.001169**	**0.000000**	**0.000800**	**0.004938**
4.00	**0.188**	**0.372**	**2.12e7**	**0.002643**	**1.000**	**0.001043**	**0.000000**	**0.000800**	**0.004486**
6.00	**0.281**	**0.559**	**3.19e7**	**0.002476**	**1.000**	**0.001642**	**0.000000**	**0.000800**	**0.004919**
7.00	**0.328**	**0.652**	**3.72e7**	**0.002417**	**1.000**	**0.003006**	**0.000000**	**0.000800**	**0.006223**
8.00	**0.375**	**0.745**	**4.25e7**	**0.002368**	**1.000**	**0.004209**	**0.000000**	**0.000800**	**0.007377**
8.50	**0.399**	**0.791**	**4.51e7**	**0.002346**	**1.000**	**0.005692**	**0.000000**	**0.000800**	**0.008838**
+ 9.00 +	**0.422**	**0.838**	**4.78e7**	**0.002325**	**1.000**	**0.009241**	**0.000000**	**0.000800**	**0.012367**
9.50 !	**0.445**	**0.884**	**5.04e7**	**0.002306**	**1.000**	**0.012134**	**0.000000**	**0.000800**	**0.015240**
10.00 !	**0.469**	**0.931**	**5.31e7**	**0.002288**	**1.000**	**0.014419**	**0.000000**	**0.000800**	**0.017508**

	RESISTANCE							
SPEED [kt]	RBARE [kN]	RAPP [kN]	RWIND [kN]	RSEAS [kN]	RCHAN [kN]	RTOWED [kN]	RMARGIN [kN]	RTOTAL [kN]
0.01 !	**0.00**	**0.00**	**0.27**	**0.00**	**0.00**	**0.00**	**0.00**	**0.27**
2.00	**0.16**	**0.03**	**0.33**	**0.00**	**0.00**	**0.00**	**0.02**	**0.53**
4.00	**0.57**	**0.11**	**0.40**	**0.00**	**0.00**	**0.00**	**0.06**	**1.14**
6.00	**1.40**	**0.25**	**0.47**	**0.00**	**0.01**	**0.00**	**0.14**	**2.27**
7.00	**2.41**	**0.34**	**0.51**	**0.00**	**0.02**	**0.00**	**0.24**	**3.52**
8.00	**3.74**	**0.44**	**0.55**	**0.00**	**0.03**	**0.00**	**0.37**	**5.13**
8.50	**5.06**	**0.50**	**0.57**	**0.00**	**0.04**	**0.00**	**0.51**	**6.66**
+ 9.00 +	**7.93**	**0.56**	**0.59**	**0.00**	**0.06**	**0.00**	**0.79**	**9.93**
9.50 !	**10.89**	**0.62**	**0.61**	**0.00**	**0.08**	**0.00**	**1.09**	**13.29**
10.00 !	**13.86**	**0.69**	**0.63**	**0.00**	**0.11**	**0.00**	**1.39**	**16.68**

	EFFECTIVE POWER		OTHER		
SPEED [kt]	PEBARE [kW]	PETOTAL [kW]	CTLR	CTLT	RBARE/W
0.01 !	**0.0**	**0.0**	**0.05570**	**0.18484**	**0.00000**
2.00	**0.2**	**0.5**	**0.01385**	**0.05850**	**0.00051**
4.00	**1.2**	**2.3**	**0.01236**	**0.05315**	**0.00187**
6.00	**4.3**	**7.0**	**0.01946**	**0.05828**	**0.00461**
7.00	**8.7**	**12.7**	**0.03561**	**0.07373**	**0.00794**
8.00	**15.4**	**21.1**	**0.04987**	**0.08740**	**0.01230**
8.50	**22.1**	**29.1**	**0.06744**	**0.10471**	**0.01664**
+ 9.00 +	**36.7**	**46.0**	**0.10949**	**0.14651**	**0.02610**
9.50 !	**53.2**	**65.0**	**0.14376**	**0.18056**	**0.03583**
10.00 !	**71.3**	**85.8**	**0.17083**	**0.20742**	**0.04561**

Propulsion

16 Mar 2021 08:29 PM
HydroComp NavCad 2020 [Premium]

Project ID	**VFPA Tug Prediction**
Description	**SS Cates20**
File name	**SSCates20.hcnc**

Analysis parameters

Hull-propulsor interaction		
Technique:	**[Calc]**	**Prediction**
Prediction:		**Holtrop**
Reference ship:		
Max prop diam:		**1117.6 mm**
Corrections		
Viscous scale corr:	**[Off]**	
Rudder location:		
Friction line:		
Hull form factor:		
Corr allowance:		
Roughness [mm]:		
Ducted prop corr:	**[On]**	
Tunnel stern corr:	**[Off]**	

System analysis	
Cavitation criteria:	**Keller eqn**
Analysis type:	**Towing**
CPP method:	
Engine RPM:	
Mass multiplier:	
RPM constraint:	
Limit [RPM/s]:	
Water properties	
Water type:	**Salt**
Density:	**1026.00 kg/m3**
Viscosity:	**1.18920e-6 m2/s**

Prediction method check [Holtrop]

Parameters	FN [design]	CP	LWL/BWL	BWL/T
Value	**0.42**	**0.65**	**2.60***	**4.99***
Range	**0.06··0.80**	**0.55··0.85**	**3.90··14.90**	**2.10··4.00**

Prediction results [System]

	HULL-PROPULSOR				ENGINE			FUEL PER ENGINE	
SPEED [kt]	PETOTAL [kW]	WFT	THD	EFFR	RPMENG [RPM]	PBENG [kW]	LOADENG [% rated]	VOLRATE [L/h]	MASSRATE [t/h]
0.01 !	**0.0**	**0.0459**	**0.0796**	**0.9737**	**1521**	**221.5**	**84.9**	**---**	**---**
2.00	**0.5**	**0.0444**	**0.0796**	**0.9737**	**1529**	**222.4**	**85.2**	**---**	**---**
4.00	**2.3**	**0.0429**	**0.0796**	**0.9737**	**1550**	**224.8**	**86.1**	**---**	**---**
6.00	**7.0**	**0.0422**	**0.0796**	**0.9737**	**1586**	**228.8**	**87.7**	**---**	**---**
7.00	**12.7**	**0.0419**	**0.0796**	**0.9737**	**1609**	**231.2**	**88.6**	**---**	**---**
8.00	**21.1**	**0.0417**	**0.0796**	**0.9737**	**1636**	**234.3**	**89.8**	**---**	**---**
8.50	**29.1**	**0.0416**	**0.0796**	**0.9737**	**1650**	**236.0**	**90.4**	**---**	**---**
+ 9.00 +	**46.0**	**0.0415**	**0.0796**	**0.9737**	**1666**	**237.8**	**91.1**	**---**	**---**
9.50	**65.0**	**0.0414**	**0.0796**	**0.9737**	**1682**	**239.3**	**91.7**	**---**	**---**
10.00	**85.8**	**0.0414**	**0.0796**	**0.9737**	**1698**	**240.1**	**92.0**	**---**	**---**

	CO2	EFFICIENCY			THRUST		
SPEED [kt]	CO2ENG [t/h]	EFFO	EFFOA	MERIT	THRPROP [kN]	DELTHR [kN]	TOWPULL [kN]
0.01 !	**---**	**0.0011**	**0.0010**	**1.582**	**47.31**	**87.09**	**86.82**
2.00	**---**	**0.1964**	**0.1805**	**1.2767**	**41.12**	**75.70**	**75.17**
4.00	**---**	**0.3436**	**0.3154**	**1.048**	**36.31**	**66.84**	**65.71**
6.00	**---**	**0.4516**	**0.4141**	**0.86589**	**32.35**	**59.55**	**57.28**
7.00	**---**	**0.4919**	**0.4509**	**0.78482**	**30.50**	**56.15**	**52.64**
8.00	**---**	**0.5226**	**0.4790**	**0.70807**	**28.74**	**52.90**	**47.77**
8.50	**---**	**0.5344**	**0.4897**	**0.67078**	**27.85**	**51.27**	**44.61**
+ 9.00 +	**---**	**0.5436**	**0.4982**	**0.63402**	**26.96**	**49.63**	**39.70**
9.50	**---**	**0.5504**	**0.5043**	**0.59733**	**26.02**	**47.90**	**34.61**
10.00	**---**	**0.5545**	**0.5080**	**0.56022**	**24.99**	**46.00**	**29.32**

	POWER DELIVERY							
SPEED [kt]	RPMPROP [RPM]	QPROP [kN·m]	QENG [kN·m]	PDPROP [kW]	PSPROP [kW]	PSTOTAL [kW]	PBTOTAL [kW]	TRANSP
0.01 !	**380**	**5.15**	**1.39**	**210.6**	**214.9**	**429.7**	**443.0**	**0.0**
2.00	**382**	**5.14**	**1.39**	**211.4**	**215.8**	**431.5**	**444.8**	**0.0**
4.00	**388**	**5.13**	**1.38**	**213.7**	**218.1**	**436.2**	**449.7**	**0.0**
6.00	**396**	**5.10**	**1.38**	**217.5**	**221.9**	**443.9**	**457.6**	**0.0**
7.00	**402**	**5.08**	**1.37**	**219.7**	**224.2**	**448.5**	**462.3**	**0.0**
8.00	**409**	**5.06**	**1.37**	**222.7**	**227.2**	**454.5**	**468.5**	**0.0**
8.50	**413**	**5.05**	**1.37**	**224.3**	**228.9**	**457.8**	**471.9**	**0.0**
+ 9.00 +	**417**	**5.04**	**1.36**	**226.0**	**230.6**	**461.2**	**475.5**	**0.0**
9.50	**421**	**5.03**	**1.36**	**227.5**	**232.1**	**464.2**	**478.5**	**0.0**
10.00	**424**	**5.00**	**1.35**	**228.3**	**232.9**	**465.9**	**480.3**	**0.0**

Resistance

14 Mar 2021 05:37 PM
HydroComp NavCad 2020 [Premium]

Project ID **VFPA Tug Prediction**
Description **SS Raider**
File name **SSRaider.hcnc**

Analysis parameters

Vessel drag	**ITTC-78 (CT)**	**Added drag**	
Technique:	**[Calc] Prediction**	Appendage:	**[Calc] Fung (Simple FPP)**
Prediction:	**Holtrop**	Wind:	**[Calc] Fujiwara**
Reference ship:		Seas:	**[Off]**
Model LWL:		Shallow/channel:	**[Calc] Schlichting**
Expansion:	**Custom**	Towed:	**[Off]**
Friction line:	**ITTC-57**	Margin:	**[Calc] Hull drag only [10%]**
Hull form factor:	**[Off]**	**Water properties**	
Speed corr:		Water type:	**Salt**
Spray drag corr:	**[Off]**	Density:	**1026.00 kg/m3**
Corr allowance:	**0.000800**	Viscosity:	**1.18920e-6 m2/s**
Roughness [mm]:	**[Off]**		

Prediction method check [Holtrop]

Parameters	FN [design]	CP	LWL/BWL	BWL/T	Lambda
Value	**0.35**	**0.63**	**3.09***	**3.27**	**0.82**
Range	**0.06··0.46**	**0.55··0.85**	**3.90··14.90**	**2.10··4.00**	**0.01··0.92**

Prediction results

	SPEED COEFS		ITTC-78 COEFS						
SPEED [kt]	FN	FV	RN	CF	[CV/CF]	CR	dCF	CA	CT
0.01 !	**0.000**	**0.001**	**1.39e5**	**0.007586**	**1.000**	**0.005085**	**0.000000**	**0.000800**	**0.013471**
2.00 !	**0.058**	**0.114**	**2.79e7**	**0.002529**	**1.000**	**0.001188**	**0.000000**	**0.000800**	**0.004517**
4.00	**0.116**	**0.229**	**5.58e7**	**0.002271**	**1.000**	**0.001003**	**0.000000**	**0.000800**	**0.004074**
6.00	**0.174**	**0.343**	**8.37e7**	**0.002138**	**1.000**	**0.000948**	**0.000000**	**0.000800**	**0.003886**
8.00	**0.231**	**0.458**	**1.12e8**	**0.002051**	**1.000**	**0.001200**	**0.000000**	**0.000800**	**0.004051**
9.00	**0.260**	**0.515**	**1.25e8**	**0.002017**	**1.000**	**0.001655**	**0.000000**	**0.000800**	**0.004472**
10.00	**0.289**	**0.572**	**1.39e8**	**0.001987**	**1.000**	**0.002746**	**0.000000**	**0.000800**	**0.005533**
11.00	**0.318**	**0.630**	**1.53e8**	**0.001960**	**1.000**	**0.004146**	**0.000000**	**0.000800**	**0.006907**
+ 12.00 +	**0.347**	**0.687**	**1.67e8**	**0.001936**	**1.000**	**0.005151**	**0.000000**	**0.000800**	**0.007888**
13.00	**0.376**	**0.744**	**1.81e8**	**0.001915**	**1.000**	**0.007000**	**0.000000**	**0.000800**	**0.009715**

	RESISTANCE								
SPEED [kt]	RBARE [kN]	RAPP [kN]	RWIND [kN]	RSEAS [kN]	RCHAN [kN]	RTOWED [kN]	RMARGIN [kN]	RTOTAL [kN]	
0.01 !	**0.00**	**0.00**	**2.81**	**0.00**	**0.00**	**0.00**	**0.00**	**2.81**	
2.00 !	**0.91**	**0.15**	**3.43**	**0.00**	**0.06**	**0.00**	**0.09**	**4.65**	
4.00	**3.29**	**0.59**	**4.12**	**0.00**	**0.23**	**0.00**	**0.33**	**8.56**	
6.00	**7.06**	**1.32**	**4.87**	**0.00**	**0.50**	**0.00**	**0.71**	**14.45**	
8.00	**13.08**	**2.35**	**5.67**	**0.00**	**0.93**	**0.00**	**1.31**	**23.34**	
9.00	**18.28**	**2.97**	**6.10**	**0.00**	**1.30**	**0.00**	**1.83**	**30.48**	
10.00	**27.92**	**3.67**	**6.55**	**0.00**	**2.01**	**0.00**	**2.79**	**42.94**	
11.00	**42.18**	**4.44**	**7.01**	**0.00**	**3.16**	**0.00**	**4.22**	**61.00**	
+ 12.00 +	**57.32**	**5.28**	**7.48**	**0.00**	**4.73**	**0.00**	**5.73**	**80.55**	
13.00	**82.86**	**6.20**	**7.97**	**0.00**	**8.09**	**0.00**	**8.29**	**113.41**	

	EFFECTIVE POWER		OTHER		
SPEED [kt]	PEBARE [kW]	PETOTAL [kW]	CTLR	CTLT	RBARE/W
0.01 !	**0.0**	**0.0**	**0.05453**	**0.14445**	**0.00000**
2.00 !	**0.9**	**4.8**	**0.01274**	**0.04844**	**0.00016**
4.00	**6.8**	**17.6**	**0.01075**	**0.04369**	**0.00059**
6.00	**21.8**	**44.6**	**0.01016**	**0.04167**	**0.00126**
8.00	**53.8**	**96.1**	**0.01287**	**0.04344**	**0.00233**
9.00	**84.6**	**141.1**	**0.01775**	**0.04795**	**0.00325**
10.00	**143.7**	**220.9**	**0.02945**	**0.05933**	**0.00497**
11.00	**238.7**	**345.2**	**0.04446**	**0.07406**	**0.00750**
+ 12.00 +	**353.9**	**497.2**	**0.05524**	**0.08458**	**0.01020**
13.00	**554.1**	**758.4**	**0.07506**	**0.10418**	**0.01474**

Propulsion

14 Mar 2021 05:40 PM
HydroComp NavCad 2020 [Premium]

Project ID	**VFPA Tug Prediction**
Description	**SS Raider**
File name	**SSRaider.hcnc**

Analysis parameters

Hull-propulsor interaction	
Technique:	**[Calc] Prediction**
Prediction:	**Holtrop**
Reference ship:	
Max prop diam:	**2400.0 mm**
Corrections	
Viscous scale corr:	**[Off]**
Rudder location:	
Friction line:	
Hull form factor:	
Corr allowance:	
Roughness [mm]:	
Ducted prop corr:	**[On]**
Tunnel stern corr:	**[Off]**

System analysis	
Cavitation criteria:	**Keller eqn**
Analysis type:	**Towing**
CPP method:	
Engine RPM:	
Mass multiplier:	
RPM constraint:	
Limit [RPM/s]:	
Water properties	
Water type:	**Salt**
Density:	**1026.00 kg/m3**
Viscosity:	**1.18920e-6 m2/s**

Prediction method check [Holtrop]

Parameters	FN [design]	CP	LWL/BWL	BWL/T
Value	**0.35**	**0.63**	**3.09***	**3.27**
Range	**0.06··0.80**	**0.55··0.85**	**3.90··14.90**	**2.10··4.00**

Prediction results [System]

	HULL-PROPULSOR				ENGINE			FUEL PER ENGINE	
SPEED [kt]	PETOTAL [kW]	WFT	THD	EFFR	RPMENG [RPM]	PBENG [kW]	LOADENG [% rated]	VOLRATE [L/h]	MASSRATE [t/h]
0.01 !	**0.0**	**0.0515**	**0.0911**	**0.9891**	**726**	**1303.4**	**97.1**	**---**	**---**
2.00 !	**4.8**	**0.0513**	**0.0911**	**0.9891**	**729**	**1304.4**	**97.2**	**---**	**---**
4.00	**17.6**	**0.0502**	**0.0911**	**0.9891**	**736**	**1307.3**	**97.4**	**---**	**---**
6.00	**44.6**	**0.0497**	**0.0911**	**0.9891**	**749**	**1311.5**	**97.7**	**---**	**---**
8.00	**96.1**	**0.0493**	**0.0911**	**0.9891**	**750**	**1220.2**	**90.9**	**---**	**---**
9.00	**141.1**	**0.0492**	**0.0911**	**0.9891**	**750**	**1160.8**	**86.5**	**---**	**---**
10.00	**220.9**	**0.0491**	**0.0911**	**0.9891**	**750**	**1093.2**	**81.4**	**---**	**---**
11.00	**345.2**	**0.0490**	**0.0911**	**0.9891**	**750**	**1017.0**	**75.8**	**---**	**---**
+ 12.00 +	**497.2**	**0.0489**	**0.0911**	**0.9891**	**750**	**931.9**	**69.4**	**---**	**---**
13.00	**758.4**	**0.0488**	**0.0911**	**0.9891**	**750**	**837.3**	**62.4**	**---**	**---**

	CO2	EFFICIENCY			THRUST		
SPEED [kt]	CO2ENG [t/h]	EFFO	EFFOA	MERIT	THRPROP [kN]	DELTHR [kN]	TOWPULL [kN]
0.01 !	**---**	**0.0010**	**0.0010**	**1.5641**	**257.40**	**467.89**	**465.08**
2.00 !	**---**	**0.1807**	**0.1678**	**1.2945**	**227.01**	**412.65**	**408.01**
4.00	**---**	**0.3194**	**0.2963**	**1.075**	**200.86**	**365.12**	**356.56**
6.00	**---**	**0.4213**	**0.3905**	**0.88704**	**177.09**	**321.90**	**307.45**
8.00	**---**	**0.4910**	**0.4550**	**0.6989**	**143.97**	**261.70**	**238.36**
9.00	**---**	**0.5084**	**0.4711**	**0.60181**	**126.04**	**229.11**	**198.63**
10.00	**---**	**0.5097**	**0.4722**	**0.50045**	**107.09**	**194.66**	**151.72**
11.00	**---**	**0.4891**	**0.4531**	**0.39327**	**86.91**	**157.98**	**96.97**
+ 12.00 +	**---**	**0.4376**	**0.4053**	**0.27954**	**65.30**	**118.70**	**38.15**
13.00	**---**	**0.3399**	**0.3148**	**0.16083**	**42.06**	**76.45**	**-36.95**

	POWER DELIVERY							
SPEED [kt]	RPMPROP [RPM]	QPROP [kN·m]	QENG [kN·m]	PDPROP [kW]	PSPROP [kW]	PSTOTAL [kW]	PBTOTAL [kW]	TRANSP
0.01 !	**242**	**48.36**	**17.14**	**1239.0**	**1264.3**	**2528.6**	**2606.8**	**0.0**
2.00 !	**243**	**48.22**	**17.09**	**1240.0**	**1265.3**	**2530.5**	**2608.8**	**0.0**
4.00	**245**	**47.82**	**16.95**	**1242.7**	**1268.1**	**2536.1**	**2614.6**	**0.0**
6.00	**250**	**47.15**	**16.72**	**1246.7**	**1272.2**	**2544.4**	**2623.1**	**0.0**
8.00	**250**	**43.82**	**15.53**	**1159.9**	**1183.6**	**2367.2**	**2440.4**	**0.0**
9.00	**250**	**41.68**	**14.78**	**1103.4**	**1125.9**	**2251.9**	**2321.5**	**0.0**
10.00	**250**	**39.25**	**13.92**	**1039.2**	**1060.4**	**2120.7**	**2186.3**	**0.0**
11.00	**250**	**36.51**	**12.95**	**966.8**	**986.5**	**1973.0**	**2034.0**	**0.0**
+ 12.00 +	**250**	**33.45**	**11.86**	**885.8**	**903.9**	**1807.8**	**1863.7**	**0.0**
13.00	**250**	**30.05**	**10.66**	**795.9**	**812.1**	**1624.3**	**1674.5**	**0.0**

Resistance

14 Mar 2021 01:54 PM
HydroComp NavCad 2020 [Premium]

Project ID **VFPA - Tug Prediction**
Description **SS Royal**
File name **SSRoyal_1.hcnc**

Analysis parameters

Vessel drag		**ITTC-78 (CT)**
Technique:	**[Calc]**	**Prediction**
Prediction:		**Holtrop**
Reference ship:		
Model LWL:		
Expansion:		**Custom**
Friction line:		**ITTC-57**
Hull form factor:	**[Off]**	
Speed corr:		
Spray drag corr:	**[Off]**	
Corr allowance:		**0.000800**
Roughness [mm]:	**[Off]**	

Added drag	
Appendage:	**[Calc] Fung (Simple FPP)**
Wind:	**[Calc] Fujiwara**
Seas:	**[Off]**
Shallow/channel:	**[Calc] Schlichting**
Towed:	**[Off]**
Margin:	**[Calc] Hull drag only [10%]**

Water properties	
Water type:	**Salt**
Density:	**1026.00 kg/m3**
Viscosity:	**1.18920e-6 m2/s**

Prediction method check [Holtrop]

Parameters	FN [design]	CP	LWL/BWL	BWL/T	Lambda
Value	**0.32**	**0.63**	**3.32***	**3.37**	**0.82**
Range	**0.06··0.46**	**0.55··0.85**	**3.90··14.90**	**2.10··4.00**	**0.01··0.94**

Prediction results

	SPEED COEFS		ITTC-78 COEFS						
SPEED [kt]	FN	FV	RN	CF	[CV/CF]	CR	dCF	CA	CT
0.01 !	**0.000**	**0.001**	**1.69e5**	**0.007200**	**1.000**	**0.004868**	**0.000000**	**0.000800**	**0.012868**
2.00 !	**0.053**	**0.107**	**3.38e7**	**0.002454**	**1.000**	**0.001113**	**0.000000**	**0.000800**	**0.004367**
4.00	**0.105**	**0.214**	**6.75e7**	**0.002207**	**1.000**	**0.000940**	**0.000000**	**0.000800**	**0.003947**
6.00	**0.158**	**0.321**	**1.01e8**	**0.002079**	**1.000**	**0.000879**	**0.000000**	**0.000800**	**0.003758**
8.00	**0.210**	**0.428**	**1.35e8**	**0.001996**	**1.000**	**0.000998**	**0.000000**	**0.000800**	**0.003793**
9.00	**0.237**	**0.481**	**1.52e8**	**0.001963**	**1.000**	**0.001281**	**0.000000**	**0.000800**	**0.004043**
10.00	**0.263**	**0.535**	**1.69e8**	**0.001934**	**1.000**	**0.001799**	**0.000000**	**0.000800**	**0.004533**
11.00	**0.289**	**0.588**	**1.86e8**	**0.001909**	**1.000**	**0.002923**	**0.000000**	**0.000800**	**0.005631**
+ 12.00 +	**0.316**	**0.642**	**2.03e8**	**0.001886**	**1.000**	**0.004255**	**0.000000**	**0.000800**	**0.006941**
13.00	**0.342**	**0.695**	**2.19e8**	**0.001865**	**1.000**	**0.005120**	**0.000000**	**0.000800**	**0.007785**

	RESISTANCE							
SPEED [kt]	RBARE [kN]	RAPP [kN]	RWIND [kN]	RSEAS [kN]	RCHAN [kN]	RTOWED [kN]	RMARGIN [kN]	RTOTAL [kN]
0.01 !	**0.00**	**0.00**	**3.32**	**0.00**	**0.00**	**0.00**	**0.00**	**3.32**
2.00 !	**1.19**	**0.22**	**4.05**	**0.00**	**0.11**	**0.00**	**0.12**	**5.69**
4.00	**4.30**	**0.89**	**4.86**	**0.00**	**0.39**	**0.00**	**0.43**	**10.88**
6.00	**9.22**	**2.00**	**5.74**	**0.00**	**0.84**	**0.00**	**0.92**	**18.72**
8.00	**16.55**	**3.55**	**6.70**	**0.00**	**1.51**	**0.00**	**1.65**	**29.96**
9.00	**22.32**	**4.49**	**7.20**	**0.00**	**2.04**	**0.00**	**2.23**	**38.29**
10.00	**30.90**	**5.54**	**7.73**	**0.00**	**2.85**	**0.00**	**3.09**	**50.11**
11.00	**46.44**	**6.71**	**8.27**	**0.00**	**4.43**	**0.00**	**4.64**	**70.48**
+ 12.00 +	**68.11**	**7.98**	**8.83**	**0.00**	**7.01**	**0.00**	**6.81**	**98.74**
13.00	**89.67**	**9.37**	**9.41**	**0.00**	**10.51**	**0.00**	**8.97**	**127.92**

	EFFECTIVE POWER		OTHER		
SPEED [kt]	PEBARE [kW]	PETOTAL [kW]	CTLR	CTLT	RBARE/W
0.01 !	**0.0**	**0.0**	**0.05681**	**0.15017**	**0.00000**
2.00 !	**1.2**	**5.9**	**0.01299**	**0.05096**	**0.00014**
4.00	**8.9**	**22.4**	**0.01097**	**0.04606**	**0.00051**
6.00	**28.5**	**57.8**	**0.01026**	**0.04386**	**0.00109**
8.00	**68.1**	**123.3**	**0.01164**	**0.04427**	**0.00196**
9.00	**103.3**	**177.3**	**0.01494**	**0.04719**	**0.00264**
10.00	**158.9**	**257.8**	**0.02100**	**0.05290**	**0.00366**
11.00	**262.8**	**398.9**	**0.03411**	**0.06572**	**0.00550**
+ 12.00 +	**420.5**	**609.6**	**0.04965**	**0.08100**	**0.00807**
13.00	**599.7**	**855.5**	**0.05975**	**0.09085**	**0.01062**

Propulsion

14 Mar 2021 01:52 PM
HydroComp NavCad 2020 [Premium]

Project ID	**VFPA - Tug Prediction**
Description	**SS Royal**
File name	**SSRoyal_1.hcnc**

Analysis parameters

Hull-propulsor interaction	
Technique:	**[Calc] Prediction**
Prediction:	**Holtrop**
Reference ship:	
Max prop diam:	**3048.0 mm**
Corrections	
Viscous scale corr:	**[Off]**
Rudder location:	
Friction line:	
Hull form factor:	
Corr allowance:	
Roughness [mm]:	
Ducted prop corr:	**[On]**
Tunnel stern corr:	**[Off]**

System analysis	
Cavitation criteria:	**Keller eqn**
Analysis type:	**Towing**
CPP method:	
Engine RPM:	
Mass multiplier:	
RPM constraint:	
Limit [RPM/s]:	
Water properties	
Water type:	**Salt**
Density:	**1026.00 kg/m3**
Viscosity:	**1.18920e-6 m2/s**

Prediction method check [Holtrop]

Parameters	FN [design]	CP	LWL/BWL	BWL/T
Value	**0.32**	**0.63**	**3.32***	**3.37**
Range	**0.06··0.80**	**0.55··0.85**	**3.90··14.90**	**2.10··4.00**

Prediction results [System]

	HULL-PROPULSOR				ENGINE			FUEL PER ENGINE	
SPEED [kt]	PETOTAL [kW]	WFT	THD	EFFR	RPMENG [RPM]	PBENG [kW]	LOADENG [% rated]	VOLRATE [L/h]	MASSRATE [t/h]
0.01 !	**0.0**	**0.0433**	**0.0810**	**0.9818**	**881**	**2227.1**	**96.3**	**---**	**---**
2.00 !	**5.9**	**0.0432**	**0.0810**	**0.9818**	**884**	**2228.7**	**96.4**	**---**	**---**
4.00	**22.4**	**0.0422**	**0.0810**	**0.9818**	**893**	**2233.4**	**96.6**	**---**	**---**
6.00	**57.8**	**0.0417**	**0.0810**	**0.9818**	**900**	**2182.7**	**94.4**	**---**	**---**
8.00	**123.3**	**0.0413**	**0.0810**	**0.9818**	**900**	**2030.6**	**87.8**	**---**	**---**
9.00	**177.3**	**0.0412**	**0.0810**	**0.9818**	**900**	**1936.0**	**83.8**	**---**	**---**
10.00	**257.8**	**0.0411**	**0.0810**	**0.9818**	**900**	**1828.3**	**79.1**	**---**	**---**
11.00	**398.9**	**0.0410**	**0.0810**	**0.9818**	**900**	**1706.6**	**73.8**	**---**	**---**
+ 12.00 +	**609.6**	**0.0409**	**0.0810**	**0.9818**	**900**	**1570.1**	**67.9**	**---**	**---**
13.00	**855.5**	**0.0408**	**0.0810**	**0.9818**	**900**	**1418.1**	**61.3**	**---**	**---**

	CO2	EFFICIENCY			THRUST		
SPEED [kt]	CO2ENG [t/h]	EFFO	EFFOA	MERIT	THRPROP [kN]	DELTHR [kN]	TOWPULL [kN]
0.01 !	**---**	**0.0012**	**0.0011**	**1.9503**	**497.36**	**914.14**	**910.82**
2.00 !	**---**	**0.2079**	**0.1921**	**1.6173**	**439.22**	**807.29**	**801.60**
4.00	**---**	**0.3690**	**0.3406**	**1.3515**	**390.22**	**717.22**	**706.35**
6.00	**---**	**0.4931**	**0.4550**	**1.1226**	**339.58**	**624.14**	**605.42**
8.00	**---**	**0.5816**	**0.5365**	**0.9006**	**279.40**	**513.53**	**483.57**
9.00	**---**	**0.6077**	**0.5605**	**0.78695**	**247.38**	**454.68**	**416.38**
10.00	**---**	**0.6172**	**0.5692**	**0.6682**	**213.51**	**392.43**	**342.32**
11.00	**---**	**0.6043**	**0.5572**	**0.54202**	**177.37**	**326.00**	**255.52**
+ 12.00 +	**---**	**0.5597**	**0.5161**	**0.40668**	**138.54**	**254.64**	**155.89**
13.00	**---**	**0.4682**	**0.4316**	**0.26217**	**96.60**	**177.55**	**49.63**

	POWER DELIVERY							
SPEED [kt]	RPMPROP [RPM]	QPROP [kN·m]	QENG [kN·m]	PDPROP [kW]	PSPROP [kW]	PSTOTAL [kW]	PBTOTAL [kW]	TRANSP
0.01 !	**176**	**112.66**	**24.14**	**2117.1**	**2160.3**	**4320.5**	**4454.1**	**0.0**
2.00 !	**177**	**112.35**	**24.08**	**2118.6**	**2161.9**	**4323.8**	**4457.5**	**0.0**
4.00	**179**	**111.48**	**23.89**	**2123.1**	**2166.4**	**4332.8**	**4466.8**	**0.0**
6.00	**180**	**108.07**	**23.16**	**2074.9**	**2117.2**	**4234.4**	**4365.4**	**0.0**
8.00	**180**	**100.54**	**21.54**	**1930.3**	**1969.7**	**3939.4**	**4061.2**	**0.0**
9.00	**180**	**95.85**	**20.54**	**1840.4**	**1878.0**	**3755.9**	**3872.1**	**0.0**
10.00	**180**	**90.51**	**19.39**	**1738.0**	**1773.4**	**3546.9**	**3656.5**	**0.0**
11.00	**180**	**84.48**	**18.10**	**1622.3**	**1655.4**	**3310.8**	**3413.2**	**0.0**
+ 12.00 +	**180**	**77.72**	**16.65**	**1492.6**	**1523.0**	**3046.1**	**3140.3**	**0.0**
13.00	**180**	**70.19**	**15.04**	**1348.0**	**1375.5**	**2751.1**	**2836.2**	**0.0**