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Predicting Tug Behaviour by Analysis of the Rated Performance of Coastal Tugs

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SYNOPSIS

When approached to develop a new generation of coastal 'line-haul' tugs for British Columbian waters, Robert Allan Ltd proposed that the first step should be a thorough review of the opinions of crews on the performance of the current tug fleet, which the new design would ultimately replace. Since the majority of the current tug fleet was built more than 30 years ago, there is a lot of sea-miles of experience attached to those designs. An extensive study was performed on a sample of 11 tugs to identify in engineering terms those design parameters which result in crew ratings of 'very good' compared to 'poor' for a wide range of performance-related characteristics. The results were critical in guiding the development of a completely new standard design.

INTRODUCTION

The coast of British Columbia, as illustrated in *Figure 1*, is extensive, rugged, remote, and has no comprehensive means of access to the various coastal communities except by air and primarily by water. The coast is, for the most part, well-protected from Pacific storms by the barrier of islands that extends for hundreds of miles from the Washington state border in the south to the Alaskan border in the north, a distance of about 700 nautical miles. The industries along the coast are almost exclusively resource-based, and comprise primarily forestry, fisheries, and to a lesser extent mining.

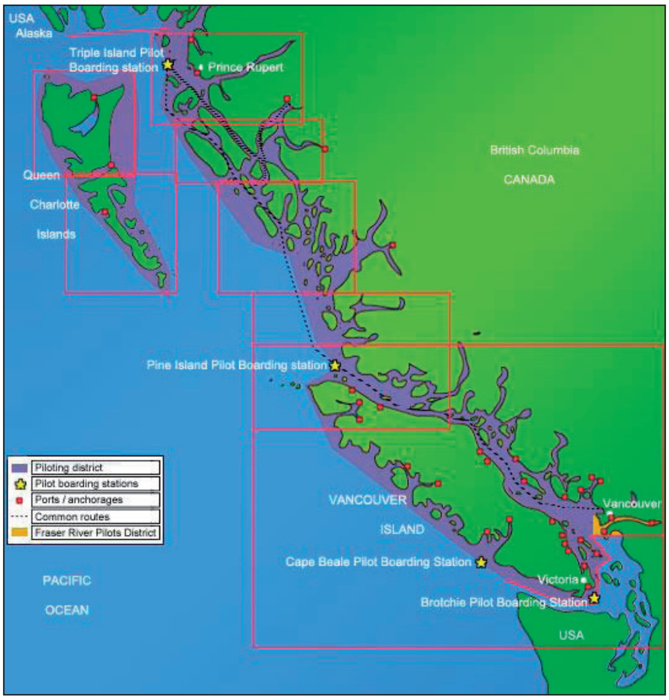


Figure 1: Coastal British Columbia (courtesy BC Coast Pilots website).

The movement of goods along the BC coast has evolved over the past century to consist now almost exclusively of tug and barge transportation. Barges typically carry logs, lumber, paper, pulp, wood chips, gravel, limerick, bulk cement, clinker, oil, general cargo and, in limited quantities, containers. Tugs tow one, two or three barges at a time, depending on the voyage.

Products are mostly relatively low value, and volumes are relatively small, hence ideal candidates for this form of transport. *Figures 2-10* illustrate some of these typical tows. The heyday of the industry in the 1960s was well-described by Robert F Allan and others at *ITS Conventions* in the 1970s[2,3].

Figures 2-10: Typical tugs and barge tows on the BC Coast.

Figure 2: Refined oil products barge under tow.

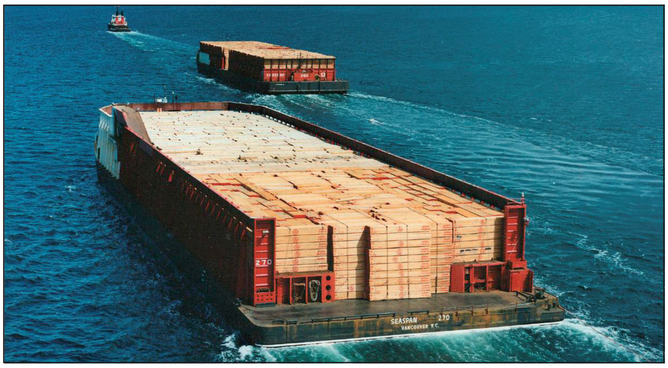


Figure 3: Tandem tow of deck barges loaded with lumber.

Figure 4: Triple tow of chip barges in Howe Sound near Vancouver. Barges are connected with short nylon 'couplers'.

Figure 5: Covered deck cargo barges are used for transport of newsprint, pulp and similar products.

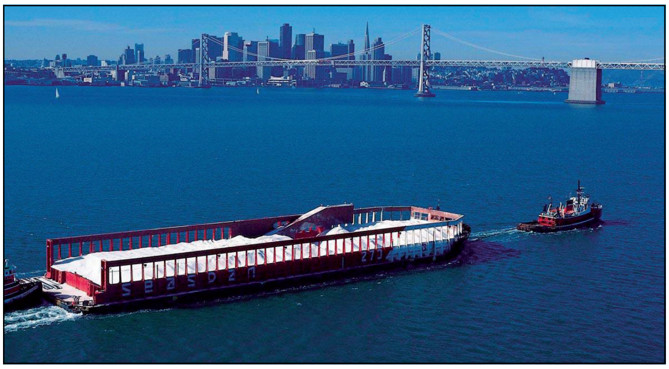


Figure 6: Large bulk cargo barges are commonly used for products such as salt (illustrated), gravel, limerock and stone. Some are equipped with built-in hoppers for cargo discharge.

Figure 7: Railcar transportation by tug and barge; common between Vancouver and Vancouver Island.

Figure 8: Special deck cargoes come in many shapes and sizes.

Figure 9: Self loading/self-dumping barges are used to transport logs from remote coastal areas to sorting grounds close to mill sites.

Figure 10: Empty limerock deck cargo barge (10,000T dwt) in Vancouver Harbour.

The majority of vessels operating in this coastal trade were built between 1963 and 1975, and many came from the drawing boards of Robert Allan Ltd. Tugs are typically less than 28m in length, and less than 1,500kW in power. The barges are for the most part less than 5,000 tonnes dwt, except for a few large bulk cargo barges (which are up to 20,000 tonnes dwt). However, the ravages of time and a demanding service are taking their ultimate toll on these vessels, and freight rates have not kept pace with the cost of transportation, making capital re-investment in modern, more fuel-efficient vessels a significant challenge to the industry. Regardless, some owners recognise the need to plan for the future replacement of the fleet, now approaching an average age of 40 years.

In 2007, Robert Allan Ltd was retained by Seaspan International Ltd of Vancouver to start planning for a new ‘standard’ coastal tug which could be built in series to ultimately replace the current fleet. Although clearly one tug design cannot be suitable for every towing duty on the coast, there are many routes where common performance requirements exist. In commencing this new study, it was proposed by Robert Allan Ltd that it would be wise to attempt to evaluate the relative merits of the tugs within the existing fleet, and thereby gain an understanding of what it is, in the eyes of a tug crew, (as well as the owner), that makes one tug ‘really good’ versus one that is covered by a less favourable (and possibly unprintable!) description.

As designers, we seldom get the direct operator feedback that enables us to make these determinations, and although on balance we get far more positive feedback than negative, it is still difficult to define the often subtle characteristics that make the key differences. Many times we are faced with having to provide a ‘proven’ design, but never is it defined precisely what that means. At the lowest common denominator it means the boat floats. At best it means that a free-running speed and a bollard pull must have been achieved. But was the boat comfortable in a seaway or did the crew get thrown about? Did it buck through rough seas well, and could it tow well in adverse conditions? Did seas get thrown well off to the side, or did they come regularly over the wheelhouse top? Faced with having to create a new generation of tug that could well be expected to last another 40 years in this BC coast service, it was deemed essential to gain a much better appreciation of the hull and performance characteristics that make these critical differences in the current fleet.

A sample of tugs from the existing fleet was selected and subjected to a fairly extensive analysis in an attempt to bring some science to the subjective commentary of the crews, and to then hopefully reflect those desirable characteristics in the design of the new standard series tug design.

All vessels evaluated are coastal towing tugs with the exception of ***Atlantic Fir***, which is a high performance, Z-drive, ship-handling tug. Although ***Atlantic Fir*** is designed for a different service, it was felt that her reputation for excellent sea-keeping made for a worthwhile addition to the historical analysis. Excluding ***Atlantic Beech*** and ***Atlantic Fir***, all vessels are currently in the Seaspan west coast fleet.

The vessels are listed below in order of increasing length, with generalised crew opinions shown. General arrangement drawings and photographs of the tugs are shown on the following pages.

Figure 11: ***Seaspan Cutlass***
– has a reputation as a poor sea boat;
– pretty good pulling boat;

Figure 12: ***Seaspan Master****
– considered a good towing boat;

Figure 13: ***Seaspan Champion****
– has a reputation as a good sea boat;
– has good rough weather characteristics;

Figure 14: ***Seaspan Lorne****
– has a reputation as a very good sea boat;
– has always been very well liked by crews;

Figure 15: ***Seaspan Queen****
– known as a good sea boat;
– has good towing performance; out-pulls her sister, ***Seaspan Pacer,*** which has 400 more bkW;

Figure 16: ***Seaspan Pacer****
– has the same hull as the ***Seaspan Queen***, but has a poor towing reputation;

Figure 17: ***Atlantic Beech*****
– known as an excellent sea boat;

Figure 18: ***Atlantic Fir*****
– this vessel, and others of the same class, have made numerous trans-Atlantic crossings and work in the North Sea and Irish Sea. Feedback from crews regarding their sea-keeping performance has been extremely positive, especially for those vessels fitted with ‘escort’ skegs;

Figure 19: ***Seaspan Monarch****
– is a good model for accommodation standards and general towing performance, but is considered under-powered for her size by modern standards;

Figure 20: ***Seaspan Sovereign***
– has a reputation as a good sea boat;

Figure 21: ***Seaspan King****
– has a reputation for severe pitching in rough weather, but known as a good pulling tug generally.

* Vessels designed by Robert Allan Ltd, between 1959 and 1973.

** ***Atlantic Beech*** and ***Atlantic Fir***, also designed by Robert Allan Ltd, operate in the Atlantic Ocean and have never been in BC. Although their performance in weather and sea conditions similar to those experienced by the local fleet has not been documented or tested to our knowledge, their operating environments are generally much more severe than on the west coast.

Figure 11: **Seaspan Cutlass**.

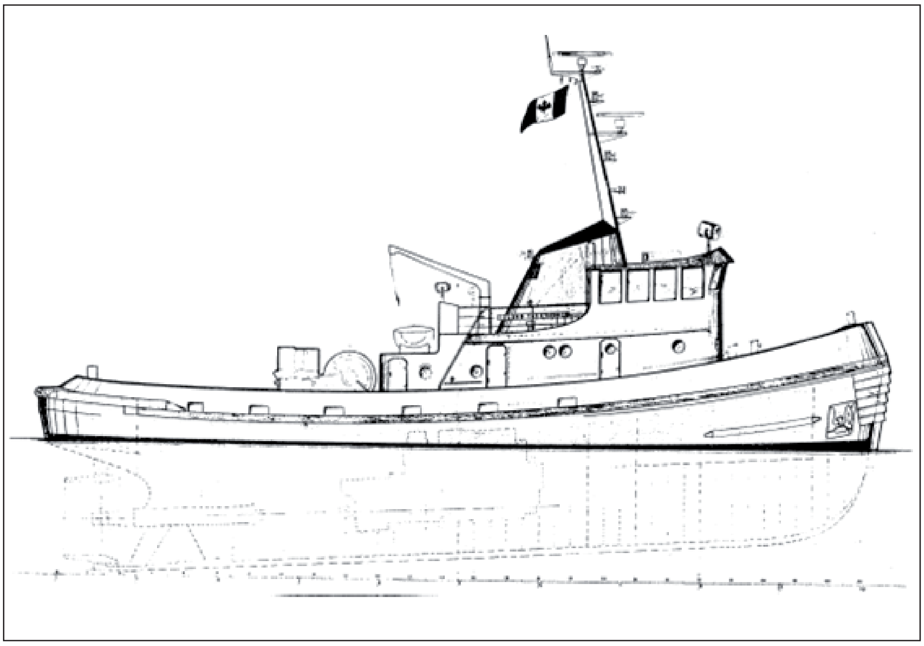


Figure 12: **Seaspan Master**.

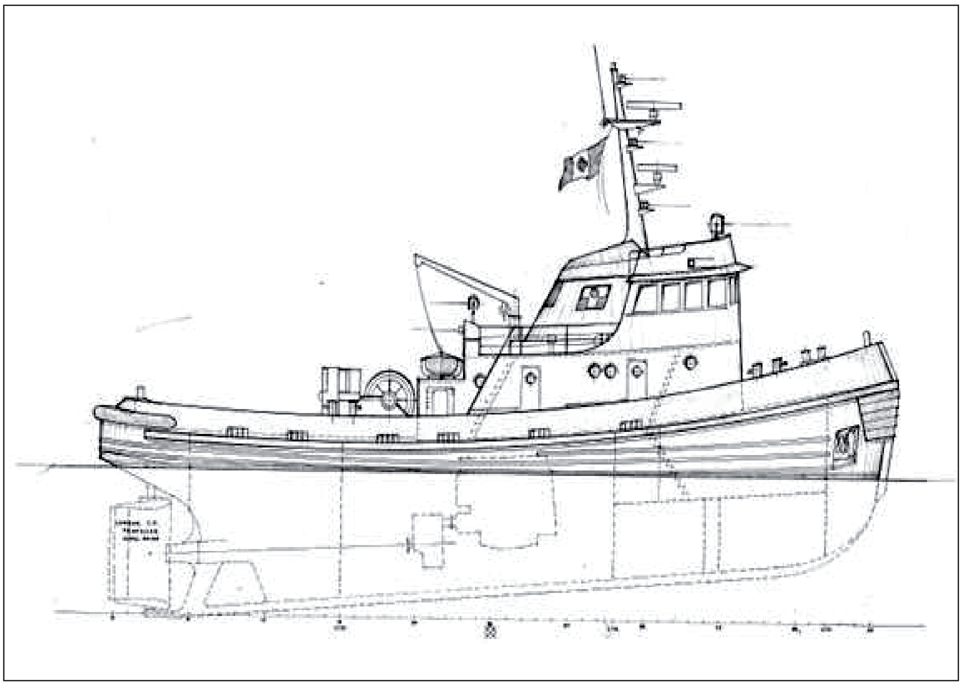


Figure 13: **Seaspan Champion**.

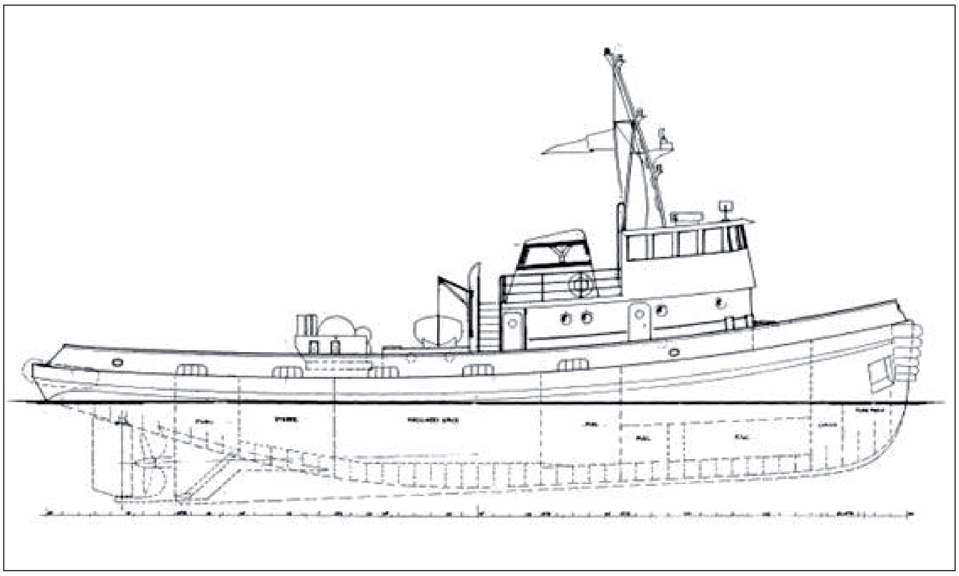


Figure 14: **Seaspan Lorne***.*

Figure 15: **Seaspan Queen**.

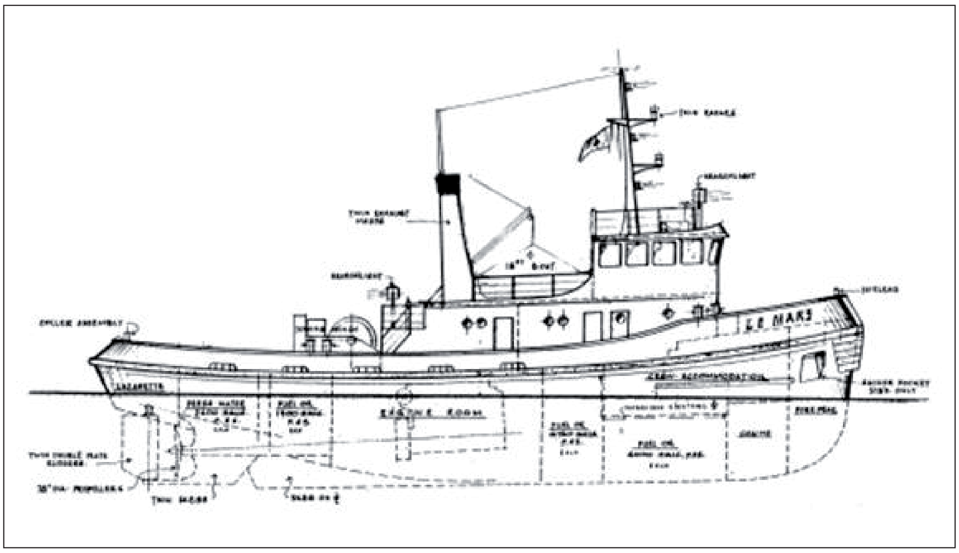


Figure 16: **Seaspan Pacer***.*

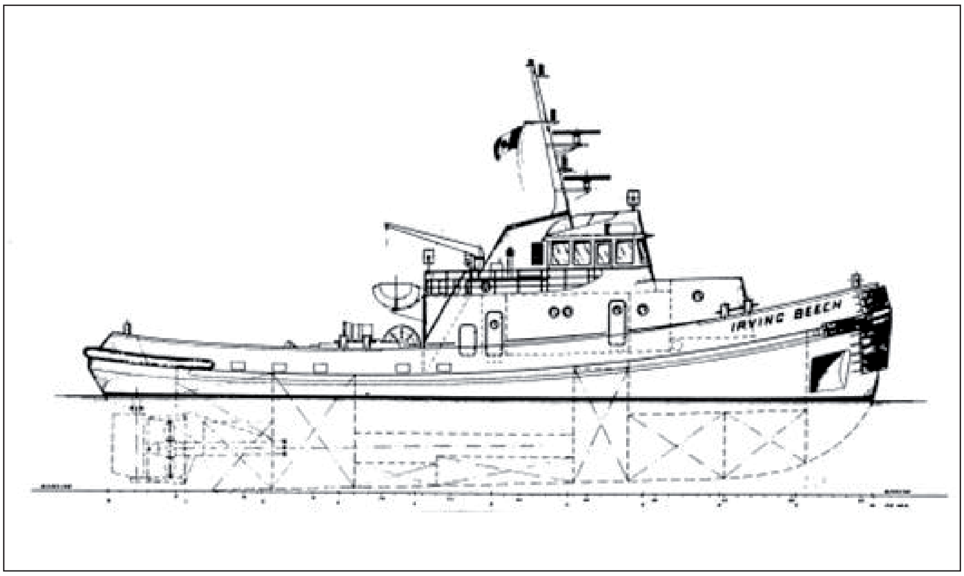


Figure 17: **Atlantic Beech**.

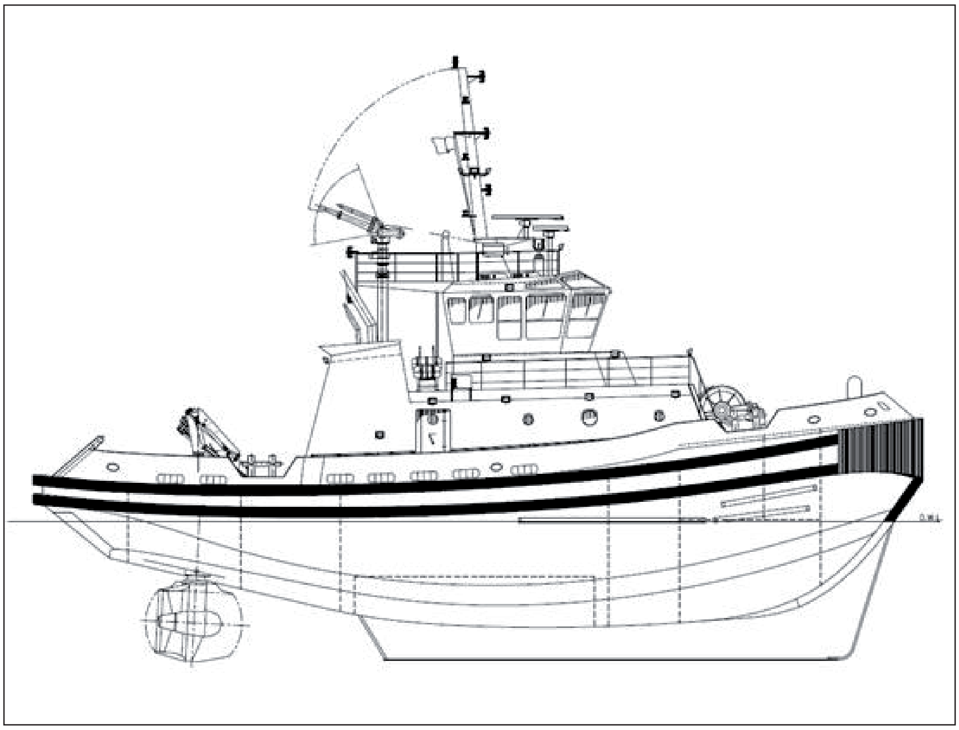


Figure 18: **Atlantic Fir**.

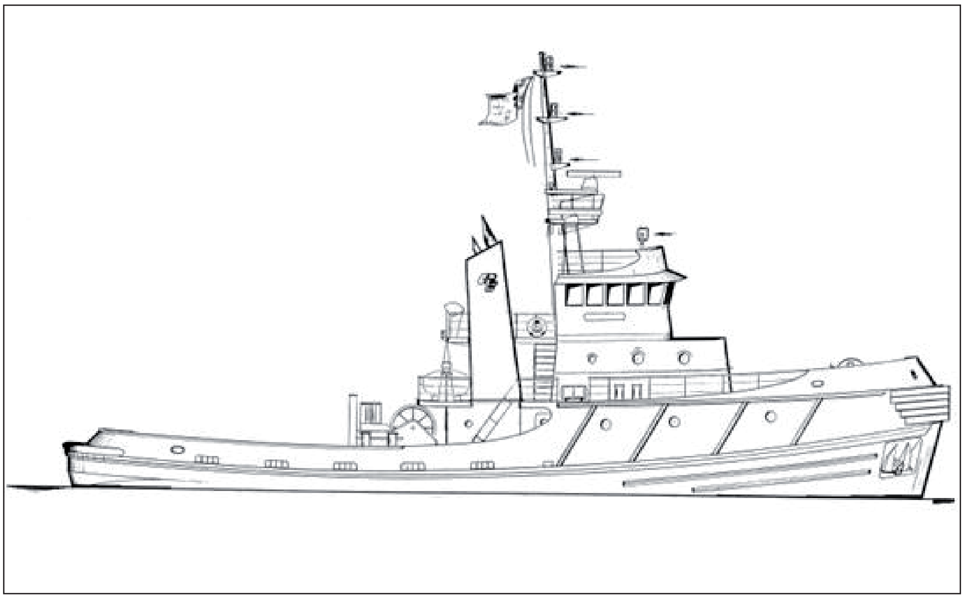


Figure 19: **Seaspan Monarch**.

Figure 20: **Seaspan Sovereign**.

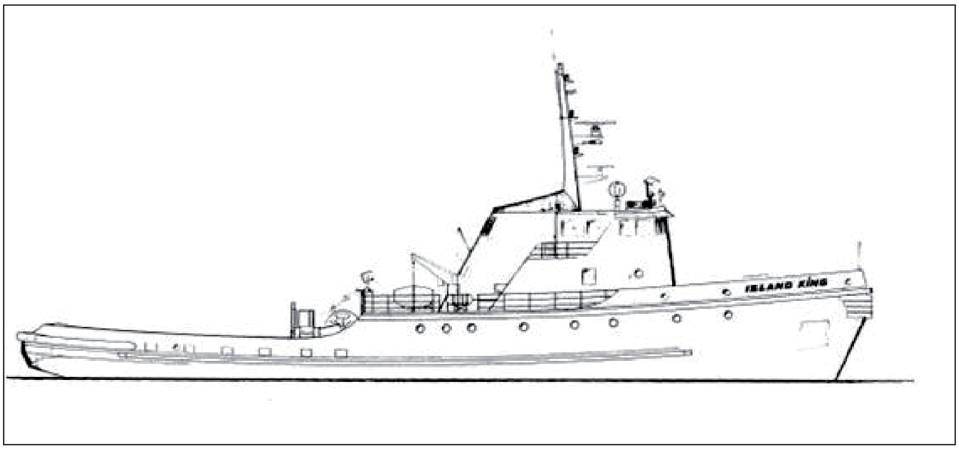


Figure 21: **Seaspan King**.

Table 1 (see next page) shows the basic particulars of the tug sample. In order to analyse and quantify the behaviour of these tugs, the following design parameters were selected as the basis of comparison:

Sea-Keeping

- Weights;
- Form coefficients: C_b, C_m, C_p, $C_{w;}$
- Displacement/Length Ratio [Disp/(0.01L)^3];
- Proportions:
  - – L/B
  - – B/D
  - – B/T
  - – KG/D Ratio
  - – GM/B Ratio;
- Sectional area curve;
- Reserve buoyancy at stations 8 and 9 (forward end);
- Section flare angles at stations 8 and 9 (forward end);
- ½ angle of entry of waterline;
- Intact stability characteristics;
- ABS towline stability criteria;
- Weight distribution characteristics;
- Calculated natural pitch period in departure condition;
- Calculated natural roll period in departure condition.

Further, in an attempt to categorise the behaviour of these tugs, they have been rated as Type A, B, or C, where:

A – generally has an all-round good reputation for towing ability and sea-keeping;

B – has a reasonable, but qualified reputation for good performance;

C – has a generally poor rating overall, or one performance characteristic which is very poor.

Towing Performance

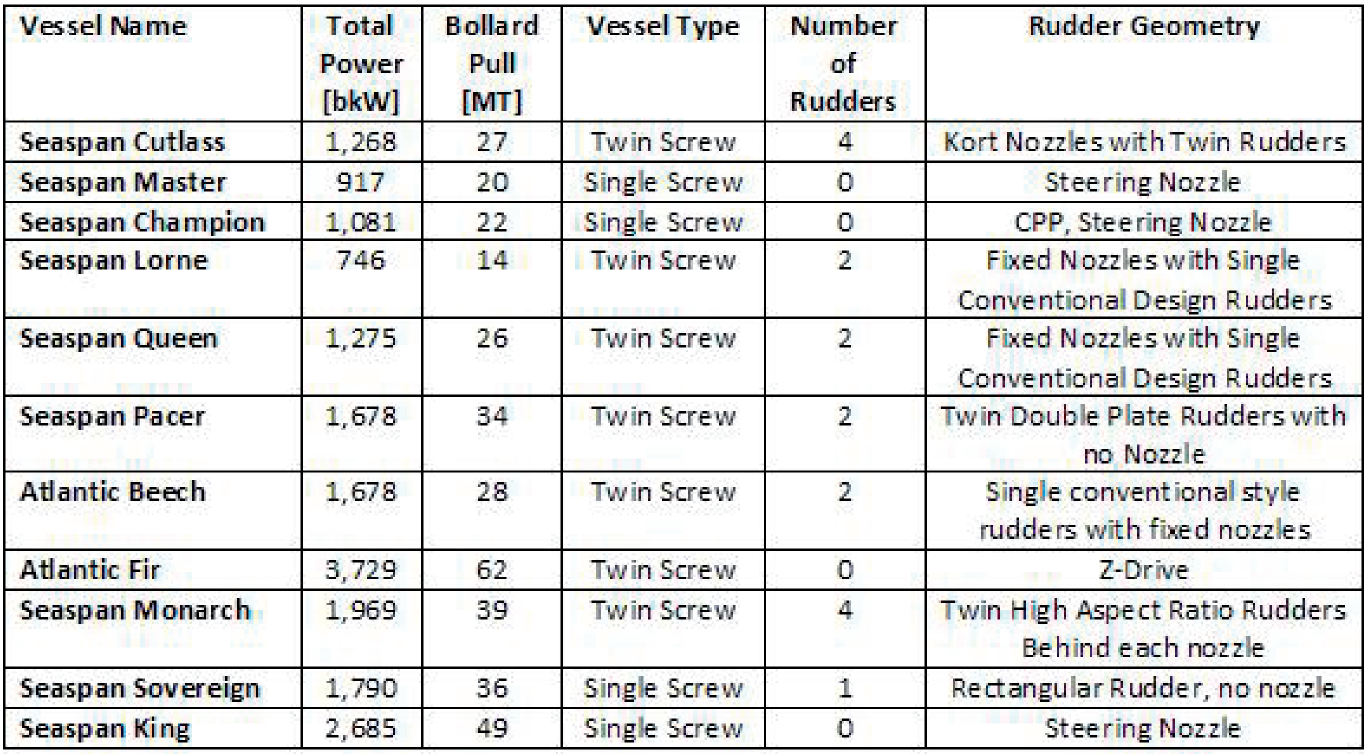
The following parameters were selected as the basis of comparison:

- Speed/Length Ratio ($V/\sqrt{L}$);
- Power/Displacement Ratio (bkW/MT);
- Power/Propeller Disc Area.

Table 2 (see next page) lists the propulsion characteristics of each vessel.

Vessel Name	Rating	Length Overall [m]	Moulded Breadth [m]	Moulded Depth [m]	Lightship Displacement [MT]	Full Load Displacement [MT]
Seaspan Cutlass	C	25.3	7.56	4.39	262	347
Seaspan Master	B	27.1	7.01	4.20	207	303
Seaspan Champion	A	27.0	7.32	4.27	208	307
Seaspan Lorne	A	28.2	7.32	4.52	217	289
Seaspan Queen	A	29.0	7.62	4.24	217	351
Seaspan Pacer	B	29.0	7.62	4.24	274	402
Atlantic Beech	A	30.8	8.53	4.42	319	521
Atlantic Fir	A	30.8	11.1	5.12	377	592
Seaspan Monarch	B	34.7	9.14	4.83	397	641
Seaspan Sovereign	B	37.5	9.14	5.49	486	743
Seaspan King	C	40.2	9.75	5.41	496	880

Table 1: Vessel particulars.



Vessel Name	Total Power [bkW]	Bollard Pull [MT]	Vessel Type	Number of Rudders	Rudder Geometry
Seaspan Cutlass	1,268	27	Twin Screw	4	Kort Nozzles with Twin Rudders
Seaspan Master	917	20	Single Screw	0	Steering Nozzle
Seaspan Champion	1,081	22	Single Screw	0	CPP, Steering Nozzle
Seaspan Lorne	746	14	Twin Screw	2	Fixed Nozzles with Single Conventional Design Rudders
Seaspan Queen	1,275	26	Twin Screw	2	Fixed Nozzles with Single Conventional Design Rudders
Seaspan Pacer	1,678	34	Twin Screw	2	Twin Double Plate Rudders with no Nozzle
Atlantic Beech	1,678	28	Twin Screw	2	Single conventional style rudders with fixed nozzles
Atlantic Fir	3,729	62	Twin Screw	0	Z-Drive
Seaspan Monarch	1,969	39	Twin Screw	4	Twin High Aspect Ratio Rudders Behind each nozzle
Seaspan Sovereign	1,790	36	Single Screw	1	Rectangular Rudder, no nozzle
Seaspan King	2,685	49	Single Screw	0	Steering Nozzle

Table 2: Propulsion and steering particulars.

PART A – SEAKEEPING ANALYSIS

Vessel particulars and capacities

The proposed new coastal tug is expected to be in the range of 28-32m in length. Referring to *Table 1,* it can be seen that the sample brackets this size range well, and although the larger tugs operate generally in the more exposed conditions of the outer west coast and the Gulf of Alaska, their reputations in that regard are no less valid to this analysis. Vessel fuel and freshwater capacities, total deadweight, and the ratio of deadweight to full load displacement ratio are listed in *Table 3 (opposite)*.

While absolute dwt increases fairly linearly with length, as expected, the dwt/displacement ratio falls within a reasonably close range, from 0.25 to 0.44 and generally increases with vessel size. There is no obvious correlation between dwt/displacement ratio and the behaviour ratings, especially when one notes that the ratios for both the best-rated and the poorest boats are very close.

Vessel Name	Rating	Fuel [MT]	Fresh Water [MT]	Total Deadweight [MT]	Deadweight/Full Load Displacement Ratio
Seaspan Cutlass	C	69	11	85	0.245
Seaspan Master	B	69	15	96	0.317
Seaspan Champion	A	80	15	99	0.322
Seaspan Lorne	A	49	18	72	0.249
Seaspan Queen	A	100	22	134	0.382
Seaspan Pacer	B	100	22	128	0.318
Atlantic Beech	A	146	28	202	0.388
Atlantic Fir	A	212	4	215	0.363
Seaspan Monarch	B	200	34	244	0.381
Seaspan Sovereign	B	184	11	257	0.346
Seaspan King	C	333	4	384	0.436

Table 3: Vessel capacities.

Vessel Name	Rating	Prismatic Coefficient C_p	Block Coefficient C_b	Midship Coefficient C_m	Waterplane Coefficient C_w
Seaspan Cutlass	C	0.604	0.499	0.832	0.803
Seaspan Master	B	0.593	0.418	0.790	0.801
Seaspan Champion	A	0.589	0.436	0.746	0.786
Seaspan Lorne	A	0.581	0.494	0.861	0.788
Seaspan Queen	A	0.603	0.478	0.798	0.789
Seaspan Pacer	B	0.619	0.500	0.811	0.807
Atlantic Beech	A	0.614	0.506	0.882	0.796
Atlantic Fir	A	0.634	0.524	0.836	0.847
Seaspan Monarch	B	0.584	0.473	0.892	0.802
Seaspan Sovereign	B	0.601	0.478	0.796	0.705
Seaspan King	C	0.600	0.418	0.788	0.778

Table 4: Form coefficient comparison at departure load condition.

Hull form

Form coefficients

The prismatic coefficient (C_p), block coefficient (C_b), waterplane coefficient (C_w), and midship coefficient (C_m), were calculated for each vessel in the full load departure condition. The prismatic and block coefficients compare the fullness of the vessels. 3D hydrostatic models of the hull and tanks were made for each vessel to help determine these coefficients and also for stability calculations discussed later in this paper. The lines plan for ***Seaspan Sovereign*** could not be located, thus the model is only a best approximation of the actual form. Results for this vessel should be judged accordingly. *Table 4* (above) compares the various form coefficients.

As ***Atlantic Fir*** is designed for a much different service, its characteristics here represent somewhat of an anomaly, and should be considered accordingly. For the remainder of the vessels the coefficients fall within a narrow range, and show no obvious correlation to the behaviour ratings.

Form ratios

The displacement to length ratio Disp/(0.01L)^3 (L.Tons/ft^3) indicates the relative weight displaced for the given vessel length. It was calculated for the departure condition for each vessel and is shown graphically in *Figure 22 (see next page)*. If one considers only the line haul boats in the sample, it can be noted that the highly regarded ***Seaspan Lorne*** has the lowest displacement/length ratio, and the poorly-rated ***Seaspan Cutlass*** has the highest ratio. Almost all the other A- and B-rated tugs fall in the range between 400 and 500.

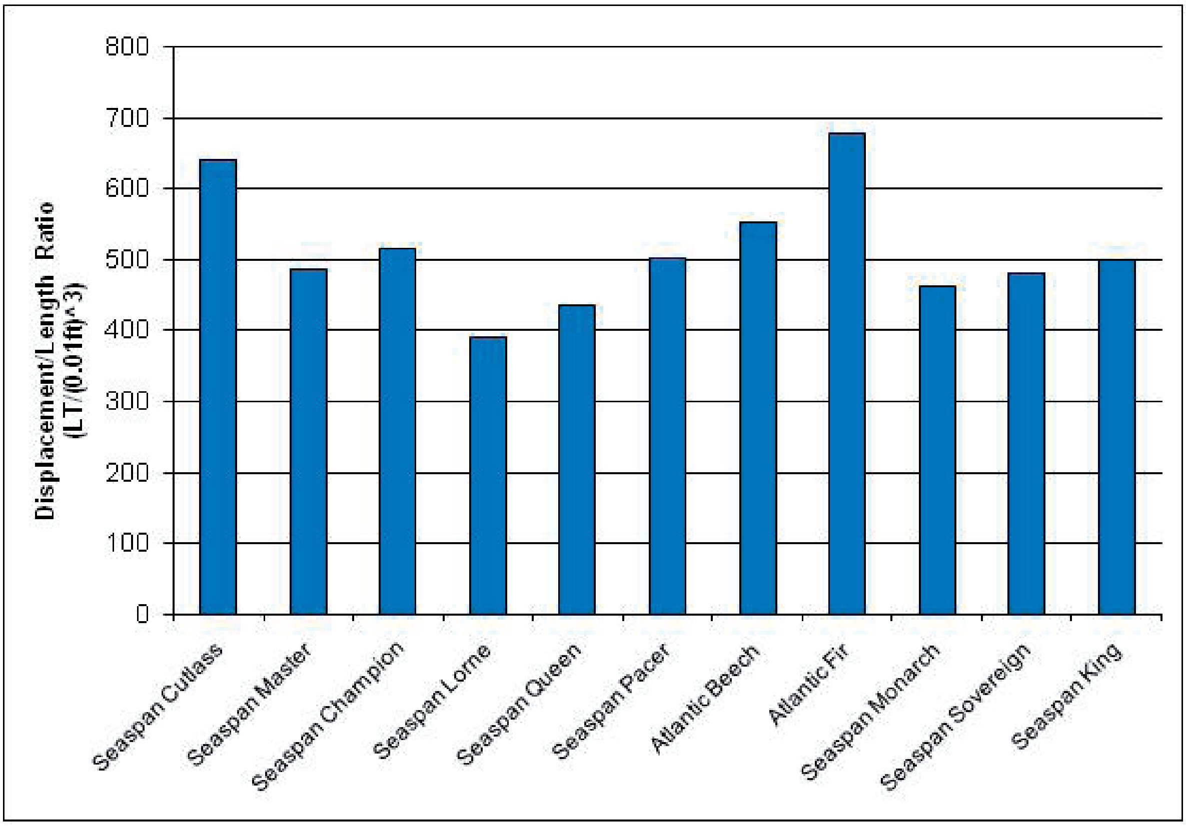


Figure 22: Displacement/length ratio at departure load.

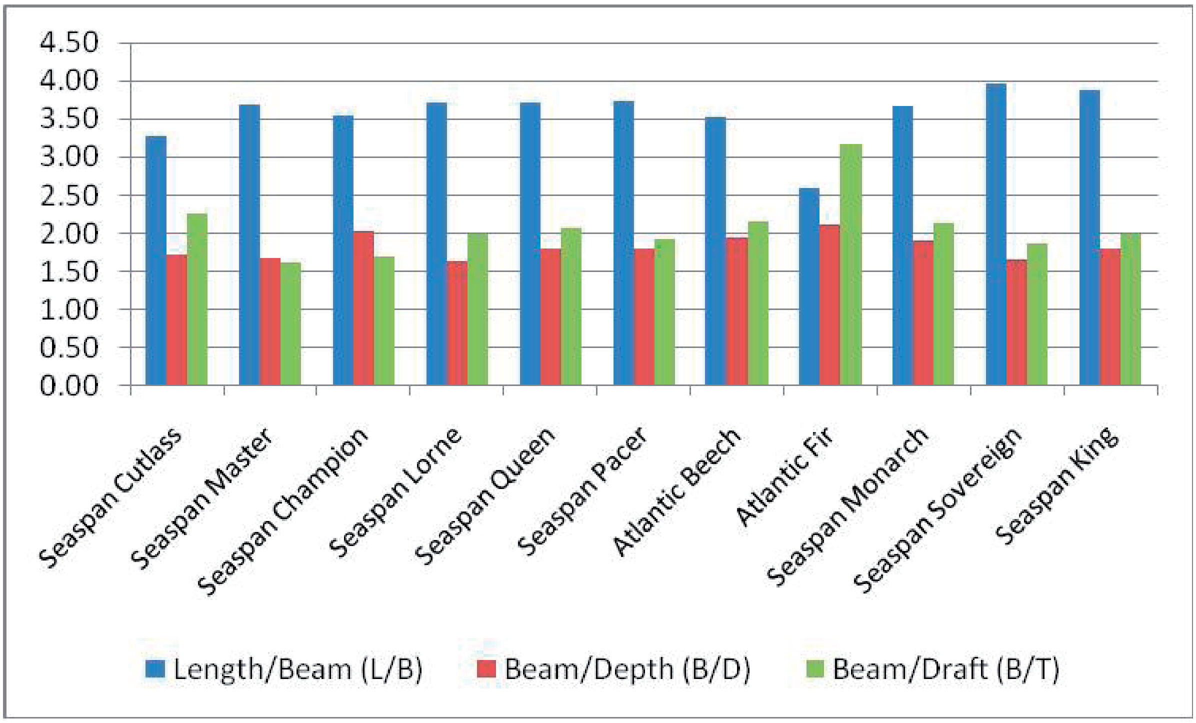


Figure 23: Form ratios at the departure condition.

The form ratios length to beam (L/B), beam to depth (B/D) and beam to draft (B/T) at the departure load condition are shown in *Figure 23 (above)*. If one disregards the relative anomaly of the ship-handling tug ***Atlantic Fir***, there is very little variation in these form ratios amongst the tugs, and certainly no obvious correlation to the behaviour ratings. But it is also noted that the C-rated tugs fall at both the low and high end of the L/B spectrum, and the remainder, all A- and B-rated vessels are very close, between 3.5 and 3.7.

Sectional area curves

The sectional area curve is a critical element of any tug design. This data was prepared for the sample fleet, however the curve for ***Seaspan Sovereign*** was only estimated. *Figure 24 (opposite)* compares the curves for those vessels with prismatic coefficients between 0.58 and 0.59. The curves have been non-dimensionalised for a more accurate comparison. As shown in *Figure 24*, ***Seaspan Monarch***, ***Seaspan Lorne*** and ***Seaspan***

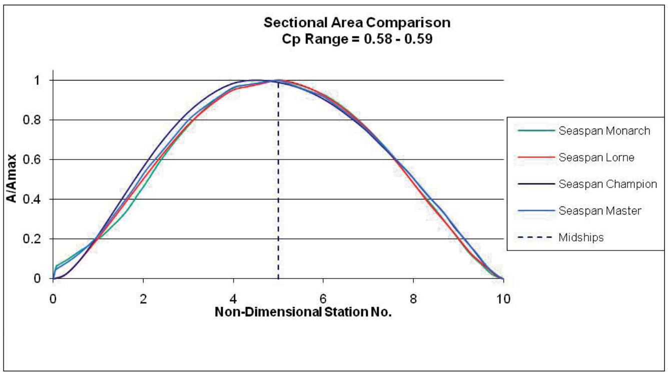


Figure 24: Sectional area comparison for Cp range of 0.58 - 0.59.

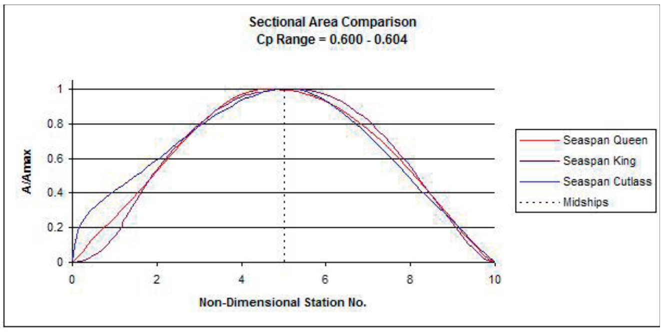


Figure 25: Sectional area comparison for Cp range of 0.600 – 0.604.

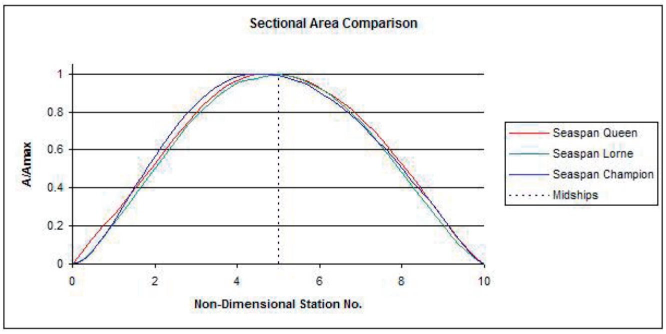


Figure 26: Sectional area curve comparison of vessels with most positive reputations.

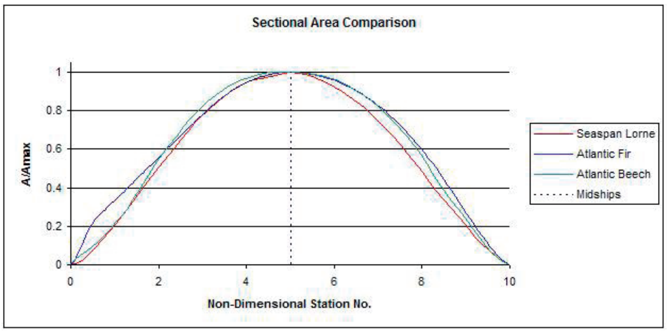


Figure 27: Sectional area curve comparison for diverse, but all highly rated tugs.

Master have their maximum area at midships, while ***Seaspan Champion*** has its maximum area aft of midships. ***Seaspan Master's*** curve is very similar to that of ***Seaspan Lorne***. All four vessels are very similar forward of midships, with ***Seaspan Lorne*** having a slightly finer entry. *Figure 25 (above)* compares the curves for vessels with prismatic coefficients ranging from 0.600-0.604. The prismatic coefficient range in *Figure 25* is very narrow, yet the area curves differ significantly more than in *Figure 24*. ***Seaspan King*** and ***Seaspan Cutlass*** have their greatest areas near midships, while ***Seaspan Queen's*** is slightly aft of midships. Also, ***Seaspan King*** is fuller around the middle and has a steeper slope aft and forward. ***Seaspan Cutlass*** has a more gradual slope and a fuller stern than the other two due to the deeply submerged transom. It is worth noting that both ***Seaspan Cutlass*** and ***Seaspan King*** are C-rated tugs, hence one could consider that neither very full nor very fine ends result in positive behaviour, which is ultimately a reasonably obvious conclusion.

Figure 26 (left) compares the curves for ***Seaspan Lorne***, ***Seaspan Champion*** and ***Seaspan Queen***, all three of which have been regarded by their crews as being very good sea boats. The shape of these curves is very similar, although ***Seaspan Champion*** has a slightly more aft bias than the other two. These characteristics can then be considered as a very good basis for any new hull form in a comparable service, but as always there are exceptions to this generalisation, as illustrated in *Figure 27*.

Atlantic Beech and ***Atlantic Fir*** have prismatic coefficients larger than the ranges analysed above. Their curves are compared to that of the Lorne in *Figure 27 (left)* in which ***Atlantic Fir*** and ***Atlantic Beech*** are significantly fuller forward than ***Seaspan Lorne***. They also both have their greatest area around midships. According to the owners, all three vessels have excellent reputations, yet their sectional area curves are quite different, reflecting the much higher Disp/(0.01L)^3 ratios of the two east coast boats. The shape of ***Atlantic Fir*** reflects the need for more buoyancy aft in a Z-drive tug.

Reserve buoyancy comparison

Reserve buoyancy is that part of the volume of a ship which is *above* the full load waterline and is watertight, so that it will provide buoyancy when immersed. The reserve buoyancy of each tug was determined by measuring the section area up to the full load waterline (Area 1), and the section area to another nominal waterline 2m above the design load waterline (Area 2). The reserve buoyancy ratio was then calculated as Area 2 divided by Area 1. The analysis was applied to Stations 8 and 9 for each vessel (with Station 0 being at the aft perpendicular); the results are shown in *Table 5 (see next page)*.

Higher area ratios imply greater reserve buoyancy. Although they have the same hull, ***Seaspan Pacer*** and ***Seaspan Queen*** have different reserve buoyancy ratios, due to the fact that once fully loaded, ***Seaspan Pacer's*** waterline is 0.3m deeper than ***Seaspan Queen's***. Once again there is no obvious correlation to the behaviour ratings, although it should be noted that the two poorest (C-rated) tugs have generally lower ratios at Station 9 than the A and B rated tugs. However, one of the best tugs has an even lower ratio.

Vessel Name	Rating	Area Ratio at Station 8	Area Ratio at Station 9
Seaspan Cutlass	C	2.14	2.60
Seaspan Master	B	2.30	2.79
Seaspan Champion	A	2.22	2.82
Seaspan Lorne	A	2.01	2.77
Seaspan Queen	A	1.95	2.40
Seaspan Pacer	B	2.51	3.37
Atlantic Beech	A	2.06	2.78
Atlantic Fir	A	2.37	2.93
Seaspan Monarch	B	2.28	2.86
Seaspan King	C	2.07	2.54

Table 5: Reserve buoyancy area ratios

Flare angles and half angle of entry

The amount of flare a vessel has will influence how dry the deck stays. More flare provides more reserve buoyancy and throws water out and away from the vessel. It is also a measure of how deeply the vessel is likely to pitch, and to a degree, the related pitch accelerations.

Flare angles were measured at Stations 8 and 9 as illustrated in *Figure 28 (below)*; taken as the angle between the vertical centre line and the tangent of the station in section at the waterline corresponding to the full load condition. The half angle of entry was measured in the plan view at the design waterline, by taking the slope of the design waterline between Stations 9 and 10.

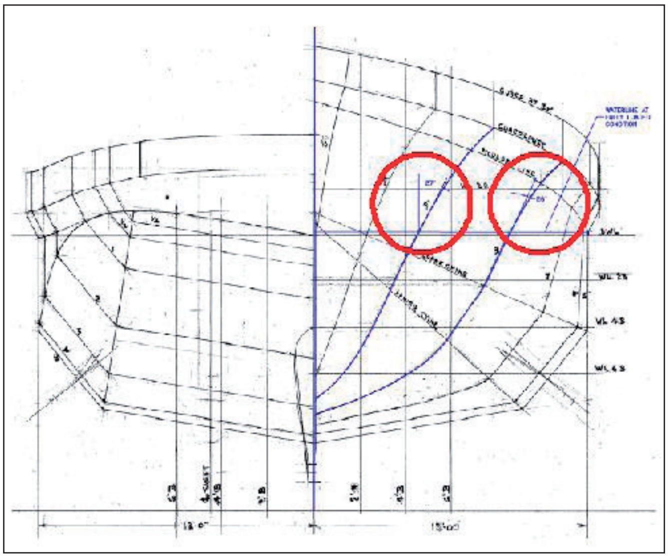


Figure 28: Sketch of flare angle measurement.

Vessel Name	Rating	Flare Angle at Station 8 [deg]	Flare Angle at Station 9 [deg]	1/2 Angle of Entry [deg]
Seaspan Cutlass	C	21	23	27
Seaspan Master	B	21	22	28
Seaspan Champion	A	22	25	30
Seaspan Lorne	A	26	27	30
Seaspan Queen	A	28	25	28
Seaspan Pacer	B	28	25	28
Atlantic Beech	A	22	29	31
Atlantic Fir	A	27	39	44
Seaspan Monarch	B	24	26	28
Seaspan King	C	18	21	27

Table 6: Comparison of flare angles and half angle of entry.

Table 6 (below left) shows the comparison of flare angles and half angle of entry. This is the first characteristic where some direct and consistent correlation to behaviour is clearly noted. The poorest rated tugs have the finest entries and the lowest flare angles. The combination clearly contributes to greater pitching and also less roll-damping capability at the ends of the tug. In particular, ***Seaspan King***, noted as having a nasty pitching behaviour in some sea conditions, has the least amount of flare of the entire sample, and by a considerable margin. This should be regarded as a critical design consideration.

The entry angle affects initial stability, as a greater angle will increase waterplane area. It is also an indication of resistance in head seas; the finer the entry (ie the smaller the angle), the less resistance in head seas, and thus the vessel will be less affected by the weather.

Intact stability characteristics

Transport Canada stability criteria

Regrettably, stability regulations for Canadian towing vessels are woefully inadequate, and do not reflect any service-related criteria such as towline forces. The governing requirement, Transport Canada Standard *TP 7301E - Stab 3: Interim Standard of Stability for Ships Built or Converted for Towing* states only that all towing vessels should meet the following criteria:

i. The initial metacentric height (GM) should not be less than 0.55 metres;
ii. The area under the righting lever (GZ) curve should not be less than 0.055 metre-radians up to 30 degree angle of heel.

These criteria do not stand up to scrutiny in the context of modern high-powered ASD or VSP tugs, but have actually proven to be reasonable for modestly-powered line haul tugs.

GM

The GM values for the departure and arrival conditions were taken from stability books compiled when the sample vessels were initially built; thus the stability information is dated and should be judged accordingly. However nearly all the boats are of a similar age, so it may be fair to assume that all have experienced similar rates of weight growth and CG 'creep'.

Atlantic Fir stands out as being very stiff, which means that it is the most stable in roll, and indeed, as will be seen later, it has one of the quickest roll periods. However this is a ship-docking tug, significantly different from the rest of the study group. The GM values for these line-haul tugs are significantly lower than what can be considered normal in the modern generation of ASD and VSP ship-handling tugs, as illustrated by the data for ***Atlantic Fir***. It is worth noting that the A-rated ***Seaspan Lorne*** has a substantially higher GM than most of the B-and C-rated tugs. Yet these other boats have operated successfully in this service for 40 years, suggesting that the regulatory minima may not be totally unreasonable for this service. *Figure 29 (below)* shows the GM values for different loading conditions.

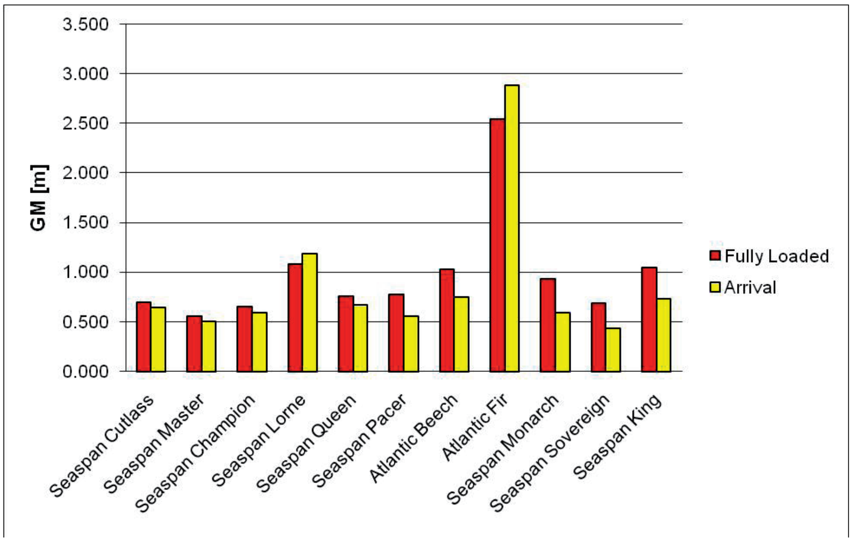


Figure 29: GM values for different loading conditions.

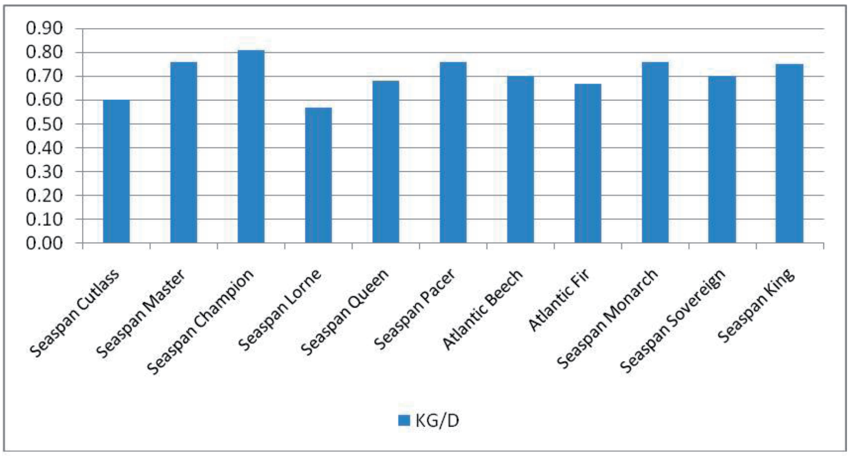


Figure 30: Comparison of the KG/D ratio for all vessels in the full load condition.

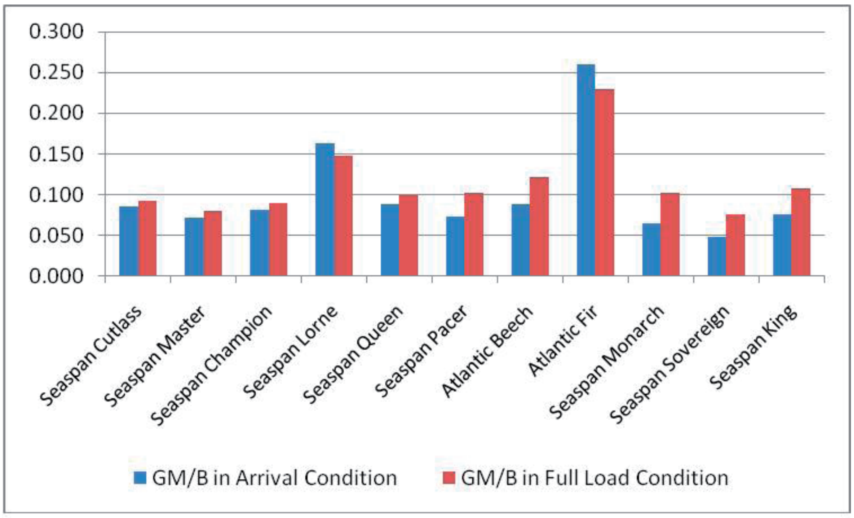


Figure 31: GM/B ratios.

KG/D and GM/B Ratios

Figure 30 (left) compares the KG/D ratio for all vessels in the full load condition. According to *Figure 30, below,* ***Seaspan Lorne*** has the lowest KG/D ratio with a value of 0.57. A low KG/D ratio implies greater stability, since a low vertical centre of gravity means a higher GM. However ***Seaspan Champion,*** also a well-regarded tug, has the highest KG/D ratio in the full load condition with a value of 0.81.

Figure 31 (left) compares the GM/B ratio in the arrival and full load conditions. It can be seen that after ***Atlantic Fir***, ***Seaspan Lorne*** has the highest GM/B ratio in both the arrival and full load conditions, with values of 0.163 and 0.148 respectively. Due to its significantly different hull configuration, ***Atlantic Fir*** should be disregarded in this comparison.

Once again, with relatively little spread in the data throughout the most relevant tugs in the sample, there is no obvious correlation between these stability ratios and rated performance, apart from the fact that ***Seaspan Lorne*** again stands out as being considerably stiffer than its fellow tugs.

Area under righting arm curves

The area under the righting arm (GZ) curve from 0-30 degrees was also tabulated. This area represents the amount of work needed to heel the vessel up to 30 degrees, or the amount of potential energy the vessel has for righting itself from 30 degrees back to the upright position.

Not surprisingly ***Atlantic Fir*** had the highest area. ***Seaspan Lorne*** and ***Seaspan King*** are the next highest at full load condition, but while ***Seaspan Lorne*** follows the same trend as ***Atlantic Fir***, ***Seaspan King*** is considerably easier to heel at light load. ***Seaspan Champion***, ***Seaspan Sovereign*** and ***Seaspan Master*** are the lowest. ***Seaspan Pacer***, ***Seaspan Cutlass***, ***Atlantic Fir***, ***Seaspan Lorne*** and ***Seaspan Champion*** increase in area with less load, while the rest of the vessels decrease in area with less load. *Figure 32 (see next page)* shows these results.

The data clearly shows that ***Atlantic Fir*** and ***Seaspan Lorne*** are both appreciably more stable than the others. As will be shown later, both vessels also have many roll damping features, which helps explain the positive crew feedback regarding sea keeping of these vessels.

Towline heel stability

Transport Canada does not require Canadian-registered towing vessels to meet any minimum towline stability criteria. However, such criteria are generally regarded internationally as an industry standard for new vessel designs, and the consideration of towline stability is an important safety consideration. In the absence of any Transport Canada criteria, the ABS towline criteria were applied to the sample.

ABS 5-8-A1/5 Standard: Intact Stability Guidelines for Towing Vessels (1998), is used as an industry standard to ensure intact stability for towing vessels. It states that: 'The area of the residual dynamic stability (area between righting arm and heeling arm curves to the right of the first intercept) up to an angle of heel of 40 degrees plus the angle of the first intercept, or the angle of downflooding, if this angle is less than 40 degrees plus the angle of the first intercept, should not be less than 0.09m-radians (16.9 ft-deg).'

The existing GHS models were used to determine whether or not the vessels met these criteria; the GHS models contained the hull and tanks only. The downflooding points were not taken into account in the analysis. Only the area under the curve between the equilibrium point and 40 degrees plus the equilibrium point was tested. The heeling arm curve was calculated using the *ABS 5-8-A1/9* procedure; the heeling arm was taken as the difference between the height of the towing bitt, and the vertical position of the centre of buoyancy, at the corresponding loading condition. The analysis results are listed as 'compliant' or 'non-compliant' in *Table 7 (below)*.

It is noteworthy that with only one exception all of the B- and C-rated tugs have at least one condition of non-compliance, whereas the A-rated tugs are universally compliant with this criteria. Compliance with this criteria is arbitrary and not a regulatory requirement for the current service. However this, or an equivalent criteria for towline-induced heel, should be a prerequisite for any towing vessel.

Vessel	Rating	Fully Loaded Condition	Half Load Condition	Arrival Condition
Seaspan Cutlass	C	Non Compliant	Non Compliant	Non Compliant
Seaspan Master	B	Non Compliant	Non Compliant	Non Compliant
Seaspan Champion	A	Compliant	Compliant	Compliant
Seaspan Lorne	A	Compliant	Compliant	Compliant
Seaspan Queen	A	Compliant	Compliant	Compliant
Seaspan Pacer	B	Non Compliant	Non Compliant	Non Compliant
Atlantic Beech	A	Compliant	Compliant	Compliant
Atlantic Fir	A	Compliant	Compliant	Compliant
Seaspan Monarch	B	Compliant	Compliant	Compliant
Seaspan Sovereign	B	Non Compliant	Compliant	Non Compliant
Seaspan King	C	Compliant	Compliant	Non Compliant

Table 7: ABS towline criteria results

Vessel motions

Pitch and roll periods

The periods of pitch and roll were estimated for each vessel at the full load, half load, and arrival conditions. These numbers are only estimates, as the weight distribution characteristics, and thus the mass moment of inertia about the centre of gravity of the vessel, were also only estimated. The analysis considered the lightship, tanks, and added weights detailed in the stability books. The period of roll was estimated based on GM and beam and an experimental constant. The pitch period was also estimated based on displacement, draft and mass moment of inertia. The longitudinal mass moment of inertia was calculated using the derived weight distribution. Although only estimates, the roll and pitch periods serve as a good *comparative* measure of the relative motion characteristics of these vessels.

Typical wave period data for the west coast of Vancouver Island and Hecate Strait was taken from *Wind and Wave Climate Atlas, Volume IV*[3]. Any motion frequency, especially roll or pitch, which matches the wave frequency in the intended area of operation must be viewed as a serious problem and the design should be altered accordingly. While this is not always possible to ascertain at the design stage, in a situation such as that described in this paper, it is both easy and important to do so.

Figure 33 (opposite) shows the calculated pitch periods for different loading conditions for each vessel, and also the per cent occurrence of the most frequent wave periods observed in Hecate Strait, as taken directly from *Wind and Wave Climate Atlas, Volume IV*: The West Coast of Canada[3]. *Figure 34 (opposite)* compares the calculated pitch periods with the most frequent wave periods observed on the west coast of Vancouver Island, as taken directly from *Wind and Wave Climate Atlas, Volume IV*.

As can be expected, the period of pitch increases with increasing load for all vessels. ***Seaspan King*** has a reputation for nasty pitching in head seas in Hecate Strait; previous analyses have credited this to the combination of the vessel's length and typical wave length and period conditions in Hecate Strait which is certainly reinforced by this analysis. None of the vessels are close to the most frequent wave periods encountered on the west coast of Vancouver Island.

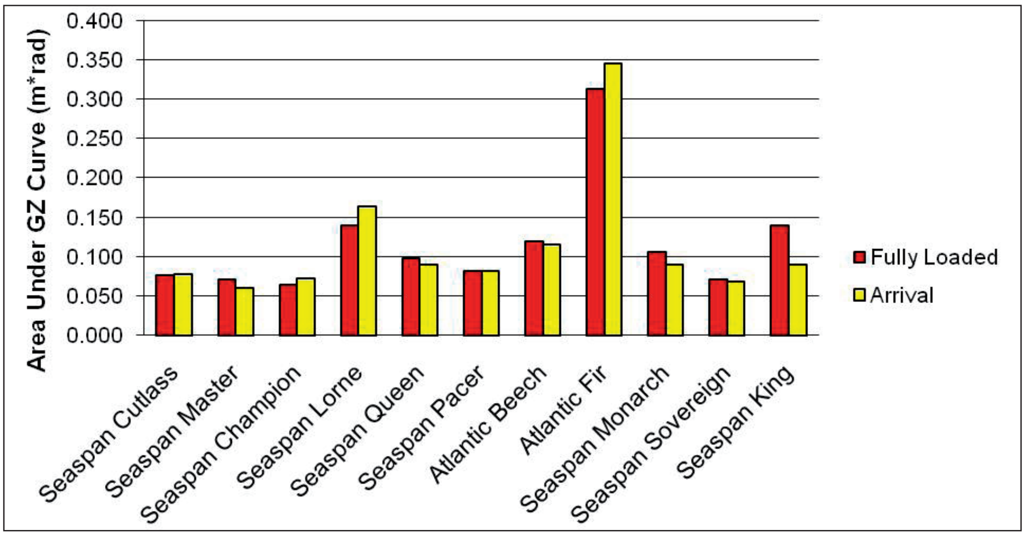


Figure 32: Area under righting arm curve from 0-30 degrees.

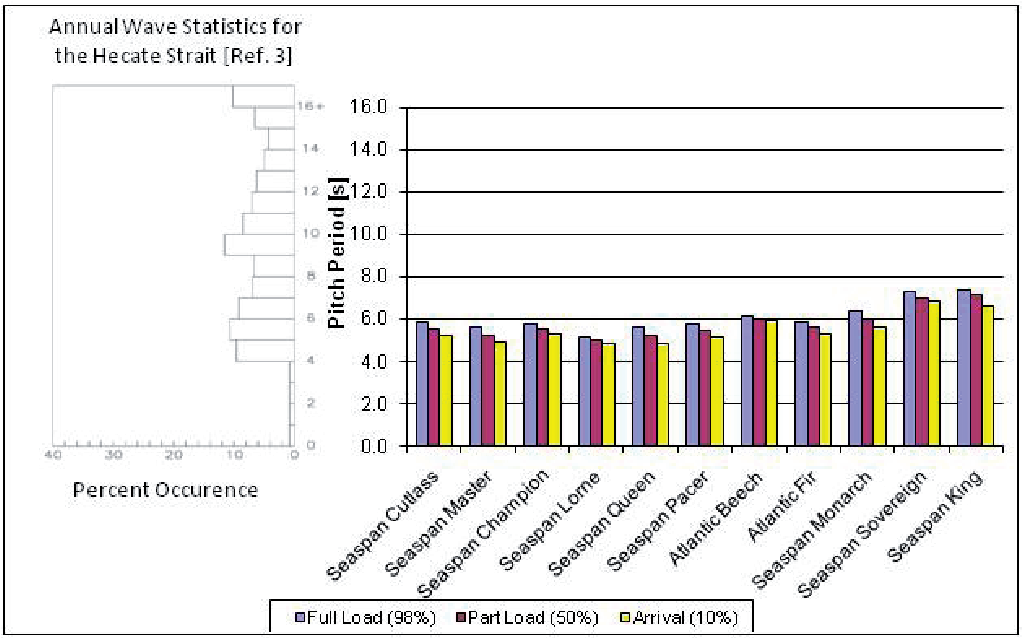


Figure 33: Period of pitch for different loading conditions and wave conditions in the Hecate Strait.

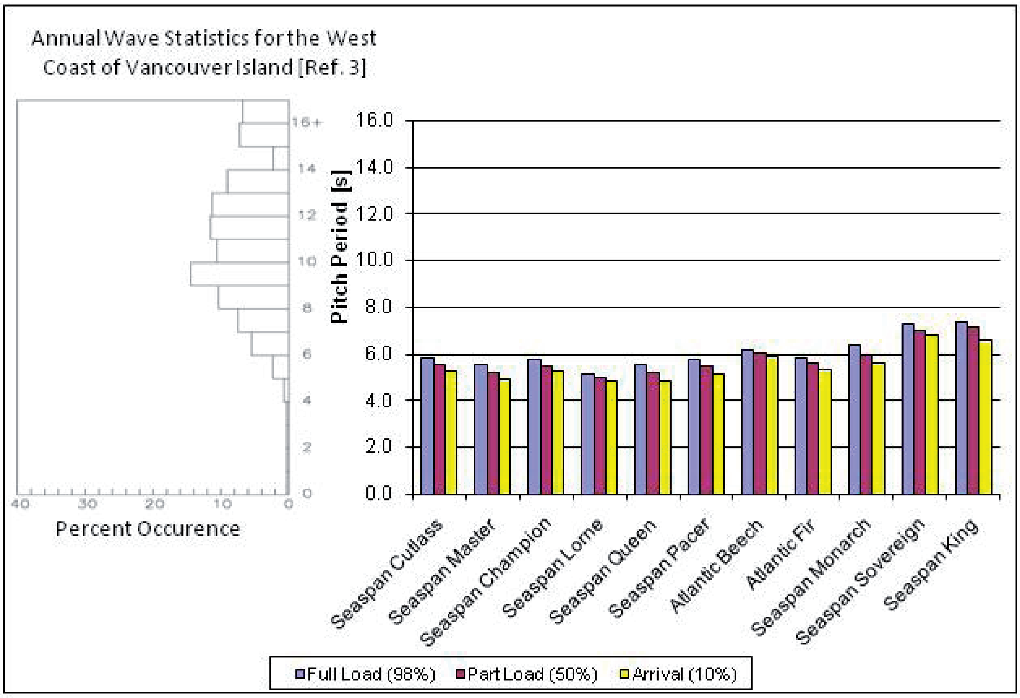


Figure 34: Period of pitch for different loading conditions and wave conditions on the west coast of Vancouver Island.

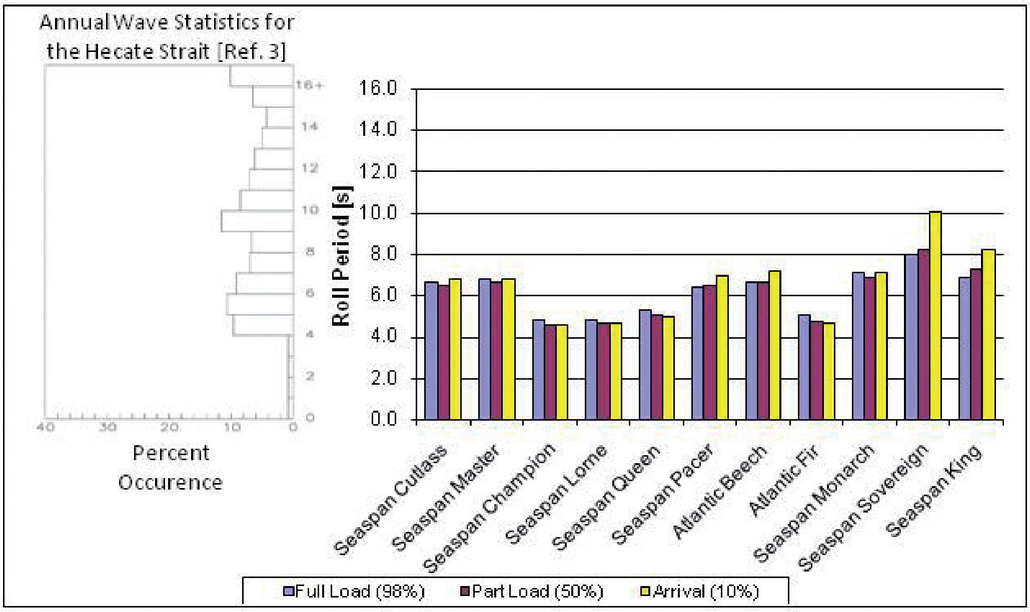


Figure 35: Period of roll for different loading conditions and wave conditions in the Hecate Strait.

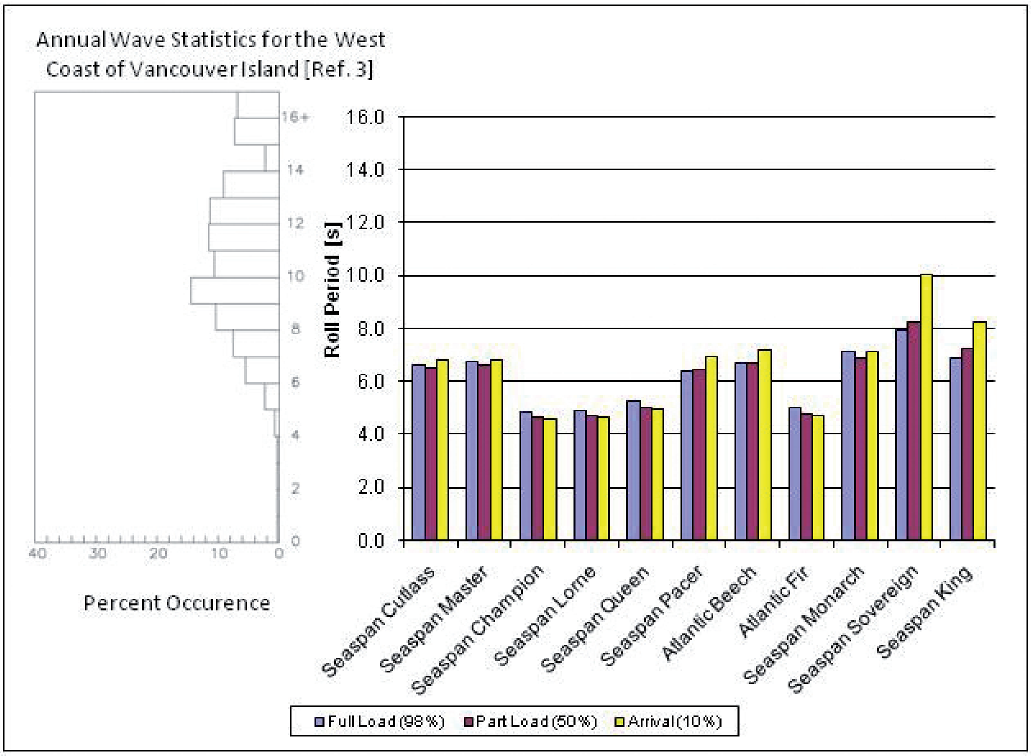


Figure 36: Period of roll for different loading conditions and wave conditions on the west coast of Vancouver Island.

Figures 35 and *36 (above)* compare the calculated roll periods for each vessel for different loading conditions with the typical wave data in Hecate Strait and on the west coast of Vancouver Island. These figures illustrate that many of the vessels could expect roll resonance in Hecate Strait, but all are well below the period of the long Pacific swells experienced on the outer coast, with the possible exception of ***Seaspan Sovereign***.

This data shows that ***Seaspan Lorne***, ***Seaspan Champion***, ***Seaspan Queen*** and ***Atlantic Fir*** have lower pitch periods than roll periods in both the departure and half load conditions. ***Seaspan King*** has very similar pitch and roll periods in both loading conditions, a combination that may be quite telling given this boat's reputation. The remainder of the vessels have slower roll periods than pitch periods for both loading conditions, a situation that would not normally be expected. However, the roll period data should also be considered along with the ABS Towline data. Although a longer roll period is often considered desirable for crew comfort, vessels with long roll periods do not comply with this criterion.

Roll Damping

Roll damping features reduce the amplitude (not frequency), of oscillation in roll and hence reduce roll accelerations. Crew comfort also depends on the stability factors discussed previously. Increasing the vessel's lateral area by adding appendages like larger keels or skegs and bilge keels increases roll damping. These appendages also have other effects such as adding resistance or impacting manoeuvrability, so should be considered carefully.

Vessel Name	Rating	Keel Area/Canoe Body Area [Ak/Acb]	Keel Projection/Draft [Lk/T]
Seaspan Cutlass	C	0.14	0.14
Seaspan Master	B	0.13	0.05
Seaspan Champion	A	0.14	0.06
Seaspan Lorne	A	0.14	0.04
Seaspan Queen	A	0.15	0.07
Seaspan Pacer	B	0.14	0.07
Atlantic Beech	A	0.05	0.00
Atlantic Fir (original design)	B	0.12	0.07
Atlantic Fir (with large skeg)	A	0.39	0.39
Seaspan Monarch	B	0.04	0.00
Seaspan King	C	0.17	0.04

Table 8: Roll damping.

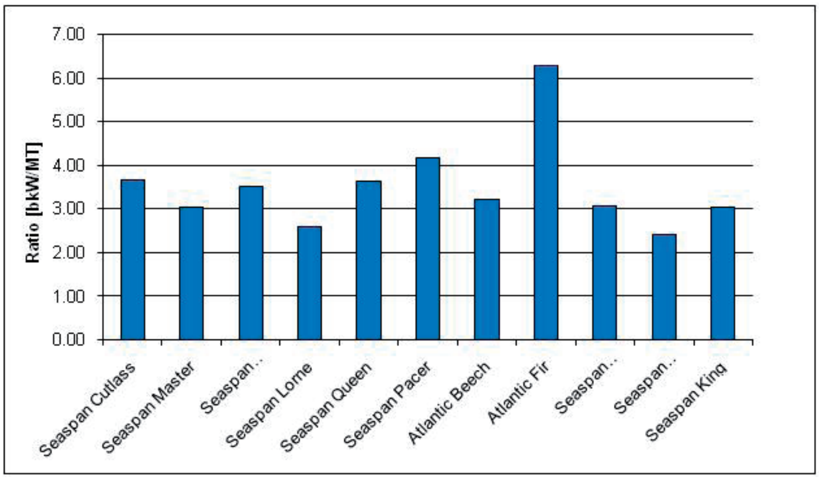


Figure 37: Power/displacement.

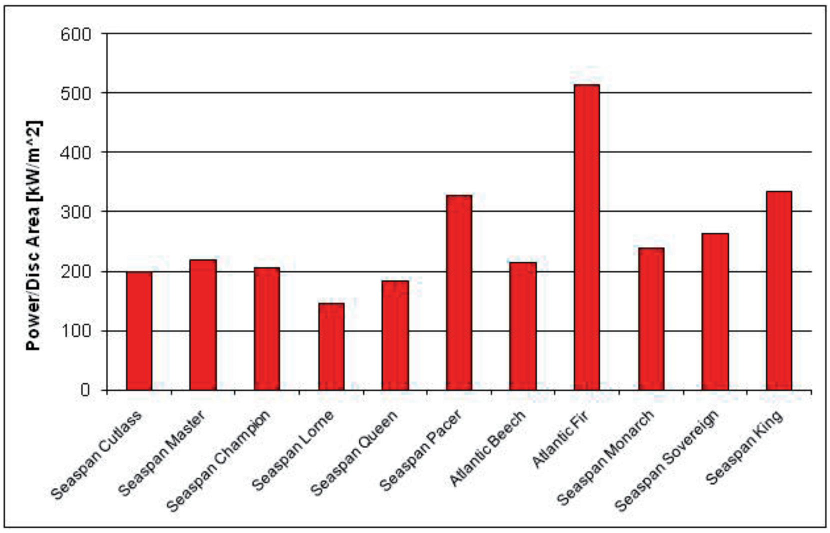


Figure 38: Power/disc area comparison.

The general arrangements shown on pages 4-7 illustrate which vessels have roll damping features. ***Atlantic Fir*** was originally designed with a small skeg, but was refitted with a larger 'escort' skeg in later years. While increasing its lateral area and thus increasing roll damping, the larger skeg also aids in directional stability. Bilge keels also increase both roll damping and directional stability. Of the vessels analysed, only ***Seaspan Lorne*** and ***Seaspan Cutlass*** have bilge keels; ***Seaspan Cutlass*** was also fitted with a larger skeg in later years. As these two boats are at the extreme ends of the crew approval ratings, clearly the presence of these devices alone cannot be directly responsible for comfortable motions.

To determine which vessels have the greatest roll damping, the keel lateral area, keel vertical projection at midships, and vessel lateral area (including any rudders and other appendages), were calculated from the corresponding lines plans for each vessel. ***Seaspan Sovereign*** was not included in this analysis due to lack of accurate information.

To compare the vessels in a non-dimensional manner, the keel area was divided by the canoe body area, and the keel projection was divided by the full load draft for each vessel, as shown in *Table 8 (left)*. If the modified (large skeg) ***Atlantic Fir*** is excluded from the group by virtue of its highly unique characteristics, there is generally very little variation in the data, hence the roll damping is either more closely related to the other factors or, as is most often the case, this is not a factor which can be easily isolated to establish its relevance.

B. TOWING PERFORMANCE

Steering and propulsion

Speed and Power

The vessels differ in propulsion and steering mechanisms, from single to multiple rudder and nozzle combinations, steering nozzles, single and twin screw, and include one Z-drive installation. *Table 2 (on page 8)* gives a summary of the different arrangements. The power to displacement ratio (P/Δ) (at full load displacement) is shown in *Figure 37 (left)* in units of kilowatts/metric ton (bkW/MT). No discernible pattern of correlation between power/displacement ratio and towing performance is obvious.

Propeller Configuration

Figure 38 (left) shows the unit power to unit propeller disc area ratio, a useful measure of overall propeller efficiency (assuming each propeller is properly designed). There are interesting elements to consider in this data:

1. ***Seaspan Pacer*** and ***Seaspan Queen*** are identical hulls but with quite different propulsion systems;
2. The modestly powered ***Seaspan Lorne*** is one of the most highly rated boats;
3. The highly powered Z-drive ***Atlantic Fir*** should not be assessed for regular line-haul towing performance, a duty for which it is not intended.

The ***Seaspan Pacer/Seaspan Queen*** comparison is interesting. ***Seaspan Queen's*** nozzle propellers are about 30cm greater in diameter than ***Seaspan Pacer's***, and its shaft centre line separation is about 20cm more. However, ***Seaspan Pacer's*** power output is also about 400kW greater than ***Seaspan Queen's***. So ***Seaspan Queen*** has better performance with bigger nozzled propellers and less power output, than a small propeller with greater power output. A power to disc area ratio between 180-250 is suggested, since ***Seaspan Queen**, **Seaspan Master*** and ***Seaspan Monarch*** are all known for good towing performance and fall within this range.

SUMMARY

Sea-Keeping

Seaspan Lorne, regarded as an excellent sea boat, stands out as being different from the rest of the vessels. It is the lightest and finest tug. It has the highest GM and area under the righting arm curve values of all the dedicated line towing tugs (***Atlantic Fir*** is excluded). Its sectional area curve has its greatest area right at midships. It also has the greatest flare at Station 8 and the lowest flare rate of change forward. Its pitch and roll periods were the lowest; its roll period decreases with decreasing load. Although one of the oldest vessels in this analysis, ***Seaspan Lorne*** complies with the ABS Towline Heel criteria in all loading conditions, and meets all the current Transport Canada standards for intact stability. Its KG/D ratio was also the lowest, and its GM/B ratios in both the full load and arrival conditions were the highest. Some fundamental line haul tug design lessons are implicit in these findings.

Seaspan Champion, also favoured by Seaspan crews, has a similar sectional area curve shape to the ***Seaspan Lorne***, yet its maximum area is further aft. It is similar to ***Seaspan Lorne*** in dimensions, prismatic coefficient, half angle of entry, roll periods and pitch periods, not surprisingly, as ***Seaspan Lorne*** was in all probability the design model used in the development of ***Seaspan Champion***. It is compliant with the ABS Towline criteria in all loading conditions, and meets the Transport Canada Intact Stability criteria. It differs from ***Seaspan Lorne*** in block and midship coefficients, being considerably lower in both cases. It also has less flare than ***Seaspan Lorne***. Despite these subtle differences, both vessels were regarded by their crews as excellent sea boats.

Seaspan Cutlass (not a Robert Allan Ltd design) was the only vessel consistently referred to by Seaspan crews as a poor sea boat. This analysis showed that the ***Seaspan Cutlass*** had the highest displacement to length and beam to draft ratios, and the lowest length to beam ratio. Its sectional area curve showed a much fuller stern than the other vessels. ***Seaspan Cutlass*** did not comply with the ABS Towline criteria in any loading condition.

Seaspan King, although a good towing tug, is known for excessive pitching in Hecate Strait. It has the longest pitch period, with an approximate value of 7.4s, and very similar pitch and roll periods. ***Seaspan King*** also carries the most deadweight, and has the lowest relative reserve buoyancy forward when compared to the rest of the vessels in this analysis. It also has relatively low flare angles forward, which certainly explains the poor pitch behaviour.

Although considered a very good sea boat, ***Atlantic Beech*** did not have any parameters that set it apart from the rest of the vessels. However, for all the parameters analysed, ***Seaspan Beech*** always fell in between other vessels with good sea-keeping reputations. It is characterised as having a very low profile superstructure, hence accelerations are low.

As a Z-drive vessel, ***Atlantic Fir*** had many unique characteristics from the rest of the vessels and in the final analysis was mostly an anomaly in almost all the results. ***Atlantic Fir*** is the fullest vessel with the highest C_p value, and also had the greatest C_b and C_w. It has the greatest displacement to length, beam to draft and beam to depth ratios, and the lowest length to beam ratio. Its sectional area curve shows it to be the fullest. ***Atlantic Fir*** has the greatest forward flare, and the highest rate of change of flare from Station 8 to 9. It also has the largest half angle of entry by a substantial margin, which means it encounters the greatest resistance in head seas; in spite of this it still has a reputation as a 'fast' boat and as an excellent sea boat. It has the highest GM and area under GZ curve values of those analysed. It complies with the ABS Towline Heel criteria for all loading conditions.

Based on the above it is clear that there is no single parameter that can differentiate vessels with good sea-keeping reputations from those with bad reputations. What can be concluded as contributing to a good 'sea boat', however, are the following general characteristics:

- Sectional area curve:
  - – maximum area close to midships;
  - – even distribution fore and aft;
  - – avoid extended fullness in the mid-length, with fine ends;
  - – avoid full ends;
- Flare angles:
  - – should be greater than 24 degrees in forward sections;
  - – higher flares provide more reserve buoyancy, which reduces pitch and roll;
- Waterline entry:
  - – fine angles reduce resistance and reduce the added resistance in waves but may increase wetness unless associated with generous flares;
  - – if fine entry angles result in inflections in the waterlines further aft, this may create more resistance than a more smooth but fuller entry;
- GM_T:
  - – must be adequate to fully satisfy towline heel criteria with a generous margin for weight growth, etc over time.

Towing Performance

Seaspan Queen and ***Seaspan Pacer*** have the same hull form, yet their reputations regarding towing performance are very different. The analysis showed that while towing at the same speed, ***Seaspan Pacer*** has greater resistance than ***Seaspan Queen***, due to the fact that ***Seaspan Pacer*** has a greater prismatic coefficient at the full load condition. Also, ***Seaspan Pacer*** had a greater power to disc area ratio, because ***Seaspan Queen*** has less power and greater propeller diameters. In fact, ***Seaspan Pacer*** had the highest ratio out of all the vessels, excluding ***Atlantic Fir*** which is a Z-drive vessel. A power to disc area ratio of 180-250 proved to indicate good towing performance.

CONCLUSIONS

The analysis of this data corroborates what every naval architect should know, namely that there is no single factor in isolation that can make a 'good' tug. It is the right combination of all aspects of the design that makes the difference between the ordinary and the exceptional. Further, it is careful matching of design characteristics to the service and to the operating area which will make the critical difference. Accordingly it is obvious that a generic or a standard design cannot be expected to be an optimal solution for every towing service.

In the circumstance of line towing on the BC coast however, there is clearly the potential to create a relatively standardised design which will serve the majority of routes very well. This examination of historical tug performance is a critical first step in ensuring that the lessons of the past are not forgotten. The data must also be reviewed in context. It was not possible within the time and fiscal constraints of the initial study to accurately measure roll and pitch periods which would have been extremely beneficial. The stability data is 'well aged' and hence must be considered as suspect in accuracy, but as mentioned, all the vessels can be expected to have similarly deteriorated characteristics.

The report also illustrates the fact that the older generation of tugs often had the advantage of being relatively large and low-powered for their size; aspects which contribute to general crew comfort. Economic pressures and the apparent need to maximise power and capacity per size will counter the objective of having a comfortable, sea-kindly and fuel efficient design. In this age of green technology, there is a lesson here too, that fundamental design issues can be some of the most critical aspects of a 'green' design.

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[2] *Inaugural Paper*; Norman Cosulich, First North American Tug Convention, Vancouver, BC, 1973.

[3] *Wind and Wave Climate Atlas, Volume IV*: The West Coast of Canada, MacLaren Plansearch (1991) Limited. Web: http://www.meds-sdmm.dfo-mpo.gc.ca/alphapro/wave/TDCAtlas/TDCAtlasWC.htm