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GUEMES ISLAND FERRY REPLACEMENT

CONCEPT DESIGN REPORT

PREPARED FOR

SKAGIT COUNTY PUBLIC WORKS
MOUNT VERNON, WASHINGTON

11 DECEMBER 2017
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Table of Contents

Revision History

Section	Rev	Description	Date	Approved
All	-	Final report.	12/11/17	DWL

References

1. 19CFR, *Customs Duties*, 2014.
2. 46CFR, *Shipping*, 2016.
3. 49CFR, *Transportation*, 2013.
4. *Car and Driver,* http:/www.caranddriver.com, 27 September 2017.
5. Ciechon, N., Hairston, L.; “Design and Construction of the New Staten Island Ferries,” *Marine Technology*, Society of Naval Architects and Marine Engineers, 16(4), October 1979.
6. *Coast Pilot 7: Pacific Coast*, US Department of Commerce, 2017.
7. Distance Between United States Ports, US Department of Commerce, 2012.
8. *Electricity Supply*, Puget Sound Energy, https://pse.com/aboutpse/energysupply/pages/electric-supply.aspx, 10 November 2017.
9. *Emergency Vehicle Size and Weight Regulation Guideline*, Fire Apparatus Manufacturers Association, White Paper, November 2011.
10. *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – 2017*, National Institute of Standard and Technology, Ed 32, May 2017.
11. *Fourteen-Year Ferry Capital Improvement Plan, 2017-2030*, Skagit County Department of Public Works, 2017.
12. *Guemes Island Ferry Replacement Concept General Arrangement*, Glosten, Drawing No. 17097-070-01, Rev. P1, 10 November 2017.
13. *Guemes Island Ferry Replacement Midship Section*, Glosten, Drawing No. 17097-100-01, Rev. -, October 24, 2017.
14. *Guemes Island Ferry Replacement, Transportation System Assessment*, Glosten Inc. Report No. 17097-000-04, Rev. –.
15. *Guemes Island Ferry Replacement, Vessel Capacity Study*, Glosten Inc. Report No. 17097-000-03, Rev. –.
16. *Guidance Notes on the Application of Ergonomics to Marine Systems*, American Bureau of Shipping, 2013.
17. *Highway Statistics 2014*, Policy and Governmental Affairs Office of Highway Policy Information, Federal Highway Administration, https://www.fhwa.dot.gov/policyinformation/statistics/2014/index.cfm#sec7, 10 October 2017.
18. *ISO 20283-5:2016 Mechanical Vibration*, International Organization for Standardization, 2016.
19. “Looking Back,” *Anacortes American*, 23 July 2014.
20. “Looking Back,” *Anacortes American*, 27 September 2017.
21. *Marine Accident Report: Allision of Passenger Ferry* Andrew J. Barberi *with St. George Terminal, Staten Island, New York, May 8, 2010*, National Transportation Safety Board, Report No. MAR-12-01, 24 April 2012.

22. *M/V* Guemes*, O.N. 601686: Ferry Replacement Plan,* Elliott Bay Design Group, Reference No. 13039-001-043-3, Rev. B, 22 November 2013.
23. *Passage to Guemes Island*, Linetime, http://www.linetime.org/pages/3977/Passage-To-Guemes-Island/, 26 Oct 2017.
24. Sea trial data logs for M/V *Guemes*, Cummins Northwest, June 2016.
25. *Tesoro Anacortes Refinery Clean Products Upgrade Project Vessel Traffic Assessment*, CH2M Rodino and Peterson Resources, March 2016.
26. *Timeline*, Samish Indian Nation, https://www.samishtribe.nsn.us/who-we-are/timeline, 26 Oct 2017.
27. Tsinker, G., *Marine Structures Engineering: Specialized Applications*, 1995.
28. United States Coast Guard Prevention Department Policy Letter 01-01, *Standardization of Certificate of Inspection Endorsements*, updated August 2015.
29. *Volume V: Owner's Model Design Report for the New 130 Auto Ferry Project*, Washington State Ferries, 30 August 2004.
30. *Washington State Commercial Vehicle Guide*, Washington State Department of Transportation, Document No. M30-39.05, 2016-2017.
31. *Diesel Exhaust/Diesel Particulate Matter*, Occupational Safety and Health Administration, United States Department of Labor, https://www.osha.gov/dts/hazardalerts/diesel_exhaust_hazard_alert.html, 9 November 2017.

Executive Summary

This report describes the concept design developed to replace the M/V *Guemes*, currently operating as a vehicle and passenger ferry between Anacortes and Guemes Island, Washington. This report, in addition to the references noted below, represents a 30% design completion.

- *Vessel Capacity Study* (Reference 15): describes past and future ridership and provides a required vehicle and passenger capacity for the replacement vessel.
- *Transportation System Assessment* (Reference 14): describes the overall transportation system including a discussion on the terminals and uplands infrastructure.
- *General Arrangement Drawing* (Reference 12): shows the layout and configuration of the concept design.
- *Structural Midship Section Drawing* (Reference 12): shows the proposed structural scheme.

Figure 1 and Figure 2 present the concept replacement vessel. The replacement vessel is a double-ended vehicle and passenger ferry, with a three-tiered deckhouse located to one side of the vessel (on the West side of the route). The design accommodates four lanes of vehicles, including highway-rated trucks and emergency vehicles.

Figure 1 View of the replacement vessel, showing the East side of the vessel

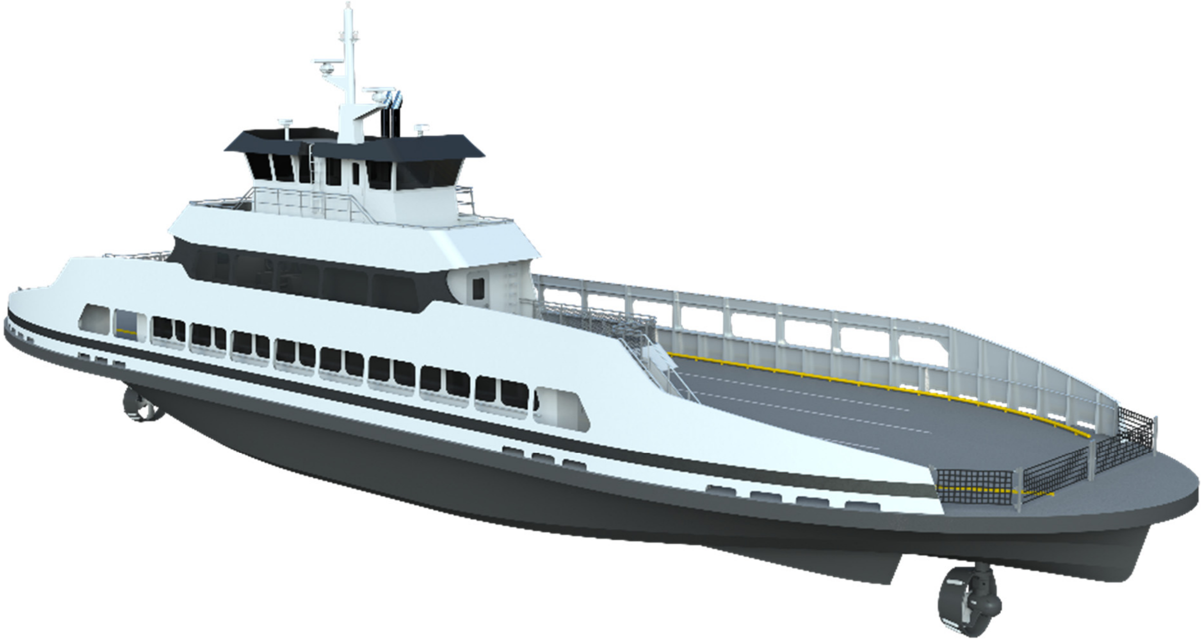


Figure 2 View of the replacement vessel, showing the West side of the vessel

Table 1 displays principal characteristics of the concept replacement vessel.

Table 1 Principal characteristics of concept replacement vessel

Parameter	Value	Parameter	Value
Length, overall	178'-0"	Vehicle capacity	32 AEQ (17'-9" long)
Length, waterline	170'-0"	Passenger capacity	150 persons
Beam, overall	53'-0"	Delivered power	2 x 725 kW
Beam, waterline	39'-11"	Propulsor type	Z-drive with Nozzles
Depth to main deck, at side	13'-6"	Main deck seating	40 seats @ 24" wide
Draft, full load	7'-6"	Upper deck seating	20 seats @ 24" wide
Displacement, at full load	615 LT	Gross registered tonnage	Less than 100

Skagit County desires to build an all-electric replacement vessel that will operate with batteries as the primary source of power. To understand the benefits and trade-offs for this type of propulsion system, a comparison to a baseline (geared diesel) and three other alternate propulsion systems (diesel-electric, series hybrid, and plug-in hybrid) has been performed.

A description of each system is provided as well as a propulsion system life cycle cost analysis. Results of life cycle cost analysis are presented below.

Capital costs shown in Figure 3 include all shore-power equipment to power the vessel (limited to all-electric and plug-in hybrid options). Additionally, shore-power infrastructure is sized for the worst-case run. Shore-side batteries are being used to reduce the peak power loads. Puget Sound Energy (PSE) has indicated that peak power demand without shore-side batteries cannot be accommodated.

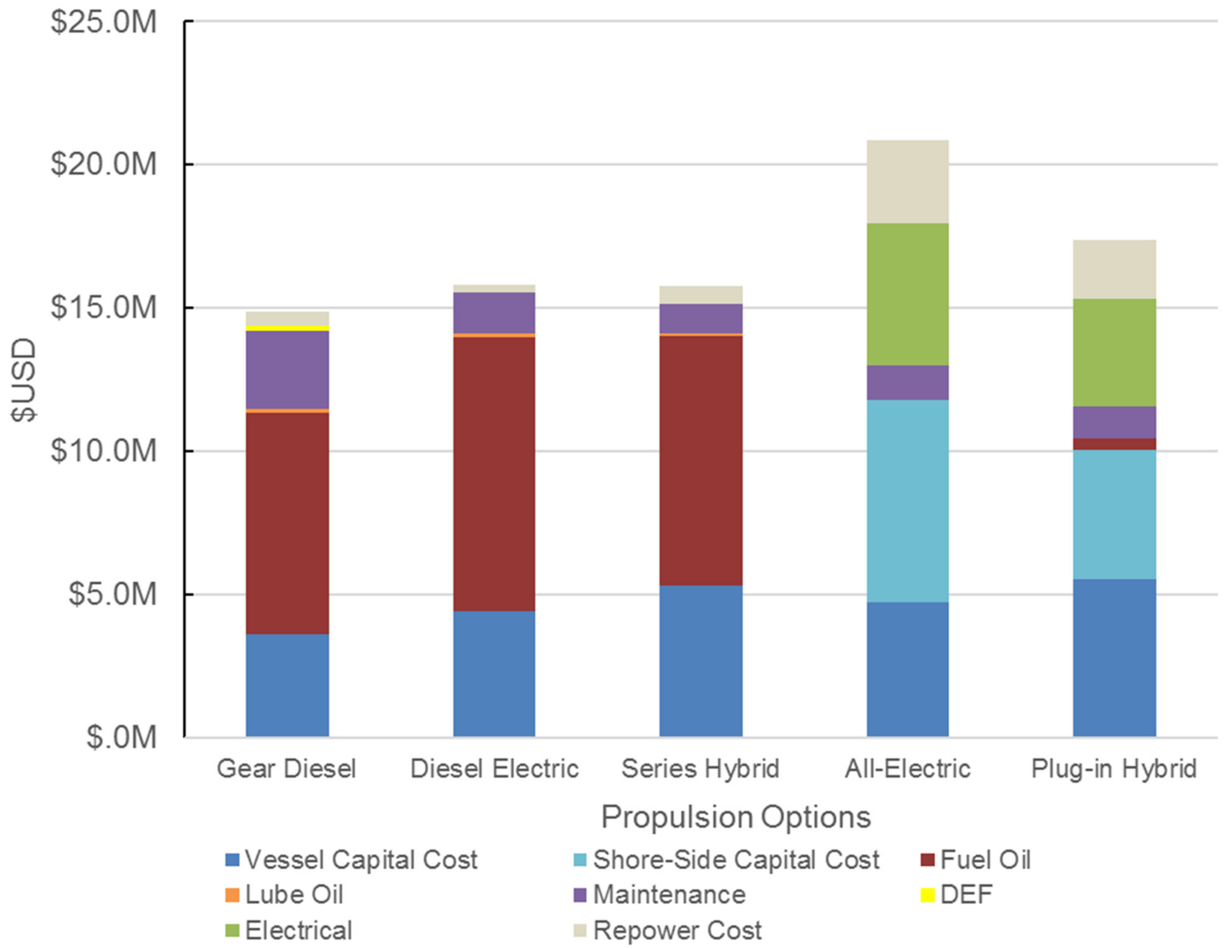


Figure 3 40-year life cycle cost of propulsion systems, showing breakdown of capital and operating costs

Glosten performed a propulsion trade study to help Skagit County consider the unique strengths of available state-of-the-art marine propulsion options. A scoring system designed to assist in selection includes the following categories:

- Capital cost.
- Operational cost.
- System weight.
- Design and build complexity.
- Reliability and availability.
- Airborne noise.
- Vessel air emissions.

The reliability and availability category used a risk to score the various propulsion options.

Each category received a raw score from 0 to 1 based on defined metrics. As an example, the raw score for “system weight” was calculated by dividing the lowest weight of all propulsion options by the individual propulsion option weight such that the lowest weight propulsion option received a score of 1. The raw score was then multiplied by the category weighting factor to provide a weighted score. Weighted scores were summed together to provide a total weighted score out of 1.

Weighting factors significantly impact the outcome of the propulsion study and readers are encouraged to develop their own weighting factors and scoring. To exemplify the scoring system, Table 2 presents weighting factors provided by Skagit County. Capital cost and operating cost were set to zero and individually compared between propulsion options in the charts below. The high weighting on reliability and availability generally reflects the consensus of the Guemes Ferry Replacement Survey conducted in the fall of 2017.

Table 2 Example weighting factors provided by Skagit County

Scoring Category	Weighting Factor
Capital Cost	0%
Operations and Maintenance Cost	0%
System Weight	10%
Design and Build Complexity	20%
Reliability and Availability	45%
Airborne Noise	10%
Vessel Air Emissions	15%
TOTAL (must equal 100%)	**100%**

The above weighting factors were used to develop total weighted scores for each propulsion option. Figure 4 provides capital cost for each propulsion option versus total weighted score, with a score of 1 being the best.

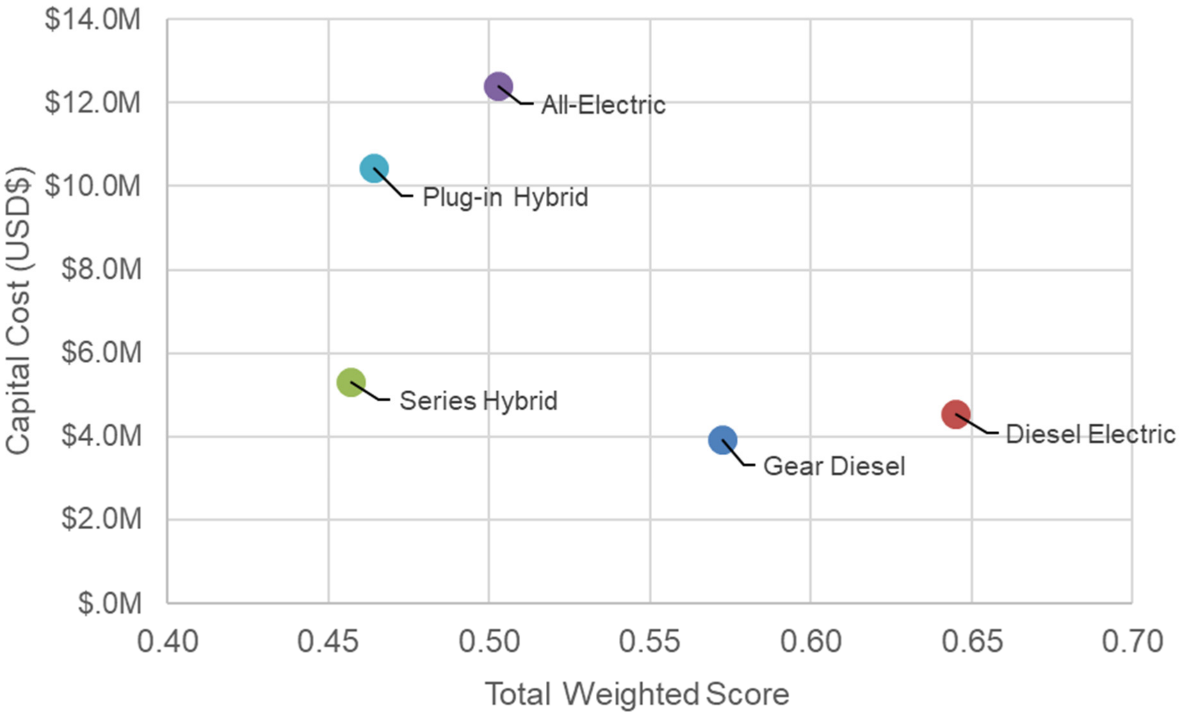


Figure 4 Propulsion system capital cost versus total weighted score

Figure 5 provides operating cost for each propulsion option versus total weighted score. These costs are expressed as a range of possible values based on a sensitivity analysis for the price of diesel and electricity for the past five years. Electricity prices are much more stable than diesel and are represented by narrower possible operating cost.

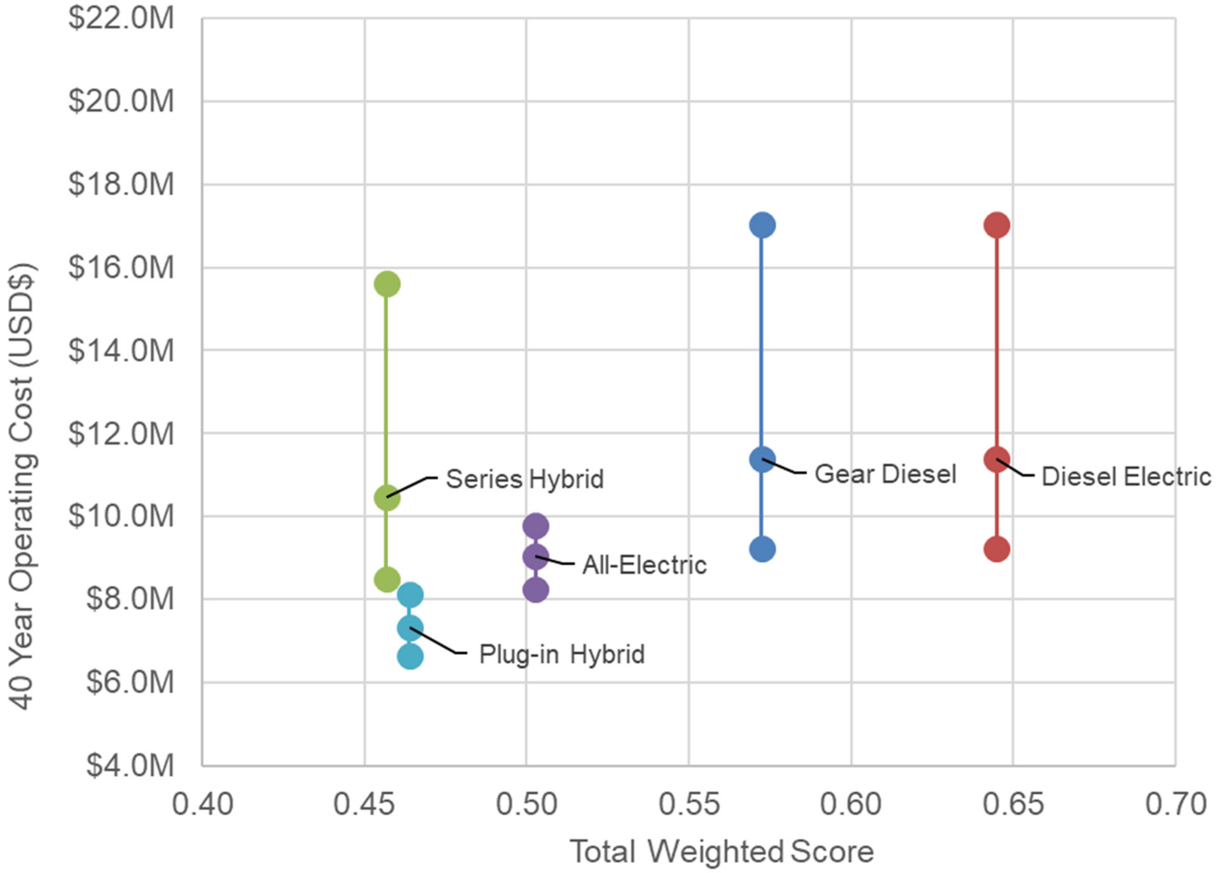


Figure 5 Propulsion system operating cost versus total weighted score

The concept design and propulsion analysis presented are governed by the vessel's design requirements. Design requirements may be imposed by the environment, terminals, ridership, regulations (including those imposed by the United States Coast Guard), and other basic requirements. The following requirements significantly affect the concept design.

- The existing terminals will receive minor modifications but in general will not be replaced. The bow shape of the replacement vessel must closely match the existing vessel and the breadth is limited by the dolphin placement.
- The vessel operates in a channel with tidal currents acting on the vessel's beam exceeding 4 kts (up to 5.5 kts at times). The installed power of the vessel is governed by maneuvering in these high currents.
- The replacement vessel is required by the Vessel Capacity Study to carry 32 vehicles. Given the beam limit imposed above, the vessel must be longer than the *Guemes* to accommodate more vehicles.
- As detailed further in the Transportation System Assessment, the required operating tempo is two round trips per hour, which would not reduce the peak frequency of the existing service. This tempo dictates the recharge time of an all-electric vessel.
- Several emergency response scenarios were developed. Each propulsion system presented meets the operational requirements of these scenarios.

- The vessel will operate under the same regulatory regime as the *Guemes*, as a US Coast Guard-inspected passenger vessel of less than 100 gross regulatory tons (GRT) and a passenger limit of 150. Crewing of the replacement vessel is not intended to change; it will be operated by one Master and two Deckhands.
- The US Environmental Protection Agency governs the emissions of marine engines. Engines of 804 hp (600 kW) and greater must be Tier 4 compliant, utilizing exhaust gas after-treatment technology, while smaller engines use on-engine Tier 3 compliant technology. The differences in capital, fuel, and maintenance costs have been incorporated.

This concept design report explores the principal characteristics and arrangement of the replacement vessel and trade-offs in both diesel and electric propulsion systems. Key findings include:

- The concept design and all propulsion systems presented herein meet the requirements for the replacement vessel.
- The capital cost of shore-power charging infrastructure more than doubles the propulsion system cost for the All-Electric and Plug-in Hybrid propulsion systems.
- All-Electric and Plug-in Hybrid options will likely have lower operating cost than diesel options, with Plug-in Hybrid offering the lowest operating cost.
- At the current price of diesel ($2.09/gallon), the All-Electric and Plug-in Hybrid propulsion systems have a higher overall life cycle cost. The Plug-in Hybrid vessel has a similar life cycle cost at approximately $2.50 to $3.00 per gallon, and a lower life cycle cost at higher diesel prices.
- Capital costs can be reduced if the frequency of service, ability to meet the emergency services, or vessel capacity is reduced.

Section 1 Existing Operation

The Samish Nation has been ferrying people and goods to and from Guemes Island for at least 14,000 years (Reference 1). Motorized ferries began serving Guemes Island on a regular schedule circa 1890. The first purpose-built Guemes ferry, *Guemes*, entered service in 1917. Later retrofitted to carry six cars, *Guemes* remained in service for 42 years. In 1959, the existing nine-car ferry *Almar* was purchased to replace *Guemes*. In 1961, the Anacortes terminal moved from the end of Q Avenue to the former San Juan ferry terminal at the end of I Avenue (Reference 1).

Skagit County purchased *Almar* in 1963, marking the beginning of public ferry service to Guemes Island. By 1974, repair and maintenance costs had grown untenable, and Skagit County began planning to replace the 27-year-old *Almar* (Reference 1). Three years passed before the county secured funding to design a new 21-car ferry, *Guemes*, which presently serves the route (Reference 20). In December 1979, five and a half years after the replacement effort began, Skagit County took delivery of *Guemes*. The docks at both terminals were replaced completely in 1980 to support the new ferry (Reference 1).

Guemes is pictured in Figure 6. It has a capacity of 100 passengers, and 21 vehicles. Its design speed is 9.5 kts; it achieves a crossing time of approximately five minutes, and a round-trip time of approximately 25 minutes. *Guemes* is 124 feet long and 50 feet wide overall following modifications to its guardrails in 2006. Its engines and generator set were also replaced in 2006, and its generator set was replaced again in 2017, but otherwise the vessel has remained largely unchanged since it entered service. The parking lots at both terminals were expanded between 2005 and 2006. The Anacortes terminal building was replaced in 2010, and the docks at both landings underwent refurbishment in 2011.

Figure 6 Existing Guemes Island ferry, M/V *Guemes*

Guemes is now 38 years old. Ferry service outages and vessel maintenance costs have reportedly increased in recent years, and a study conducted in 2013 found that it would be more economical to replace the ferry than to refurbish it (Reference 21). Skagit County began considering replacement options in earnest in 2014, and in 2017 the County retained Glosten to assist with the replacement effort.

Section 2 Concept Design Description

This section describes the concept design for the Guemes Island Ferry Replacement. This design results from design constraints and regulatory requirements detailed in Section 3 (Propulsion Analysis), Section 4 (Design Requirements), and Section 5 (Regulatory Requirements).

2.1 House Location

To maintain vehicle and passenger segregation throughout the entire loading and unloading evolution, access to the passenger cabin must be located on the West side of the vessel (discussed further in Section 4.4). Two options are discussed below.

A main passenger cabin located on the West side of the vessel and on the main deck allows passengers to remain segregated from vehicles, while not requiring passengers to negotiate stairs. This simple design, as shown in Reference 12, reduces the structural weight and complexity of the design when compared with other designs. One of the largest drawbacks to this arrangement is the off-center weight that must be corrected for by using fixed ballast. However, it is believed that this arrangement will achieve a lower cost and an improved arrangement over the centered and elevated passenger cabin as discussed below.

A passenger cabin elevated over the vehicle deck and centered about vessel centerline would provide ample space for passenger accommodations, and would reduce or eliminate the need for permanent ballast. An elevated passenger cabin would however require each passenger to use stairs or an elevator, that later needed to satisfy the Americans with Disabilities Act (ADA) requirements for this arrangement. A water deluge system would also be required to protect the superstructure against a vehicle fire. These additional complexities lead to the former arrangement (off center house) being selected for the concept design.

2.2 Aesthetics

A ferry is a workboat, first and foremost, and the function of the vessel is paramount. Yet ferries often become icons of a community, appearing on everything from logos to tourist merchandise. Aesthetics and design style of a vessel is too often saved for late in the design when there is little that can be done to significantly improve the look. Many Guemes Island residents care deeply about the look of their beloved *Guemes*, and given an adjustment period, the new vessel will hopefully become an equally loved ferry, both in function and style.

Many sketches were developed to explore the flow of passenger and crew traffic and to understand the look and feel of the replacement vessel. Sample sketches are shown in Figure 7.

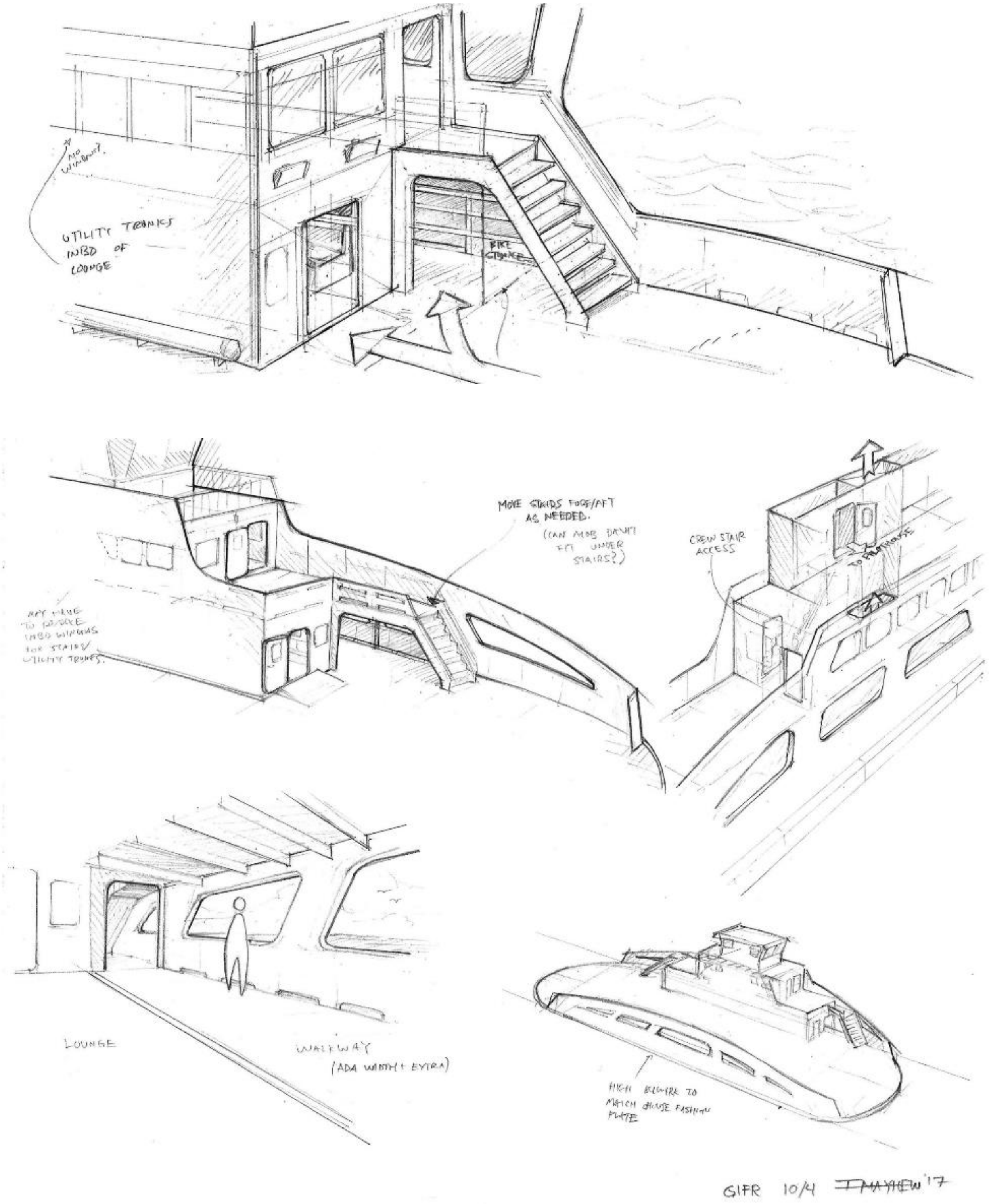


Figure 7 Sample sketches used to explore access pathways and the style of the vessel

Through this process, several arrangement concepts became prominent, some of which are discussed below.

- A breezeway, located outboard of the deckhouse and shown in the General Arrangement drawing, is incorporated to provide a pathway for crew and passengers to use that avoids both the vehicle deck and the main passenger cabin. The breezeway provides fresh air and views for passengers wishing to stay on the exterior main deck. It also moves the deckhouse house inboard which simplifies access to the below main deck spaces.

- A single pilothouse simplifies the arrangement and recalls the aesthetics of the existing vessel.
- Fashion plates provide a weather brake for passengers on the West side of the vessel, and for vehicles on the East side of the vessel, while improving the overall aesthetics.
- Exterior access to the upper deck allows the interior volume of the main passenger cabin to be used efficiently. Interior stair access to the pilothouse allows security measures to be easily employed.

Concept views shown below in Figure 8 and Figure 9 provide a sense of arrangement and style not easily obtained from the two dimensional General Arrangement drawing.

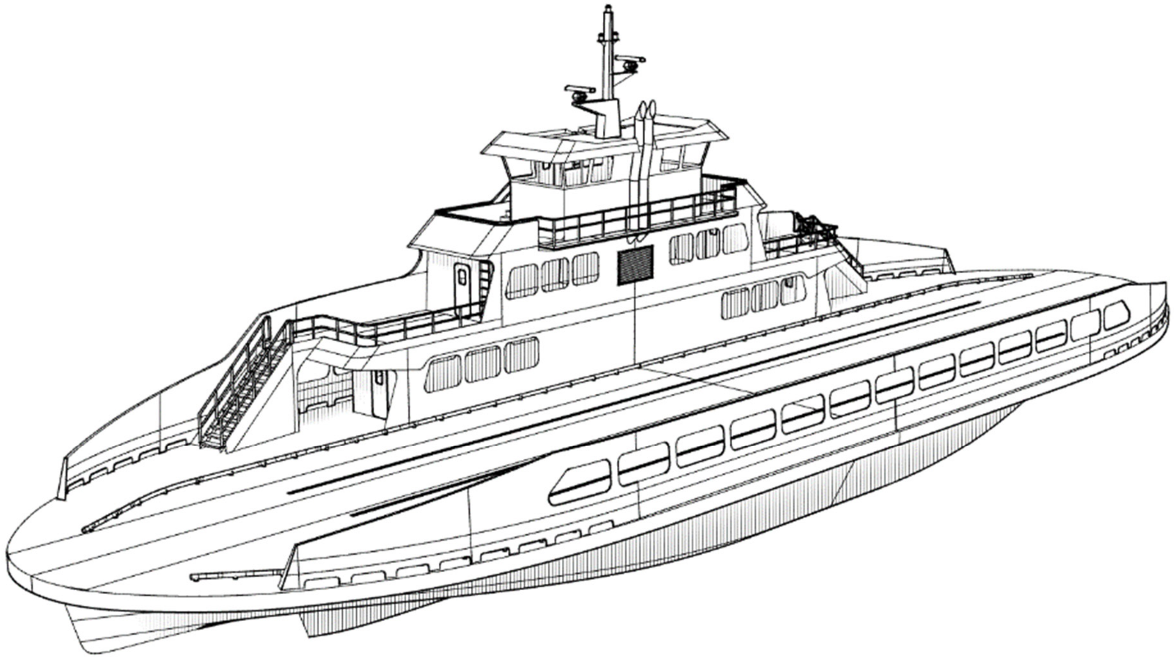


Figure 8 View of the replacement vessel, showing off center and three-tiered deckhouse

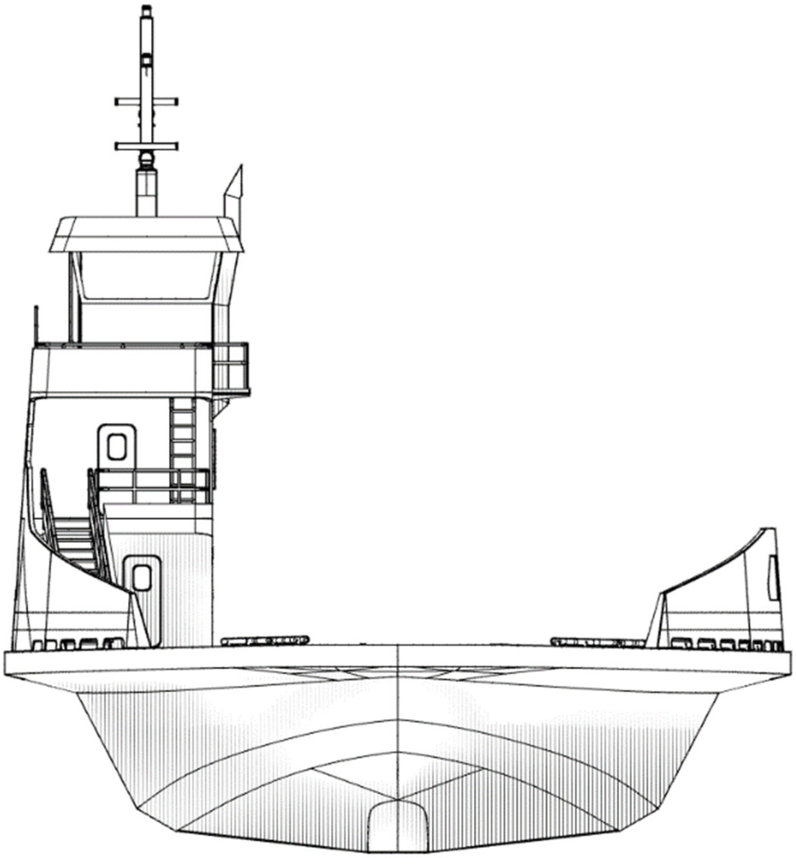


Figure 9 End view of the concept replacement vessel, as seen approaching Anacortes terminal.

2.3 Passenger Accommodations

The concept vessel is designed to accommodate 107 walk-on passengers, with space for two wheelchairs and seating for 36 to 52 passengers (Section 4.4). The design segregates passengers from vehicles, with the passenger space on the West side of the vessel (Reference 14 and discussed further in Section 4.2). The vessel's arrangement allows passengers to progress from one end of the vessel to the other without entering vehicle space.

A passenger lounge on the main deck offers space for two wheelchairs, bench seating for 40 passengers, and standing room for 23 additional passengers. A covered breezeway outboard of the main passenger lounge offers a way for crew, bicycles, and other loads to move from one end of the vessel to the other without entering the vehicle deck. A partially covered exterior passenger space at each end of the vessel offers standing overflow capacity for passengers, and it offers a queuing space for embarking and disembarking passengers.

Stairs at each end of the vessel lead to a passenger lounge on the upper deck. This lounge offers table-and-bench seating for twenty passengers and standing room for sixteen passengers. An uncovered exterior space at each end of the upper deck offers additional standing room, and it offers a queuing space for embarking and disembarking passengers. The upper passenger deck can be closed when it is not needed.

Passenger lounges with perimeter windows allow the entry of natural light, to promote sightlines to the exterior views, and to encourage a continued sense of community between walk-ons and passengers in vehicles.

Racks for six bicycles at each end of the passenger space can accommodate a total of 12 bicycles (Section 4.5). The rack locations minimize the impact of stored bicycles on passenger and vehicle flow, and allow bicyclists the option of either walking with the passengers or cycling behind the vehicles.

2.4 Crew Accommodations

The vessel is equipped to operate with a crew of three (master and two deckhands, discussed further in Section 5.1.3). A crew lounge on the upper deck is accessed through the upper passenger lounge. A single head (toilet and sink), also accessed through the upper passenger lounge, is provided for crew use, in order to allow continuous operations without shore-side breaks (as required with the existing operation). The primary access to the pilothouse is through the crew lounge, limiting access to the pilothouse through a lockable door.

The break room is conceptually provided with a small booth and table, counter, sink, under counter refrigerator, under counter cabinet storage, microwave, coffee pot, and waste bin. A storage locker, accessed from within the break room, provides a hanging locker and space for general stores.

2.5 Pilothouse Layout

In the design of the pilothouse, exceptional visibility in all directions is paramount, as the route is busy with crossing recreational and commercial marine traffic, and requires maneuvering in confined spaces at each terminal. For this reason, a ship-assist tugboat type pilothouse is incorporated, featuring large outward-canted windows on all sides and an overhead visor to reduce glare.

The pilothouse itself is located amidships and elevated enough to achieve a commanding view of the surrounding area, as well as unobstructed lines of sight from the control consoles to the deck edge on both ends, with operator heights ranging from 5'-0" to 6'-3".

The pilothouse is isolated from the passenger spaces, and accessed by one lockable door. The space is heated with separate controls from the passenger spaces, and all windows are provided with directional blowers to eliminate fogging on the inside of the windows.

Two matching (identical) control consoles are installed on each end of the pilothouse. A desk with a single upholstered seat on either end is provided. The layout of all controls and seating is simple and ergonomically designed, meeting ASTM F1166 human engineering design standards.

Navigation electronics and other equipment located in/on the pilothouse include at least the following:

a) Two radars (scanners mounted on opposite sides of mast) with displays at each console

b) Lighting panel

c) Alarm panel

d) Two VHF radios

e) Z-drive steering controls and indicators

f) Engine monitors

g) Transducer/fathometer

h) Two searchlights (each mounted on opposite sides of mast)

i) LED deck floodlights

j) Magnetic compass
k) GPS
l) AIS transceiver
m) Malfunction display
n) Electronic chart plotter
o) Window wipers
p) Window defroster vents/fans
q) Two or more horizontal sliding windows

2.6 Hull Design

The preferred hull design for the new Guemes ferry is a shallow-draft, double-chine monohull with one azimuthing thruster located on centerline at each end. A perspective view of the concept hull is shown in Figure 10.

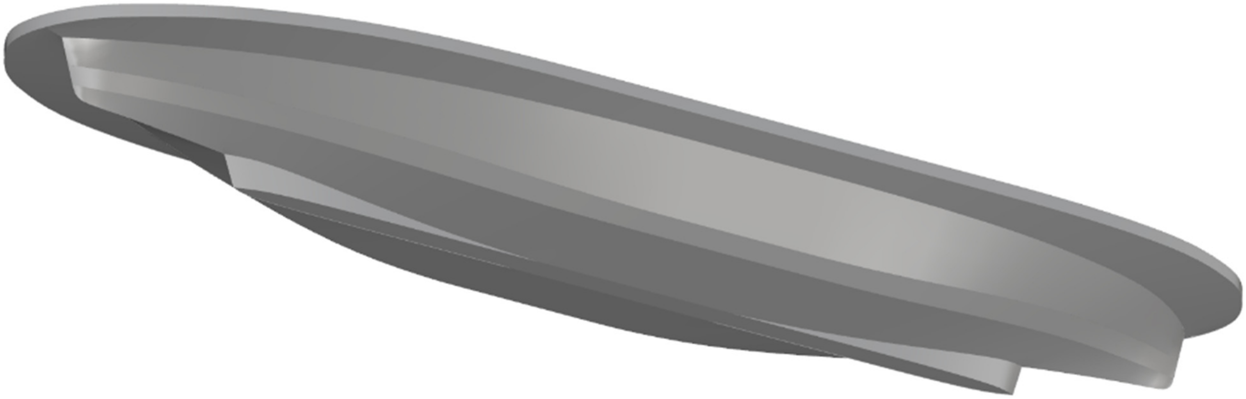


Figure 10 Perspective view of the concept replacement vessel's hull, looking upward from below

Key aspects of the hull design and their associated tradeoffs are as follows:

- *Low resistance to transverse current*. Beamy, shallow-draft hulls with high flare, low deadrise, and large bilge radii are well suited to minimizing transverse forces. These attributes negatively impact powering and constructability, so they were applied in moderation. A double chine is used in place of a rounded bilge in order to reduce construction cost.
- *High maneuverability*. Hulls with low resistance to transverse current and no skegs tend to turn easily, but they also have difficulty tracking straight. Short skegs improve directional stability and reduce docking loads. The nozzles on the azimuthing thrusters collimate flow, improving directional stability when they are aligned with centerline. Both the new and existing Guemes Island ferries favor maneuverability (i.e. turning quickly) over directional stability (i.e. tracking straight), as this compromise best fits a short ferry route with a strong current running perpendicular to the route.
- *Low resistance to forward travel*. Narrow, fine, fair hulls have lower resistance to forward travel, but they offer less stability, less maneuverability, and higher resistance to transverse current. In order to reduce breadth on the waterline, the vehicle deck is cantilevered. The hull is as fine as possible at the ends, where fineness matters most.

Modest bow rake is used in order to maximize waterline length and thus slenderness. The double chine more closely approximates a fair shape than a single chine does, and it is easier to construct domestically than a round-bilge hull is. The frames under the cantilevered vehicle deck on the replacement vessel will be enclosed within the hull.

- *Adequate stability*. The vessel must meet US Coast Guard transverse stability requirements (discussed further in Section 5.1.2). The vessel must also have sufficient longitudinal and transverse stability to avoid assuming undesirable angles of trim and heel during loading and unloading.
- *Adequate seakeeping*. The freeboard of the replacement ferry is two feet higher than that of the existing ferry in its present condition, in part to keep the vehicle deck drier. See Section 4.3 for additional information on the operating environment. Some bow rake is kept to deflect run-up and spray. The angles of hull flare and of the deck cantilever deflect spray while avoiding high slam pressures.
- *Compatibility with propulsors*. The region around the azimuthing thrusters is open to ensure good inflow and outflow when they are operating at any angle. The thrusters are located sufficiently below the design waterline to avoid cavitation and ventilation. The thrusters protrude below the baseline, as they do on the existing vessel. Although this arrangement offers less protection from grounding and colliding with submerged objects, the vessel's normal route is not particularly prone to these risks, and the benefits are seen to outweigh the drawbacks.
- *Compatibility with terminals*. The ends of the concept vessel's main deck have the same shape as the ends of the existing vessel's main deck in order to ensure a similar fit with the wingwalls. The overall length and breadth of the vessel are limited to 200 feet and 53 feet respectively (discussed further in Section 4.2).
- *Design flexibility*. The concept design's hull has 21 feet of parallel midbody in order to simplify the removal of a row of vehicles in the event that only a smaller ferry could be funded. Although future design refinement may change the length of parallel midbody, a short segment of parallel midbody is built into the replacement ferry so that it can be lengthened later in its life.

Table 3 contains principal particulars of the replacement ferry, and Figure 11 shows a body plan.

Table 3 Principal particulars of the replacement ferry concept design

Parameter	Variable	Value
Length, overall	***LOA***	178'-0"
Length, waterline	L_{WL}	170'-0"
Beam, overall	B	53'-0"
Beam, waterline	B_{WL}	39'-11"
Depth to main deck, at side	D	13'-6"
Draft, full load	T	7'-6"
Displacement, at full load	Δ	615 LT
Length-beam ratio	L_{WL}/B_{WL}	4.26
Length-displacement ratio	$L_{WL}/Vol^{1/3}$	6.11
Beam-draft ratio	B_{WL}/T	5.32
Block coefficient	C_B	0.42

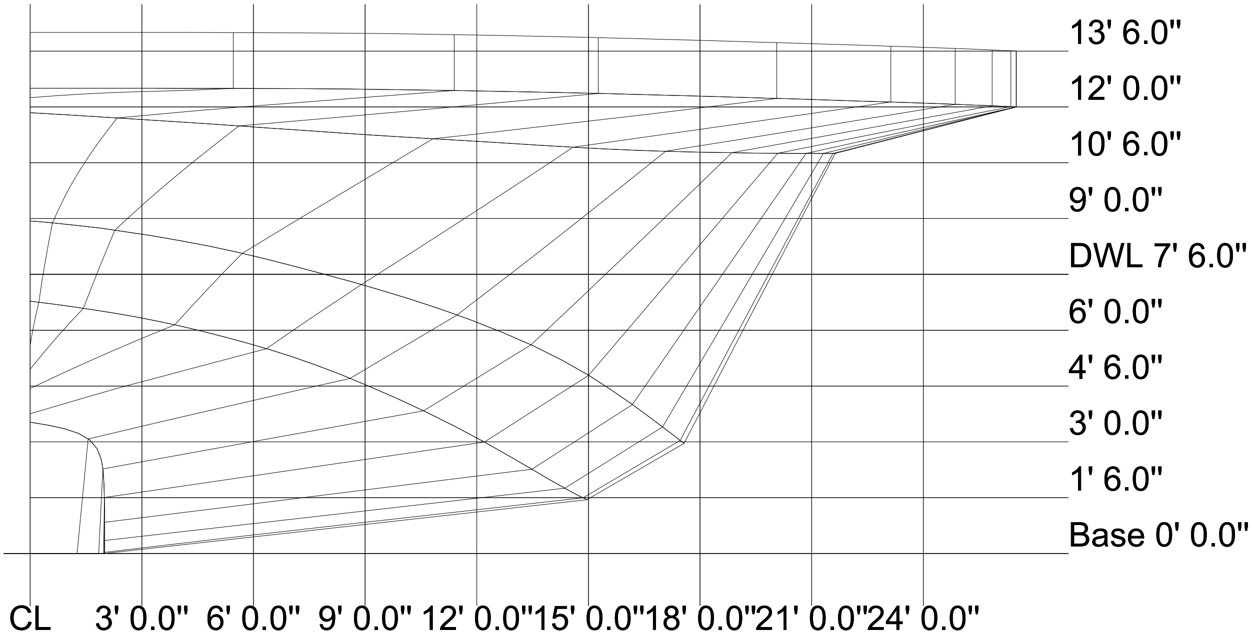


Figure 11 Body plan for the replacement ferry concept design

2.7 Structure and Tonnage

The steel hull will be designed in accordance with ABS Rules for Building and Classing Steel Vessels under 90 Meters in Length as required by the Code of Federal Regulations (CFR; 46 CFR §177.300; Reference 2). The Structural Midship Section Drawing (Reference 12) shows the proposed structural midship section arrangement. The notable design elements are outlined below.

The hull will be of single-bottom construction and longitudinally framed to seek the most lightweight arrangement. Similarly, the deck will be longitudinally framed to help mitigate “wash-boarding” of the deck due to heavy wheel loads.

Transverse web frames spaced at the maximum spacing of 48 inches on center for “ordinary frames” satisfy US Coast Guard MTN No. 01-99 (Tonnage Technical Policy). The ordinary frames must not have pass-through openings for continuous plate stiffeners for the line of ordinary frames to be maintained. Therefore, all hull and deck plate stiffening will be flat bars that will pass through slots fully welded on both sides of the ordinary frame intersections to close off the opening. This detail stems from the Design for Production (DFP) method of reducing part count as the alternative of adopting rolled stiffener shapes would necessitate the addition of watertight collars to close off the opening.

An explicit tonnage calculation has not been performed during concept design, but steps have been taken as described above and as shown on Reference 12 allowing the vessel to have a tonnage below 100. The deckhouse will use tonnage openings as necessary to eliminate the tonnage contribution of the above deck structures. As a point of comparison, both Pierce County ferries (the *Christine Anderson* and the *Steilacoom II*) have a tonnage below 100, yet these are considerably larger ferries.

The main deck plating will be generally 3/8" A588 Corten Steel plate with 5/8" wear plate inserts at the ends in way of the boarding ramp. All deck plating is supported by the aforementioned longitudinal flat bar stiffeners at 12" spacing. All deck stiffening (girders, transverses and longitudinal frames) will be made from A572 steel (50 ksi yield stress). The main deck scantlings are governed by the axle loads discussed in Section 4.5.

Alternatively, the main deck may be arranged similar to the existing vessel with 1/2" A588 Corten Steel plate assuming 24" stiffener spacing. This arrangement results in a 10% weight penalty for the main deck, or approximately 8 LT.

The hull shell plating and internal stiffening will be made from A36 (36 ksi yield stress) steel. The sponson will be fitted with a 3/4" thick 18" tall guard to help resist deformation during hard impacts.

The deckhouse and bulwarks shown in Reference 12 is of aluminum construction. Aluminum was selected to reduce the amount of compensatory ballast required as described in Section 2.1, redoubling the weight savings and ultimately reducing lifetime energy costs.

The deckhouse sides and decks are and longitudinally framed with 1/4" 5083-H116 plate at 18" and 12" frame spacing, respectively. The framing is supported by transverse web frames and deck transverses aligned with the hull ordinary frames. The pilot house utilizes heavy flat bar window mullions to improve visibility. Bi-metallic strips or a bolting flange would be used around the perimeter of the deckhouse and bulwarks to enable the connection of the aluminum to steel structure.

In addition to the aforementioned weight savings, aluminum also requires less maintenance, which further reduces the annual cost of ownership. The unstiffened exposed sides will generally be covered with vinyl film coating in lieu of remaining bare in effort to retain the aesthetic without the additional maintenance. The disadvantage of an aluminum structure is that it costs more to manufacture, but it is believed that this disadvantage is more than offset by the advantages.

Manufacturing the deckhouse out of carbon fiber reinforced plastic (CFRP) could yields some weight savings, but at a significant increase in capital cost. Weight savings can account for up to 50% of an aluminum deckhouse, but the use of low smoke and toxicity adhesives reduces the potential weight savings. Additional insulation may also be necessary to meet US Coast Guard (USCG) regulations. The aluminum deckhouse structure weights approximately 21 long tons. Given that the weight off the center deckhouse must be countered with fixed ballast, a total vessel weight savings of 10 long tons could likely be achieved.

Rough cost estimates of a CFRP deckhouse are five to ten times the cost of an aluminum deckhouse, which is currently estimated at approximately $750,000. Spending multiple millions of dollars to save 10 long tons of weigh is not recommended.

2.8 Electrical

Electrical distribution largely depends on propulsion system selection. The initial concept design description below is based on the baseline geared-diesel configuration and will be updated as the propulsion system is selected and evolves.

The geared-diesel propulsion configuration results in a relatively simple power plant architecture. Without the necessity to distribute power to propulsion loads, the power plant does not require a 690, 600, or 480 VAC main distribution bus. A lower voltage distribution system will reduce size and cost of the ship service power plant.

The current vessel operates with a 24 VDC power distribution system, facilitated by engine alternators that do not run continuously. Increased heating and ventilation requirements for the replacement vessel necessitate a higher voltage distribution system for ship service loads. Additionally, a higher AC voltage allows for more efficient cable sizes to be run for larger ship service loads. Large loads will be powered with 208 VAC 3-phase or 120 VAC 1-phase power input. A 24 VDC system will also be provided for small loads.

Based on the criterion of size, cost, complexity, and availability, a grounded wye multiphase power distribution system will provide the most flexible and efficient option for the replacement vessel. For the purpose of this concept design, 208 wye 120 VAC will be considered for the primary voltage of the ship service power distribution system.

Two ship service generators will supply redundant power to a main 208 wye 120 VAC distribution bus. The main bus will provide control for automatic generator synchronization and automatic voltage regulation, allowing two ship service generators to share the total ship service load demand. Means of generator and bus control will be provided through power management, as well as through analog instrumentation, as a means of backup control. Power management for the main distribution bus will provide automated generator and bus control, as well as overload protection under all operating conditions.

Power will be distributed from the main bus to a network of smaller load centers, as well as larger ship service loads. Larger ship service loads include the following:

- Steering
- Bilge and fire Pumps
- Shore-side ramp operation
- HVAC

Additional 208 wye 120 VAC load centers will provide power for the remaining vital and non-vital systems, including 24VDC power supplies for LED lighting and ship controls.

2.9 Piping Systems

Piping systems are largely dependent on propulsion system selection. The initial concept design description is based on the baseline geared-diesel configuration and will be updated as the propulsion system selection evolves.

The piping systems in the vessel will be simple to keep the capital costs as low as possible but of highly corrosion resistant materials to keep maintenance costs low. Pumps for seawater service will be of bronze construction. All piping exposed to the weather, such as vents and fills, will be stainless steel.

2.9.1 Fuel Oil

A diesel fuel oil system will be installed on the vessel to deliver fuel to all diesel engines. The system will be kept as simple as possible, as reliable fuel sources are readily available. The system will be comprised primarily of stainless steel tubing as relatively small diameter fuel lines are required.

Fuel will be routed from the tank(s) through a Racor type filter and water separator to the diesel engine(s). Appropriate shutoff valves and crossover connections will be provided.

2.9.2 Sanitary Drains

Black and gray sanitary drains will be provided from the sink, toilet, and interior deck drains. All gray and black water will lead to the wastewater holding tank, which will be of plastic construction. The holding tank will be of sufficient capacity to match the fueling frequency.

Non-mechanical macerating toilets will be used. Flushing water will be provided by the potable water system, which will be fitted with a reduced pressure-zone-type backflow preventer.

PVC piping and fittings will be used above the main deck and to the extent practical, below the main deck. Copper nickel piping will be used where metallic piping is required.

2.9.3 Potable Water

A potable water supply system will be installed on the vessel to supply hot and cold potable water to sink(s) and to the head. Potable water will be stored in a single plastic tank. This system will be comprised of cross-linked polyethylene (PEX) type plastic piping to the maximum extent possible. Copper pipe will be used where metallic pipe is required. A single pump and accumulator tank will maintain system pressure at all times. A small electric hot water heater will also be provided. The potable water tank will be of sufficient capacity to match the fueling frequency.

2.9.4 Bilge and Firemain

A bilge and firemain system will be provided with cross connections necessary for each system to be backed up by the other pump. The pumps will be redundant and either electrically, hydraulically, or PTO driven. Suction for the pumps will come from two separate seachests. This system will be comprised primarily of copper nickel piping where adjacent to steel structure, and aluminum piping where adjacent to aluminum structure. All valving necessary for the emergency operation of these system(s) will be easily accessible.

2.9.5 Fire Suppression

A fixed fire suppression system, utilizing Novec 1230 as the fire suppression agent, will be installed in the engine room. The system will have audible and visual alarms provided above deck and will shut down engines and ventilation louvres upon activation.

2.9.6 Hydraulic and Lube Oil

All hydraulic lines for z-drive steering and lubrication will be made of stainless steel tubing.

2.9.7 Cooling Water

The main engines will be cooled by a circulating freshwater loop with keel coolers, which are mounted on the exterior of the hull and reject heat directly into the sea. This system will be comprised primarily of steel piping. The system will be provided with corrosion inhibitors without the use of glycol for freeze protection.

2.9.8 Engine Exhaust

The main propulsion engines and diesel generator engines will have dry exhaust systems utilizing high-attenuation silencers and resiliently mounted piping to reduce airborne and structure-borne noise.

2.9.9 Vents, Fills, and Sounds

Tank vents, fill pipes, and sounding tubes will be provided where necessary and include required containment coamings. This system will be made primarily of steel piping internally and stainless steel piping externally to reduce vessel maintenance. Tank level indication will be provided for the fuel tanks.

2.9.10 Deck Drains and Scuppers

Weather deck drains and scuppers will be provided where necessary, made of aluminum piping. All weather drains will lead overboard.

2.10 HVAC

Sufficient natural ventilation will be provided so as not to require air conditioning (cooling) in the crew and passenger spaces. Doors and windows with adjustable opening areas will allow for airflow modulation through the spaces during the summer months. Windows will in general be double-pane with low-e glass to reduce solar heat gain and interior condensation.

The Pilot House will be provided with a small roof mounted air conditioning unit to help control the heat in this largely glass walled structure.

Table 4 HVAC criteria

Criteria	Cooling Season	Heating Season
Seawater	65°F	40°F
Ambient Air	90°F	20°F
All Spaces	78°F DB, 55% relative humidity (Pilot House only)	70°F
T/S and Public Toilets	4 minute rate of change	70°F
Ventilated spaces and other spaces	In accordance with SNAME T&R Bulletin No. 4-16	

2.11 Lightship Weight

A lightship weight estimate was developed for the baseline (geared diesel) concept. Lightship weight includes the completed vessel with all operating liquids in equipment, but no liquids in tanks and no people or effects aboard. Hull and house weights are estimated from structural calculations per the ABS 90-meter Rules and a 3D model of the hull and deckhouse. Other weights are based on regression analyses of other ferries with geared diesel propulsion systems and diesel generator sets. Table 4 presents these weights and their design margins and allowances.

Table 4 Lightship weight estimate for baseline (geared diesel) concept

Group Description	Margin	Weight	Margin	LCG	TCG	VCG
	%	LT	LT	ft +Aft Fr 0	ft +Stbd CL	ft +Abv BL
Hull and House Structure	10.00%	284.41	28.44	0.00	1.00	11.12
Propulsion Plant	20.00%	31.25	6.25	0.00	-4.00	8.10
Electric Plant	20.00%	11.84	2.37	0.00	-2.00	20.25
Command and Surveillance	20.00%	2.67	0.53	0.00	16.00	35.50
Auxiliary Systems	20.00%	40.06	8.01	0.00	0.00	13.50
Outfit and Furnishings	20.00%	29.83	5.97	0.00	13.00	22.50
Heel Ballast in Guard	0.00%	23.80	0.00	0.00	-24.03	12.46
Lightship (Without Margins)		**423.88**		**0.00**	**0.17**	**12.48**
Design and Build Weight Margin (Total)	12.17%	51.57				
Design and Build VCG Margin	9.50%					1.19
Contract Mods. Weight Margin	1.45%	6.15				
Contract Mods. VCG Margin	1.25%					0.16
Lightship (With Margins)		**481.60**		**0.00**	**0.17**	**13.82**

The concept vessel's lightship weight is estimated to be 482 long tons (LT) when new. The longitudinal, transverse, and vertical coordinates of the center of gravity (LCG, TCG, and VCG respectively) are estimated for the purpose of evaluating trim, heel, and stability. The vessel's coordinate system is described in the following section.

The off-centerline house on one side of the vessel must be compensated to minimize the imbalance in weight. The most common method of compensation is fixed ballast.

2.11.1 Stability Model

The concept vessel's stability model is shown in Figure 12 with the principal axes defined. The buoyant hull is gray, and a simplified estimated wind profile is orange. The origin is at the intersection of the amidships (*y*-*z*) plane (also identified in this vessel as Frame 0 or Fr. 0), the centerline (*x*-*z*) plane (also identified as CL), and the baseline (*x*-*y*) plane (also identified as BL). The vessel is reflectionally symmetrical about the amidships plane and the centerline plane.

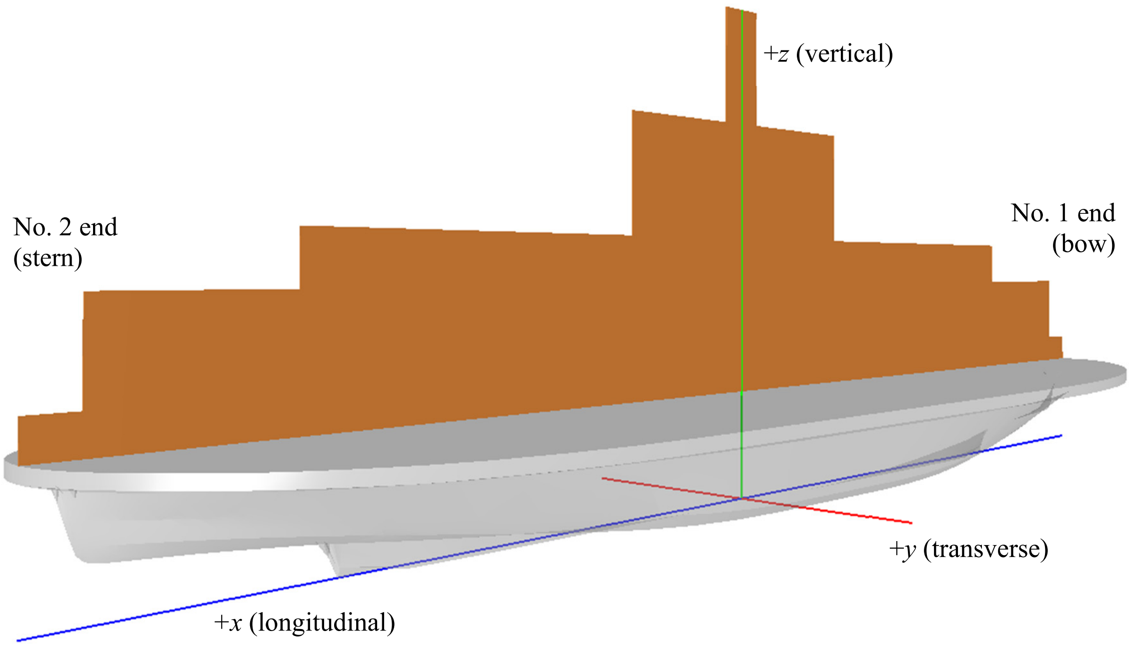


Figure 12 Stability model with coordinate system

Permeability is the fraction of total volume in each compartment, tank, or void that could be filled with fluid. Tanks and voids are assumed to have a permeability of 97.5% for intact stability. Table 5 presents the assumed permeabilities of compartments, tanks, and voids for damage stability as prescribed by 46 CFR § 171.066(b) (Reference 2).

Table 5 Compartment permeability for damage stability

Space Designation	Permeability
Machinery space	85%
All other spaces	95%

The margin line is an imaginary line on the side of the vessel that is not allowed to be submerged in the damaged condition. The margin line is prescribed by 46 CFR § 171.015(b) (Reference 2) for a vessel with a continuous bulkhead deck and no sheer (i.e. a vessel with a flat main deck that does not increase in height toward the bow or stern), as shown in Figure 13.

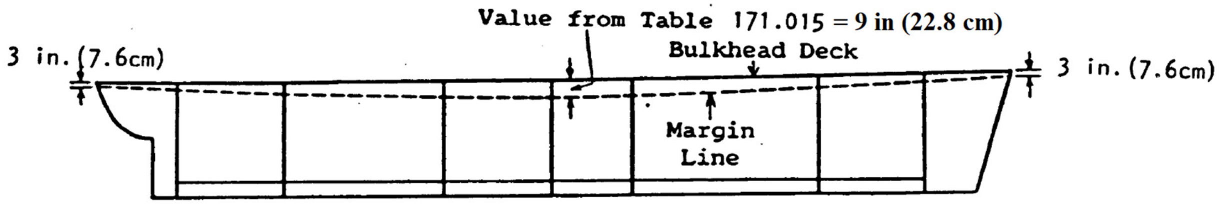


Figure 13 Margin line for a vessel with a continuous bulkhead deck and no sheer (from Reference 2)

The undesired ingress of water through openings such as door sills or vents is called downflooding. Tank and void vents are assumed to be fitted with float check valves to prevent downflooding, so they were not considered to be downflooding points per 46 CFR 170.055(i) (Reference 2). Presently the only downflooding point is the machinery space intake; its most vulnerable corner is noted in Table 6. This point is modeled symmetrically about the *x* and *y* axes to make the model insensitive to heel and trim direction. Openings located more than six feet above the main deck ($z > 20$ ft) are not modeled under the assumption that they would not be the first points where downflooding would occur. It is required that all watertight doors and hatches are kept closed and therefore would not pose downflooding risks. Rules require that all watertight doors and hatches be kept closed; therefore, they would not pose downflooding risks.

Table 6 Downflooding point

Downflooding Point	Longitudinal Location (ft + Aft Fr 0)	Transverse Location (ft + Stbd CL)	Vertical Location (ft + Abv BL)
Machinery space intake	±9.75	±12.50	17.00

2.11.2 Load Conditions

Tank capacities are listed in Table 7. Capacities will be refined as the design progresses.

Table 7 Tank capacities

Tank	Capacity (gal)	Weight (LT)	VCG (ft + Abv BL)
Diesel fuel (only required for vessels with diesel) engines)	6,000	19.00	8.00
Potable water	200	0.74	31.25
Sewage	200	0.74	8.00
Lube oil	TBD	TBD	TBD
Waste oil	TBD	TBD	TBD
Oily water	TBD	TBD	TBD

Operating loads are listed in Table 8. The weights of passengers are grouped because the weight of an individual passenger is so small. The weights of vehicles are reported per vehicle. Vehicle weight and capacity are established in Section 4.5.

Table 8 Operating loads

Operating Load	Weight (LT)	VCG (ft + Abv BL)
Crew and effects (3 @ 250 lb, including effects)	0.33	19.25
General stores	0.22	11.00
Ship’s stores and spares	0.33	5.00
Passengers on main deck (120 @ 185 lb)	9.90	16.50
Passengers on upper deck (30 @ 185 lb)	2.48	25.50
Standard vehicle	2.08	16.50
Large truck (51'-8")	35.71	22.25

Table 9 describes the three load conditions evaluated in this early design stage.

Table 9 Load condition summary

Load Component	Light Load	Full Load	Max Load
Potable water	10%	100%	100%
Sewage	10%	10%	10%
Fuel	10%	98%	98%
Crew and effects	100%	100%	100%
General stores	100%	100%	100%
Ship's stores and spares	100%	100%	100%
Passengers, main deck	0	120	120
Passengers, upper deck	0	30	30
Standard vehicles	0	29	23
Trucks (51'-8")	0	1	3

Each load condition is corrected for free surface, which is caused by liquids in partially filled tanks (slack tanks) shifting transversely. The reduction in transverse stability is accounted for as a virtual increase in VCG. Guidelines for accounting for free surface are set forth in 46 CFR § 172.225(c) (Reference 2). In order not to create any operating restrictions, all tanks were considered slack in all conditions, resulting in an estimated free-surface moment of 200 LT-ft.

2.11.3 Trim and Heel

As vehicles are loaded and unloaded, a vessel's draft, trim angle, and heel angle will change. It is important to ensure that the replacement vessel does not trim or heel excessively during loading and unloading. Glosten chose the existing ferry's trim and heel characteristics, which are reportedly acceptable, as the standard by which to judge the replacement ferry's trim and heel characteristics. For each of these two vessels, Glosten calculated the force required at the farthest forward point to trim the vessel one degree, and the force required at the farthest outboard point to heel the vessel one degree. Table 10 compares the existing vessel with the replacement vessel in their design full load conditions.

Table 10 Trim and heel sensitivity comparison

Characteristic	Existing Vessel	Replacement Vessel
Force to trim 1° (LT)	14.9	38.0
Force to heel 1° (LT)	2.2	4.6

The replacement vessel will have lower sensitivity to weight on deck, which is desirable.

2.11.4 Intact Stability

Per Section 5.1.2, Glosten evaluated the replacement ferry to the following intact stability criteria (Reference 2):

1. 46 CFR §170.170: Weather
2. 46 CFR §170.173(e)(1): Righting energy
3. 46 CFR §171.050: Passenger heel

Criterion (2) was evaluated with zero trim and with one degree of trim to ensure that the replacement vessel would meet applicable stability requirements throughout the range of possible load configurations per 46 CFR §170.110(c) (Reference 2). Figure 14 shows a curve of the greatest VCG that meets these three criteria at a range of displacements. Criterion (1) was the limiting criterion throughout the range of displacements shown. The load conditions from Table 9 are plotted on Figure 14. All evaluated load conditions satisfy the intact stability criteria.

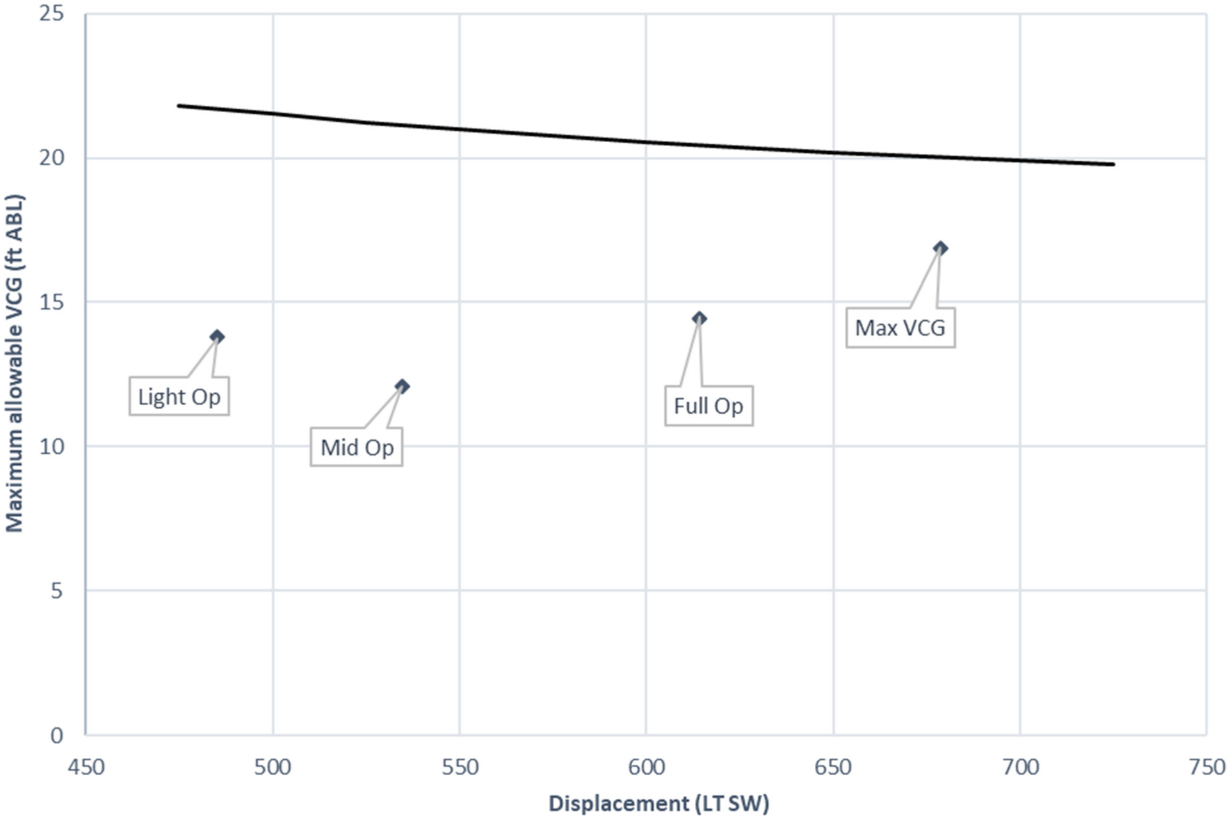


Figure 14 Intact stability curve with load cases plotted as points

2.11.5 Damage Stability

The hull is subdivided longitudinally in accordance with 46 CFR §171.060 and §171.070 through §171.073 in order to survive instances of flooding without submerging the margin line (Reference 2). Floodable length is the allowable distance between transverse watertight bulkheads at a given point along the ship's length. Floodable length is often used in the concept design phase to arrange transverse watertight bulkheads in a way that is likely to comply with detailed damage stability criteria usually evaluated in future design phases.

Figure 15 shows the floodable length curve and the lengths assumed flooded (based on the bulkhead arrangement and applicable regulations) overlaid on a profile of half of the vessel (it is symmetrical about amidships). The floodable length curve in Figure 15 represents the maximum load condition with one degree of trim because it is the least compliant condition. The locations of transverse watertight bulkheads (28, 52, and 76 ft to either end of amidships) are also shown in Figure 15. The bulkheads 76 ft to either end of amidships serve as the collision bulkheads. Per 46 CFR § 171.070(b), the vessel must be able to withstand simultaneous flooding in the two compartments on either side of the collision bulkhead (Reference 2). The vessel must also be able to withstand flooding in any one compartment at a time. The proposed arrangement of transverse watertight bulkheads satisfies the criteria for floodable length, although the machinery compartment at amidships is quite large, and may be subdivided as the design progresses. A detailed damage stability analysis would follow in further design development.

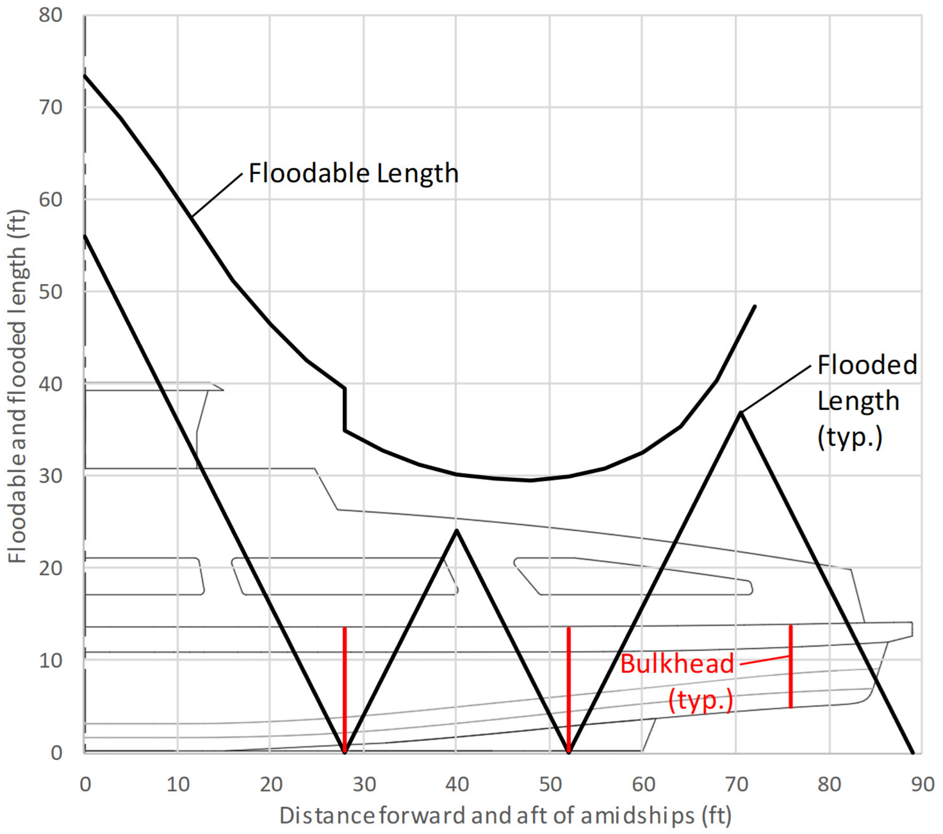


Figure 15 Floodable length and flooded length with transverse watertight bulkheads shown

Section 3 Propulsion Analysis

Skagit County would like to understand better the state of the art of marine propulsion systems for small short-haul ferries, with the goal of making a responsible and forward-looking decision regarding its new vessel. This section reviews a range of concept propulsion system options that fit the replacement vessel's operational requirements and operating profile are reviewed. Then, the characteristics of the system are compared using an objective, weighted scoring system.

3.1 Propulsors

Most double-ended ferries in the Pacific Northwest have a "conventional" propulsion arrangement with one propeller and rudder at each end (Figure 16). The propeller can be fixed-pitch to maximize simplicity and cruising efficiency, or it can be controllable-pitch to allow faster changes in thrust and better low-speed performance. Conventional systems use a rudder to steer when cruising and to divert the propeller's thrust when maneuvering. A conventional propulsion arrangement can have low initial cost, but changes in the direction and even the magnitude of thrust can be relatively slow, and the rudder cannot divert more than about half of the propeller's thrust to the side. A conventional propulsion arrangement therefore does not meet the design requirement for the replacement vessel to divert full thrust in any horizontal plane direction (discussed further in Section 4.7).

Figure 16 Conventional propulsion arrangement: fixed-pitch propeller with flat-plate rudder (© Sol Duc Photography)

Azimuthing drives are capable of diverting full thrust in any horizontal plane direction, which makes them a more appropriate propulsion arrangement for the replacement vessel. Two types of azimuthing drives are shown in Figure 17. On the left is a Z-drive, where the power input shaft is parallel to the propeller shaft (the three shafts at right angles form a modified "Z"). On the right is an L-drive, where the power input shaft is perpendicular to the propeller shaft (the two shafts at a right angle form an "L"). The L-drive can be slightly more efficient because it utilizes one less set of bevel gears. Where propulsion motors are used, the motors can be close-coupled with the drive, as Figure 17 shows. Manufacturers also offer electrically driven azimuthing drives that incorporate the motor within the hub or rim of the drive unit, but the offerings are very limited in the size range applicable to the replacement vessel.

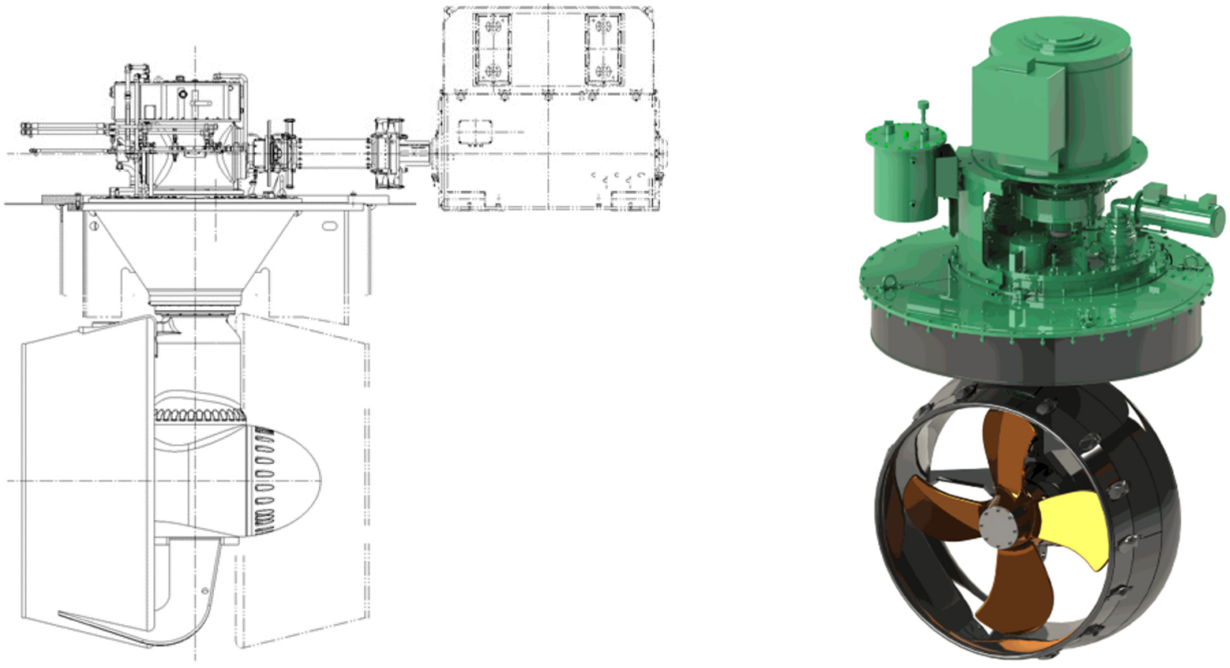


Figure 17 Azimuthing drives: Z-drive (left) and L-drive (right)

For the purpose of this report, the term Z-drive will be used to identify the general thruster, incorporating both Z and L-drive configurations.

Wells can be built within the vessel so that the Z-drives can be lowered into place through the main deck. This arrangement allows the drive unit to be maintained or replaced while the vessel is afloat, reducing the need for drydocking. If the operator were to keep a spare unit, then either drive unit could be swapped and maintained with minimal service interruptions.

Guemes uses two Ulstein Z-drives, driven by geared diesels, to provide propulsion power. The crew is familiar with, and generally pleased with, their performance and control. Issues have arisen with maintenance and parts availability as the drives have aged. Modern azimuthing drives are more robust and, when careful consideration is given to gear loading and duty cycle, they do not suffer the same failure modes or maintenance issues of the past.

Cycloidal propellers (Figure 18) are also capable of producing full thrust in any horizontal plane direction. Cycloidal propellers are most commonly seen on large escort tugs where operations necessitate quick, precise control over the thrust vector. Staten Island Ferries (SIF) is the only major ferry operator in the United States that has expressed a preference for cycloidal propellers. This preference emerged in the late 1970s out of a desire to improve the maneuverability of its conventionally propelled fleet (Reference 5). Cycloidal drives are larger, more complex, more maintenance-intensive, and less efficient than drives that use screw propellers with nozzles. Work by Glosten for others has shown that the capital and operating costs of cycloidal drives are significantly higher than those of Z-drives.

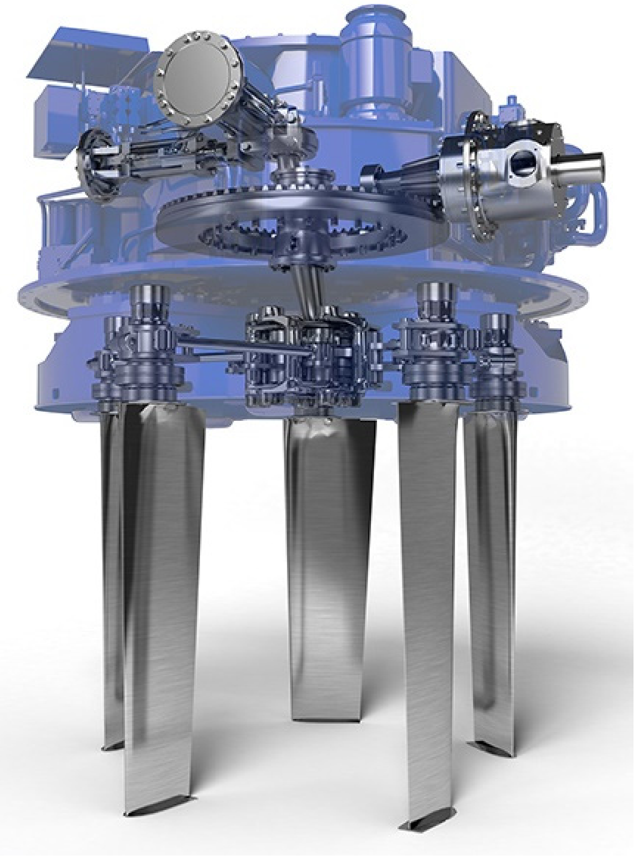


Figure 18 Cycloidal propulsion unit, by Voith

Modern azimuthing Z-drives appear to be the best technical and operational solution for the replacement vessel.

Manufacturers offer azimuthing drives either with open propellers (as fitted on *Guemes*) or with nozzled propellers (as shown in Figure 17). Nozzles increase thrust at low vessel speeds, thereby improving propulsor performance when the vessel is positioning, maneuvering, and accelerating. A standard 19a type nozzle will have a decreasing benefit as speeds increase. High-efficiency nozzles will improve performance across the full speed range, and should be considered to reduce fuel/energy consumption of the replacement vessel.

3.2 Delivered Power

Three powering cases were considered for the concept design:

- A cruising speed case with a light load (tanks 10% full; no passengers, no vehicles), calm weather, and no hull aging or fouling.
- A cruising speed case with a full load (tanks 98% full; 150 passengers, 29 cars, one truck), an approximately 80th-percentile weather event (15-kt headwind, 1-ft significant wave height), and substantial hull aging and fouling.
- A transverse speed case with a full load in calm weather with no current.

For many ships, the greatest propulsion power requirement occurs at cruising speed. The standard International Towing Tank Conference (ITTC) 1957 calculation method is typically used to estimate the concept vessel's power requirement at cruising speed. Residuary (primarily wave-making) resistance was calculated using a regression made from model-test data for five double-ended ferries. This regression is intended for use in concept-level design work.

In the case of the Guemes Island ferry, the propulsion power required to resist a transverse current event could possibly exceed the propulsion power requirement at cruising speed. In order to investigate the transverse speed case, the results of *Guemes*'s transverse speed test (Section 4.7) were used to calibrate a method developed by the US Navy for estimating current forces on moored ships (Reference 27). The observed transverse force was estimated to be 7% greater than the transverse force initially calculated by the US Navy method, resulting in a force calibration coefficient of 1.07.

Figure 19 presents the concept vessel's speed-power curves for the two cruising cases and the calibrated transverse speed case. Two 725-kW nozzled azimuthing thrusters are the smallest commercially available units that meet the requirements in Section 3.1, achieve the average cruising speed of 11.5 to 12 kts using one propulsor, and slightly exceed (by 7%) *Guemes*'s 4.3-kt transverse speed using two propulsors. These values are read off Figure 19 at the horizontal line indicating 90% of the propulsion system's maximum continuous rating (90% MCR), which is a common marine operational limit. To be clear, the range of cruising speeds at 90% MCR is 10.9 to 12.3 kts, depending on the condition of the vessel and the environment. The average of this range is 11.6 kts; this result is considered satisfactory given the present level of design refinement. It is worth noting that the power represented in Figure 19 is delivered power, i.e. the power delivered to the propeller. The origin and path of this power is discussed in Sections 3.5.1 and 3.5.

Many double-ended ferries share the propulsion load between the fore and aft propellers. Prior work has shown that the majority of propulsion load (70 to 90% of the total) should come from the aft propeller to gain the highest propulsive efficiency. Further design efforts will optimize this ratio. To remain conservative during concept design, 100% of the propulsion load is assumed to come from the aft thruster.

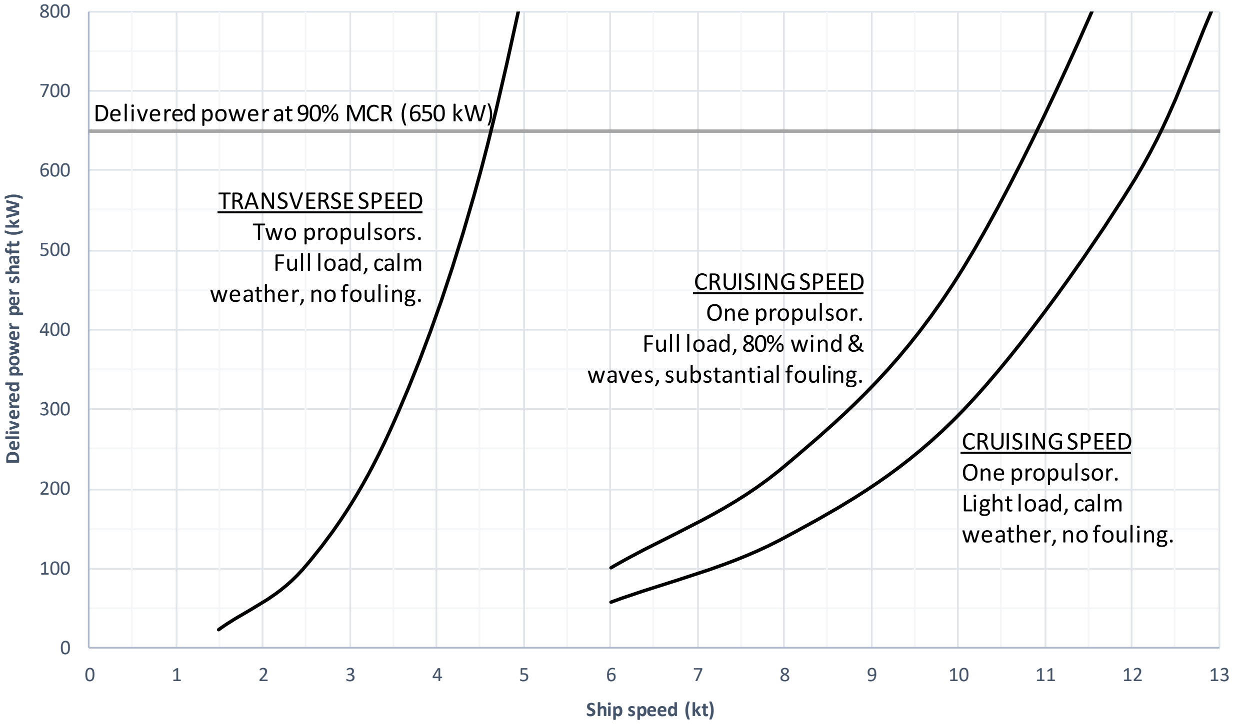


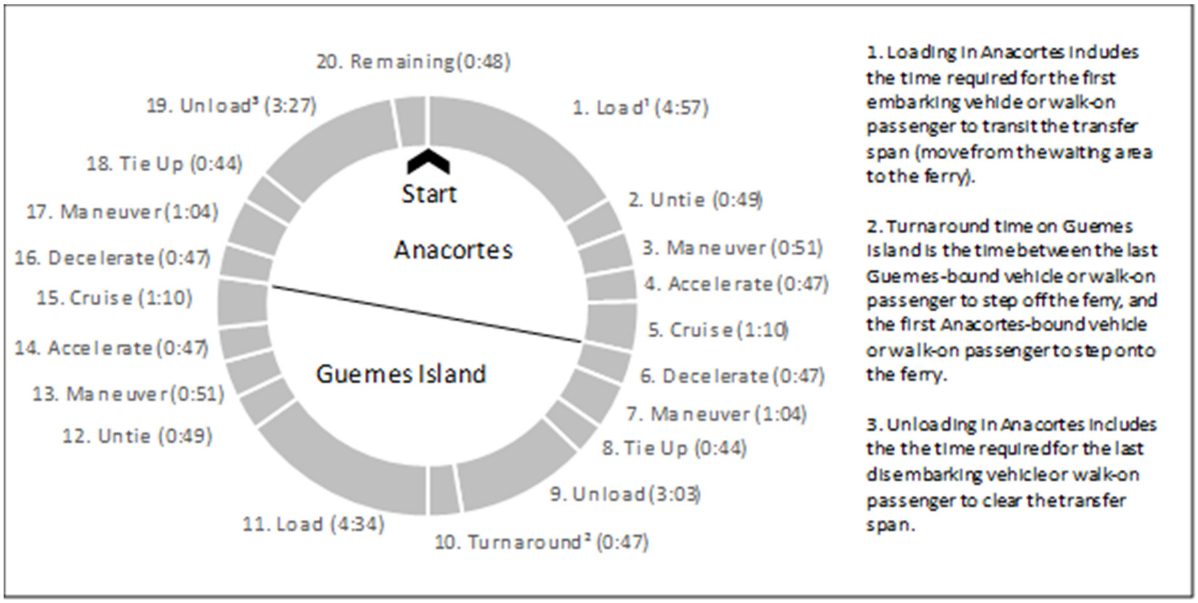
Figure 19 Replacement vessel speed prediction, twin nozzled azimuthing thrusters

As discussed in Section 4.7, the existing Guemes ferry's propellers appear to be optimized for slow speeds. Further design efforts will determine the best point for designing the propellers;

somewhere between zero (like many tugboats) and cruise speed (like most ferries). The goal of the optimization would be to meet the requirements of the design while achieving the highest efficiency during transit.

3.3 Operating Profiles

The standard operating profile was derived from work done in the Transportation System Assessment Report (Reference 7). The major underlying assumption of the replacement vessel scheduling was to maintain two round trips per hour. The average operational durations can be visualized below for a 32-vehicle ferry. Key assumptions of this analysis are presented on the right side of the graphic and further detailed in the Transportation System Assessment.



1. Loading in Anacortes includes the time required for the first embarking vehicle or walk-on passenger to transit the transfer span (move from the waiting area to the ferry).

2. Turnaround time on Guemes Island is the time between the last Guemes-bound vehicle or walk-on passenger to step off the ferry, and the first Anacortes-bound vehicle or walk-on passenger to step onto the ferry.

3. Unloading in Anacortes includes the the time required for the last disembarking vehicle or walk-on passenger to clear the trarsfer span.

Figure 20 Typical round-trip transit – 32-vehicle ferry

These durations were used to break each operation into various propulsion loads. It was assumed the ferry was pushing the dock during loading, unloading, and mooring operations (1, 2, 8, 9, 10, 11, 12, 18, 19, and 20). Table 11 summarizes the delivered power assumed for an average 15 minute one-way trip.

Table 11 Average one-way trip delivered power

Operation	Time (min)	Delivered Power, Pd (kW)
Load / Unload	10.35	150
Maneuver	0.85	556
Accelerate	0.78	798
Cruise	1.17	743
Decelerate	0.78	524
Maneuver	1.07	476

Cruising delivered power was calculated under average loading conditions, transiting at 11.5 kts. As shown in Figure 19, the assumed 675 kW delivered power occurs between the two speed curves dependent on vessel loading. An additional 10% power was provided to the forward propulsor to account for overcoming drag associated with the propulsor, increasing total delivered power to 743 kW. A power distribution between forward and aft propulsors of 60/40 and 90/10 has proven to be the most efficient allocation of power for double-ended ferries.

Other vessels in the Pacific Northwest have found a 90/10 split to be the most advantageous. Based on this, a 90/10 split was assumed for the replacement vessel.

Maneuvering, acceleration, and deceleration power was scaled from cruising power of the existing vessel to the replacement vessel. Cummins provided vessel torque and power data logging of the existing vessel operations in their report (Reference 24). These numbers were scaled proportionally by the increase in required transit power, providing a baseline operating profile.

Power required to push the dock during loading and unloading was approximated based on current vessel fuel consumption. Skagit County indicated the existing vessel refuels between 2,000 and 2,500 gallons every two weeks. Assuming the vessel power scales proportionally to installed power, a time weighted average engine load table was developed (Table 12). Pushing power is a function of vessel motions and was assumed unchanged with a larger vessel. Pushing power was iterated until fuel consumption for the existing vessel fell within the currently observed range, approximately 2,400 gallons. Average pushing power was assumed at 150 kW for the replacement vessel using this method.

Table 12 Time-weighted average engine load

Operation	Time (min)	End 1 (% MCR)	End 2 (% MCR)	Avg (% MCR)
Load / Unload	10.35	11	11	11
Maneuver	0.85	40	40	40
Accelerate	0.78	100	11	55
Cruise	1.17	98	10	54
Decelerate	0.78	69	7	38
Maneuver	1.07	34	34	34
Time-weighted Average		29	14	21

3.4 Emissions

Recent regulations pertaining to the engine sizing are discussed in Section 3.3. It is economically advantageous to keep engines at or below 599 bkW to eliminate the need for exhaust gas after-treatment and handling systems. This was not always possible for each propulsion configuration but was considered when feasible. Each propulsion system description includes the assumed EPA tier level of propulsion engines.

3.5 Propulsion Configuration

3.5.1 Available Technologies

Hybrid and electric vessel development is an emerging technology. Technologies developed from other industries are being adapted to vessels both large and small. Battery technology is trending towards increasing energy density and reducing battery cost. Electric motors, generators, drives, and converters are becoming more compact and efficient.

Lithium-ion battery chemistries have become the most popular in marine applications because of the high specific energy density and volumetric energy density. A number of cells have now been approved by Det Norske Veritas and Germanischer Lloyd (DNV-GL), most of which use Nickel Manganese Cobalt (NMC) as the cathode. NMC batteries are one of the cheapest cells per unit of energy. Figure 21 details the benefits of each lithium-ion cell chemistry, further from center representing most advantageous. This figure was provided for convenience from one possible battery vendor, Spear Power Systems, although there are many alternative suitable vendors.

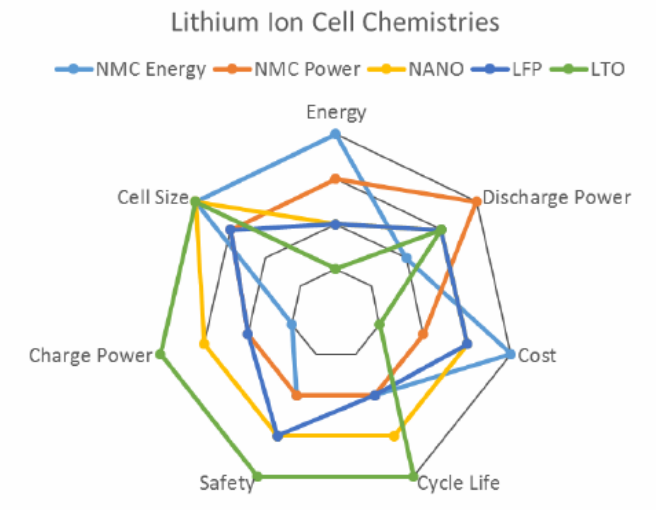


Figure 21 Battery chemistry comparison

Benefits of electric and hybrid propulsion systems extend beyond potential fuel savings, and include reduced point emissions, less engine maintenance, and lower noise and vibration. Limitations of hybrid and battery technology include significantly higher capital cost, reduced range, increased weight, greater system complexity, specialized maintenance, and periodic battery replacement and disposal.

Battery charging from shore-power offers the lowest cost of energy, especially when electric power is available at low rates, as in the Pacific Northwest. Most implementation of batteries in the industry have been with predictable short transit routes such as ferries. Although major benefits exist, substantial charging apparatus and infrastructure upgrades are required.

Other technologies have been developed to save operating costs by reducing fuel consumption without the use of batteries. One of these is variable speed electric power generation. This technology allows the engine RPM to vary for optimal fuel efficiency based on the load demand rather than being limited to synchronous speed, offering additional fuel savings and operational flexibility. Although this technology is not included in any of the alternative propulsion systems, it will be investigated further during a future efficiency exploration if diesel-electric configuration is chosen.

3.5.2 Battery Sizing

Expected battery life is critical to sizing the vessel battery banks as it is directly related to the cycle life, the number of charge and discharge cycles of the batteries. The cell cycle life is approximately logarithmically associated with the depth of discharge (DOD) during battery operation.

An average industry standard battery bank life is six to ten years. An eight-year battery life was chosen as a baseline for the comparison in this report. Based on single-side charging, the replacement vessel can be expected to undergo approximately 67,200 cycles. With margin, the battery bank sizes were chosen to not exceed 20% DOD during average operations. Peak operations will likely discharge the battery bank beyond 20% DOD. Figure 22 details the relationship of cycle life to DOD. This figure was provided for convenience from one possible battery vendor, Spear Power Systems, although there are many alternative suitable vendors.

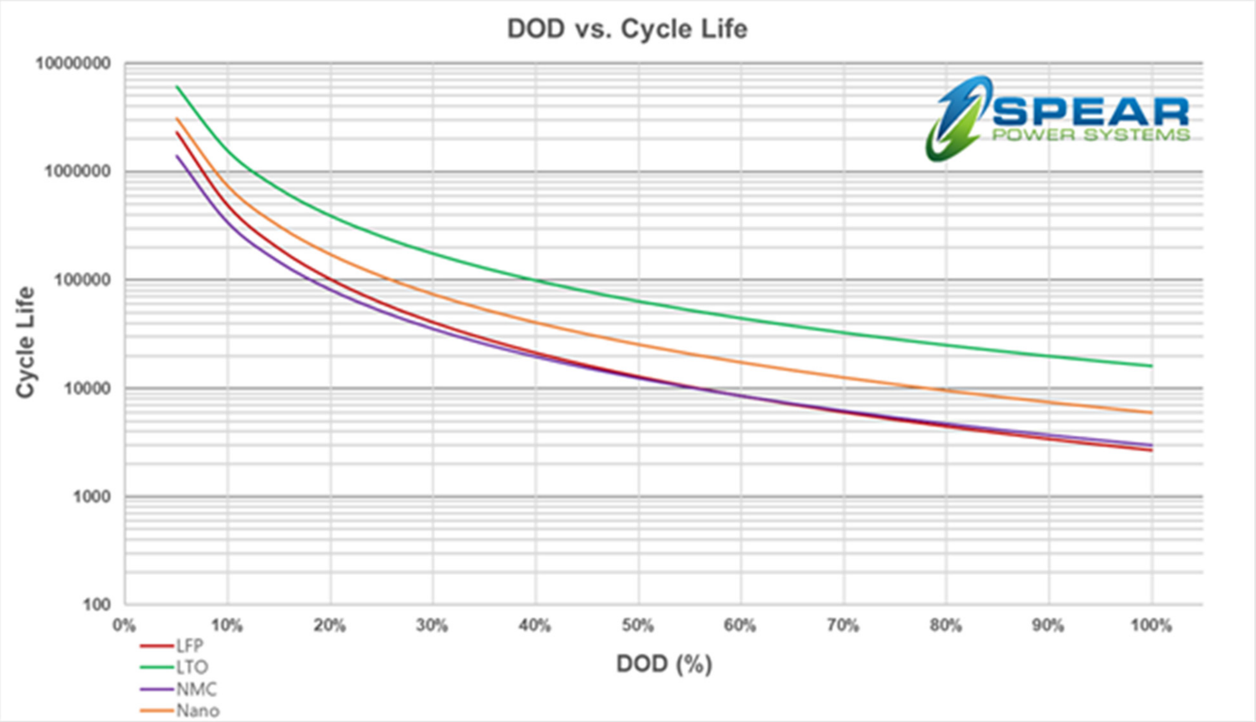


Figure 22 Spear Power Systems, battery bank expected cycle life

The rate of charge and discharge is another important factor in battery sizing, and is often expressed as C-rate. Traditional carbon-based anodes are limited to ~3C charge rates, and exceeding this can lead to lithium plating, causing battery capacity degradation. Even approaching this charge rate requires special construction of the batteries and rack. Charge rate is a function of cell current during charging and the kWh rating of the battery bank. High peak loading and large DODs are particularly difficult with typical NMC technology. If high charge power is required, it may be necessary to increase battery bank size by adding more modules in parallel. A larger battery bank size will reduce charge current to each module and maintain a lower C-rate. All battery banks presented in this report have had charge rates verified below requirements.

3.5.3 Baseline Propulsion Configuration (Geared Diesel)

Five possible configurations are reviewed in this propulsion analysis. The baseline propulsion system is a geared diesel system, the current system in use on M/V *Guemes*.

In a geared diesel propulsion system, also referred to as diesel-mechanical, propulsion diesel engines drive the vessel's propulsors directly though mechanical shafting and gears. In this arrangement, the diesel engine is a variable speed propulsion engine. Much like the system on the M/V *Guemes,* a geared diesel arrangement for the new vessel would consist of two identical propulsion systems, one at each end of the vessel, each consisting of a single propulsion diesel engine driving a single propeller though a Z-drive with integrated reduction gears. Separate ship service diesel generators (SSDGs) would provide ship service power in this arrangement.

<u>Benefits of Geared Diesel:</u>

- *Simple*: There are less components in the system, with less complex control schemes when compared to the other systems.

- *Robust*: Geared diesel is a well-proven system, with easily maintained components.
- *Common*: Operators will be familiar with the components and functionality of a gear-diesel system.
- *Efficient*: Direct-driven Z-drives are typically more efficient than electric drive arrangements.

Drawbacks of Geared Diesel:

- *Engine Size*: Each engine must be sized to meet peak power requirements, causing operational inefficiencies.
- *Main Engine Redundancy*: The vessel cannot operate if one main engine has a failure.
- *Torque Limitations*: Torque limitations impose restrictions on operation when rotating the Z-drives for thrust reversal, as most engines must maintain adequate speed to keep from stalling.

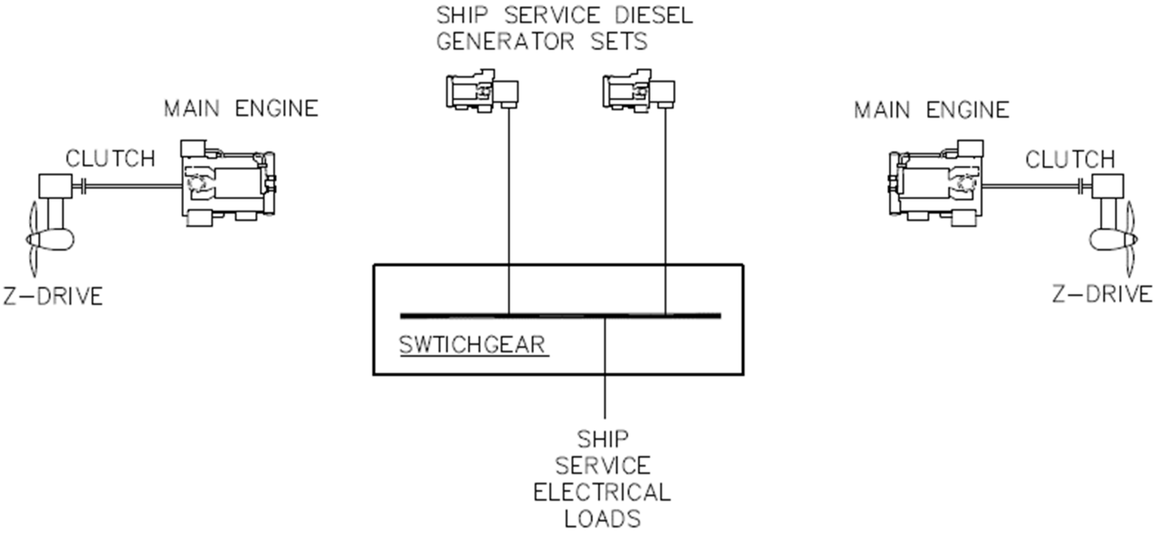


Figure 23 Baseline geared diesel configuration

The replacement vessel geared diesel configuration includes two Tier 4 1,000 HP direct drive diesel engines and two small 66ekW ship service generator sets. The vessel systems and components will be similar to the existing vessel with the exception of exhaust gas after-treatment and related systems required for Tier 4 engines.

3.5.4 Alternative Propulsion Configurations

Four alternatives to geared diesel propulsion were evaluated; diesel-electric, series hybrid, all-electric, and plug-in hybrid. Other configurations are possible, although the chosen configurations aimed to fully encompass the most practical options.

3.5.4.1 Diesel Electric

A diesel-electric propulsion system uses diesel generator sets to produce propulsion power and electric propulsion motors to power the propeller shafts. In a diesel-electric system, the diesel engines drive the alternators to produce the electrical power that is sent to the main propulsion switchboard. Motor drives convert the power from the switchboard and send it to the propulsion motors. Most modern diesel-electric vessels use an integrated diesel-electric plant where the generators provide both propulsion and ship service power making elimination of separate SSDGs possible.

Benefits of Diesel-electric:

- *Fast Response*: Electric motors provide faster response to requested load changes than a diesel engine.
- *Constant Torque*: The electric drive for a diesel-electric provides a near constant torque, regardless of engine speed. Constant torque provides more rapid change in propeller load, especially for reversal of thrust by turning the Z-drives.
- *Load Sharing*: A diesel-electric configuration allows multiple engines to share propulsion loads, allowing for smaller engines to be used, as well as increasing redundancy. Smaller engines would not require Tier 4 exhaust after-treatment.

Drawbacks of diesel-electric:

- *Efficiency*: Efficiency of the propulsion system suffers from the losses of converting mechanical power into electricity and then back into mechanical power.

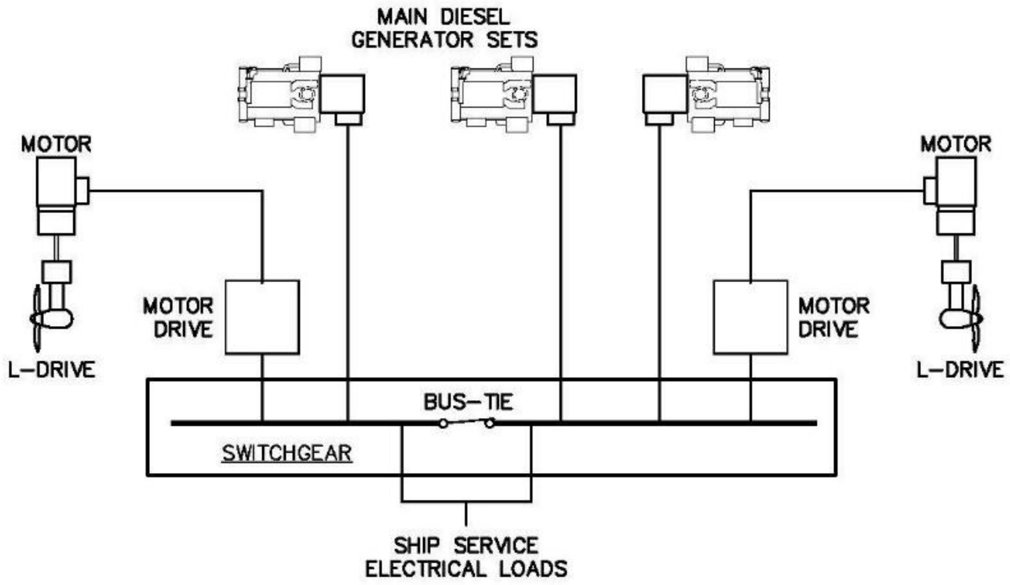


Figure 24 Diesel electric configuration

The replacement vessel diesel-electric configuration includes three EPA Tier 3 599bkW diesel generator sets. The vessel auxiliary systems will be similar to the existing vessel with larger switchgear and electrical components. The engines can also be arranged for convenience rather than on each end of the engine room in line with the shafting.

3.5.4.2 Series Hybrid

A series hybrid propulsion system is essentially a diesel-electric propulsion plant with the addition of batteries. The system incorporates energy storage (batteries) to provide a more efficient load profile for the plant. During periods of low propulsion demand (i.e. pushing the dock in fair weather), the excess power available from the generators can be used to charge the batteries so that the batteries can be used to augment the diesel generators during periods of peak demand, often resulting in smaller generator sets. The overall effect is that load on the generator sets can be leveled and relatively constant. For the replacement vessel, smaller generator sets have not been assumed, to allow for extended operations in heavy weather and currents. The result of this is that the generator sets for the new vessel have been sized to provide the full propulsion load without additional power from the battery, making them the same size as for a diesel-electric plant. Similar to the diesel-electric system, a series hybrid system can be configured for an integrated electric plant where the propulsion generator sets also provide the ship service power.

Benefits of Series Hybrid:

In addition to the benefits of a diesel-electric plant, the series hybrid configuration also has the following benefits:

- *Load Sharing*: The batteries allow the engine load to be leveled, which may increase fuel efficiency.

Drawbacks of Series Hybrid:

In addition to the drawbacks of a diesel-electric plant, the series hybrid configuration also has the following drawbacks:

- *Complexity*: Adding the battery system creates additional complexity.
- *Cost*: The capital and maintenance costs of a series hybrid are higher due to the addition of the battery system.

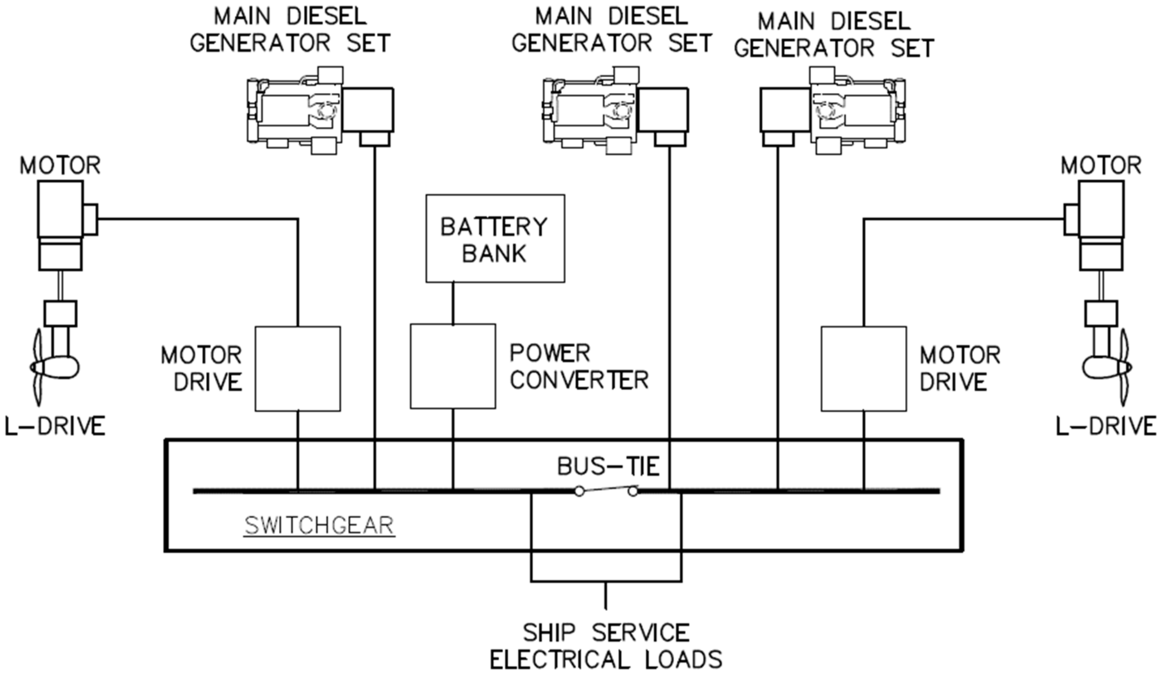


Figure 25 Series hybrid configuration

The replacement vessel series hybrid configuration includes three Tier 3 599bkW diesel generator sets and a 300kWh battery bank. The vessel auxiliary systems are identical to diesel-electric with additional complexity associated with power management and battery pack safety systems.

3.5.4.3 All-Electric

An all-electric propulsion system uses electrical power for all propulsion and ship service electrical loads. No diesel engines are used. In this arrangement electrical power is provided to the main switchboard by two sets of battery banks. Electric motors are used to power the propeller shafts. The batteries are charged from shore-power while the vessel is at the terminal.

Benefits of All-Electric:

- *Fast Response*: Electric motors provide faster response to requested load changes than a diesel engine.
- *Emissions*: Point source emissions are significantly reduced and smell from diesel engine exhaust is eliminated.
- *Noise*: With no diesel engine noise, vessel operation is much quieter.
- *Maintenance*: Battery maintenance is simple compared to necessary maintenance for diesel engines.
- *No Diesel Fuel*: With fuel completely removed from the vessel, there is no risk associated with bunkering or transferring fuel.

Drawbacks of All-Electric:

- *Shore Infrastructure*: Charging electric vessels requires significant infrastructure and may require modifications to piers or vessel operations.
- *Vessel Range*: Based on size of the battery system, the vessel is restricted to operations only where charging infrastructure is installed and is significantly reliant on shore infrastructure for operations.

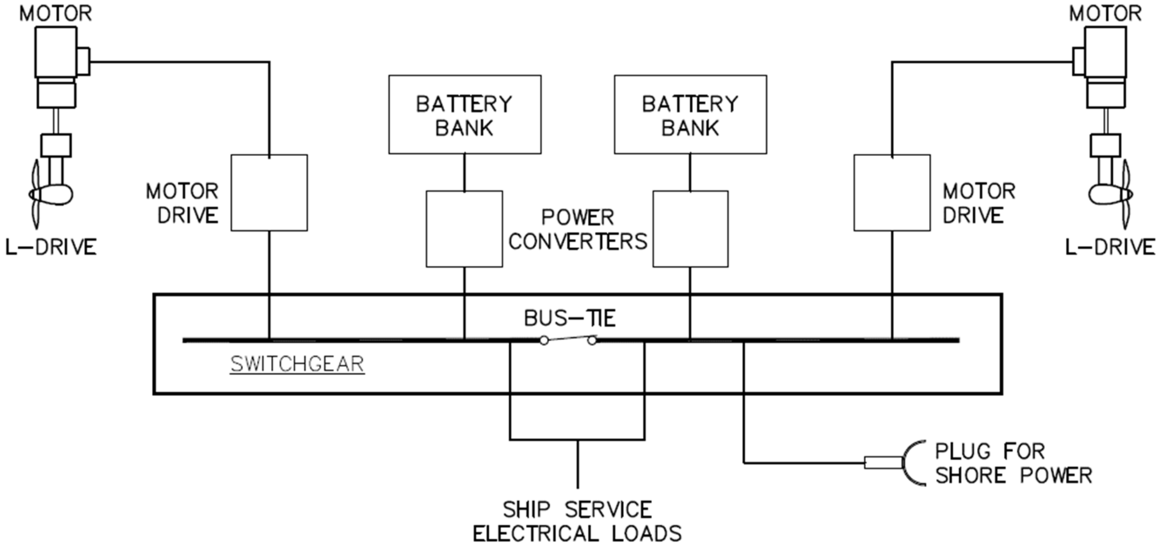


Figure 26 All-electric configuration

The replacement vessel all-electric configuration includes two battery banks with a total 1,050kWh capacity. The all-electric configuration requires substantially fewer auxiliary systems and will likely operate with a DC switchgear. Section 3.5.5 discusses details required for shore-power infrastructure to accommodate this propulsion configuration.

3.5.4.4 Plug-in Hybrid

A plug-in hybrid propulsion system uses electrical power to supply all propulsion and ship service electrical loads while providing diesel generator sets for use during high energy demand operation. Typical operation is identical to the all-electric propulsion system.

A diesel generator provides additional power when energy loads become too high for the batteries, such as during maneuvering in heavy weather. The plug-in hybrid will reduce the load on the batteries and allows optimized sizing for charging apparatus and battery banks.

Benefits of Plug-in Hybrid:

In addition to the benefits of an all-electric plant, the series hybrid configuration also has the following benefits:

- *Capital Cost*: Generators can be used to reduce loads in bad weather conditions, limiting the necessary shore-power components size. This provides greater operational flexibility of the vessel.

Drawbacks of Plug-in Hybrid:

Due to the very low operating time of the diesel generators, most benefits of an all-electric system are still realized. Additional drawbacks include:

- *Complexity*: The vessel will incorporate both diesel generator sets and battery banks while requiring shore-power infrastructure. This configuration has the most components of any option.

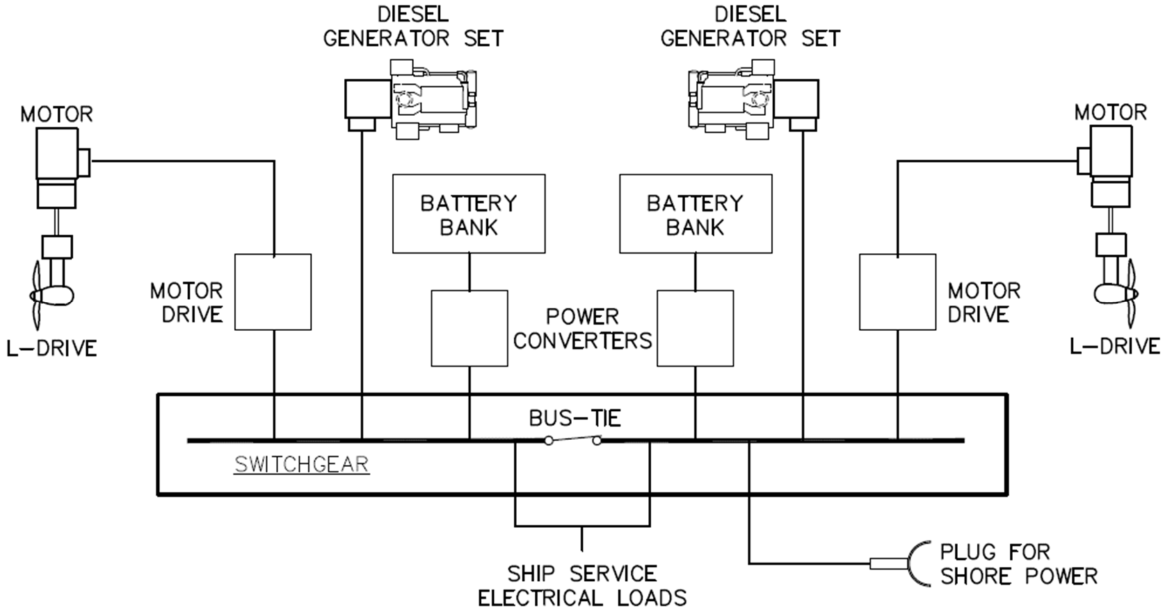


Figure 27 Plug-in hybrid configuration

The replacement vessel plug-in hybrid configuration includes two battery banks with a total 850kWh capacity and two 599bkW generator sets. The vessel combines the auxiliary system requirements of all-electric and diesel-electric configurations, providing the most complex vessel systems arrangement. Section 3.5.5 discusses details required for shore-power infrastructure to accommodate this propulsion configuration.

3.5.5 Shore Power Design

Shore power infrastructure will be required for both all-electric and plug-in hybrid propulsion systems configurations. Although ratings and sizes may vary between the two options, this section details the general design concepts that are required.

One of the major hurdles with electric ferries is the magnitude of shore-side infrastructure modifications that are often required. The M/V *Guemes* ferry schedule dictates quick turnaround times with limited time at the dock for additional tasks when a full load of vehicles is waiting to be loaded. With only two deckhands, who are both required for vessel loading and unloading, there are no crew members available to perform tasks such as manual connection of shore-power plugs or assisting in additional mooring requirements. Either an additional crew member will be required, or automatic systems will be required for power connections and mooring. Skagit County has indicated they would like to maintain the current manning aboard the replacement vessel. As such, potential options have been investigated that can be performed automatically.

3.5.5.1 Automatic Battery Charging

There are several options for automatic battery charging such as automatic plug-in systems, inductive charging, and pantographs. All of these systems are in the pilot project and/or testing phase. Commercially available pre-engineered solutions are not readily available. This report does not aim to design the shore charging system, but rather to determine that the technology exists and to identify the engineering needed to develop a viable system for the replacement vessel. Initial inquiries have provided promising technologies and rough cost estimates.

Figure 28 illustrates the pilot projects for three charging systems.

Figure 28 (Top) Pantograph, example Stemmann Technik; (middle) automatic plug-in, example Cavotec; (bottom) wireless inductive charging, example Wartsila

The pilot projects for the three charging systems pictured above range between 1.2 and 2.0 MW. If charging power for the replacement vessel exceeds 2.0 MW the technology scaling introduces further complexity and cost, and a custom engineered solution will be required.

3.5.5.2 One versus Two-Side Charging

Figure 29 details the average round trip energy required by the replacement vessel. Total energy consumed by the vessel is not represented, rather vessel battery energy consumption is shown. When the vessel is plugged in, additional power may be required to account for pushing power and ship service loads. Apparent energy consumption is far greater for one-side charging with respect to vessel battery sizing.

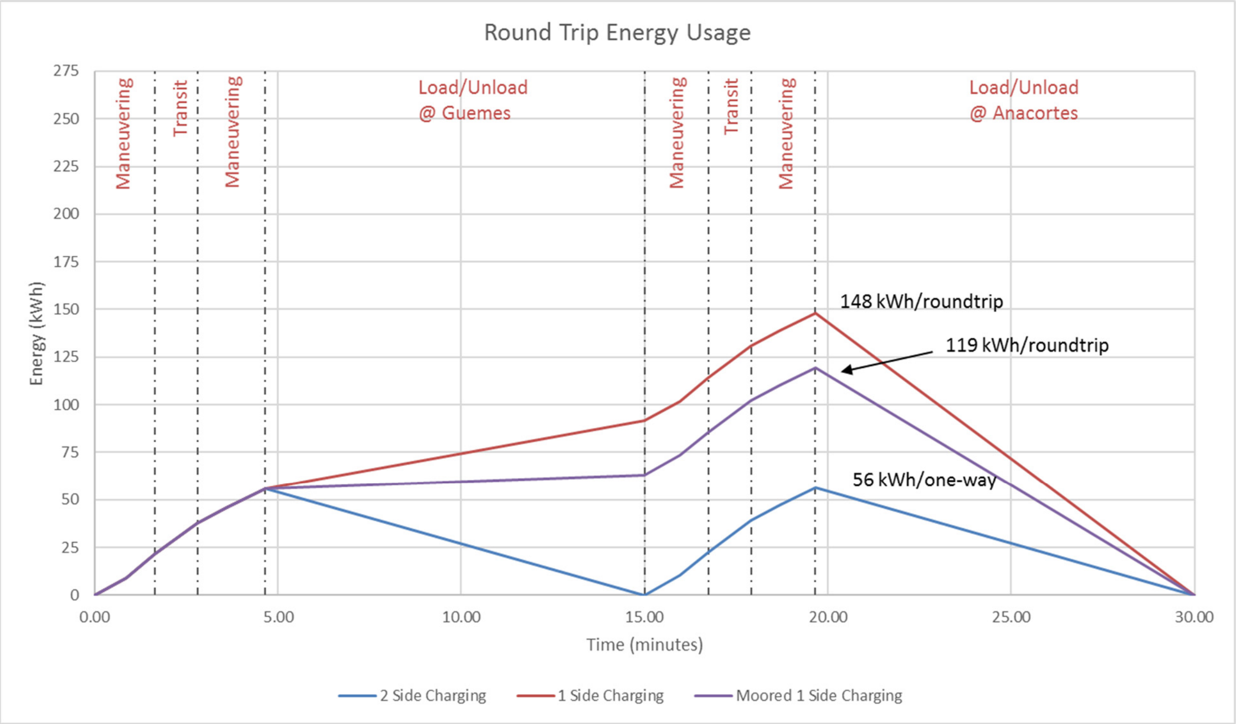


Figure 29 Comparison of charging, one-side versus two-side

Pushing the dock with one-side charging was assumed as the baseline requirement. It is possible to moor the vessel on each end to reduce pushing loads. Mooring will not affect battery energy required for two-side charging, but reduces the charging apparatus ratings, as less power is required to compensate for pushing power. For one-side charging, mooring on the Guemes side reduces vessel roundtrip energy by 20%.

Based on this analysis, two-side charging reduces battery bank sizing on the vessel by approximately 60%. However, Guemes Island would also require expensive infrastructure upgrades to support battery charging. Battery costs are significantly less in comparison to the infrastructure upgrades required to provide adequate charging on either side. The most economic option would incorporate larger battery banks and one-side charging at the Anacortes terminal.

3.5.5.3 Automatic Mooring

The current vessel pushes while loading and unloading vehicles at both docks. The vessel pushing assists in maintaining ramp contact and reduces vessel motions due to wind, waves, and current. The use of an automatic vacuum mooring system was investigated to hold the vessel in place while it charged at the Anacortes terminal.

Figure 30 Vacuum mooring system, example Cavotec

Based on eliminating pushing loads, Skagit County could save approximately $22,000 annually in electric energy costs by implementing a vacuum mooring system. Reduced pushing power may also reduce ratings of shore-power charging components and vessel battery sizing.

In order for vacuum mooring to be feasible, a 20-year return on investment was expected. Each unit was quoted at approximately $300,000 with high likelihood two units would be required to fully support the vessel. Based on annual savings, $440,000 could be expected in the 20 year period. The capital cost of two units exceeds allowable 20-year cost before allowances for infrastructure upgrades to support the units. Unfortunately, it was concluded vacuum mooring was not feasible unless required for vessel motions during automatic charging. Present estimates do not include the use of vacuum mooring.

3.5.5.4 Utility Connection

The connection to the utility is a critical aspect of providing adequate shore-power for the ferry battery banks at the Anacortes terminal. Discussions with Puget Sound Energy (PSE) have indicated peak power loading associated with charging the batteries is a major concern for their electrical infrastructure. Due to the vessel's possible operation during heavy winds and tidal currents, required energy per round trip varies greatly. Table 13 below summarizes the power and energy required for battery charging during average and peak conditions.

Table 13 Round trip power comparison

	Power		**Total Shore Energy (kWh)**	**Vessel Battery Energy (kWh)**
	No Shore-side Batteries (kW)	Shore-side Batteries (kW)		
All-Electric Average	1458	389	194	148
All-Electric Peak	3939	1051	525	352
Plug-in Hybrid Average	1393	372	186	142
Plug-in Hybrid Peak	2610	696	348	190

Installing shore-side batteries substantially reduces average and peak loading on the utility connection. PSE has stated based on initial modelling of their system, shore-side batteries will be required.

Peak power during each month of utility connection is also used by PSE to set the demand charge during that month. Reducing frequency and aggregate peak power will provide lower demand charges, reducing the cost per kWh.

3.5.5.5 Shore Power Architecture

Several options were explored for shore-side power architecture. Figure 31 and Figure 32 provide one-line overviews of what AC and DC shore-side power arrangements require. The propulsion configuration serves as the primary driver for shore-side power configuration.

The plug-in hybrid propulsion configuration will be arranged with AC primary power distribution (Figure 31), making AC shore-power the most efficient option for that configuration. The all-electric propulsion configuration will be arranged with DC primary power distribution, making DC shore-power the most efficient option for that configuration (Figure 32). Shipboard power plant configurations are discussed in further detail in the following sections.

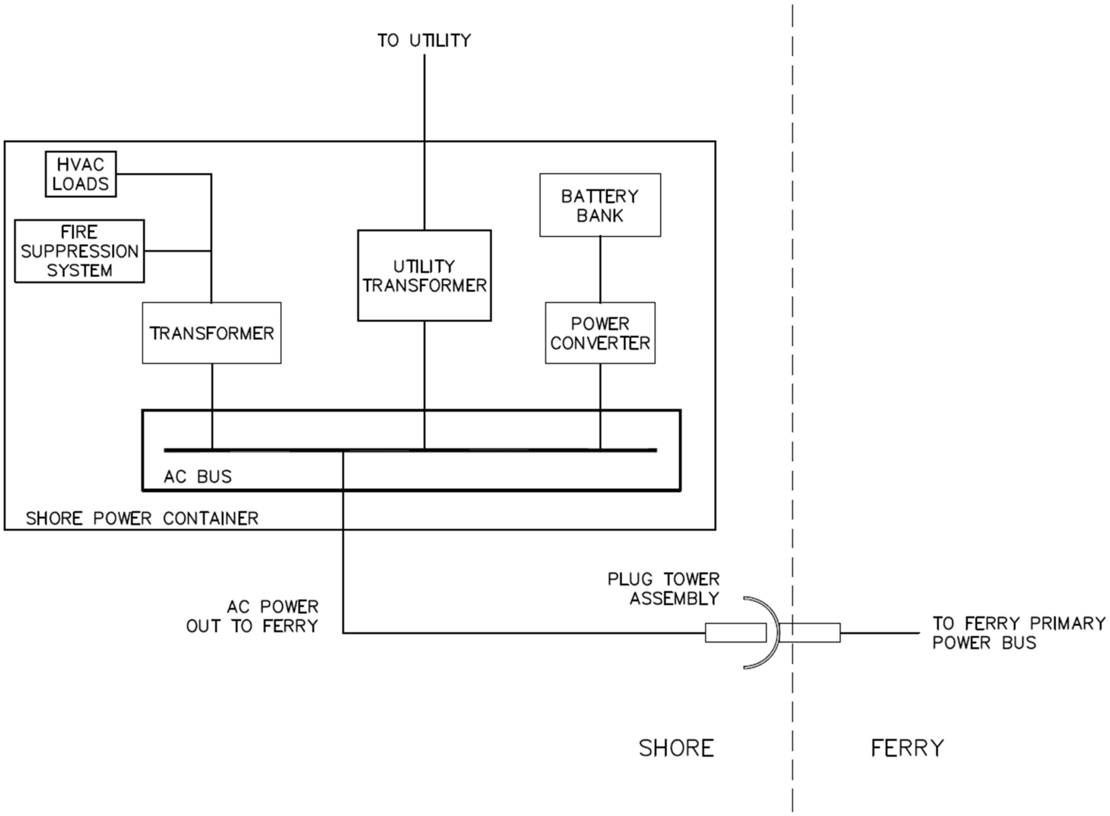


Figure 31 Shore-side power, AC arrangement for the plug-in hybrid configuration

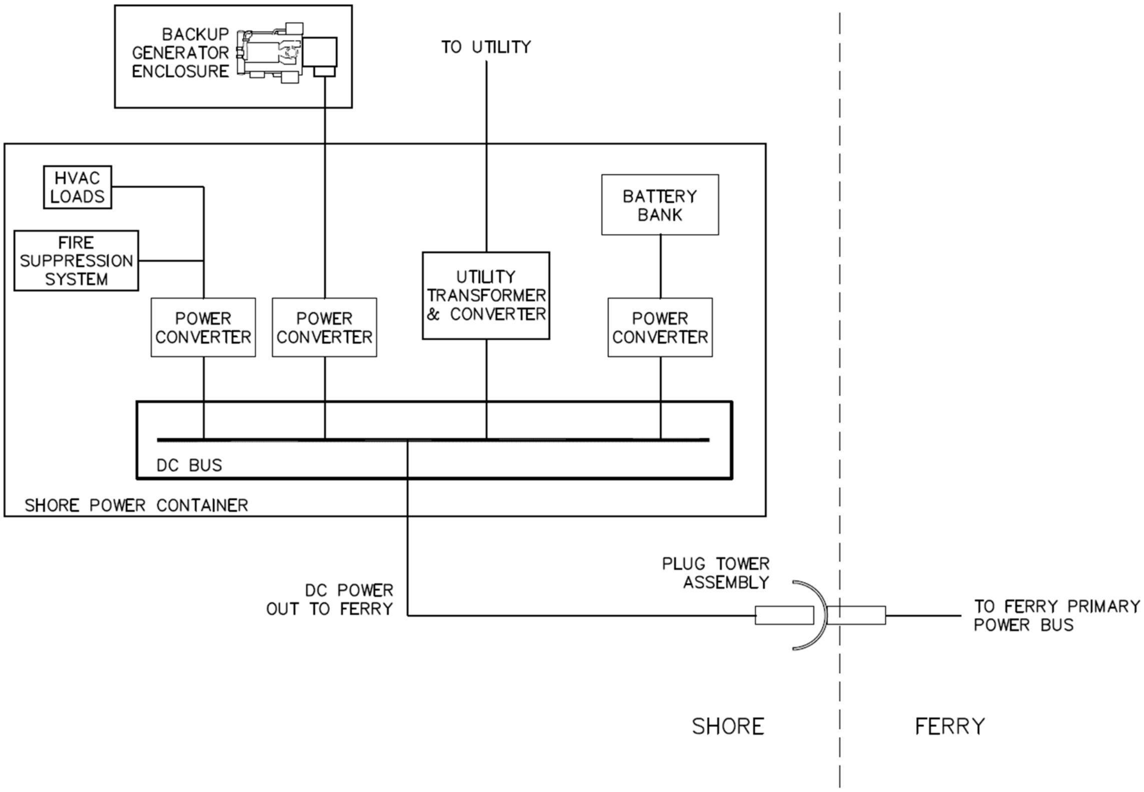


Figure 32 Shore-side power, DC arrangement for the all-electric configuration

Figure 32 shows a shore-side backup generator, while Figure 31 does not. In the case of utility power loss, the plug-in hybrid configuration has backup generators onboard, allowing continued operation without any delay. However, an all-electric ferry must have a means of charging the battery banks even in the case of utility power loss. The shore-side backup generator provides a means for the all-electric ferry to continue operation, upon loss of power from the utility.

3.5.6 Ship Power Design

3.5.6.1 Main Power Bus

The architecture of an electrical power plant largely depends on the requirements of heavy consumers. In the case of the replacement vessel, the most influential heavy consumers are the propulsion motors, when fitted. Therefore, the propulsion configuration serves as the main driver in determining the main bus configuration.

AC vs DC power distribution has been considered separately for each propulsion bus configuration. An AC electric plant most suitably supports diesel-electric, series hybrid, and plug-in hybrid propulsion configurations, since the majority of the source power is alternating current. A DC electric plant most suitably supports the all-electric propulsion configuration, since the battery power is direct current. These power plant configurations limit the number of AC/DC power conversions, and therefore provide the most efficient, as well as the least complex, power plant configurations.

The geared diesel propulsion configuration eliminates the need for a main propulsion bus. The ship service power configuration is discussed in Section 2.8.

For diesel-electric, series hybrid, and plug-in hybrid configurations, a main AC bus facilitates distribution to two propulsion drives, as well as ship service power through transformers. Generators and battery inverters will be selected with matching output voltages in order to further reduce equipment cost, complexity, and footprint. 690 VAC, 600 VAC, 480 VAC are all viable options for primary bus voltage, and will be selected based on propulsion drive and motor requirements.

For an all-electric configuration, a DC bus facilitates distribution to two propulsion drives, as well as ship service power through DC/AC power inverters. Two battery banks will provide separate power connections to the DC bus, in order to maintain a fail-safe, redundant power architecture. 1000 VDC and 690 VDC are both viable options for DC bus voltage, and will be selected based on propulsion drive and motor requirements.

3.5.6.2 Power Management

The power management system (PMS) must provide circuit protection and load control that meet regulatory requirements. Notable regulatory requirements include: maintain propulsion loads and vital auxiliaries, maintain essential service loads for passenger safety, and prevent ship blackout. The PMS will load shed non-vital loads and/or startup diesel generators to maintain the required loads.

Beyond regulatory requirements, the PMS must provide automation to facilitate safe, efficient use of the power plant. This includes automatic voltage regulation, bus frequency control, and all associated power quality monitoring. PMS requirements are largely driven by power plant architecture. Due to the variations in power plant architecture each propulsion configuration has unique power management requirements.

Required PMS features include source paralleling, load balancing, and live shore-power connection. Source paralleling provides voltage and frequency paralleling between batteries and generators. Load balancing utilizes total generator capacity as well as total battery capacity to determine the best distribution of loading. Live shore-power connection provides control voltage and frequency while the ship is being charged from shore, with no interruption to propulsion power.

In addition to these requirements, there are additional features that offer operational and life cycle cost advantages. Some of these additional features include automatic generator start/stop, asymmetric load sharing (for all propulsion configurations), and split bus operation. Automatic generator start and stop offers reduced operator duties, allowing PMS to control generator start/stop upon load fluctuation. Asymmetric load sharing reduces generator/battery bank burden by focusing swing load on one power source, allowing other power sources to be base loaded. Split bus paralleling works to increase system fault tolerance, allowing half of the main bus to remain operable upon a fault.

The advantages of these additional features are noteworthy, considering the small crew size and the significant load fluctuation over such a short period of time. Table 14 below provides a breakdown of assumed features of the PMS for each propulsion configuration.

Table 14 PMS comparison

	Geared Diesel	Diesel Electric	Series Hybrid	All-Electric	Plug-in Hybrid
Source paralleling	-	-	X	-	X
Load balancing	-	-	X	-	X
Live shore-power connection	-	-	-	X	X
Automatic generator start/stop	-	X	X	-	-
Asymmetric load sharing	-	-	X	-	X
Split bus paralleling	-	X	X	X	X

3.6 Life Cycle Analysis

A 40-year life cycle cost was performed for each propulsion configuration. This analysis includes the entire propulsion and power generation plant, and all engines operating within the mission profile. This analysis was not intended to detail total cost of ownership, but instead to highlight differentiators for the various propulsion system configurations.

A real discount rate of 3% was used to calculate future savings into present day dollars for each option. Real discount rate is a net factor which incorporates discount rate (i.e. interest) and expected inflation. Discount factors for consumables were derived from regional tables from National Institute of Standards and Technology (Reference 10). Discount factors are multiplied by current consumable prices to calculate the present value of future consumable usage.

Table 15 provides a breakdown of life cycle cost for the baseline and four alternative propulsion configurations. All values were evaluated to Net Present Value (NPV) for accurate comparison.

Table 15 Life cycle cost comparison of propulsion systems

Relative Cost (compared to baseline)	Geared Diesel	Diesel Electric	Series Hybrid	All-Electric	Plug-in Hybrid
Capital Cost	-	23.0%	47.1%	227.7%	178.9%
Fuel, Lube, DEF, & Electrical	-	21.5%	10.2%	-39.5%	-50.3%
Operations & Maintenance	-	-48.5%	-63.6%	-56.2%	-58.8%
Repower (Engines & Batteries)	-	-43.8%	26.4%	452.9%	297.6%
Total Life Cycle Cost	**-**	**6.3%**	**6.0%**	**40.2%**	**16.8%**

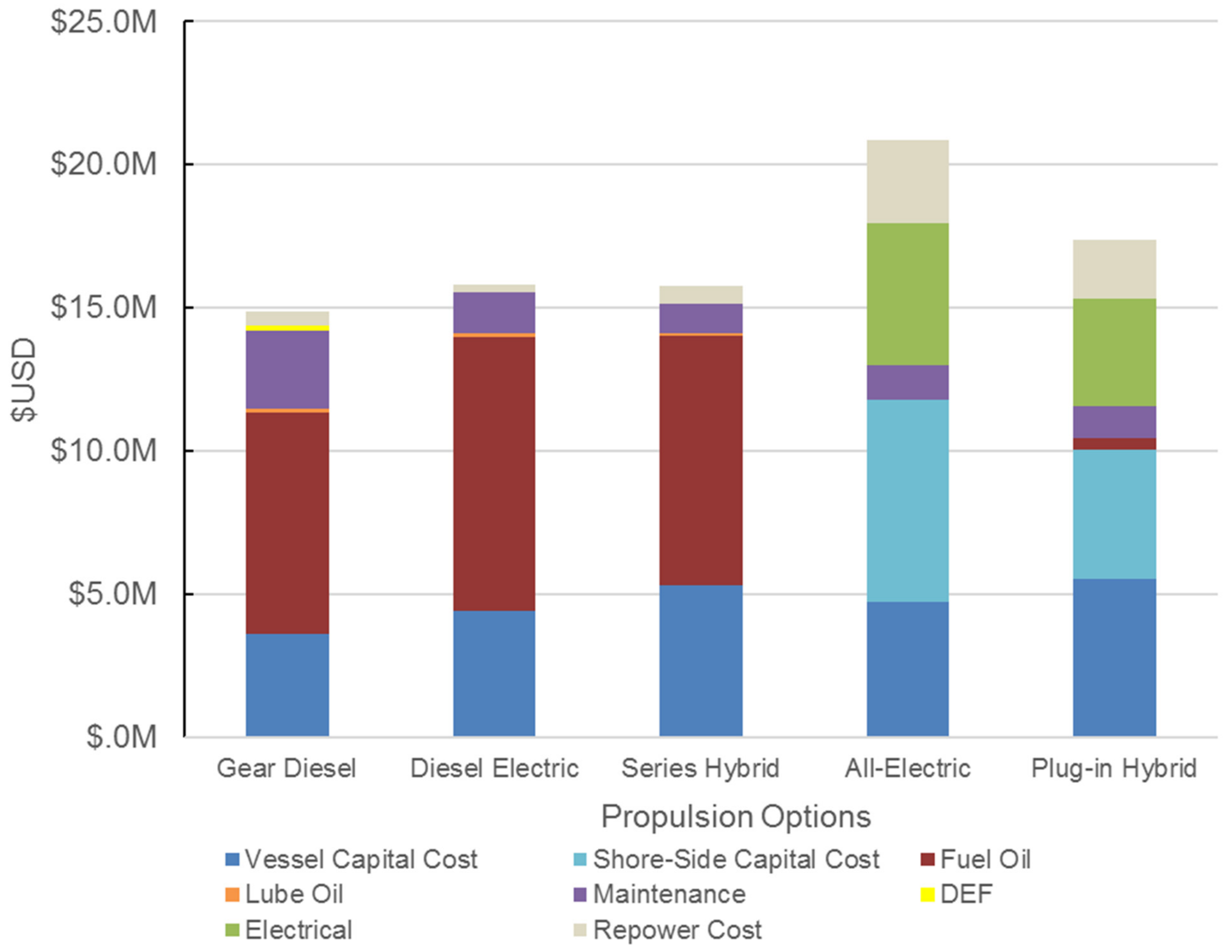


Figure 33 40-year life cycle cost of propulsion systems

The major categories evaluated are described in further detail in subsequent sections. Appendix A provides a detail breakdown of all life cycle cost calculations.

3.6.1 Capital costs

Total capital costs were substantially higher for the all-electric and plug-in hybrid propulsion systems. The variables associated with higher costs are outlined below. Note the significant contribution of the shore-side capital costs for all-electric and plug-in hybrid options.

Table 16 Capital cost comparison, in millions

	Gear Diesel	Diesel Electric	Series Hybrid	All-Electric	Plug-in Hybrid
Vessel Capital Costs (M USD$)	$3.7	$4.6	$5.5	$4.9	$5.7
Shore-Side Capital Costs (M USD$)	$.0	$.0	$.0	$7.3	$4.7
Total Capital Cost (M USD$)	$3.7	$4.6	$5.5	$12.2	$10.4

3.6.1.1 Vessel Costs

Vessel capital cost for each configuration varies based on the size and number of major components necessary. Diesel-electric and series hybrid provide more automation and integration than the baseline configuration leading to increased costs. Battery costs and associated safety systems are also large drivers in increased costs.

3.6.1.2 Shore-Side Costs

Shore-side infrastructure and charging apparatus were the major driver in costs associated with all-electric and plug-in hybrid systems, the only two configurations with shore-side costs accounted for in this analysis. Section 3.5.5 gives detailed requirements for feasibility of these systems.

All shore-power infrastructure is sized for the worst-case run. This is critical to maintain schedule, but comes at a significant increase to cost and size of components. If schedule requirements are relaxed in poor weather conditions, then capital costs for all-electric and plug-in hybrid may be reduced. The assumptions for worst-case run are outlined below.

3.6.1.3 Worst-Case Run

Due to the nature of the M/V *Guemes* operation, large variations in energy consumption can be seen when tidal currents and winds are combined to form specific wave conditions. As discussed in Section 3.2, the vessel must be capable of operating each 725 kW thruster at full power to account for maneuvering in heavy currents. Each propulsion configuration was provided with enough installed power to meet this requirement, even if some engines are not required to operate during typical runs.

For simplicity the worst-case run was taken as the 95 percentile winds, or approximately 20 mph, from Table 31 discussed in Section 4.3.3. This means the worst-case run will occur 5% of the time annually. In order to approximate the round-trip energy consumption; an approximate worse case run was developed for powering, as seen in Table 17.

Table 17 Worst case one-way trip delivered power

Operation	Time (min)	Delivered Power, Pd (kW)	Notes
Load / Unload	10.35	800	Current vessel maximum observed
Maneuver	0.85	834	1.5 multiplier on average power
Accelerate	0.78	1,196	1.5 multiplier on average power
Cruise	1.17	1,114	1.5 multiplier on average power
Decelerate	0.78	786	1.5 multiplier on average power
Maneuver	1.07	1,450	Max installed power

The worst-case run is a particular challenge for an all-electric vessel and plug-in hybrid vessel. All shore-power infrastructure and charging apparatus must be sized to accommodate the worst-case run as previously outlined. The plug-in hybrid propulsion system assumed an on-board generator could be run during the worst-case run, providing a maximum shore-power transfer requirement of 2.6 MW. The all-electric vessel worst-case run provides a maximum shore-power transfer requirement of 4.0 MW.

The power transfer required through the shore-side charging apparatus is crucial for design feasibility. As stated in Section 3.5.5.1, current charging technology pilot projects are rated at or below 2.0 MW. Scaling this technology significantly poses a major engineering challenge, increasing design risk substantially.

3.6.1.4 Emergency Services Premium

Emergency scenarios are described in Section 4.8. The existing vessel is capable of providing a variety of response scenarios, and it is assumed that the replacement vessel must also be able to do so.

The all-electric and plug-in hybrid propulsion systems make this requirement difficult to meet. These vessel configurations rely on connection to a shore-side utility to charge every round trip under the current assumptions. As described in Scenario 2 and Scenario 3 (Section 4.8), continuous 24-hour ferry operation with limited charging and rendering assistance to distressed vessel or person in Bellingham Channel.

The all-electric system includes a large generator set on shore to charge the shore-side batteries during utility down time. This generator set would be run during Scenario 2 in order to provide power if utility connection is limited. Calculations for Scenario 3 indicate a battery DOD of approximately 50%. This is well within allowable margin of battery discharge for an extremely rare occurrence.

The plug-in hybrid system requires one additional small generator set onboard for a total of two generator sets to provide additional power when vessel cannot be charged from shore. Scenario 2 and 3 can be accomplished by running both of these generators. Adequate transit power is achieved but total maneuvering power will exceed 1000 kW. The vessel batteries will function similar to a series hybrid configuration to make-up the additional power necessary for maneuvering.

Operational costs were not calculated for supporting an emergency services scenario as they are unplanned events.

3.6.2 Fuel, Lube Oil, DEF, & Electrical

Each propulsion configuration has a large portion of the life cycle cost associated with the consumables used for developing power. Each propulsion system configuration uses a variation of consumables depending on how power generation is primarily achieved. Diesel fuel and lube oil are consumed for all diesel engines and generators. Diesel exhaust fluid (DEF) is used for diesel exhaust after-treatment and is only consumed when Tier 4 engines are installed. An electrical grid connection is for charging vessel batteries.

Table 18 Annual consumable comparison

	Gear Diesel	Diesel Electric	Series Hybrid	All-Electric	Plug-in Hybrid
Fuel (gal/yr)	100,000	124,000	113,000	0	5,000
DEF (gal/yr)	2,700	0	0	0	0
Electrical (MWh/yr)	0	0	0	1,600	1,600
Lube Oil (gal/yr)	510	500	290	0	10
Total Cost (M USD$)	$8.0	$9.7	$8.8	$5.0	$4.1

There are two main drivers for variations between consumables for each propulsion option; specific fuel consumption associated with selected engines, and propulsion efficiency of the plant.

Tier 4 engines used in the baseline geared diesel configuration provide better engine-specific fuel consumption. These engines are tuned for the lowest fuel consumption and DEF is used in after-treatment to remove particulate matter from the exhaust. Tier 3 engines, which are used in all other configurations where engines are installed, provide slightly higher specific fuel consumption as the engines are tuned for emissions standards as well as fuel consumption.

A series hybrid is more efficient than diesel-electric by using energy storage, in the form of batteries, to optimize the operation. Generators are run at their best efficiency point (BEP), usually around 90% maximum continuous rating. Batteries are charged when energy is available and discharged when energy is needed by the propulsion system. This configuration allows the specific fuel consumption to be optimized and provides a lower cost of operation.

All assumed propulsion efficiencies are listed below in Table 19 for comparison between configurations. The efficiencies listed are from power source (varies in some configurations) to propulsor, representing the delivered power.

Table 19 Propulsion efficiency comparison

	Propulsion Efficiency (%)
Geared Diesel	92%
Diesel Electric	88%
Series Hybrid	88% - 1.5%
All-Electric	92%
Plug-in Hybrid	91% - 1.5% or 5%

Geared diesel efficiency was assumed at 92% including shafting and Z-drive losses. This percentage included carden shafting (U-joints) which would likely be required based on engine angle and placement. Diesel electric efficiency was assumed at 88% including L-drive losses, motor efficiency, generator efficiency, and drive conversion efficiency. Series hybrid was assumed the same 88% as diesel-electric with an additional 1.5% loss when using battery power. All-electric efficiency was assumed at 92% including L-drive efficiency, motor efficiency, and drive conversion. Plug-in hybrid efficiency was assumed 91%, similar to the all-electric configuration with an additional electrical conversion loss as well as potential 5% loss when using the generators and 1.5% when using batteries for power.

Additional shore-power conversion efficiency is included at 90% for the all-electric and plug-in hybrid configuration when comparing energy consumption from the utility connection. Even with this additional efficiency, the low cost of electricity in the Pacific Northwest is highly advantageous to the all-electric and plug-in hybrid propulsion systems. This low cost is reflected in the much lower total expenditure on electricity over the 40-year life cycle. Although both configurations show approximately similar electrical use, the plug-in hybrid has a much lower demand charge due to lower peak loads, providing a lower total cost.

3.6.3 Maintenance

Maintenance costs were substantially less for all propulsion configurations compared to the baseline geared diesel configuration. The results are summarized below as annual expenses. Values were calculated based on maintenance intervals provided by engine manufacturers and using engine operating hours from the load profile. The values presented are not actual annual costs, but average costs annualized from oil changes to engine overhauls.

Table 20 Maintenance comparison

	Gear Diesel	Diesel Electric	Series Hybrid	All-Electric	Plug-in Hybrid
Maintenance (USD$/yr)	$125,100	$64,400	$45,600	$54,800	$51,600

Batteries inherently have very little associated maintenance compared to diesel engines. Diesel engine maintenance is directly associated with fuel consumption and hours of operation. The more the engine operating hours can be reduced using batteries the more maintenance costs will be reduced. This is a major benefit of series hybrid, all-electric, or plug-in hybrid design.

The baseline geared diesel configuration uses the largest engines and requires exhaust after-treatment. The larger engines have much higher maintenance costs, additionally adding systems and module replacement associated with after-treatment makes geared diesel maintenance cost substantially worse.

The all-electric and plug-in hybrid configurations include a large portion of the maintenance cost for shore-side infrastructure. Vessel side maintenance is very limited for these configurations.

3.6.4 Repower (Engines & Batteries)

Repower costs include the cost to replace the vessel's diesel engines as well as battery replacement. Diesel engine repower was assumed to happen at vessel mid-life, year 20 of operation. Battery replacement was assumed every eight years. A 5% real discount rate was assumed when calculating future cost of batteries to account for technology improvements and decrease in battery costs over time. This is compared to the 3% real discount rate assumed for all other life cycle cost calculations.

Table 21 Repower costs, all values in NPV

	Gear Diesel	Diesel Electric	Series Hybrid	All-Electric	Plug-in Hybrid
Engines (USD$)	$522,000	$294,000	$294,000	$0	$0
Batteries (USD$)	$0	$0	$366,000	$1,282,000	$1,038,000
Shore Batteries (USD$)	$0	$0	$0	$1,604,000	$1,038,000

Even with accounting for technology improvements, battery costs are still a substantial driver in total life cycle costs. The battery banks required for the replacement vessel were sized with reserve capacity but will still likely need replacement every eight years.

3.7 Scoring system

Each propulsion system was evaluated considering the following categories: capital cost, operational cost, system weight, design and build complexity, reliability and availability, airborne noise, and vessel air emissions. Each category received a raw score based on the metrics discussed below. A weighted score is reached after multiplying the raw score by the category weighting factor.

Table 22 was provided by Skagit County as an example weighting factor break-down. Table 23 discusses each scoring category and the calculations required to compute the raw score. Capital cost and operating cost were set to zero and are individually compared between propulsion options in Section 3.8 Sensitivity Analysis. The high weighting on reliability and availability generally reflects the consensus of the Guemes Ferry Replacement Survey conducted in the fall of 2017.

Table 22 Example weighting factors

Scoring Category	Weighting Factor
Capital Cost	0%
Operations and Maintenance Cost	0%
System Weight	10%
Design and Build Complexity	20%
Reliability and Availability	45%
Airborne Noise	10%
Vessel Air Emissions	15%
	Total must equal 100%

Table 23 Scoring categories with calculation method

Capital Cost

Capital cost of all propulsion equipment installed on the vessel and associated shore-side infrastructure to meet design requirements.

Score	*Description*
0 to 1	Lowest cost of all options divided by the individual option cost such that the lowest cost option receives a score of 1.

Operations and Maintenance Cost

40-year operations and maintenance cost of all propulsion equipment installed on the vessel and associated shore-side infrastructure.

Score	*Description*
0 to 1	Lowest cost of all options divided by the individual option cost such that the lowest cost option receives a score of 1.

System Weight

Weight of all propulsion equipment installed on the vessel. Weight affects the total mass of the vessel, consuming more power to accelerate and generally increasing cost.

Score	*Description*
0 to 1	Lowest weight of all options divided by the individual option weight such that the lowest weight option receives a score of 1.

Design and Build Complexity

The design and build complexity of the vessel may affect cost of engineering to complete the design, cost to complete build the vessel and shore side infrastructure, and impact the schedule of design and building.

Score	*Description*
0	Rare propulsion system worldwide, additional risk to design, significant additional risk to build, has shore side components.
1/3	Unusual propulsion system in the US, some additional risk to design, some additional risk to build, no shore side components.
2/3	Proven propulsion system, common in the US, no additional risk to design, some additional risk to build, no shore side components.
1	Proven propulsion system, common in the Pacific Northwest, no additional risk to design and build.

Reliability and Availability

Reliability is the probability of failures. Availability is the probability that the propulsion system is functioning normally. A risk assessment was conducted to review propulsion system, power plant, and shore-side components as it relates to the reliability and availability of each propulsion configuration.

Score	*Description*
0 to 1	Lowest risk of all options divided by the individual option risk such that the lowest risk option receives a score of 1.

Airborne Noise

Airborne noise created on the vessel from engine operation.

Score	*Description*
0	Continuous engine/exhaust noise.
1/3	Intermittent engine/exhaust noise.
2/3	Exhaust noise only during high load situations.
1	No exhaust noise, fan noise only.

Vessel Air Emissions

The local engine exhaust emissions, measured in particulates, produced by the vessel. Calculated based on engine data and engine running hours.

Score	*Description*
0 to 1	Lowest particulates of all options divided by the individual option particulates such that the lowest emissions option receives a score of 1 (no emissions).

3.7.1 Costs

The life cycle cost for each propulsion system was broken into capital cost and operation and maintenance cost. Capital costs are presented in Table 16 above. Operation and maintenance costs were developed as the summation of fuel, lube oil, DEF, electricity, maintenance, and repower costs. These values were included separately in the scoring system for individual comparison and weighting.

Design and build complexity as well as airborne noise have raw score calculations that are not numerically driven but can be developed based purely on rankings from Table 23.

3.7.2 Weight

A weight estimate was performed for major components of each propulsion configuration. Only vessel weights were included and fluid weights were assumed 50% of installed tankage. The variance presented directly affects the weight and stability of the vessel as discussed in Section 2.11. Weight can be a large driver of vessel design and a heavier vessel could result in additional propulsion power required. Results of the weight estimate are presented in Table 24, and used to develop raw scores.

Table 24 Weight summary of propulsion configurations

	Gear Diesel	Diesel Electric	Series Hybrid	All-Electric	Plug-in Hybrid
Weight subtotal (lbs)	81,000	103,000	112,000	61,000	96,000
% Difference	-	27.2%	38.3%	-24.7%	18.5%

3.7.3 Design and Build Complexity

Design and build complexity has a raw score calculation that is not numerically driven but can be developed based purely on rankings from the table above.

3.7.4 Reliability and Availability

A simplified risk assessment was performed to model the reliability and availability of each propulsion configuration. Reliability and availability pertain to risk of failures that are not captured in the operation and maintenance cost previously evaluated. Only major components which vary between propulsion configurations were evaluated. The risk assessment matrix is presented below to outline the impact and likelihood scales used to evaluate each component. The probability and consequence multipliers increase exponentially by a factor of 5.0 and 2.5 respectively. The multiplication of these two factors results in risks that vary linearly on a log-linear graph. Please note significant financial impact is defined as greater than $100,000.

Table 25 - Risk assessment matrix

	Severity Scale	Descriptor	Consequence Multiplier	Risk Assessment Matrix (Consequence Multiplier x Probability Multiplier)				
Impact	**5**	**Catastrophic** - Schedule delay more than 1 day, signficant financial impact	625	Medium	High	High	High	High
	4	**Critical** - Schedule delay more than 1 day, no significant financial impact	125	Medium	Medium	Medium	High	High
	3	**Significant** - Requires operator attention, continued operation with schedule delays	25	Low	Low	Medium	Medium	High
	2	**Marginal** - Failure requires operator attention, no schedule delay	5	Low	Low	Low	Medium	Medium
	1	**Minor** - No Disruption	1	Low	Low	Low	Low	Low
			Probability Multiplier	1.0000	2.5000	6.2500	15.6250	39.0625
			Descriptor	**Unlikely -** More than 25 years between failures	**Possible -** 10 to 25 years between failures	**Probable -** 4 to 10 years between failures	**Likely -** 1.6 to 4 years between failures	**High -** less than 1.6 years between failures
			Probability Scale	**1**	**2**	**3**	**4**	**5**
				Likelihood				

The risk assessment results were broken into major categories; propulsion system, power plant, and shore-power system. Each category is composed of multiple components, each having a probability of failure value and impact value calculated individually. Table 26 combines all components and presents the sum and component average for each category as a whole. The combined system risk summation was used to calculate raw scores. The average component risk value is provided for comparison between each propulsion configuration but does not represent true risk values as number of components varies between systems. Appendix B provides a detailed scoring breakdown of all components for reference.

Table 26 Risk assessment results

Risk Assesment Matrix		Risk Values (Range for Average: 1 - 24414)				
		Geared Diesel	**Diesel Electric**	**Series Hybrid**	**All-Electric**	**Plug-In Hybrid**
Propulsion System Risk Assessment Summary	**Sum**	3867	1617	2742	1141	1517
	Average	645	231	392	285	217
Power Plant System Risk Assesment Summary	**Sum**	125	650	708	1740	1000
	Average	125	325	118	249	143
Shore Power System Risk Assessment Summary	**Sum**	0	0	0	5589	3476
	Average	0	0	0	329	267
Combined Systems Risk	**Sum**	3992	2267	3450	8470	5993
	Average	257	185	170	288	209

Table Notes:
- The Sum rows are the sums of risk values for all equipment within the described category
- The Average rows are the mean risk value for all equipment within the described category

3.7.5 Airborne Noise

Airborne noise has a raw score calculation that is not numerically driven but can be developed based purely on rankings from the table above.

3.7.6 Vessel Air Emissions

The total lifecycle environmental impact of any motorized vehicle extends far beyond the space that it occupies. Diesel fuel must be extracted as crude oil, refined, and transported multiple times before it is burned in vessels. Electricity is produced from several different energy sources—all of which have their own environmental impacts—and then it is transmitted over long distances with some losses. Figure 34 shows the blend of energy sources that would power an all-electric Skagit County ferry. In order to make the problem quantifiable for scoring purposes, this analysis focuses on point emissions from the ferry itself.

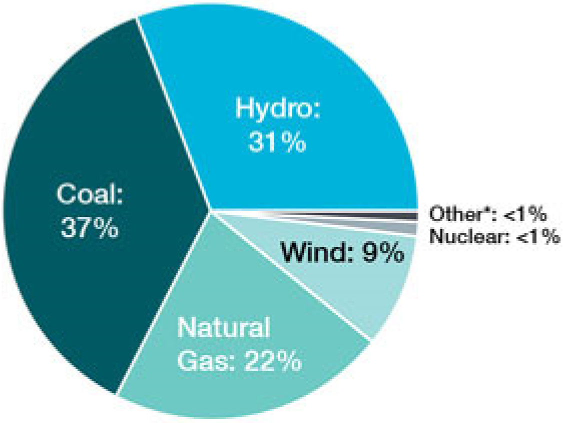


Figure 34 Blend of energy sources serving the Anacortes terminal, Reference 8

Diesel Particulate Matter (DPM) was used as a proxy for local vessel air emissions as it presents greater localized health risks than other diesel exhaust pollutants (Reference 31). The Tier 3 and Tier 4 g/bkWh requirement levels were used due to lack of specific engine data. Table 27 below summarizes the total kg per year for each propulsion configuration. Average engine load was approximated as the time-weighted average from the load profile developed for the life cycle cost analysis. Average engine operating hours were similarly developed from the life cycle cost analysis.

Table 27 Engine DPM annually

	Gear Diesel	Diesel Electric	Series Hybrid	All-Electric	Plug-in Hybrid
Engine DPM - 1000hp (g/bkWh)	0.04	-	-	-	-
Generator DPM - 550 kW (g/bkWh)	-	0.27	0.27	-	0.27
Generator DPM - 66 kW (g/bkWh)	0.27	-	-	-	-
Total DPM (kg/yr)	107.5	339.6	124.7	-	5.6

3.7.7 Scoring Results

The results of the example scoring are presented below in Table 28. The total score is the sum of the weighted scores from each of the weighted categories.

Table 28 Scoring system results

Propulsion System ⇨	**Geared Diesel**		**Diesel Electric**		**Hybrid**		**All Electric**		**Plug-in Hybrid**		Weighting
Scoring Category ⇩	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted	**Factor**
Capital Cost	1.00	0.00	0.81	0.00	0.65	0.00	0.25	0.00	0.31	0.00	0%
Operations and Maintenance Cost	0.65	0.00	0.64	0.00	0.71	0.00	0.81	0.00	1.00	0.00	0%
System Weight	0.75	0.08	0.59	0.06	0.54	0.05	1.00	0.10	0.64	0.06	10%
Design and Build Complexity	1.00	0.20	0.67	0.13	0.33	0.07	0.00	0.00	0.00	0.00	20%
Reliability and Availability	0.64	0.29	1.00	0.45	0.66	0.30	0.34	0.15	0.41	0.19	45%
Airborne Noise	0.00	0.00	0.00	0.00	0.33	0.03	1.00	0.10	0.67	0.07	10%
Vessel Air Emissions	0.05	0.01	0.02	0.00	0.04	0.01	1.00	0.15	0.98	0.15	15%
Total Weighted Score		**0.57**		**0.64**		**0.46**		**0.50**		**0.46**	100%

A blank table is provided below for the reader to develop their own weighting factors and scoring results. For each category and each propulsion system, multiply the raw score by the category weighting factor to compute individual weighted scores. Add all weighed scores for each propulsion system to compute a total weighed score for each propulsion system.

Table 29 Scoring system with empty cells for custom weighting calculation

Propulsion System ⟹	**Geared Diesel**		**Diesel Electric**		**Hybrid**		**All Electric**		**Plug-in Hybrid**		Weighting
Scoring Category ⇩	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted	**Factor**
Capital Cost	1.00		0.81		0.68		0.31		0.36		
Operations and Maintenance Cost	0.65		0.64		0.70		0.81		1.00		
System Weight	0.75		0.59		0.54		1.00		0.64		
Design and Build Complexity	1.00		0.67		0.33		0.00		0.00		
Reliability and Availability	0.64		1.00		0.66		0.34		0.41		
Airborne Noise	0.00		0.00		0.33		1.00		0.67		
Vessel Air Emissions	0.05		0.02		0.04		1.00		0.98		
Total Weighted Score											

3.8 Sensitivity Analysis

The life cycle cost analysis accounted for energy price forecasts developed by the Energy Information Administration (EIA) of the US Department of Energy. The escalation is included in the discount factors applied to NPV calculation. Sensitivity analysis was performed by varying the price of fuel or electricity and subsequently the annual cash amount of each. The discount factors and forecasts were not changed.

Diesel and electrical prices in the Pacific Northwest region were gathered from EIA data ranging from 2011 to present. The maximum and minimum deviation from the current price of fuel and electricity are presented below in Table 30. The current price paid by Skagit County is also included for reference.

Table 30 Fuel and electricity price deviation as a percentage of current price since 2011

	Skagit County Price	**Minimum Price**	**Maximum Price**
Diesel	2.09 $/gallon	25.0%	52.0%
Electricity	0.554 $/kWh	16.9%	15.2%

Diesel fuel is much more volatile than electricity as seen by the minimum and maximum price deviation since 2011. In order to account for this, sensitivity analysis conducted utilized the percentages in Table 30 as the variance in current price.

3.8.1 Fuel Sensitivity

Below is a graphical representation of how change in current fuel price affects total life cycle cost. The all-electrical and plug-in hybrid propulsion systems appear much more advantageous as fuel prices rise above $3.25/gallon and $2.50/gallon respectively. Skagit County indicated the current diesel fuel price is $2.09.

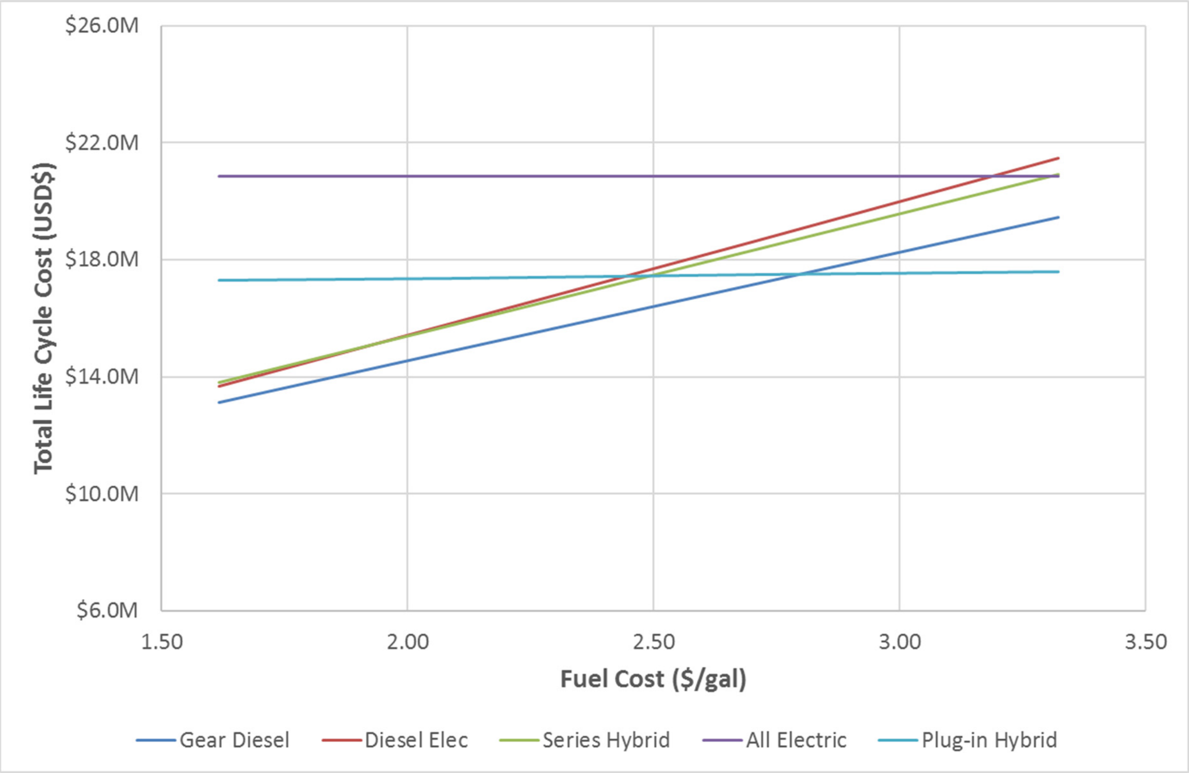


Figure 35 Fuel price sensitivity

3.8.2 Electrical Sensitivity

Below is a graphical representation of how change in current electricity price affects total life cycle cost. Demand charges were scaled for this approach by a percentage difference in the current price of electricity. PSE indicated the current electrical rate is approximately $0.0554/kWh for primary general service.

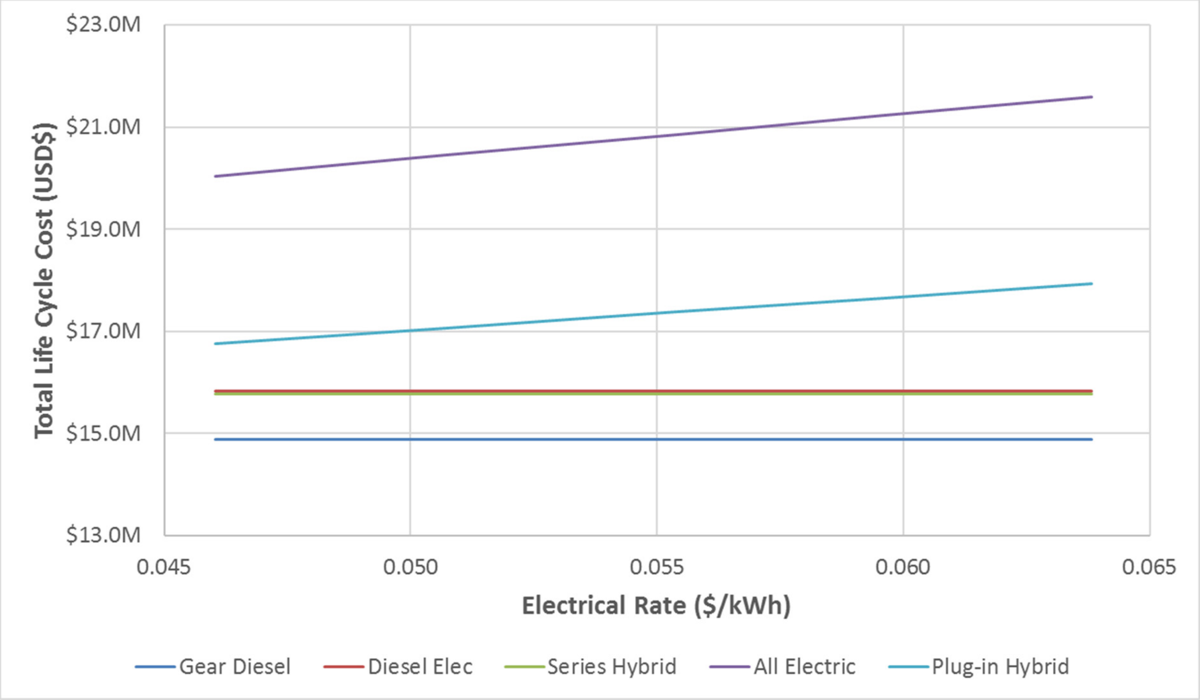


Figure 36 Electrical price sensitivity

The total life cycle costs do not vary significantly based on the changing electrical prices, suggesting electrical price is not a sensitive variable.

3.8.3 Scoring

Propulsion system scoring may be affected as operating costs change due to the sensitivity analysis. In order to evaluate the propulsion systems, the total weighted scores from Section 3.7.7 were presented in relation to cost. Figure 37 provides capital cost for each propulsion option versus total weighted score, with a score of 1 being the best.

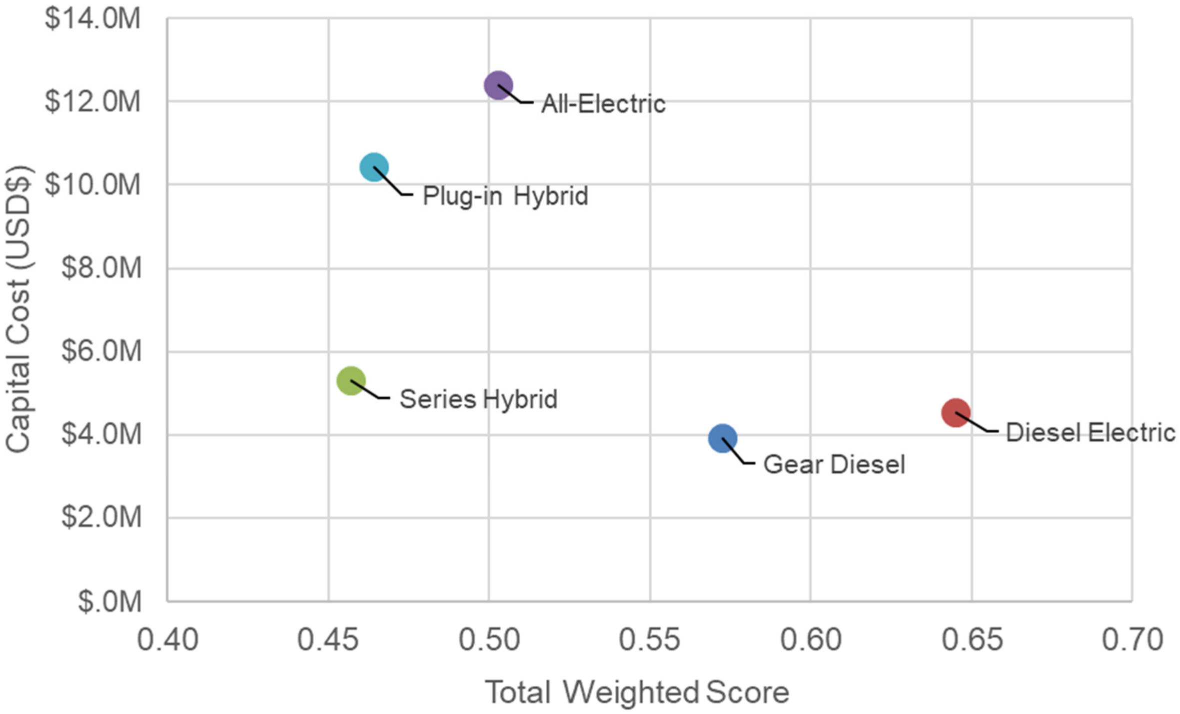


Figure 37 Propulsion system capital cost versus total weighted score

Figure 38 provides operating cost for each propulsion option versus total weighted score. These costs are expressed as a range of possible values based on a sensitivity analysis for the price of diesel and electricity.

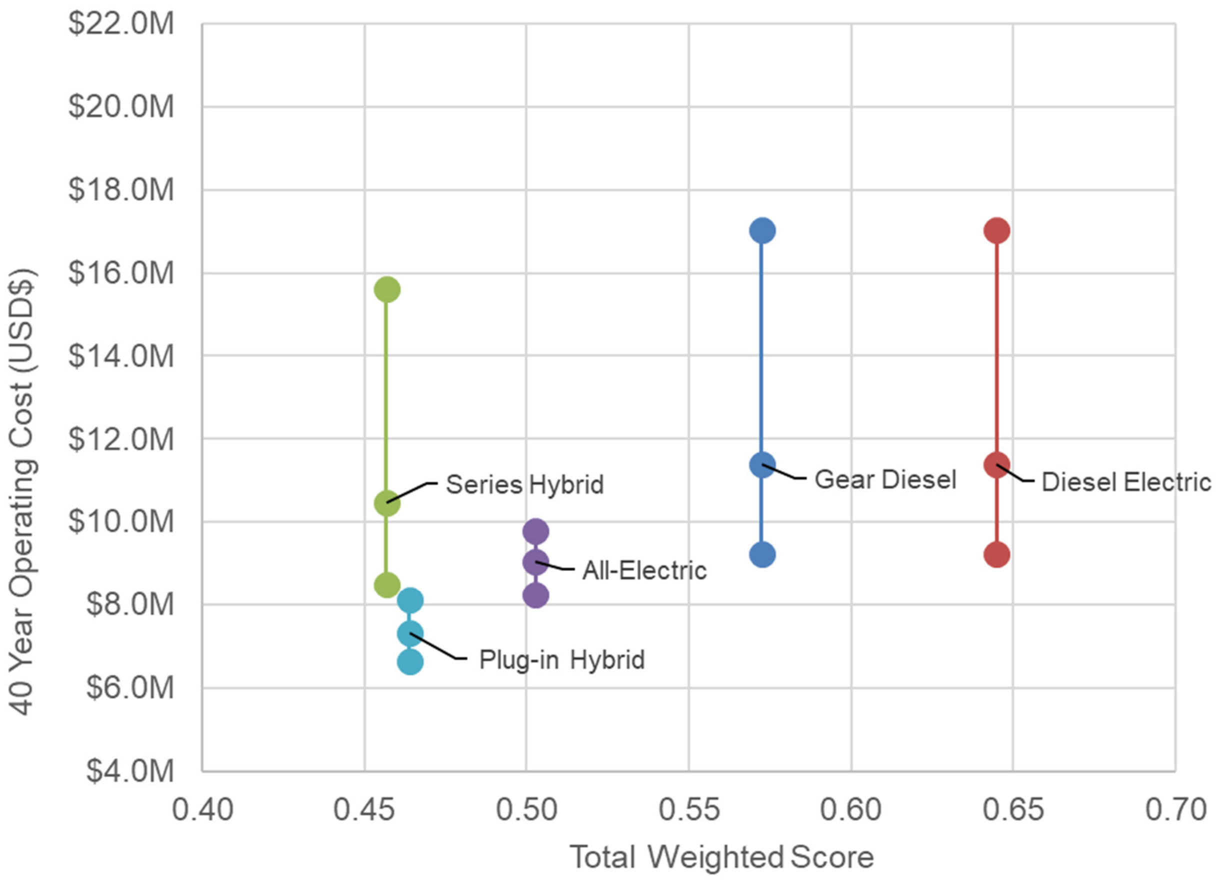


Figure 38 Propulsion system operating cost versus total weighted score

Section 4 Design Requirements

This section discusses the various requirements for the design emanating from non-regulatory sources. The Vessel Capacity Study (Reference 15) contains additional information on the vehicle and passenger ridership. The Transportation System Assessment (Reference 7) contains additional information on the terminals and emergency services. Requirements originating from regulations are discussed in Section 5.

4.1 Route

The replacement vessel will operate in Guemes Channel, which is the body of water that separates Guemes Island to the north and Fidalgo Island to the south, and leads east from Rosario Strait to Padilla Bay. The channel is about 3 nautical miles (nm) long and 0.5 nm wide at its narrowest point, with depths ranging from 4 to 18 fathoms (48 to 108 feet), Reference 1.

Guemes Channel is part of the Salish Sea, and is thus marine (salt) water with significant tidal fluctuation. The current velocity in Guemes Channel exceeds 5 kts at times (see Section 2.5 for additional information on environmental conditions).

Figure 39 and Figure 40 show the established route, of which there are no planned changes.

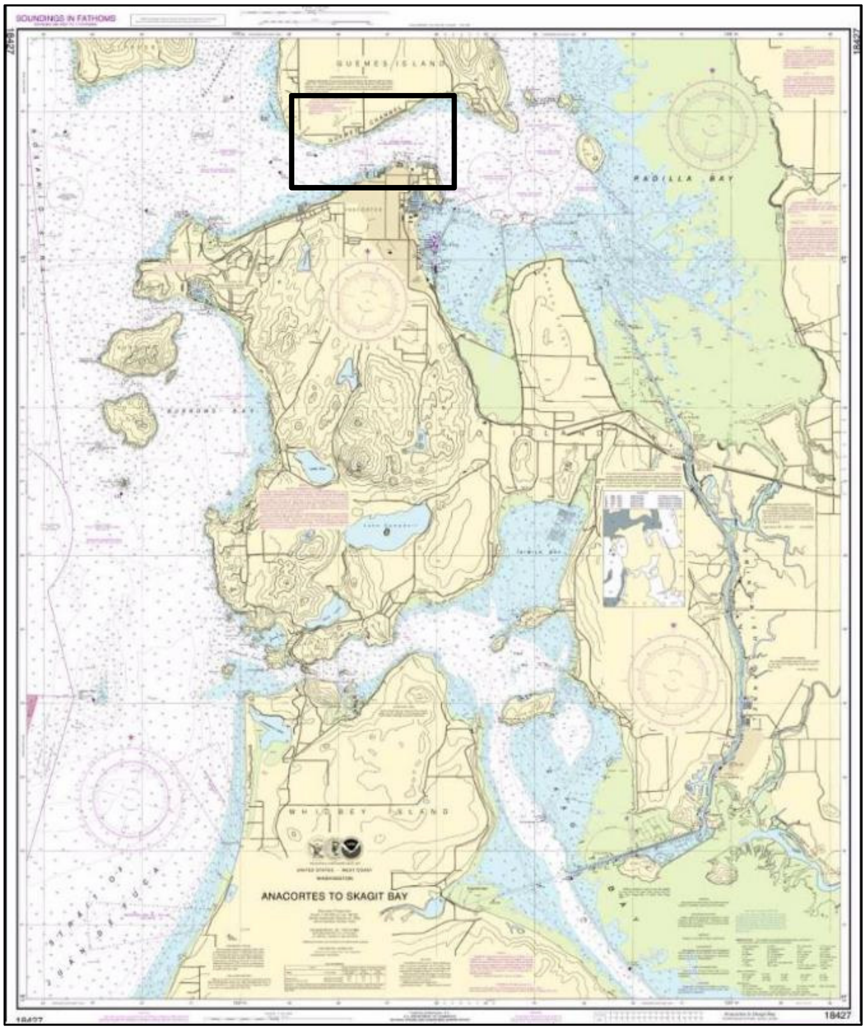


Figure 39 NOAA Nautical Chart No. 18427, with box showing the zoomed-in area in Figure 40

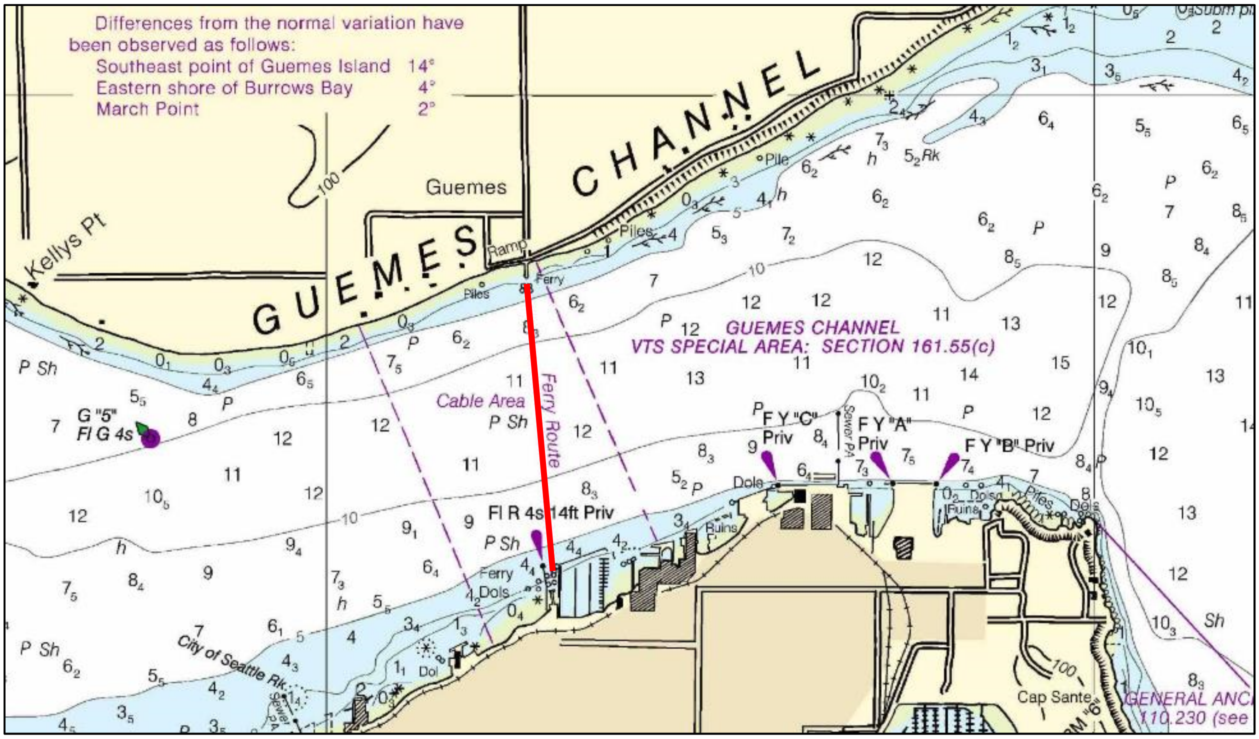


Figure 40 Excerpt from NOAA Nautical Chart No. 18427 showing established route between Anacortes and Guemes Island, depth in fathoms

The waters where the vessel operates are defined in the current vessel's certificate of inspection (COI) as "Guemes channel, on an established ferry route between Anacortes, Washington and Guemes Island, Washington, not more than 1 mile from land." This area is determined by the US Coast Guard (USCG) to be "Lakes, Bays, and Sounds." The limited operating distance from shore and the designation of "Lakes, Bays, and Sounds" determine the required lifesaving complement for the ferry (see Section 3.1).

The route itself crosses Guemes Channel near its narrowest point, and is approximately 0.5 nm in length. Water depth is at least 60 ft for the majority of the route, and at least 14 ft at each terminal. Water depth should not be a limiting factor for the new ferry, in terms of draft limitations (for sufficient underkeel clearance) or shallow water effects on speed and maneuverability.

4.2 Terminal Interface

Berths at each terminal are standard vehicular ferry slips with V-shaped wingwalls supported by a system of steel piles, as shown in Figure 41 and Figure 42.

Figure 41 Guemes Island Ferry Terminal, Guemes Island

Figure 42 Guemes Island Ferry Terminal, Anacortes

Both terminals have outer (freestanding) fendered dolphins constructed of steel piles. The terminal on Guemes Island has two pairs of dolphins, one on each side of the slip. The terminal in Anacortes has three dolphins on the west side of the slip, and four dolphins on the east side of the slip. According to operators, a vessel of up to 53 feet in overall breadth (three feet wider than the existing vessel) would be capable of maneuvering between the dolphins. A vessel of up to about 200 feet in length would be capable of holding itself against the existing dolphins to maintain position in the slip.

When not in use, the ferry is moored at the Anacortes slip. The Anacortes slip has a purpose-built breakwater on the west side, and it takes advantage of Anchor Cove Marina's breakwater on the east side. With these two breakwaters, a vessel of up to about 200 feet in length would be reasonably well protected in the Anacortes slip. The Guemes slip has no breakwaters; while holding position in the slip there, the ferry must resist full exposure to wind, waves, and current. Additional details of the terminals are presented in the Transportation System Assessment (Reference 7).

The vehicle deck of the existing ferry has a bow radius of 15'-0" that fairs into an ellipse with a semimajor axis of 42'-0" and a semiminor axis of 23'-0". In order to use the existing terminals, the new vessel will have the same 15'-0" bow radius and a similar elliptical transition to full breadth.

The freeboard of *Guemes* was measured on 12 October 2017 to be 4'-6" without vehicles and passengers. The Transportation System Assessment recommends a freeboard of at least 5'-9" for the new vessel in all load conditions in order to be compatible with the existing terminal at all times and to meet ADA slope requirements on the ramp and transfer span approximately 92% of the time (100% compliance is not practically achievable).

4.3 Operating Environment

Weather near the eastern part of the Strait of Juan de Fuca can be described as mild, windy, and rainy in winter; cool and pleasant in summer; and with periods of fog. In winter, low-pressure systems moving through the region can produce rain on 15 to 25 days each month and snow on occasion (Reference 24).

Westerly winds prevail in summer, increasing in the late afternoon to early evening hours. Southerly winds prevail during the winter months, with the strongest winds blowing from the southeast, generally as low-pressure systems approach the coast (Reference 24). Gale-force winds from this direction are common, but usually last less than 24 hours per storm system. Intervals between storms normally range from one to five days, but can extend up to two weeks if a strong high-pressure system centers on the region (Reference 1).

4.3.1 Tidal Currents

Guemes Channel is a relatively narrow waterway connecting Rosario Strait and Padilla Bay. As such, tidal currents in the area of the ferry crossing are swift and nearly continuous, interrupted only by brief periods of slack water. Current velocity is reported to be generally between one and three knots during maximum ebb/flood, but it can exceed 5 kts at times (Reference 1). Operators of the Guemes ferry have observed local currents of up to 5.5 kts.

Current data were collected over the month of August 2017 by NOAA equipment deployed at the east and west entrances of Guemes Channel. A maximum current of 4.24 kts occurred on a new moon spring ebb tide on 21 August 2017. It is likely that spring ebb currents in the Winter/Spring runoff months could be higher considering the greater tidal range and the additional flow of water from the Skagit River basin, or that current velocities could be higher than those observed by the NOAA buoys in the narrowest part of the channel where the Guemes ferry docks are located.

4.3.2 Visibility

Sea fog is common and dense in the eastern portion of the Strait of Juan de Fuca during the latter part of the summer season, while land fog causes poor visibility during the winter season. Fog-producing conditions are most prevalent from September through February. During prolonged periods of cold, clear, calm weather, fog may persist for several days at a time. Visibilities fall below 0.75 mile on about 20 days of the year, but this can increase to 60 days of the year in some locations (Reference 1). Fog and visibility data specific to Guemes Channel were not readily available.

4.3.3 Wind Conditions

Winds in Guemes Channel are strongest during the winter months, from October through March. Low-pressure systems moving through the area during this time can create local wind effects, as the mountainous terrain of the region plays an important part in determining the direction and speed of the wind (Reference 1).

There are normally two wind seasons: winter lasts from October through March, while summer lasts from April through September (Reference 1).

To characterize winds in Guemes Channel, hourly wind data from Naval Air Station (NAS) Whidbey Island were used (Figure 43).

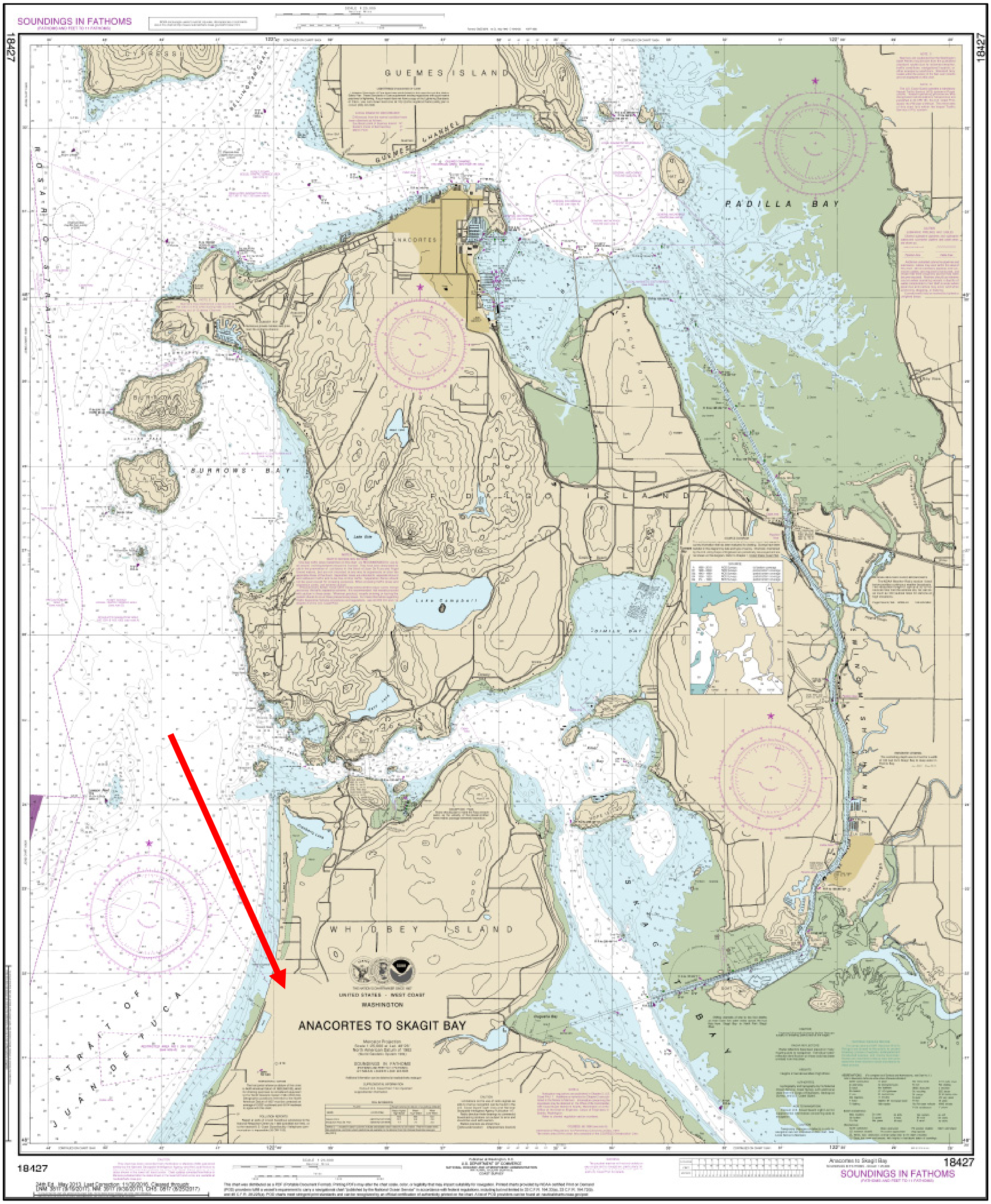
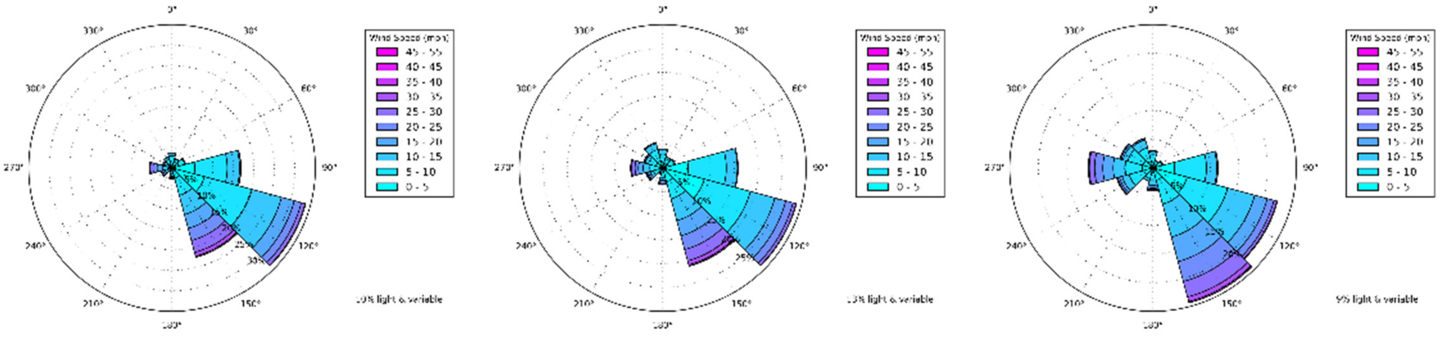


Figure 43 Approximate location of NAS Whidbey Island

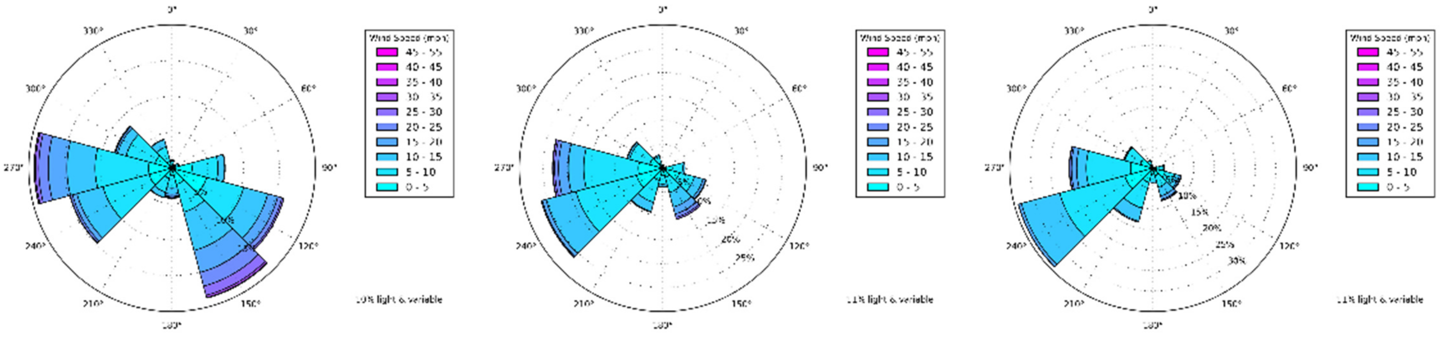
NAS Whidbey Island wind data were available for the period from 1990 to 2016. Wind speed and direction were recorded every hour, thus the data were treated as one-hour averages. The anemometer was assumed to be located at a height of 10 meters above the ground.

Monthly wind roses are shown in Figure 44.

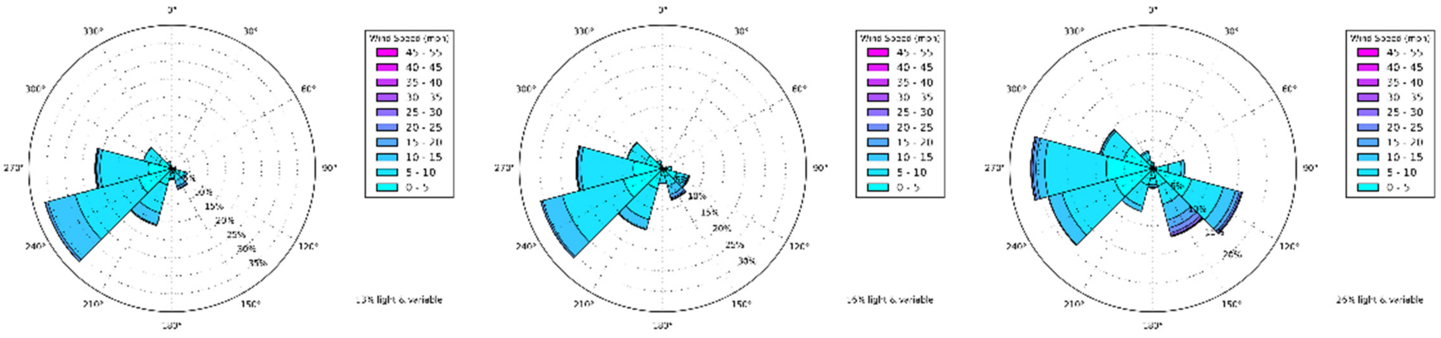
January February March



April May June



July August September



October November December

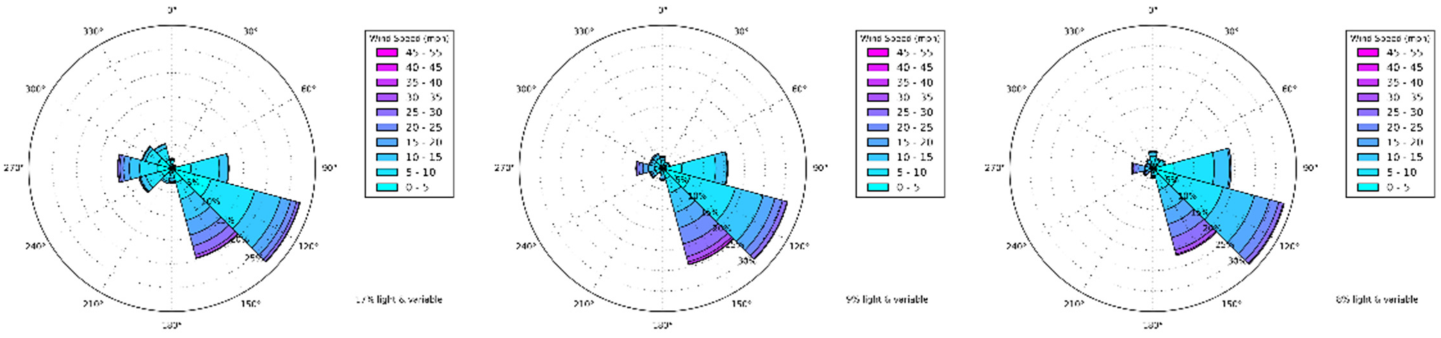


Figure 44 Monthly wind roses for NAS Whidbey Island, 1990-2016; one-hour average wind speed

An annual wind rose is shown in Figure 45, while annual wind speed statistics are shown in Table 31.

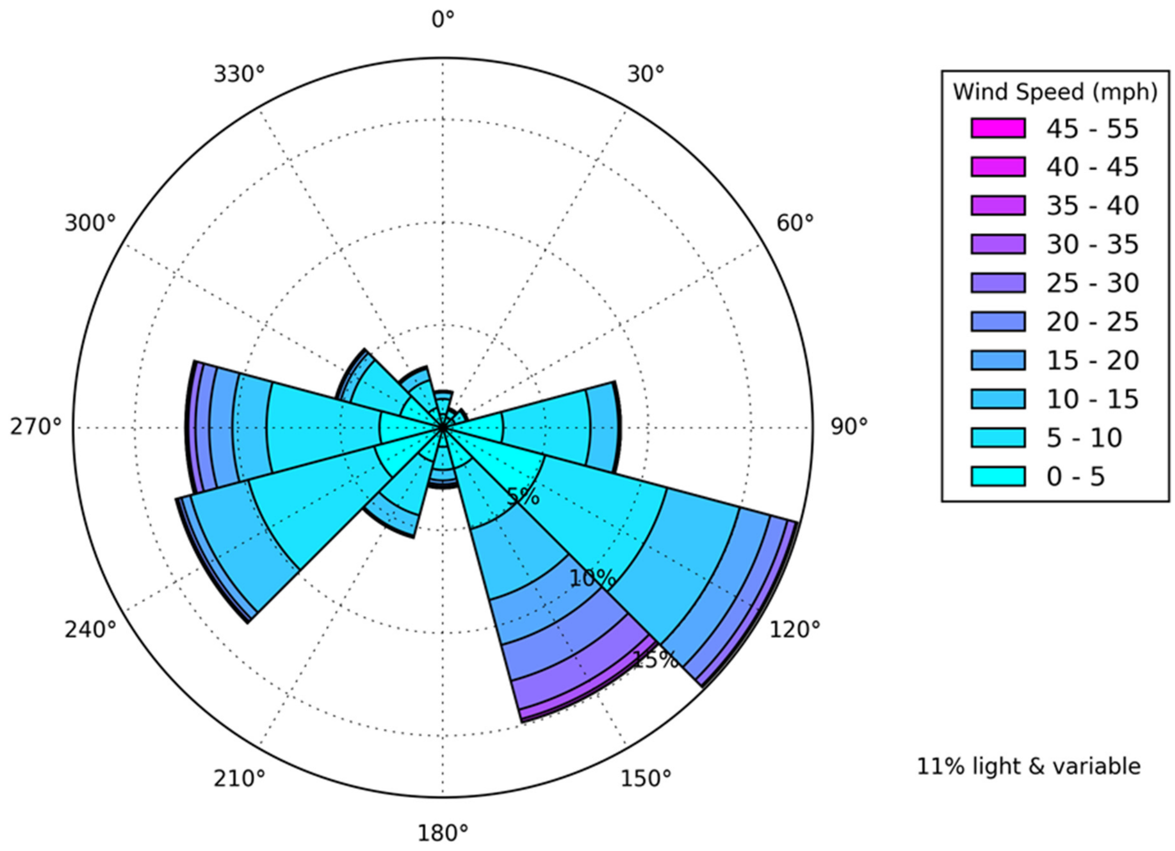


Figure 45 Annual wind rose for NAS Whidbey Island, 1990-2016; one-hour average wind speed

While these figures are consistent with the regional description of the operating environment, it should be noted that the underlying data do not reflect any local wind effects in Guemes Channel caused by the topography of surrounding land masses or other factors.

Table 31 Annual wind speed statistics for NAS Whidbey Island, 1990-2016; one-hour average wind speed at 10m

Annual Statistic	Wind Speed (mph)
95th percentile	21
99th percentile	29
99.9th percentile	37
Maximum recorded	51

4.3.4 Wave Conditions

Wave conditions in Guemes Channel were determined using the fetch-limited wave growth formulation from ACES, originally developed by the US Army Corps of Engineers. The method uses a straight-line fetch distance coupled with wave growth equations based on wind speed, wind duration and direction, and the difference between air and water temperatures. The model is essentially one-dimensional in that it only considers the upwind shoreline as a limit to wave propagation. It does not consider wave refraction or diffraction due to bottom composition and bathymetric effects. The interaction between wind, waves, and current is also not considered.

The fetch radials developed for the intended route are shown in Figure 46.

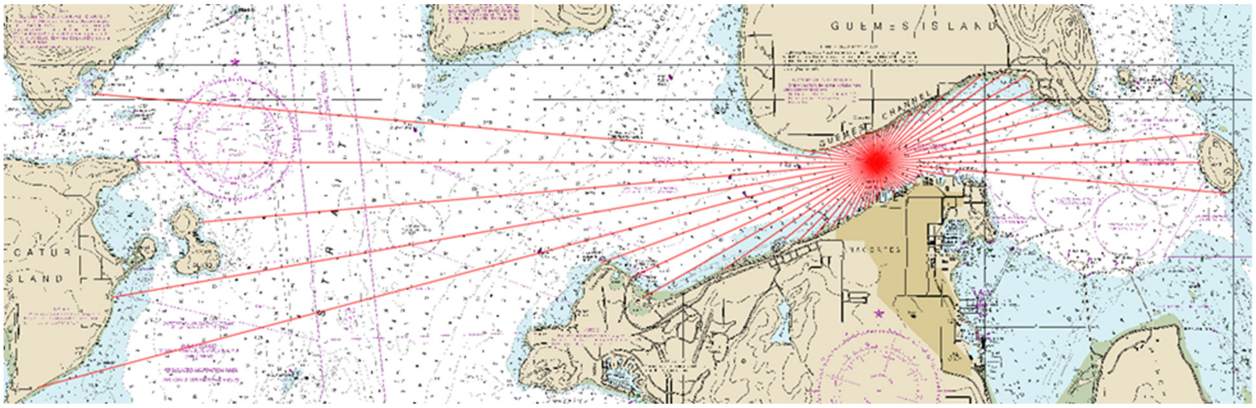


Figure 46 Fetch radials for Guemes Island/Fidalgo Island ferry crossing

Wave conditions were determined for wind speeds from 5 mph to 40 mph (in 5 mph increments) for winds from the east (090° true) and west (260° true), given that the longest fetch distances lie in these two directions. A 5°C temperature difference between air and water was assumed for this hindcast.

Wave hindcast results and monthly wind speed statistics at NAS Whidbey Island are shown in Figure 47. For example, a 35-mph wind from the west produces a wave condition characterized by a 3.1-ft significant wave height (H_S) and 3.6-second peak period (T_P).

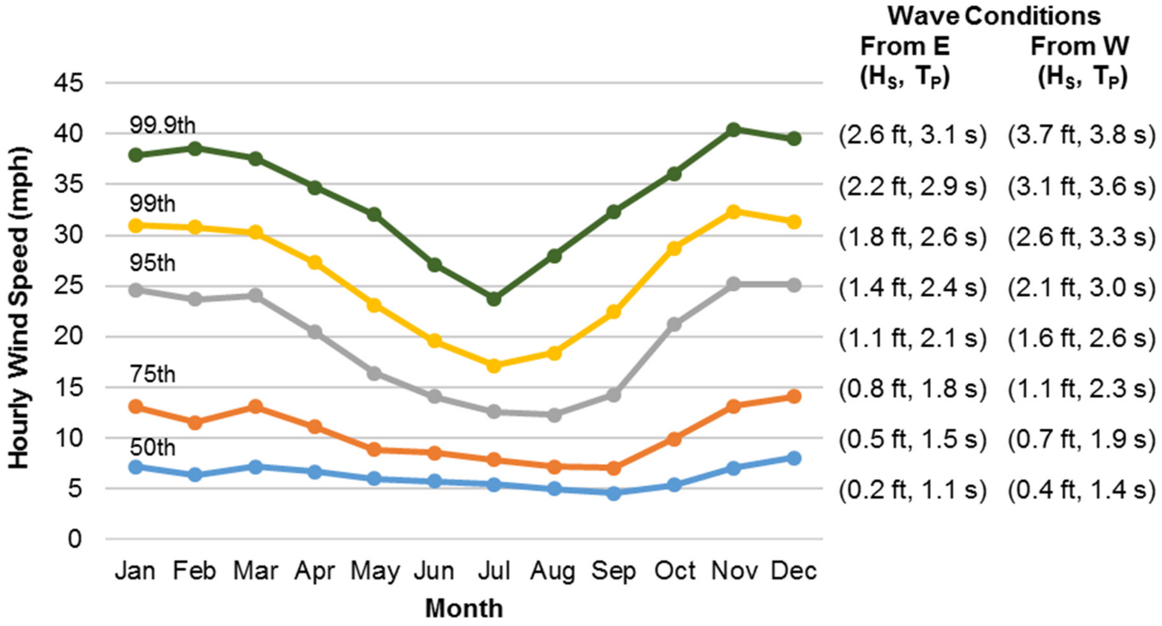


Figure 47 Monthly wind speed statistics based on NAS Whidbey Island data, 1990-2016, and associated wave conditions in Guemes Channel

Wave conditions based on the annual maximum wind speed were determined using the same method and are shown in Table 32.

Table 32 Maximum recorded wind speed at NAS Whidbey Island, 1990-2016, and associated wave conditions in Guemes Channel

Wind Direction (deg T)	Wind Speed (mph)	H_S (ft)	T_P (sec)
90 (From E)	51	3.5	3.6
260 (From W)	51	5.2	4.4

4.4 Passengers

The Vessel Capacity Study (Reference 15) discusses in detail the past and projected ridership. By 2060, ridership is anticipated to increase approximately 77% from 2016 levels and approximately 62% from the peak level in 2007. The study estimates that a passenger capacity of 162 passengers in the replacement vessel's busiest year (assumed to be 2060) would be equivalent to *Guemes*'s 100-person capacity in its busiest year (2007). A global 1.62 scale factor is used in the discussion below.

USCG requirements limit Subchapter T passenger vessels to 150 passengers. A passenger vessel carrying more than 150 passengers must either satisfy the requirements of Subchapter K or H, both of which would increase the cost and complexity of the vessel in terms of capital and operating expenses. Given the projected ridership level, a total capacity of 150 passengers provides the most flexibility without substantially increasing the cost of the vessel.

4.4.1 Drive-on Passengers

The Vessel Capacity Study (Reference 15) suggests 1.7 passengers per vehicle, resulting in approximately 54 passengers in vehicles (including drivers) for a given load of 32 vehicles.

4.4.2 Walk-on Passengers

The *Guemes* has a nominal walk-on capacity of 36 passengers, resulting in a 98.8% availability, and a nominal seating capacity of 19, resulting in an approximate 93.4% availability (Reference 15). Approximately 200 trips per year (currently) exceed the walk-on capacity, resulting in passengers' spilling onto the vehicle deck. While not desirable, it appears to be an accepted practice.

Using the walk-on passenger work from Reference 15, the walk-on load size is adjusted to account for the medium-low passenger growth factor (1.62) and the current-to-new vehicle capacity ratio (1.52). The 95th, 98th, and 99.9th percentile load is 33, 47, and 106 walk-on passengers, respectively. As guidance for the concept design, seating is to be provided for between the 95th and 98th percentile load, while total passenger space (both interior and exterior) is to accommodate the 99.9th percentile load.

The passenger lanes at both terminals are on the west side. To keep passenger flow separated from vehicle flow, the passenger cabin should be on the west side of the replacement vessel as well.

4.4.3 Bicycles

Bicycles are more closely related to passengers than to vehicles, so bicycle storage should be located within the dedicated walk-on passenger space, on the west side of the vessel.

The replacement vessel will need to accommodate groups of bicyclists that routinely travel to and from Guemes Island, mostly during the summer months, and a smaller but consistent group of bicycle riders throughout the year. The replacement vessel should have stowage for six bicycles outside each end of the deckhouse, arranged in a way that does not encroach on crew and passenger access paths.

4.5 Vehicles

Baseline vehicle dimensions were established for the design of the car deck of the replacement vessel. Based on prior years' ticket sales and per Reference 15, approximately 90% of the lane feet on the existing ferry is associated with vehicles 20 feet or less in length, referred herein as passenger vehicles.

Passenger vehicles were used for the maximum vehicle configuration and lane arrangement. Commercial vehicles (large trucks) were used for overhead height of the car deck, maximum lane width, and maximum weight configuration.

4.5.1 Passenger Vehicles

The Automobile Equivalent (AEQ) is the common measure of a ferry's vehicle carrying capacity, but is not standardized across ferry designers or operating organizations. It includes a perimeter space around each vehicle for bumper-to-bumper and door opening clearances. The AEQ is derived from the actual vehicle dimensions, but does not explicitly represent them.

Table 33 provides AEQ dimensions for various organizations, including the proposed 17'-9" × 8'-6" AEQ for the replacement vessel.

Table 33 Automobile Equivalent (AEQ) dimensions for various agencies, tight with no spaces

Organization	Lane Length (ft)	Lane Width (ft)	Lane Height (ft)
Washington State Ferries, Olympic Class	18.5	8.5	7.5
British Columbia (BC) Ferries	20.0	8.5	-
Alaska Marine Highway Systems	20.0	8.5	10.0
Alaska DOT (*Ken Eichner - 2*)	16.0[2]	8.0	-
Pierce County (*Steilacoom II*)	17.0	8.5	-
Skagit County (*Guemes* design)	18.0	8.5	-
Proposed for Replacement Vessel[1]	17.75	8.5	7.5

1. Determined by fitting 21 vehicles (the most probable full load) on *Guemes*
2. This vessel primarily carries rental vehicles, which tend to be smaller than average

The original design drawings for the *Guemes* show AEQ dimensions at 18'-0" long and 8'-6" wide, with the total capacity of 19 AEQs; however, data from Reference 15 indicate that full loads are most likely to have 21 vehicles. Using the main deck arrangement of the *Guemes*, 21 vehicles are accommodated if the AEQ length is reduced to 17'-9", while allowing the standard 2'-0" side-to-side clearance of vehicles near the ends to be reduced, as shown in Figure 48. Note that although an 18'-0" long AEQ could be accommodated on the center lane, it is too long to accommodate 21 vehicles while using a consistent AEQ size.

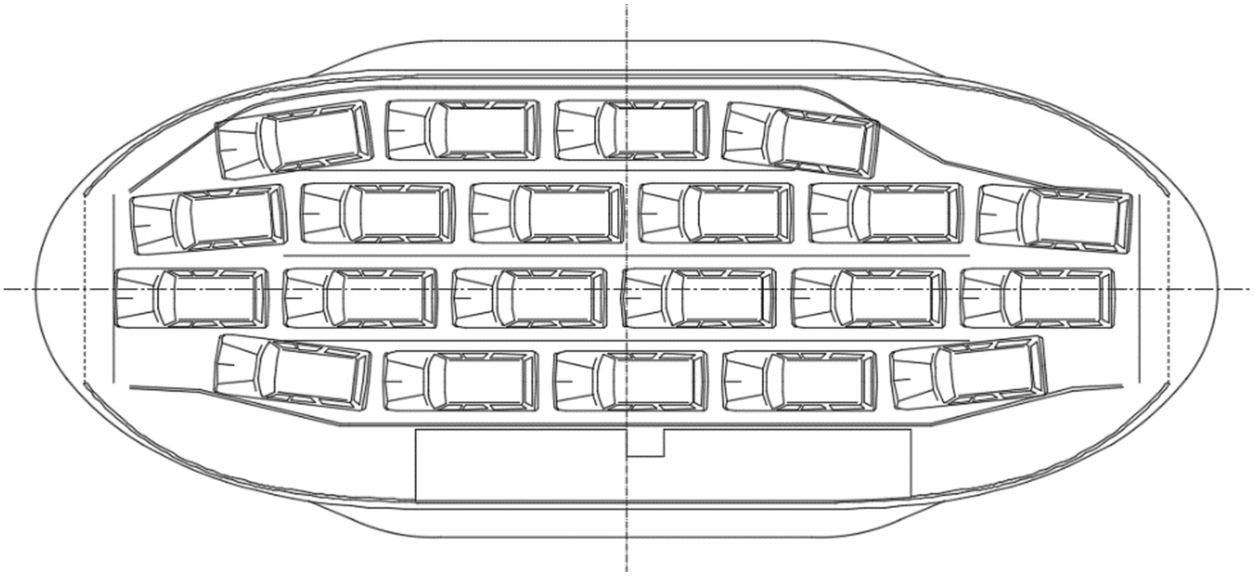


Figure 48 M/V Guemes shown with 21 vehicles, 17'-9" AEQ length

Skagit County attempts to place vehicles with a 12" to 18" bumper-to-bumper gap, leaving approximately 16'-3" to 16'-9" of actual vehicle for an AEQ length of 17'-9". Dimensions of common vehicles are shown in Table 34 for reference. The AEQ dimensions used in the replacement vessel design are shown in Figure 49.

Table 34 Passenger vehicle dimensions (width excludes mirrors) and weights, 2017 models, Reference 1 and Reference 27

Vehicle Class	Vehicle Example	Length (ft)	Width (ft)	Height (ft)	Max Curb Wt (lbs)	Max GVW (lbs)	~% of Market Share
Passenger Sedan	Toyota Prius	15.2	5.8	4.8	3,080	3,915	16%
Passenger Sedan Large	Toyota Camry	15.9	6.0	4.8	3,340	4,242	16%
Passenger Crossover	Subaru Outback	15.8	6.0	5.5	3,856	4,850	16%
Passenger SUV	Ford Explorer	16.5	6.6	5.8	4,901	6,160	25%
Passenger Van	Honda Odyssey	16.9	6.6	5.7	4,613	6,019	7%
Passenger Truck	Ford F150	17.4	6.7	6.4	5,238	7,050	21%
Weighted average of above	-	16.3	6.3	5.6	4,258	5,480	-

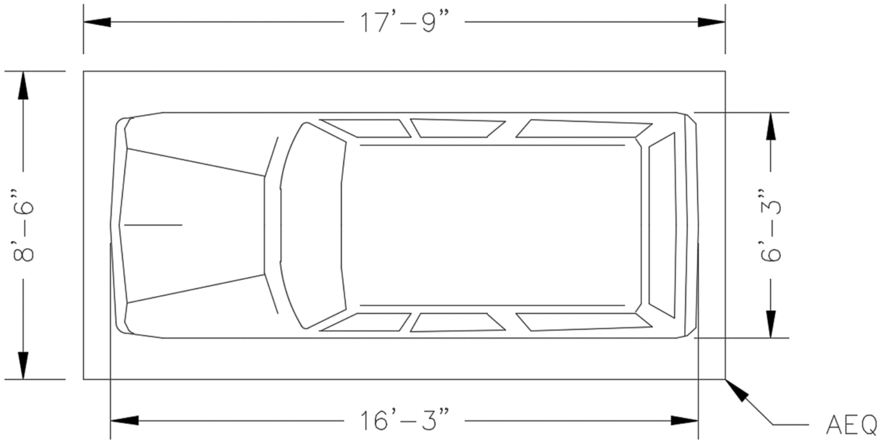


Figure 49 Guemes Island replacement vessel AEQ

Curb weight and maximum gross vehicle weights are also shown in Table 34. Washington State vehicle registration data from year 2014 is applied by vehicle type to arrive at weighted average dimensions and weight. From these data, a half-load passenger vehicle weight of 4,900 lbs (average of curb weight and gross vehicle weight) is used for typical operating scenarios, while a 5,500 lb vehicle weight is used for maximum weight calculations.

4.5.2 Commercial Vehicles

Table 35 presents the commercial vehicle dimensions for each design vehicle.

Table 35 Commercial vehicle dimensions, width excluding side mirrors

Vehicle	Length overall (ft)	Width of trailer (ft)	Max Height (ft)	Max Weight (lbs)
40' Box Truck	40.0	8.5	14.0	54,000
40' Tractor - Trailer	51.7	8.5	14.0	80,000[1]
48' Tractor - Trailer	65.0	8.5	14.0	80,000[1]
53' Tractor - Trailer	73.0	8.5	14.0	80,000[1]
Ladder Truck - Tandem	43.0	8.3	12.5	68,500

1. Assumed two tandem axles at 34,000 lbs each and one steer axle at 12,000 lbs (Reference 1)

The Washington State Department of Transportation legal limit for width and height is 8.5' and 14.0' respectively. The legal length of a single unit truck is 40.0'. The legal length of a log truck with single steered pole trailer and a truck/trailer combination is 75.0'. The maximum gross load on any single axle and tandem axle is 20,000 lbs and 34,000 lbs respectively. The maximum weight of any vehicle, regardless of length or axles, is 105,500 lbs (Reference 27). All of the above dimension and weight limits can be exceeded with permits.

The largest fire truck operated by the Anacortes Fire Department is shown in Figure 50. All dimensions, including the 8.5' width, fall within legal limits. The total weight of 68,500 lbs is distributed over a rear tandem axle at 47,000 lbs and a forward steer axle at 21,500 lbs. These axle weights are higher than the legal limit. While more of an unusual load, this forward steer axle weight represents the highest deck load that the main deck structure will need to be designed to accommodate.

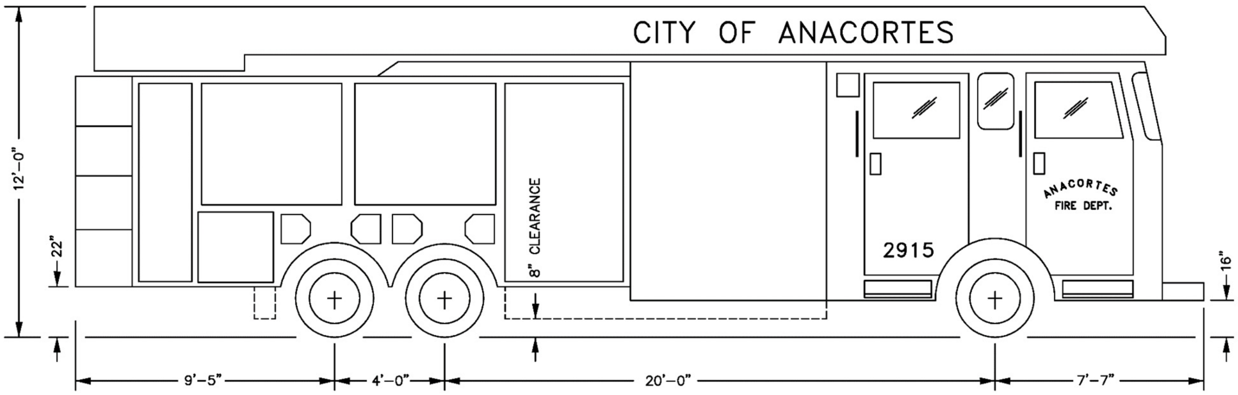


Figure 50 Aerial ladder – tandem rear axle

4.6 Noise and Vibration

Noise and vibration can cause fatigue, discomfort, and maladies among crew and passengers. Guidance on exposure limits for noise and vibration can be found in the following documents:

- *Guidance Notes on the Application of Ergonomics to Marine Systems* (Reference 16).
- *ISO 20283-5:2016: Mechanical Vibration* (Reference 31).

The replacement vessel should incorporate good design practices regarding noise and vibration, including consideration of the aforementioned documents. The following airborne noise limitations are proposed for when the vessel is operating at full speed with all auxiliaries operating, including HVAC systems:

- 75 dB(A) at any location on exterior decks accessible to passengers.
- 65 dB(A) at any location within the enclosed passenger spaces.
- 65 dB(A) within the Pilothouse(s) and other enclosed crew-only spaces above the Main Deck (mechanical rooms not included).

4.7 Speed, Acceleration, and Maneuvering

The economical speed of a typical displacement hull is limited by wave-making resistance. As speed increases, the steepness of the resistance curve also increases, creating a situation where a substantial increase in applied thrust achieves only a marginal increase in speed. For a given ship type, a longer hull is usually capable of a higher economical speed.

When discussing wave-making resistance, ship speed is nondimensionalized by Froude number. A Froude number of 0.28 is a reasonable speed for a double-ended ferry, which equates to a speed of approximately 12 kts for the replacement vessel concept design (170-ft waterline length).

The Transportation System Assessment assumes a cruising speed of 11.5 kts for the replacement ferry in its throughput analysis. This assumption provides a margin of 0.5 kts below the 12-knot target speed to allow for variations in vessel displacement, weather, and hull aging and fouling, all of which affect speed and performance. The vessel will be designed to make this speed using one propulsor: the aft propulsor, because the hull substantially blocks the effectiveness of the forward propulsor's thrust.

Acceleration and deceleration are important because the crossing is so short. The Transportation System Assessment assumes the following target values for vessel acceleration and deceleration:

- 9.90 kts/min between 0 kts and 5 kts
- 8.25 kts/min above 5 kts

These target values are between those observed on *Guemes* (ca. 10-11 kts/min) and those observed on a larger county ferry with a more conventional propulsion system, *Christine Anderson* (ca. 6-7 kts/min). *Guemes* accelerates uncommonly quickly because its propellers appear to be optimized for low speed: they can absorb full engine power during acceleration, but only half of engine power during cruise (Reference 24). This unusual optimization point (for a ferry at least) may have been intended to improve performance or economy when pushing the dock in strong current.

Typical operational practice in strong current is to round up into the current when approaching the berth, and then to turn upon entering the berth to make controlled contact with the wingwalls. This maneuver requires very strong yaw control, which is difficult to define quantitatively in early design stages. The qualitative maneuvering requirements for the concept replacement ferry are as follows:

- The hull will be shaped to have limited directional stability, thereby increasing the maneuverability of the hull.
- The propulsors will be capable of diverting full thrust in any horizontal plane direction.

The replacement vessel must also resist a significant transverse current while maneuvering and holding at the docks, especially when at Guemes Island, where there is no breakwater. Operators of the *Guemes* indicate that full power is sometimes needed simply to counteract the forces of the current while maneuvering into the terminals. The general feeling of the operators is that *Guemes*'s power is barely adequate in such scenarios. While these ultra-high-current events are rare (occurring only a few times a year), it is critical that the replacement vessel have enough power to hold position at the dock and to maneuver safely in such extreme currents.

In order to quantify the capability of *Guemes* in a transverse current for use as a design standard for the replacement vessel, Glosten conducted a transverse speed test on 12 October 2017, at approximately 12:30 pm. The test occurred in Guemes Channel near the Anacortes terminal, with calm water and SSE wind at 5 to 10 kts. The test was conducted at high tide with little current influence. The first speed run was parallel to the shore running east, and the second test was running west. Both engines were operated at full rpm (1800). Both runs yielded an average transverse speed of 4.3 kts. Given operators' sense that the existing ferry's performance in strong current is marginal, the replacement vessel should achieve a slightly higher transverse speed.

4.8 Range and Emergency Services

The *Guemes* presently refuels every two weeks during normal operation and travels as far as Seattle, 66 nm away, for periodic maintenance (Reference 7). Seattle is easily reachable with a fuel capacity sized for two weeks of normal operation. Larger fuel tanks are not advised, because it is costly to carry extra weight. Endurance and range are also important for meeting the emergency response scenarios outlined below. These response scenarios were developed in the Transportation System Assessment (Reference 7).

1. A catastrophic event requires evacuation of the island and the electrical grid is disabled. The island population varies seasonally, ranging from approximately 750 to 2,750 persons. This could significantly increase in the next 40 years. The duration of

continuous operation would be up to 24 hours. The ferry would have to provide power to the ramp and apron on each side.

2. Significant fire/emergency on the island requiring continuous operation of the ferry for up to 24 hours. The vessel must be able to complete two round trips without charging.
3. Rendering assistance to a distressed vessel or person in Bellingham Channel. Approximately 2-nm distance from ferry route to site of assistance. On station for 1 hour in 18 kts of wind (95th percentile), with associated waves, and 1 knot of current.
4. Man overboard recovery of a ferry passenger. On station for ½ hour in 32 kts of wind (99.9th percentile), with associated waves, and 2 kts of current. Man overboard recovery is a required operation of all USCG inspected ferries.

All five propulsion systems discussed in Section 3 meet these scenarios.

4.9 Reliability, Availability, Maintainability

The Guemes ferry is the only practical means of traveling to and from Guemes Island, including for most emergency responders. Downtime (time when the ferry is out of service) therefore poses a risk to the community served by the Guemes ferry. Downtime also results in lost fare revenue and increased operating cost (to lease a replacement vessel), making it undesirable to Skagit County in purely financial terms as well. Nearby vessels can provide limited passenger and vehicle service during planned and unplanned outages, but they are inferior to the purpose-built ferry that presently serves the route. The replacement ferry should be designed to minimize the probability of downtime to the greatest practical extent. When estimating downtime, the following three terms are commonly used, known collectively as RAM (reliability, availability, and maintainability):

- *Reliability* is the probability of no system failures occurring in a given time window.
- *Availability* is the probability that the system would be functioning normally in a given time window. Availability accounts for the downtime required to maintain the system and to repair the system after a failure (see *maintainability* below), as well as any redundancies that would allow the system to continue operating normally after the failure of a component within the system. If the system has very high reliability but is expected to require one day of downtime for maintenance each year, then its availability would be approximately 99.7% (364 / 365).
- *Maintainability* is the downtime required to perform periodic system maintenance. Maintainability can also be applied to the downtime required to repair the system after a failure, noting that different failure modes may cause different amounts of downtime. An example of a highly maintainable component is a common filter element that is easy to reach and easy to isolate, with spares kept in Skagit County's inventory. An example of a component with low maintainability is a bevel gear located inside a reduction gear that is no longer supported by the manufacturer.

Aspects that improve availability (i.e. that minimize downtime) include simplicity, parallel or redundant system architecture, ease of access, and components that are robust, mature, widely available in the vessel's operating region, and easily installed and maintained by a technician with a general mechanical background.

The propulsion analysis in Section 3 compares options of roughly equivalent RAM where possible, and where that is not possible, the scoring system presented in Section 3.7 accounts for the differences in RAM.

Section 5 Regulatory Requirements

This section discusses the regulatory requirements that impact the concept design, the majority of which emanate from USCG regulations: Title 46 of the Code of Federal Regulations (CFR, Reference 2). The Americans with Disabilities Act (ADA) is incorporated through the Passenger Vessel Accessibility Guidelines as well as engine emissions governed by the US Environmental Protection Agency (EPA).

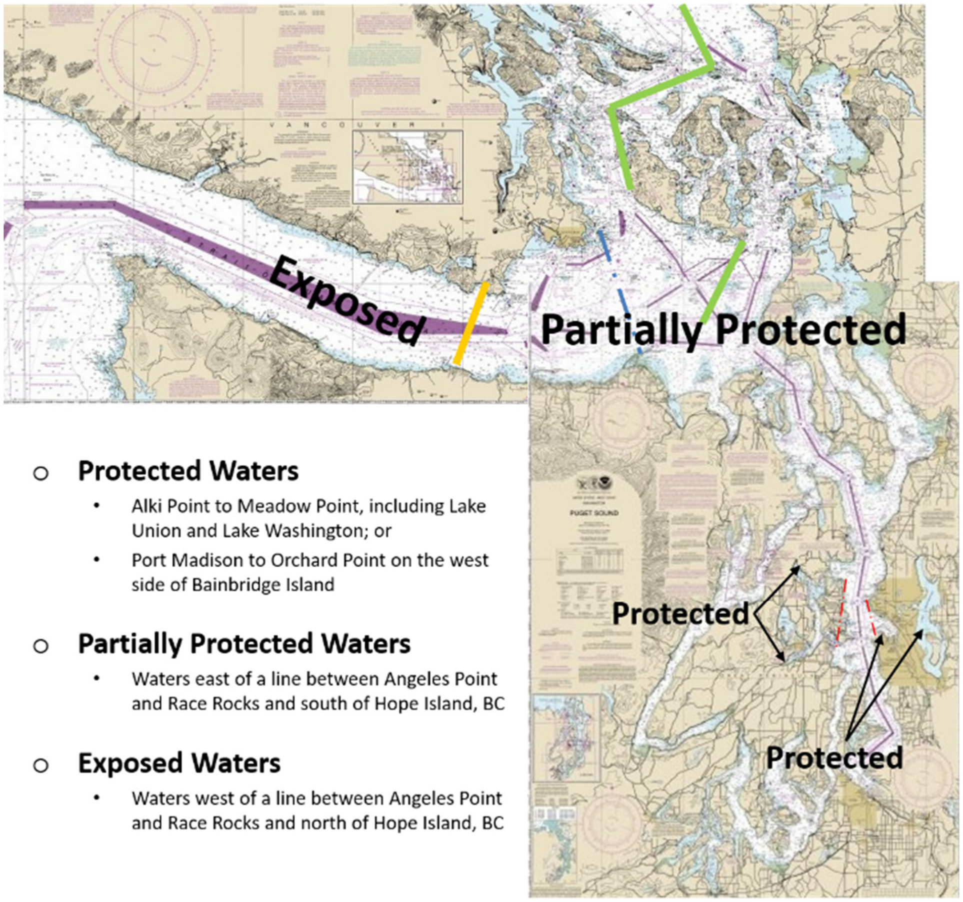
5.1 US Coast Guard

As the replacement vessel will be a passenger ferry carrying more than six passengers, it will be required to be inspected by the USCG. A Certificate of Inspection (COI) will be administered by the USCG under Subchapter T (small passenger vessels) as the vessel will be less than 100 gross registered tons (GRT) and will carry 150 or less passengers.

The vessel must be United States-flagged and domestically built in order to obtain the coastwise endorsement necessary to transport passengers between coastwise ports as required in 19 Code of Federal Regulations (CFR) §4.80, which is part of the Customs and Border Protection regulations governing the Passenger Vessel Services Act (Reference 1).

The vessel will not require a load line as it will not operate beyond the boundary line. The vessel will not be built to the rules of, nor will it be classed by, a classification society.

The operating area designation for the vessel will be *partially protected waters* of Puget Sound and adjacent waters, east of a line between Angeles Point and Race Rocks. Figure 51 depicts Puget Sound zones of operation designations, as described in Reference 10.



- Protected Waters
  - Alki Point to Meadow Point, including Lake Union and Lake Washington; or
  - Port Madison to Orchard Point on the west side of Bainbridge Island
- Partially Protected Waters
  - Waters east of a line between Angeles Point and Race Rocks and south of Hope Island, BC
- Exposed Waters
  - Waters west of a line between Angeles Point and Race Rocks and north of Hope Island, BC

Figure 51 Puget Sound zone of operation designations, per USCG Prevention Department Policy Letter 01-01 (Reference 10)

5.1.1 Lifesaving

The waters where the vessel operates are defined in the current vessel's COI as "Guemes channel, on an established ferry route between Anacortes, Washington and Guemes Island, Washington, not more than 1 mile from land." This area is determined by USCG to be "Lakes, Bays, and Sounds." Along with the operating distance from shore, operating on Lakes, Bays, and Sounds determines the required lifesaving complement for the ferry. Requirements for lifesaving equipment can be found in 46 CFR §180 (Reference 2). Lifesaving equipment on the replacement ferry is expected to be similar to lifesaving equipment on the existing ferry, namely:

- Distress signals (§180.68)
- Ring life buoys (§180.70)
- Lifejackets: adult size for 100% of complement, plus child size for at least 10% (§180.71)
- Means of recovering a helpless person from the water (§180.210)

Per 46 CFR Table 180.200(c), survival craft are not required. Per 46 CFR §180.210, a rescue boat is not required if the ferry is equipped to recover a helpless person from the water.

5.1.2 Stability

In accordance with the Code of Federal Regulations (Reference 2), a Subchapter T small passenger vessel operating in partially protected waters is required to comply with the applicable requirements of:

- 46 CFR §170.170: Weather Criteria
- 46 CFR §170.173(e)(1): Righting Energy
- 46 CFR §171.050: Passenger Heel
- 46 CFR §171.060 & 070-073: Type II Watertight Subdivision
- 46 CFR §171.080(f): Damage Stability

As noted above, the vessel operates solely on Guemes channel, which for stability purposes, is determined by the USCG to be "Partially Protected Waters."

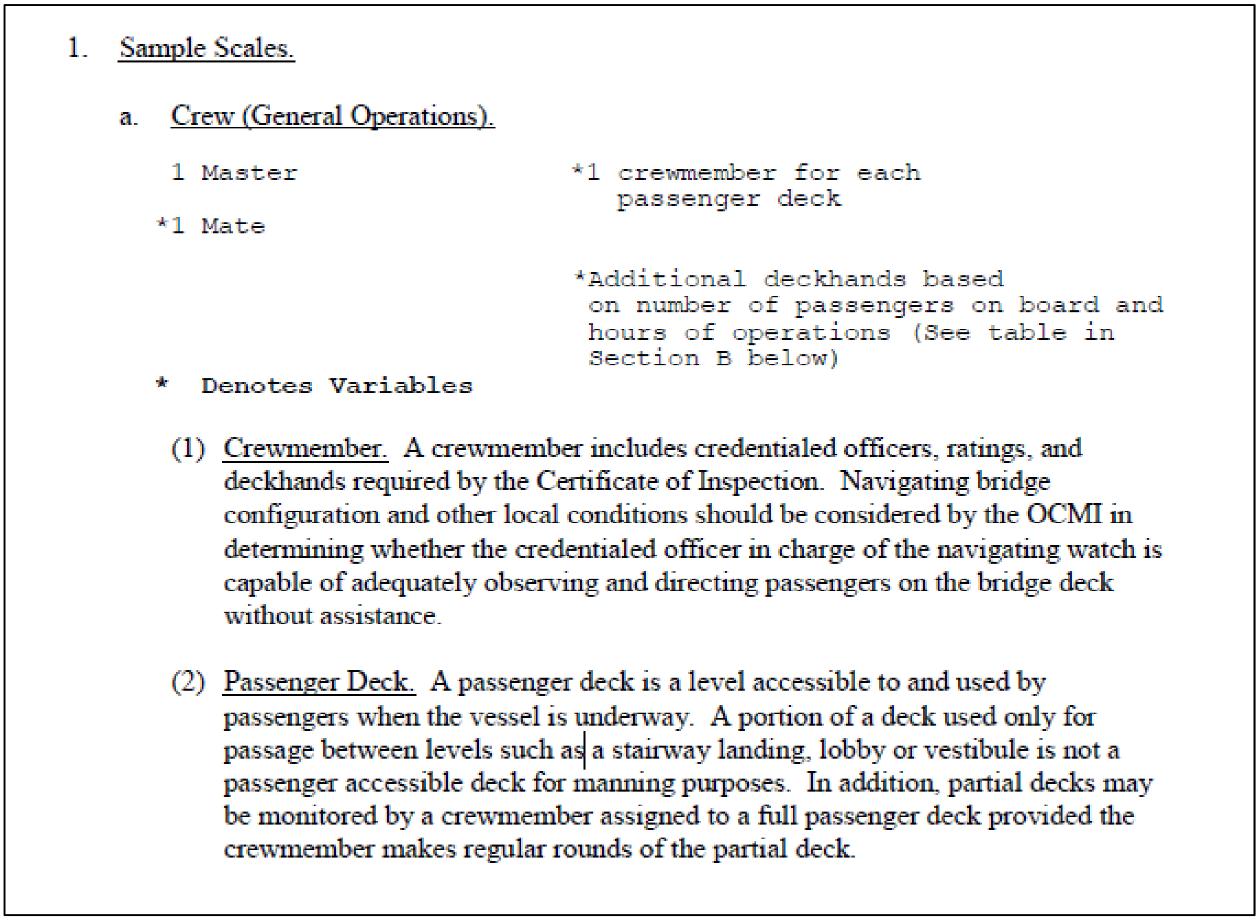
5.1.3 Manning

The COI for the *Guemes* requires the vessel to be manned with one Master and two Deckhands, for a total crew complement of three persons. To control operating costs, it is desirable to maintain the same number of crew on the replacement vessel, while providing increased vehicle and passenger capacity.

Regulatory provisions for vessel manning can be found in Part B of the USCG Marine Safety Manual, Volume III: Marine Industry Personnel (Reference 11). Chapter 1, Part D, *Determining Minimum Manning*, directs readers to sample manning scales in Chapters B2 and B7 for further guidance. Section C of B2 pertains to Small Passenger Vessels (SPVs) under 100 gross regulatory tons (GRT), and states:

> *The types, sizes, and operating conditions of small passenger vessels are so varied among the [Officer in Charge of Marine Inspections (OCMI)] zones, and within each OCMI zone it would be difficult, if not impossible, to develop a uniform national manning standard for the entire class of vessels. The following manning scales and guidance are provided to assist the OCMI in determining the manning requirements for small passenger vessels. The variations within this vessel class demand the OCMI evaluate each vessel and exercise good judgment in establishing the minimum safe manning. It is emphasized that the OCMI is not compelled to assign manning according to the sample scales in this section as they are neither mandatory, nor all inclusive. The OCMI should consider the manning levels presented as a starting point then determine whether fewer or more personnel are required for the safe operation of the vessel based on local conditions and other considerations noted in Section B1.C. The scales are considered a valid reference that could be quoted to a prospective builder or Small Passenger Vessel (SPV) buyer as a conceptual manning level.*

Given the case-by-case variability described above, the manning requirements for the replacement vessel cannot be determined in advance with absolute certainty. That noted, the sample scale provided in Section C indicates one Master, one Crewmember for each passenger deck, and one additional Deckhand for vessels engaged in operation for more than 12 hours (see Figure 52 and Figure 53).



1. Sample Scales.

a. Crew (General Operations).

1 Master

*1 Mate

*1 crewmember for each passenger deck

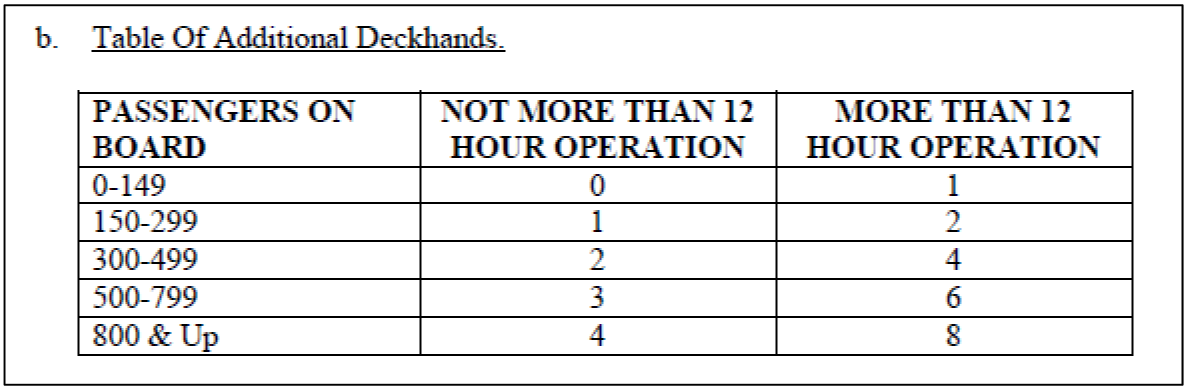
*Additional deckhands based on number of passengers on board and hours of operations (See table in Section B below)

* Denotes Variables

(1) Crewmember. A crewmember includes credentialed officers, ratings, and deckhands required by the Certificate of Inspection. Navigating bridge configuration and other local conditions should be considered by the OCMI in determining whether the credentialed officer in charge of the navigating watch is capable of adequately observing and directing passengers on the bridge deck without assistance.

(2) Passenger Deck. A passenger deck is a level accessible to and used by passengers when the vessel is underway. A portion of a deck used only for passage between levels such as a stairway landing, lobby or vestibule is not a passenger accessible deck for manning purposes. In addition, partial decks may be monitored by a crewmember assigned to a full passenger deck provided the crewmember makes regular rounds of the partial deck.

Figure 52 Sample vessel manning scale – small passenger vessels (under 100 GRT)



b. Table Of Additional Deckhands.

PASSENGERS ON BOARD	NOT MORE THAN 12 HOUR OPERATION	MORE THAN 12 HOUR OPERATION
0-149	0	1
150-299	1	2
300-499	2	4
500-799	3	6
800 & Up	4	8

Figure 53 Table of additional deckhands

Informal conversations with USCG Chief Warrant Officer Chris Schilling revealed the following:

- Current regulatory guidance on manning of Small Passenger Vessels (Under 100 GRT) remains unchanged.
- It is unlikely that the required number of personnel on the replacement Guemes Island ferry would increase or decrease, based on the operating profile of the vessel and the maximum number of passengers onboard (0-150; the number 149 in the USCG's table is a typo).

The requirement for credentialed mates on vessels of less than 100 GRT is found in 46 CFR §15.810. A Mate is required on vessels engaged in voyages exceeding 12 hours in duration (46 CFR §15.810(b)(5), Reference 2). Therefore, considering that no Mate is required on *Guemes*, it is reasonable to assume that a credentialed Mate will also not be required on the replacement vessel.

While the replacement vessel may have two passenger decks (whereas *Guemes* has only one), it is not expected that the required number of Deckhands will increase. The definition of "Passenger Deck" states explicitly: "partial decks may be monitored by a crewmember assigned to a full passenger deck provided the crewmember makes regular rounds of the partial deck." Given that the second deck on the replacement vessel would be an elevated enclosure with significantly less area than the main deck, it is anticipated that USCG would consider this a partial deck.

As noted above, final manning and complement requirements will be determined by the local USCG Officer in Charge of Marine Inspections (OCMI), based on the vessel's class (Small Passenger Vessel), guidelines in the Marine Safety Manual, and her or his own best judgment.

5.1.4 Dangerous Cargoes

The USCG requires that no additional passengers or vehicles be permitted on the vessel when transporting dangerous cargoes such as gasoline, liquefied propane gas (LPG), etc. *Guemes* currently makes one round-trip per week specifically for hazardous and dangerous materials. The replacement vessel will need to handle dangerous cargoes in a similar manner and frequency.

5.1.5 Battery Requirements

USCG is currently treating each Subchapter T passenger vessel fitted with lithium ion (Li-ion) batteries on a case-by-case basis. An ongoing dialog with USCG must be maintained as the design progresses to ensure that an equivalent level of safety (to a conventionally propelled passenger vessel) will be achieved.

Conversations with USCG Marine Safety Center on prior Li-ion battery projects have led to the following understanding for Subchapter T passenger vessels.

Subchapter T and the portions of Subchapters F and J to which it refers address electric propulsion systems and traditional lead-acid batteries. However, the use of Li-ion batteries was not envisioned when these regulatory standards were developed. The vessel should incorporate additional safety features to address the unique hazards presented by Li-ion batteries, and to ensure that the design achieves an equivalent level of safety. Design considerations for use of Li-ion batteries aboard Subchapter T vessels are discussed below:

- Batteries shall be segregated from other potential sources of fire, such as internal combustion engines and fuel.
- The compartment boundaries between each compartment containing Li-ion batteries and passenger spaces should meet at least A-0 structural fire protection standards. Note; 1/4" steel meets this requirement without supplemental insulation.
- Batteries shall be monitored by a battery management system to prevent thermal runaway.
- Battery compartments shall be protected by a fire detection and suppression system of a suitable chemistry.

- Battery temperature must be controlled through air or water cooling.
- The propulsion system shall demonstrate compliance with Subchapters F and J through the requirements for a Qualitative Failure Analysis (QFA), Design Verification Test Procedure (DVTP), and Periodic Safety Test Procedure (PSTP).

5.1.6 Tonnage

Tonnage is a measurement of enclosed volume within a vessel where cargo could theoretically be carried. The gross registered tonnage (GRT) of the vessel must be less than 100 tons to meet USCG Subchapter T requirements. The hull structure will be designed to make best use of the below main deck volume while minimizing the structural weight and complying with Marine Safety Center Technical Note (MTN) No. 01-99, Change 7. US tonnage regulations rely on exemptions granted for openings within structures. The structures above main deck may be fitted with removable tonnage openings to reduce the tonnage contribution of these spaces.

5.2 Americans with Disabilities Act

The vessel will be required to comply with 49 CFR §39 (Reference 3), which sets forth rules to prevent discriminating against passengers on the basis of disability. The design and operation of the vessel will be required to comply with this regulation. In addition, the United States Access Board has developed proposed Passenger Vessels Accessibility Guidelines (PVAG) to supplement the ADA Accessibility Guidelines for Transportation Vehicles, which is defined in 49 CFR §38 (Reference 3). To the maximum extent practicable, the new vessel will comply with all parts of the PVAG and 49 CFR §39.

5.3 Environmental Protection Agency

The Environmental Protection Agency (EPA) is currently phasing in new exhaust gas emissions regulations for marine diesel engines. These regulations group engines based on their cylinder displacement and power output. For small-displacement, high-speed diesel engines, a cutoff between tiers occurs at 800 HP (599 kW). This is significant to the replacement vessel because it is anticipated that its propulsion requirement will be near 800 HP.

The new EPA regulations mandate engines over 800 HP meet Tier 4 emissions requirements, while the less stringent Tier 3 requirements will remain for lower-powered engines. Tier 4 regulations typically result in large off-engine exhaust gas after-treatment systems. Tier 3 regulations can be met with on-engine technologies.

A Tier 4 engine with after-treatment has several economic and operational drawbacks. The after-treatment systems are relatively new and developmental, especially for lower-horsepower engines. The after-treatment systems are also expensive. Several engine manufacturers have estimated the capital cost of the after-treatment unit to be approximately 50% of the engine cost. After-treatment also requires the use of diesel exhaust fluid (DEF), an aqueous urea solution that is injected into the after-treatment system to reduce the NOx pollutants; a process known as Selective Catalytic Reduction (SCR). The DEF solution is consumed at a volumetric rate of 5-7% of the diesel fuel consumption. In addition to being another consumable that must be purchased and managed, DEF is also corrosive to steel and sensitive to contamination. As a result, DEF must be specially handled and stored.

Alternate means to achieve EPA Tier 4 regulations include using exhaust gas recirculation (EGR). Although this method is acceptable, it is not commercially available in this power range.

Section 6 Future Work

The design discussed in the above sections meets the requirements set forth in Section 4 and Section 5. However, much work is needed to develop the design sufficient for contractors to provide fixed price bids. The next phase of design work will bring the design from a 30% level of completion to approximately 60% completion.

Several items are discussed below for consideration in the preliminary phase.

6.1 Propulsion System Selection

The propulsion system affects many elements of the design. A propulsion system must therefore be selected for the design to progress significantly. Multiple designs can be carried forward but would require additional design cost.

6.2 Cost Reduction

If all-electric is the preferred option but is financially challenging, reducing the emergency service capability of the vessel or reducing service frequency during adverse weather (assumed to be 5% or less of the operating time) would result in reduced capital expenditure in shore side equipment. The plug-in hybrid also offers significant capital savings over the all-electric ferry.

The vehicle capacity drives the principal dimensions of the ferry, which largely determine the overall cost. Reducing the vehicle capacity of the replacement vessel would lower the capital, operations, and maintenance costs. Further reductions in hull depth may also be possible during the next design iteration.

6.3 Shore Power Infrastructure

The shore power infrastructure represents the largest area of uncertainty in the all-electric and plug-in hybrid designs. Future design efforts should prioritize the shore-side electrical and plug design to better understand the required capital investment and necessary terminal interfaces.

6.4 Propulsion Power

The installed power of the vessel and to a larger extent, the actual consumed power, will have a significant impact on capital and operating costs. Powering calculations discussed in Section 3.2 are consistent with typical concept level design analysis, but future estimates should rely on a more rigorous approach. Computational Fluid Dynamics (CFD) may be employed to more accurately analyze the required delivered power in several operating modes. Hull optimization could be employed in the later stages of preliminary design to further reduce propulsion loads.

6.5 Navigation Lights

The navigation lights on a double-ended ferry are particularly challenging to meet when the vessel is over 50 meters in length and has an offset deckhouse. The next phase of design should include discussions with USCG to find an acceptable solution, as a strict interpretation of the Collision Regulation (COLREG) rules will result in an awkward design. Note that reducing the vehicle capacity of the ferry would likely bring the vessel to an overall length less than 50 meters (164 feet).

Appendix A Life Cycle Cost Analysis

Life Cycle Cost Analysis (modified from 1996 NIST FEMP LCC Analysis)

Analysis uses constant dollars with Present Value (PV) discounted to the Base Date
Cash flow convention is year-end.

Project Specific Data and Parameters

Base Date		1-Nov-17		Fuel Specific Gravity	*(S.G.)*	0.85
Construction Date		1-Jan-19		Ultra Low Sulfur Dies	*(USD$/gal)*	2.09
Service Date		1-Jan-20		Lube Oil	*(USD$/gal)*	7.00
Service Period	*(years)*	40		Urea	*(USD$/gal)*	1.50
Discount Rate, Real		3.0%	*DOE rate from NIST 2017*	Electrical Rate	*(USD$/kWh)*	0.0554
				Demand Charge Oc	*(USD$/kW)*	11.32
				Demand Charge Ap	*(USD$/kW)*	7.55
				Basic Charge	*(USD$/month)*	339.51

Project Specific Calculated Values					**Discount Factor, delay**	**Discount Factor, project**
Period of Project (n)	*(years)*	42.0		Fuel/Lube	2.21	39.22
Time till Construction	*(years)*	1.0	*Rounded for discount factors*	Electrical	1.88	*30.14*
Time till In-Service	*(years)*	2.0		DEF	2.15	*40.22*

Relative Costs (compared to baseline)	**Gear Diesel**	**Diesel Elec**	**Series Hybrid**	**All-Electric**	**Plug-in Hybrid**
Capital Cost	-	23.0%	47.1%	227.7%	178.9%
Fuel, Lube, DEF, & Electrical	-	21.5%	10.2%	-39.5%	-50.3%
Operations & Maintenance	-	-48.5%	-63.6%	-56.2%	-58.8%
Repower (Engines & Batteries)	-	-43.8%	26.4%	452.9%	297.6%
Total Life Cycle Cost	**-**	**6.3%**	**6.0%**	**40.2%**	**16.8%**

Option		**Gear Diesel**	**Diesel Electric**	**Series Hybrid**	**All-Electric**	**Plug-in Hybrid**	**Notes**
Life Cycle Cost	*(USD$)*	**14,881,436**	**15,821,540**	**15,772,886**	**20,856,831**	**17,375,370**	
Vessel Capital Investment (Propulsion subtotal)	*(USD$)*	**3,601,774**	**4,429,117**	**5,299,636**	**4,733,603**	**5,528,813**	
Capital Investment (Propulsion subtotal)	*(USD$)*	3,709,827	4,561,991	5,458,625	4,875,611	5,694,678	
Shore-Side Capital Investment (Propulsion subtotal)	*(USD$)*	**0**	**0**	**0**	**7,068,670**	**4,515,391**	
Capital Investment (Propulsion subtotal)	*(USD$)*	0	0	0	7,280,730	4,650,853	
Operational Cost	*(USD$)*	**11,279,662**	**11,392,423**	**10,473,250**	**9,054,559**	**7,331,166**	
Fuel	*(USD$)*	**7,744,876**	**9,566,119**	**8,734,308**	**0**	**381,571**	*UPV = Entire Period - Delay Period*
UPV (project period)	*(USD$)*	8,207,393	10,137,399	9,255,913	0	404,358	*UPV Factor from table Ba-4 fuel escalation (NISTIR 85-3273-32)*
UPV (delay period)	*(USD$)*	462,517	571,280	521,605	0	22,787	*UPV Factor from table Ba-4 fuel escalation (NISTIR 85-3273-32)*
Annual cash amount	*(USD$/yr)*	209,284	258,498	236,020	0	10,311	
Consumption	*(gal/yr)*	100,136	123,683	112,928	0	4,933	
Consumption	*(MT/yr)*	313	387	353	0	15	
DEF	*(USD$)*	**154,996**	**0**	**0**	**0**	**0**	*UPV = Entire Period - Delay Period*
UPV (project period)	*(USD$)*	163,750	0	0	0	0	*UPV Factor from table Ba-4 ntgas escalation (NISTIR 85-3273-32)*
UPV (delay period)	*(USD$)*	8,754	0	0	0	0	*UPV Factor from table Ba-4 ntgas escalation (NISTIR 85-3273-32)*
Annual cash amount	*(USD$/yr)*	4,072	0	0	0	0	
Consumption	*(gal/yr)*	2,714	0	0	0	0	
Consumption	*(MT/yr)*	8	0	0	0	0	
Electrical Grid	*(USD$)*	**0**	**0**	**0**	**4,974,854**	**3,747,287**	*UPV = Entire Period - Delay Period*
UPV (project period)	*(USD$)*	0	0	0	5,305,758	3,996,539	*UPV Factor from table Ba-4 elec escalation (NISTIR 85-3273-32)*
UPV (delay period)	*(USD$)*	0	0	0	330,904	249,252	*UPV Factor from table Ba-4 elec escalation (NISTIR 85-3273-32)*
Annual cash amount	*(USD$/yr)*	0	0	0	176,013	132,581	*Includes Basic Charge, Demand Charge, Energy Charge, & Reactive Charge*
Consumption	*(MWh/yr)*	0	0	0	1,633	1,560	
Demand	*(kW)*	0	0	0	720	372	*Utility demand based on peak demand draw per month*
Lube Oil	*(USD$)*	**131,372**	**129,599**	**85,974**	**0**	**3,328**	*UPV = Entire Period - Delay Period, only considers engines and generators*
UPV (project period)	*(USD$)*	139,217	137,339	91,108	0	3,526	*UPV Factor from table Ba-4 fuel escalation (NISTIR 85-3273-32)*
UPV (delay period)	*(USD$)*	7,845	7,740	5,134	0	199	*UPV Factor from table Ba-4 fuel escalation (NISTIR 85-3273-32)*
Annual cash amount	*(USD$/yr)*	3549.96	3502.05	2323.20	0.00	89.92	
Consumption (burned)	*(gal/yr)*	160.22	197.89	180.69	0.00	7.89	
Service (replacement)	*(gal/yr)*	347	302	151	0	5	
Maintenance	*(USD$)*	**2,726,525**	**1,403,140**	**993,528**	**1,193,976**	**1,123,807**	
UPV (project period)	*(USD$)*	2,965,976	1,526,368	1,080,782	1,298,834	1,222,503	
UPV (delay period)	*(USD$)*	239,451	123,227	87,254	104,858	98,696	
Annual cash amount	*(USD$/yr)*	125,139	64,400	45,600	54,800	51,579	
Repower	*(USD$)*	**521,893**	**293,565**	**659,440**	**2,885,729**	**2,075,173**	
Engines (UPV)	*(USD$)*	521,893	293,565	293,565	0	0	*See calc in Maintenance Spreadsheet, once at midlife*
Batteries (UPV)	*(USD$)*	0	0	365,876	1,281,504	1,037,587	*See calc in Maintenance Spreadsheet, every 8 years*
Shore Batteries (UPV)	*(USD$)*	0	0	0	1,604,225	1,037,587	*See calc in Maintenance Spreadsheet, every 8 years*
Annual Engine hours (1000hp)	*hrs*	8,400	-	-	-	-	
Annual Generator hours (550 kW)	*hrs*	-	8,400	4,200	-	138	
Annual Generator hours (66 kW)	*hrs*	4,200	-	-	-	-	
Engine Particulate Matter (1000hp)	*g/bkWh*	0.04	-	-	-	-	*Tier IV requirement, approximately 25% average load*
Generator Particulate Matter (550 kW)	*g/bkWh*	-	0.27	0.27	-	0.27	*Tier IV requirement, approximately 25% average load*
Generator Particulate Matter (66 kW)	*g/bkWh*	0.27	-	-	-	-	*Tier III requirement, Approximately 60% average load*
Total PM	*kg/yr*	108	340	170	-	6	
Lube Oil Calculations		-	-	-	-	-	
LO Change interval (1000 hp)	*hrs*	1000	-	-	-	-	
capacity (1000 hp)	*gal*	38.5	-	-	-	-	
LO Change interval (550 kW)	*hrs*	-	500	500	-	500	
capacity (550 kW)	*gal*	-	18	18	-	18	
LO Capacity (66kW)	*hrs*	500	-	-	-	-	
capacity (66 kW)	*gal*	2.8	-	-	-	-	
LO Burn Rate	*%/fuel rate*	0.160%	0.160%	0.160%	-	0.160%	*% of fuel burn rate*

Gear Diesel Fuel Consumption

Assumptions:

1. Assumed 24 runs per day, 350 days per year
2. 675 kW required power for 11.5 knots transit
3. All operating loads were based on scaling power data (from torque monitoring) up from 425 to 675
4. Vessel pushing power was calculated based on average fuel consumption of existing ferry
5. 10% additional power is used for front end to makeup resistance during transit
6. All durations based on throughput model

Description	Constants	Units	Reference
round trip runs per day	24	runs	From Guemes Island Ferry schedules and fares, Skagit county, 1977-2017
Operation per year	350	days	
Diesel Density	0.8389	kg/l	CAT SAEJ1995 test data
Diesel Density	7.000950206	lb/gal	Converted units
Shaft Efficiency	0.97		See U Joint efficiency paper 2% & SNAME T&R 3-27 1% line shaft beraings and strut bearings
Z-drive Efficiency	0.95		Schottel - Technical Paper WMTC 2009
Generator Efficiency	0.95		Caterpillar Generator Data_C18_from TMI

Polynomial Regression Coefficients		
	Fuel	DEF
x6	2.77E-11	
x5	-8.99E-09	
x4	1.13E-06	7.26E-07
x3	-6.96E-05	-1.48E-04
x2	2.17E-03	9.97E-03
x	-3.27E-02	-1.35E-01
C	5.37E-01	4.16E-01

Engine Information					
		bHP	ekW	No. Installed	Notes
Cat C32 Tier IV	MCR	1007.0		2	
Cat C4.4	MCR	93.2	66	1	load % based on ekW

	Propulsion Power End 1		Propulsion Power End 2		Ship Service Load		Engines Running	Engine Load End 1	Engine Load End 2	Fuel Consumption End 1	Fuel Consumption End 2	Duration	Fuel Consumption
	Pd (kW)	Engine bHP	Pd (kW)	Engine bHP	eKW	Engine bHP		% MCR	% MCR	lb/(bhp-hr)	lb/(bhp-hr)	hours/yr	gal/yr
Loading Cars	75.00	109	75	109	-	-	2	10.8	10.8	0.363	0.363	1449	16,416
Maneuver	277.94	404	278	404	-	-	2	40.2	40.2	0.340	0.340	238	9,357
Ramp Up	725	1,055	75	109	-	-	2	100.0	10.8	0.340	0.363	219	12,470
Cruise	675	982	68	98	-	-	2	97.5	9.8	0.329	0.369	327	16,783
Ramp Down	476.47	693	48	69	-	-	2	68.9	6.9	0.339	0.394	219	8,230
Maneuver	238.24	347	238	347	-	-	2	34.4	34.4	0.347	0.347	299	10,267
Unload	75.00	109	75	109	-	-	2	10.8	10.8	0.363	0.363	1449	16,416
Ship Service	-	-	-	-	40	42	1	60.6	0.0	0.404	0.000	4200	10,197
		0.922		0.922		0.950						Total:	100,136

Total:	312.97	MT/Yr
Fuel Cost	2.09	$/gal
Cost:	$209,284	

	Propulsion Power End 1		Propulsion Power End 2		Engines Running	Engine Load End 1	Engine Load End 2	DEF Consumption End 1	DEF Consumption End 2	Duration	DEF Consumption
	kW	bHP	kW	bHP		% MCR	% MCR	L/hr	L/hr	hours/yr	L/hr
Loading Cars	75.00	109	75	109	2	10.8	10.8	0.000	0.000	1449	0
Maneuver	277.94	404	278	404	2	40.2	40.2	3.347	3.347	238	421
Ramp Up	725.00	1,055	75	109	2	100.0	10.8	11.021	0.000	219	639
Cruise	675.00	982	68	98	2	97.5	9.8	10.293	0.000	327	888
Ramp Down	476.47	693	48	69	2	68.9	6.9	6.309	0.000	219	366
Maneuver	238.24	347	238	347	2	34.4	34.4	2.542	2.542	299	401
Unload	75.00	109	75	109	2	10.8	10.8	0.000	0.000	1449	0
		0.922		0.922					Total:		2,714
									DEF/Fuel Consumption		2.7%

Current Vessel Comparison	Average Fuel Consumption for existing vessel is between 2,000 and 2,500 every two weeks	
Installed Power	1200	bhp
SFC	0.40	lb/bhp-hr
% MCR	21.25	%
Duration (daily)	12	hrs
Duration (2 weeks)	168	hrs
Fuel Consumption	2447.40	gal

Diesel Electric Fuel Consumption

Assumptions:

1. Assumed 24 runs per day, 350 days per year
2. 675 kW required power for 11.5 knots transit
3. All operating loads were based on scaling power data (from torque monitoring) up from 425 to 675
4. Vessel pushing power was calculated based on average fuel consumption of existing ferry
5. 10% additional power is used for front end to makeup resistance during transit

Description	Constants	Units	Reference
round trip runs per day	24	runs	From Guemes Island Ferry schedules and fares, Skagit county, 1977-2017
Operation per year	350	days	
Diesel Density	0.8389	kg/l	CAT SAEJ1995 test data
Diesel Density	7.000950206	lb/gal	Converted units
L-drive Efficiency	0.97		Schottel - Technical Paper WMTC 2009
Drive Conv. Efficiency	0.97		Average Sinamics pulse frequency drives published numbers
Generator Efficiency	0.95		Caterpillar Generator Data_C18_from TMI
Motor Efficiency	0.98		Per Schottel @ 662 kW, AG_WitschelA_000759_000_170103.pdf

Polynomial Regression Coefficients	
x6	3.51E-12
x5	-1.63E-09
x4	3.02E-07
x3	-2.82E-05
x2	1.41E-03
x	-3.69E-02
C	8.11E-01

Engine Information					
		bHP	ekW	Installed #	Notes
Cat C18	MCR	803.0	550	3	

	Required Propulsion Power		Ship Service Load		Engines Running	Engine Load	SFC*	Duration	Fuel Consumption
	Pd (kW)	Engine bkW	eKW	Engine bkW		% MCR	lb/(bhp-hr)	hours/yr	gal/yr
Loading Cars	150	171	40	42	2	17.81	0.467	1449	27,677
Maneuver	556	635	40	42	2	56.50	0.375	238	11,571
Ramp Up	798	910	40	42	2	79.54	0.349	219	13,971
Cruise	743	848	40	42	2	74.29	0.353	327	19,634
Ramp Down	524	598	40	42	2	53.48	0.380	219	10,212
Maneuver	476	544	40	42	2	48.93	0.386	299	12,942
Unload	150	171	40	42	2	17.81	0.467	1449	27,677
		0.876		0.950				Total:	123,683

Total:	386.56	MT/Yr
Fuel Cost	2.09	$/gal
Cost:	$309,208	

Series Hybrid Fuel Consumption

Assumptions:

1. Assumed 24 runs per day, 350 days per year
2. 675 kW required power for 11.5 knots transit
3. All operating loads were based on scaling power data (from torque monitoring) up from 425 to 675
4. Vessel pushing power was calculated based on average fuel consumption of existing ferry
5. 10% additional power is used for front end to makeup resistance during transit

Description	Constants	Units	Reference
Runs per day	24	runs	From Guemes Island Ferry schedules and fares, Skagit county, 1977-2017
Operation per year	350	days	
Diesel Density	0.8389	kg/l	CAT SAEJ1995 test data
Diesel Density	7.000950206	lb/gal	Converted units
L-drive Efficiency	0.97		Schottel - Technical Paper WMTC 2009
Electric Power Conv. Efficiency	0.985		Per phone conversation w/ Tony Davis at American Traction Systems
Drive Conv. Efficiency	0.97		Average Sinamics pulse frequency drives published numbers
Motor Efficiency	0.98		Per Schottel @ 662 kW, AG_WitschelA_000759_000_170103.pdf

Polynomial Regression Coefficients	
x6	3.51E-12
x5	-1.63E-09
x4	3.02E-07
x3	-2.82E-05
x2	1.41E-03
x	-3.69E-02
C	8.11E-01

Engine Information:

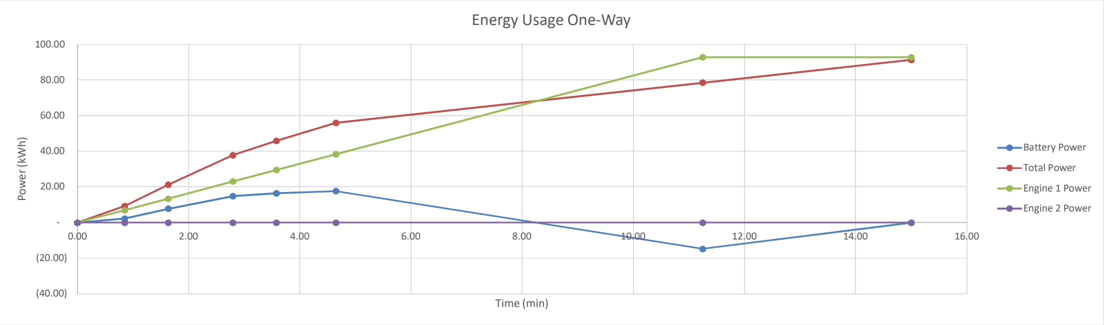
		bHP	ekW	Installed #	Notes
Cat C18	MCR	803.0	550	3	

	Time			Propulsion Power		Ship Service Load	Total Power Req	Genset 1 power @90% MCR	Battery Power Required		Engine Load	SFC*	Duration	Fuel Consumption
	%	min	Total (min)	Pd (kW)	SWBD ekW	eKW	SWBD ekW	ekW	ekW	kWh	% MCR	lb/(bhp-hr)	hours/yr	gal/yr
Maneuver	6%	0.85	0.00	556	612	40	652	495	159.43	2.26	90	0.347	238	8,536
Ramp Up	5%	0.78	0.85	798	878	40	918	495	429.50	5.61	90	0.347	219	7,867
Cruise	8%	1.17	1.63	743	818	40	858	495	368.03	7.16	90	0.347	327	11,716
Ramp Down	5%	0.78	2.80	524	577	40	617	495	123.92	1.62	90	0.347	219	7,867
Maneuver	7%	1.07	3.58	476	525	40	565	495	70.66	1.26	90	0.347	299	10,712
Unload/Load	69%	10.35	4.65	150	165	40	205	-	-	-	-	-	-	-
Total Time			15.00											
Unload/Load Gen On	-	6.59	-	150	165	40	205	495	-294.26	-32.34	90	0.347	1847	66,230
Unload/Load Gen Off	-	3.76	-	150	165	40	205	0	208.28	13.03	0	0.811	1051	0
		15.00			0.908				0.985				Total:	112,928

Battery sized for average 20% DOD per round trip	323.4	kWh
Chosen Battery size	350	kWh
Required Energy	91.4	ekWh
Energy from Gen 1 @ 90% MCR	123.8	ekWh
Operating Time Gen 1	11.24	min
Engine 2 Power	495	ekW
Engine 2 SFC	0.347	lb/(bhp-hr)
Operating hours	3149	hours/yr
Fuel Consumption	112,928	gal/yr

Total:	352.95	MT/Yr
Fuel Cost	2.09	$/gal
Cost:	$236,020	

Time	Total time	Total Power Req			Engine 1 Power			Engine 2 Power			Battery Disch		
(min)	(min)	bkW	kWh	kWh	bkW	kWh	kWh	bkW	kWh	kWh	kW	kWh	kWh
0.85	0.00	652	9.24	-	495.00	7.01	-	-	-	-	157	2.22	-
0.78	0.85	918	11.99	9.24	495.00	6.46	7.01	-	-	-	423	5.52	2.22
1.17	1.63	858	16.67	21.22	495.00	9.63	13.48	-	-	-	363	7.05	7.75
0.78	2.80	617	8.06	37.90	495.00	6.46	23.10	-	-	-	122	1.59	14.80
1.07	3.58	565	10.04	45.95	495.00	8.80	29.56	-	-	-	70	1.24	16.39
6.59	4.65	205	22.55	55.99	495.00	54.41	38.36	-	-	-	(294)	(32.34)	17.63
3.76	11.24	205	12.84	78.54	-	-	92.77	-	-	-	208	13.03	(14.72)
	15.00		-	91.38		-	92.77		-	-		-	-



All-Electric Power Consumption

Assumptions:

1. Assumed 24 runs per day, 350 days per year
2. 675 kW required power for 11.5 knots transit
3. All operating loads were based on scaling power data (from torque monitoring) up from 425 to 675
4. 10% additional power is used for front end to makeup resistance during transit
5. All durations based on throughput model
6. Battery life was assumed 8 years
7. Worst case run was based on power assumptions from "Plug-in Hybrid" sheet
8. Demand power for utility was taken as the average of Poweravg and Powerworst

Description	**Constants**	**Units**	**Reference**
Runs per day	24	runs	From Guemes Island Ferry schedules and fares, Skagit county, 1977-2017
Operation per year	350	days	
Diesel Density	0.8389	kg/l	CAT SAEJ1995 test data
Diesel Density	7.000950206	lb/gal	Converted units
L-drive Efficiency	0.97		Schottel - Technical Paper WMTC 2009
Electric Power Conv. Efficiency	0.985		Per phone conversation w/ Tony Davis at American Traction Systems
Drive Conv. Efficiency	0.97		Average Sinamics pulse frequency drives published numbers
Motor Efficiency	0.98		Per Schottel @ 662 kW, AG_WitschelA_000759_000_170103.pdf
Shore power transfer efficiency	0.9		

Round-Trip Charging

Battery Information	**kWh**	**Notes**
Battery Size	1050	

Pushing	**Time**		**Propulsion Power**		**Ship Service**	**Battery Power**		**Shore**		**Battery**	
	min	**Total min**	**Pd kW**	**SWBD ekW**	**eKW**	**kW**	**kWh**	**kW**	**kWh**	**kWh**	**%**
Maneuver	0.85	0.00	556	603	40	653	9			1050	100%
Ramp Up	0.78	0.85	798	865	40	919	12			1041	99%
Cruise	1.17	1.63	743	805	40	858	17			1029	98%
Ramp Down	0.78	2.80	524	568	40	618	8			1012	96%
Maneuver	1.07	3.58	476	517	40	565	10			1004	96%
Unload/Load	10.35	4.65	150	163	40	206	35			994	95%
Maneuver	0.96	15.00	556	603	40	653	10			958	91%
Ramp Up	0.79	15.95	798	865	40	919	12			948	90%
Cruise	1.17	16.75	743	805	40	858	17			936	89%
Ramp Down	0.79	17.91	524	568	40	618	8			919	88%
Maneuver	0.96	18.70	476	517	40	565	9			911	87%
Unload/Load	10.34	19.66	150	163	40	206	35	1458	194	902	86%
		30.00								1050	100%
Total				0.92		0.99	147.93	0.90	194.39		
										SOC from 100%	86%
										DOD	14%

Charging	1	sides	Basic Charge	104.46	$			
Cycles	8400	cycles/year	Energy/round trip	194	kWh	Power_{avg}	388.78	kW
Battery Life	8	years	Energy/year	1633	MWh	Power_{worst}	1050.52	kW
Total Cycles	67200	cycles		0.0554	$/kWh		83,810	$ avg demand charge/year
			Annual Cost	$175,524			48%	

Battery Information	**kWh**	**Notes**
Battery Size	1050	

MoorMaster Automatic Mooring	**Time**		**Propulsion Power**		**Ship Service**	**Battery Power**		**Shore**		**Battery**	
	min	**Total min**	**Pd kW**	**SWBD ekW**	**eKW**	**kW**	**kWh**	**kW**	**kWh**	**kWh**	**%**
Maneuver	0.85	0.00	556	603	40	653	9			1050	100%
Ramp Up	0.78	0.85	798	865	40	919	12			1041	99%
Cruise	1.17	1.63	743	805	40	858	17			1029	98%
Ramp Down	0.78	2.80	524	568	40	618	8			1012	96%
Maneuver	1.07	3.58	476	517	40	565	10			1004	96%
Unload/Load	10.35	4.65	150	163	40	206	35			994	95%
Maneuver	0.96	15.00	556	603	40	653	10			958	91%
Ramp Up	0.79	15.95	798	865	40	919	12			948	90%
Cruise	1.17	16.75	743	805	40	858	17			936	89%
Ramp Down	0.79	17.91	524	568	40	618	8			919	88%
Maneuver	0.96	18.70	476	517	40	565	9			911	87%
Unload/Load	10.34	19.66	0	0	40	41	7	1277	170	902	86%
		30.00								1050	100%
Total				0.92			154.92		170.29		
										SOC from 100%	86%
										DOD	14%

Charging	1.00	sides		Basic Charge	104.46	$			
Cycles	8400.00	cycles/year		Energy/round trip	170.29	kWh	Power	341	kW
Battery Life	8.00	years		Energy/year	1430.42	MWh	Power	920	kW
Total Cycles	67200.00	cycles			0.06	$/kWh		73419	$ demand charge/year
				Cost	$153,918			48%	

Automatic Mooring	
Annual Savings	$21,605.93
20 Year Savings	$432,118.53

All-Electric Power Consumption, cont'd

Worst Case Run

Pushing, Worst Case Loads	Time		Propulsion Power		Ship Service	Battery Power		Shore		Battery	
	min	**Total min**	**Pd kW**	**SWBD ekW**	**eKW**	**kW**	**kWh**	**kW**	**kWh**	**kWh**	**%**
Maneuver	0.85	0.00	833.82	904	40.00	959	14			1050	100%
Ramp Up	0.78	0.85	1196.25	1297	40.00	1358	18			1036	99%
Cruise	1.17	1.63	1113.75	1208	40.00	1267	25			1019	97%
Ramp Down	0.78	2.80	786.18	853	40.00	906	12			994	95%
Maneuver	1.07	3.58	1450.00	1573	40.00	1637	29			982	94%
Unload/Load	10.35	4.65	800.00	868	40.00	921	159			953	91%
Maneuver	0.96	15.00	833.82	904	40.00	959	15			794	76%
Ramp Up	0.79	15.95	1196.25	1297	40.00	1358	18			779	74%
Cruise	1.17	16.75	1113.75	1208	40.00	1267	25			761	72%
Ramp Down	0.79	17.91	786.18	853	40.00	906	12			736	70%
Maneuver	0.96	18.70	1450.00	1573	40.00	1637	26			724	69%
Unload/Load	10.34	19.66	800.00	868	40.00	921	159	3939	525	698	67%
		30.00								1171	112%
Round Trip				0.92		0.99	352	0.90	525		
										SOC from 100%	67%
										DOD	33%

Charging	**1.00**	**sides**		**Basic Charge**	**104.46**	**$**			
Cycles	8400.00	cycles/year		Energy/round trip	525.26	kWh	Power	1051	kW
Battery Life	8.00	years		Energy/year	1632.86	MWh		122344	$ demand charge/year
Total Cycles	67200.00	cycles			0.06	$/kWh			
				Cost	$214,057			57%	

Emergency Scenario

Pushing	Time		Propulsion Power		Ship Service	Battery Power		Battery	
	min	Total min	Pd kW	SWBD ekW	eKW	kW	kWh	kWh	%
Maneuver	0.85	0.00	556	603	40	653	9	1050	100%
Ramp Up	0.78	0.85	798	865	40	919	12	1041	99%
Cruise	6.30	1.63	743	805	40	858	90	1029	98%
On Station	60.00	7.93	250	271	40	316	316	939	89%
Cruise	6.30	67.93	743	805	40	858	90	623	59%
Ramp Down	0.78	74.23	524	568	40	618	8	533	51%
Maneuver	1.07	75.02	476	517	40	565	10	525	50%
Unload	-	76.08	0	0	40			515	49%
Round Trip							535		
								SOC from 100%	50%
								DOD	50%

Plug-in Hybrid Fuel & Electric Power Consumption

Assumptions:

1. Assumed 24 runs per day, 350 days per year
2. 675 kW required power for 11.5 knots transit
3. All operating loads were based on scaling power data (from torque monitoring) up from 425 to 675
4. 10% additional power is used for front end to makeup resistance during transit
5. All durations based on throughput model
6. Bad weather operational frequency based on climotology report, greater than 20 mph winds
7. Bad weather power requirements were assumed 1.5 times average operation; except maneuver into dock was assumed full power, and pushing was assumed 800 kW to match existing operations
8. Pushing power during Normal Operation was scaled to equal total kWh required during the average run

Description	Constants	Units	Reference
Runs per day	24	runs	From Guemes Island Ferry schedules and fares, Skagit county, 1977-2017
Operation per year	350	days	
Diesel Density	0.84	kg/l	CAT SAEJ1995 test data
Diesel Density	7.00	lb/gal	Converted units
L-drive Efficiency	0.97		Schottel - Technical Paper WMTC 2009
Electric Power Conv. Efficiency	0.985		Per phone conversation w/ Tony Davis at American Traction Systems
Drive Conv. Efficiency	0.97		Average Sinamics pulse frequency drives published numbers
Motor Efficiency	0.98		Per Schottel @ 662 kW, AG_WitschelA_000759_000_170103.pdf
Shore Power Efficiency	0.9		
Normal Operation	0.95		
Bad Weather Operation	0.05		Climotology Report, greater than 20 mph winds

Polynomial Regression Coefficients	
x6	3.51E-12
x5	-1.63E-09
x4	3.02E-07
x3	-2.82E-05
x2	1.41E-03
x	-3.69E-02
C	8.11E-01

Generator Information		bHP	ekW	Installed #	Notes
Cat C18	MCR	803.0	550	2	

Battery Information	kWh	Notes
Battery	850.0	

	time			Propulsion Power		Ship Service Load	Total Power Req	Genset 1 power @90% MCR	Battery Power Required		Engine Load	SFC*	Duration	Fuel Consumption	Shore		Battery	
	%	min	Total (min)	Pd (kW)	SWBD ekW	eKW	WBD ekW	ekW	ekW	kWh	% MCR	lb/(bhp-hr)	hours/yr	gal/yr	kW	kWh	kWh	%
Normal Operation																		
Maneuver	6%	0.85	0.00	556	612	40	652	0.00	661.97	9.38	0.00	0.811	113	0			850	100%
Ramp Up	5%	0.78	0.85	798	878	40	918	0.00	932.04	12.17	0.00	0.811	104	0			841	99%
Cruise	8%	1.17	1.63	743	818	40	858	0.00	870.56	16.93	0.00	0.811	155	0			828	97%
Ramp Down	5%	0.78	2.80	524	577	40	617	0.00	626.46	8.18	0.00	0.811	104	0			812	95%
Maneuver	7%	1.07	3.58	476	525	40	565	0.00	573.20	10.19	0.00	0.811	142	0			803	95%
Unload/Load	69%	10.35	4.65	99	109	40	149	0.00	150.78	26.01	0.00	0.811	688	0			793	93%
Maneuver	6%	0.85	0.00	556	612	40	652	0.00	661.97	9.38	0.00	0.811	113	0			767	90%
Ramp Up	5%	0.78	0.85	798	878	40	918	0.00	932.04	12.17	0.00	0.811	104	0			758	89%
Cruise	8%	1.17	1.63	743	818	40	858	0.00	870.56	16.93	0.00	0.811	155	0			746	88%
Ramp Down	5%	0.78	2.80	524	577	40	617	0.00	626.46	8.18	0.00	0.811	104	0			729	86%
Maneuver	7%	1.07	3.58	476	525	40	565	0.00	573.20	10.19	0.00	0.811	142	0			720	85%
Unload/Load	69%	10.35	4.65	99	109	40	149	0.00	150.78	26.01	0.00	0.811	688	0	1329	177	710	84%
			30.00							139.70							850	100%
Bad Weather Operation																		
Maneuver	6%	0.85	0.00	834	918	40	958	495.00	463.05	6.56	90.00	0.347	6	213			850	100%
Ramp Up	5%	0.78	0.85	1,196	1,317	40	1,357	495.00	862.09	11.26	90.00	0.347	5	197			843	99%
Cruise	8%	1.17	1.63	1,114	1,226	40	1,266	495.00	771.26	15.00	90.00	0.347	8	293			832	98%
Ramp Down	5%	0.78	2.80	786	866	40	906	495.00	410.59	5.36	90.00	0.347	5	197			817	96%
Maneuver	7%	1.07	3.58	1,450	1,596	40	1,636	495.00	1141.48	20.29	90.00	0.347	7	268			812	96%
Unload/Load	69%	10.35	4.65	800	881	40	921	495.00	425.81	73.45	90.00	0.347	36	1,299			792	93%
Maneuver	6%	0.85	0.00	834	918	40	958	495.00	463.05	6.56	90.00	0.347	6	213			718	84%
Ramp Up	5%	0.78	0.85	1,196	1,317	40	1,357	495.00	862.09	11.26	90.00	0.347	5	197			712	84%
Cruise	8%	1.17	1.63	1,114	1,226	40	1,266	495.00	771.26	15.00	90.00	0.347	8	293			700	82%
Ramp Down	5%	0.78	2.80	786	866	40	906	495.00	410.59	5.36	90.00	0.347	5	197			685	81%
Maneuver	7%	1.07	3.58	1,450	1,596	40	1,636	495.00	1141.48	20.29	90.00	0.347	7	268			680	80%
Unload/Load	69%	10.35	4.65	800	881	40	921	495.00	425.81	73.45	90.00	0.347	36	1,299	2610	348	660	78%
			30.00							190.38							850	100%
		30.00			0.908				0.985				Total:	4,933	0.900			

Pushing Power Calculation		
Average Energy Required	180.6	ekWh
Bad Weather Energy Required	511.3	ekWh
Normal Operation Energy	163.2	ekWh
Normal Operation Energy (all but Pushing)	112.0	ekWh
Pushing Energy	51.2	ekWh
Pushing Power	148.5	kW
Delivered Power	98.6	kW
Normal Operation Energy Check	163.2	Total ekWhr

l SOC from 100%	84%
DOD	16%
r SOC from 100%	78%
DOD	22%

Capital Investment Costs

Item	Qty	Cost (each)	Geared Diesel	Diesel Electric	Series Hybrid	All Electric	Plug-in Hybrid
Vessel Costs							
Main Diesel Engines							
New 1000 hp - Cat C32	2	$ 400,000	$ 800,000	$ -	$ -	$ -	$ -
Propulsion Generators							
550 ekW - Cat C18	Various	$ 150,000	$ -	$ 450,000	$ 450,000	$ -	$ 150,000
Ship Service Diesel Generators							
66 ekW - CAT C4.4	2	$ 40,000	$ 80,000	$ -	$ -	$ -	$ -
Auxiliaries							
Components	lot	$ -	$ 536,197	$ 497,197	$ 504,822	$ 423,947	$ 521,847
Swbd & Transformer							
Propulsion Switchboard	1	$590,000	$ -	$590,000	$ 590,000	$ -	$ 590,000
208/120V Switchboard	1	$10,000	$ 10,000	$10,000	$ 10,000	$ 10,000	$ 10,000
208/120V Power Distribution	8	$1,750	$ 14,000	$14,000	$ 14,000	$ 14,000	$ 14,000
DC Bus Components	1	$640,000	$ -	$ -	$ -	$ 640,000	$ -
AC/DC Converters	2	$80,000	$ -	$ -	$ 160,000	$ -	$ 160,000
208/120V Transformer	2	$10,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000
Ship Service Equipment							
Motor Controllers	10	$1,250	$ 12,500	$ 12,500	$ 12,500	$ 12,500	$ 12,500
Power Cable	Various	$0.75	$ 27,750	$31,913	$ 33,300	$ 31,913	$ 34,688
Exterior Lighting	lot	$3,900	$ 3,900	$3,900	$ 3,900	$ 3,900	$ 3,900
Interior Lighting	lot	$17,500	$ 17,500	$17,500	$ 17,500	$ 17,500	$ 17,500
Propulsion							
750 kW Motors	2	$ 82,000	$ -	$ 164,000	$ 164,000	$ 164,000	$ 164,000
Converter Drive	2	$ 116,000	$ -	$ 232,000	$ 232,000	$ 232,000	$ 232,000
Schottel L-Drive	2	$ 251,000	$ -	$ 502,000	$ 502,000	$ 502,000	$ 502,000
Schottel Z-Drive	2	$ 269,000	$ 538,000	$ -	$ -	$ -	$ -
Battery Banks							
Series Hybrid Batteries (300kWhr)	lot	$ 195,000	$ -	$ -	$ 195,000	$ -	$ -
All-Electric Batteries (1050kWhr)	lot	$ 683,000	$ -	$ -	$ -	$ 683,000	$ -
Plug-in Hybrid Batteries (850kWhr)	lot	$ 553,000	$ -	$ -	$ -	$ -	$ 553,000
Navigation & Pilothouse Equipment							
Conventional Geared	1	$ 125,000	$ 125,000	$ 125,000	$ 125,000	$ 125,000	$ 125,000
Power Management System							
Conventional Geared	1	$ 30,000	$ 30,000	$ -	$ -	$ -	
Diesel Electric	1	$ 50,000	$ -	$ 50,000	$ -	$ -	
Hybrid	1	$ 90,000	$ -	$ -	$ 90,000	$ -	
All Electric	1	$ 70,000	$ -	$ -	$ -	$ 70,000	
Plug-in Hybrid	1	$ 100,000	$ -	$ -	$ -	$ -	$ 100,000
Alarm and Monitoring System							
Conventional Geared	1	$ 200,000	$ 200,000	$ -	$ -	$ -	$ -
Diesel Electric	1	$ 250,000	$ -	$ 250,000	$ -	$ -	$ -
Hybrid	1	$ 400,000	$ -	$ -	$ 400,000	$ -	$ -
All Electric	1	$ 300,000	$ -	$ -	$ -	$ 300,000	$ -
Plug-in Hybrid	1	$ 400,000	$ -	$ -	$ -	$ -	$ 400,000
Shafting							
Shaft, seals, bearings	2	$ 20,000	$ 40,000	$ -	$ -	$ -	$ -
Steering	2	$ 15,000					
Emergency Services Infrastructure							
Generator for Battery Charging	1	$ 150,000	$ -	$ -	$ -	$ -	$ 150,000
System Integrator							
Propulsion System	lot	$ -	$ 50,000	$ 100,000	$ 250,000	$ 250,000	$ 250,000
Installation							
Installation	lot	$ -	$ 1,204,980	$ 1,491,980	$ 1,684,603	$ 1,375,850	$ 1,684,242
Subtotal			$ 3,709,827	$ 4,561,991	$ 5,458,625	$ 4,875,611	$ 5,694,678
Shore-Side Costs							
Charging Apparatus							
Charging Apparatus (2.6 MW)	1	$ 954,000	$ -	$ -	$ -	$ -	$ 954,000
Charging Apparatus (4.0 MW)	1	$ 1,908,000	$ -	$ -	$ -	$ 1,908,000	$ -
Vessel Plug (2.6 MW)	1	$ 149,500	$ -	$ -	$ -	$ -	$ 149,500
Vessel Plug (4.0 MW)	1	$ 299,000	$ -	$ -	$ -	$ 299,000	$ -
Charging Installation							
Installation	lot	$ -	$ -	$ -	$ -	$ 1,103,500	$ 551,750
Utility							
Utility Connection	lot	Varies	$ -	$ -	$ -	$ 240,000	$ 200,000
Infrastructure							
Mooring Equipment	2	$ 313,000	$ -	$ -	$ -	$ -	$ -
Pier Infrastructure Upgrades	lot	$ 100,000	$ -	$ -	$ -	$ 100,000	$ 100,000
Shore-side Batteries (800 kWh)	lot	$ 515,000	$ -	$ -	$ -	$ -	$ 515,000
Shore-side Batteries (1400 kWh)	lot	$ 855,000	$ -	$ -	$ -	$ 855,000	$ -
Shore-side Battery Converter	lot	$ 80,000	$ -	$ -	$ -	$ 80,000	$ 80,000
Shore Power House	lot	$ 1,250,000	$ -	$ -	$ -	$ 1,250,000	$ 1,250,000
Infrastructure Installation							
Installation	lot	$ -	$ -	$ -	$ -	$ 571,250	$ 486,250
Emergency Services							
Shore Generator (1000 KW)	1	$ 400,000	$ -	$ -	$ -	$ 264,000	$ -
Emergency Services Installation							
Installation	lot	$ -	$ -	$ -	$ -	$ 39,600	$ -
Subtotal			$ -	$ -	$ -	$ 7,280,730	$ 4,650,853
Total Cost			**$ 3,709,827**	**$ 4,561,991**	**$ 5,458,625**	**$ 12,156,340**	**$ 10,345,530**
% Difference to Lowest Cost			**-**	**22.97%**	**47.14%**	**227.68%**	**178.87%**

Propulsion Weight Estimate

Item	Qty	Weight (Each, lb)	Geared Diesel	Diesel Electric	Series Hybrid	All Electric	Plug-in Hybrid
Main Diesel Engines							
New 1000 hp - Cat C32	2	*7160*	14320	0	0	0	0
Exhaust Gas Aftertreatment	2	*1492*	2984	0	0	0	0
Propulsion Generators							
550 ekW - Cat C18	3	*9713*	0	29139	29139	0	19426
Ship Service Diesel Generators							
66 ekW - CAT C4.4	1	*2238*	2238	0	0	0	0
Auxiliaries							
Exhaust & Aftertreatment	1	*3033*	3791	2426	1820	0	0
Fire Fighting	1	*1308*	1308	1308	1308	2616	2616
Fuel & Lube	1	*3456*	3456	2765	2074	0	2074
SW Systems	1	*2516*	2516	2516	2516	1006	3019
Swbd & Transformer							
600V/480V Switchboard	1	*3875*	0	3875	3875	0	3875
208/120V Switchboard	1	*1550*	1550	0	0	0	0
208/120V Main Distribution	1	*750*	0	750	750	750	750
DC bus Components	1	*7000*	0	0	0	7000	0
AC/DC Converters	2	*2750*	0	0	5500	0	5500
208/120V Transformer	2	*1100*	0	2200	2200	2200	2200
Propulsion							
750 kW motors	2	*4480*	0	8960	8960	8960	8960
Converter Drive	2	*4400*	0	8800	8800	0	8800
Schottel L-Drive	2	*8960*	0	17920	17920	17920	17920
Schottel Z-Drive	2	*8960*	17920	0	0	0	0
Battery Banks							
Hybrid Batteries (300kWhr)	lot	*5581*	0	0	5581	0	0
Batteries (1050kWhr)	lot	*19535*	0	0	0	19535	0
Batteries (850kWhr)	lot	*15814*	0	0	0	0	15814
Power Management System							
Automatic Genset Starting	1	*500*	0	0	500	0	0
Conventional System	1	*500*	500	500	0	500	500
Shafting							
Shaft, seals, bearings	2	*3328*	6655	0	0	0	0
Steering	2	*250*	500	500	500	500	500
Liquids							
Fuel	lot	*lot*	21003	21003	21003	0	4201
DEF	lot	*lot*	2086	0	0	0	0
Propulsion System Weight Subtotals			**81,000**	**103,000**	**112,000**	**61,000**	**96,000**
% Difference to Lowest Weight			**-**	**27.2%**	**38.3%**	**-24.7%**	**18.5%**

Maintenance Costs

Item	Interval	Unit	Cost (ea)	Gear Diesel	Diesel Electric	Series Hybrid	All Electric	Plug-in Hybrid
Main Diesel Engine (1000hp) Hours Per Year				**8400**	**-**	**-**	**-**	**-**
Quantity Installed				**2**	**-**	**-**	**-**	**-**
Clean engine crank case	500	hrs	$100	$ 1,680	$ -	$ -	$ -	$ -
Fuel filter replacement	500	hrs	$100	$ 1,680	$ -	$ -	$ -	$ -
Initial aftercooler/heat ex inspection	1000	hrs	$200	$ 1,680	$ -	$ -	$ -	$ -
Air filter replacement and turbo inspect	1000	hrs	$200	$ 1,680	$ -	$ -	$ -	$ -
Fumes disposal filter element replace	2000	hrs	$200	$ 840	$ -	$ -	$ -	$ -
Inspect/replace auxiliary water pump	3000	hrs	$100	$ 280	$ -	$ -	$ -	$ -
Inspect/replace various	3000	hrs	$500	$ 1,400	$ -	$ -	$ -	$ -
Water pump inspect and replace	5000	hrs	$500	$ 840	$ -	$ -	$ -	$ -
Overhaul (minor)	10000	hrs	$65,000	$ 54,600	$ -	$ -	$ -	$ -
Overhaul (major)	20000	hrs	$80,000	$ 33,600	$ -	$ -	$ -	$ -
Emission critical components check/replace	20000	hrs	$4,000	$ 1,680	$ -	$ -	$ -	$ -
SCR module replacement	20000	hrs	$10,200	$ 4,284	$ -	$ -	$ -	$ -
Main Gensets (599bkW)				**-**	**8400**	**4200**	**-**	**138**
Quantity Installed				**-**	**3**	**3**	**-**	**1**
Initial coolant sample	500	hrs	$100	$ -	$ 1,680	$ 840	$ -	$ 27.51
Initial aftercooler/heat ex inspection	1000	hrs	$200	$ -	$ 1,680	$ 840	$ -	$ 27.51
Air filter replacement and turbo inspect	1000	hrs	$200	$ -	$ 1,680	$ 840	$ -	$ 27.51
Fumes disposal filter element replace	2000	hrs	$100	$ -	$ 420	$ 210	$ -	$ 6.88
Inspect/replace various	3000	hrs	$500	$ -	$ 1,400	$ 700	$ -	$ 22.93
Water pump inspect and replace	5000	hrs	$500	$ -	$ 840	$ 420	$ -	$ 13.76
Overhaul (minor)	10000	hrs	$27,000	$ -	$ 22,680	$ 11,340	$ -	$ 371.39
Overhaul (major)	20000	hrs	$41,000	$ -	$ 17,220	$ 8,610	$ -	$ 281.98
Ship Service Diesel Generator (66kW)				**4200**	**-**	**-**	**-**	**-**
Quantity Installed				**2**	**-**	**-**	**-**	**-**
Inspect/clean/replace various	500	hrs	$19	$ 162.63	$ -	$ -	$ -	$ -
Inspect/clean various	1000	hrs	$19	$ 81.32	$ -	$ -	$ -	$ -
Engine crankcase breather replace	1500	hrs	$58	$ 162.63	$ -	$ -	$ -	$ -
Inspect various	2000	hrs	$77	$ 162.63	$ -	$ -	$ -	$ -
Replace alternator and fan belts	3000	hrs	$116	$ 162.63	$ -	$ -	$ -	$ -
Replace aftercooler core	4000	hrs	$97	$ 101.65	$ -	$ -	$ -	$ -
Overhaul (major)	6000	hrs	$10,000	$ 7,000.00	$ -	$ -	$ -	$ -
Add coolant extender	6000	hrs	$660	$ 462.00	$ -	$ -	$ -	$ -
Batteries				**-**	**-**	**-**	**-**	**-**
Quantity Installed				**-**	**-**	**1**	**1**	**1**
Check up and servicing	1	yrs	$5,000	$ -	$ -	$ 5,000	$ 5,000	$ 5,000
Propulsion Motors				**-**	**8400**	**8400**	**8400**	**8400**
Quantity Installed				**-**	**2**	**2**	**2**	**2**
Overhaul	10000	hrs	$10,000	$ -	$ 8,400	$ 8,400	$ 8,400	$ 8,400
Z-Drives				**8400**	**8400**	**8400**	**8400**	**8400**
Quantity Installed				**2**	**2**	**2**	**2**	**2**
Overhaul	10000	hrs	$10,000	$ 8,400	$ 8,400	$ 8,400	$ 8,400	$ 8,400
Shafting				**8400**	**-**	**-**	**-**	**-**
Quantity Installed				**2**	**-**	**-**	**-**	**-**
Replace seals, bearings, and couplings	20000	hrs	$10,000	$ 4,200.00	$ -	$ -	$ -	$ -
Shore-side Equipment				**-**	**-**	**-**	**-**	**-**
Quantity Installed				**-**	**-**	**-**	**1**	**1**
Inspect/Maintain switchgear + transformer	1	yrs	$24,000	$ -	$ -	$ -	$ -	$ 24,000.00
Inspect/Maintain switchgear + transformer + genset	1	yrs	$28,000	$ -	$ -	$ -	$ 28,000.00	$ -
Battery check up and servicing	1	yrs	$5,000	$ -	$ -	$ -	$ 5,000.00	$ 5,000.00
Annual Maintenance Cost				**$ 125,139.49**	**$ 64,400.00**	**$ 45,600.00**	**$ 54,800.00**	**$ 51,579.45**

Repower Calculations

Item	Unit	Applicable Propulsion Configuration					Notes
Main Engine		**Geared Diesel**					
Time	(yrs)	20					
Time until purchase	(yrs)	22					
Cost	($USD)	$800,000					
Additional installation costs		25%					Accounts for additional cost of repowering
Total	($USD)	$1,000,000					
Investment, current dollars	($USD)	$521,893					Midlife repower cost
Gensets		**Diesel Electric**	**Series Hybrid**				
Time	(yrs)	20	20				
Time until purchase	(yrs)	22	22				
Cost	($USD)	$450,000	$450,000				
Additional installation costs		25%	25%				Accounts for additional cost of repowering
Total	($USD)	$562,500	$562,500				
Investment, current dollars	($USD)	$293,565	$293,565				Midlife repower cost
Batteries (300 kWh)		**Series Hybrid**					
Time	(yrs)	8	16	24	32		5% real discount rate of batteries to account for decrease in battery costs over time
Time until purchase	(yrs)	10	18	26	34		
Cost	($USD)	$195,000	$195,000	$195,000	$195,000		
Additional installation costs		25%	25%	25%	25%		
Total	($USD)	$243,750	$243,750	$243,750	$243,750		
Investment, current dollars	($USD)	**$149,641**	**$101,283**	**$68,552**	**$46,399**	**$365,876**	Total cost, replacing batteries every 8 years
Batteries (1050 kWh)		**All-Electric**					
Time	(yrs)	8	16	24	32	Totals	5% real discount rate of batteries to account for decrease in battery costs over time
Time until purchase	(yrs)	10	18	26	34		
Cost	($USD)	$683,000	$683,000	$683,000	$683,000		
Additional installation costs		25%	25%	25%	25%		
Total	($USD)	$853,750	$853,750	$853,750	$853,750		
Investment, current dollars	($USD)	**$524,128**	**$354,751**	**$240,109**	**$162,515**	**$1,281,504**	Total cost, replacing batteries every 8 years
Batteries (850 kWh)		**Plug-In Hybrid**					
Time	(yrs)	8	16	24	32	Totals	5% real discount rate of batteries to account for decrease in battery costs over time
Time until purchase	(yrs)	10	18	26	34		
Cost	($USD)	$553,000	$553,000	$553,000	$553,000		
Additional installation costs		25%	25%	25%	25%		
Total	($USD)	$691,250	$691,250	$691,250	$691,250		
Investment, current dollars	($USD)	**$424,368**	**$287,229**	**$194,408**	**$131,583**	**$1,037,587**	Total cost, replacing batteries every 8 years
Batteries (1400 kWh)		**Plug-in Hybrid and All-Electric**					
Time	(yrs)	8	16	24	32		5% real discount rate of batteries to account for decrease in battery costs over time
Time until purchase	(yrs)	10	18	26	34		
Cost	($USD)	$855,000	$855,000	$855,000	$855,000		
Additional installation costs		25%	25%	25%	25%		
Total	($USD)	$1,068,750	$1,068,750	$1,068,750	$1,068,750		
Investment, current dollars	($USD)	**$656,120**	**$444,088**	**$300,576**	**$203,442**	**$1,604,225**	Total cost, replacing batteries every 8 years

Appendix B Risk Assessment Analysis

Risk Analysis		Project	Skagit County Ferry	Propulsion Configuration Options														
		Job no.	17097															
Identified hazard				**Geared Diesel**			**Diesel Electric**			**Series Hybrid**			**Plug-In Hybrid**			**All-Electric**		
Risk ID	**Activity**	**Significant hazard**	**Consequence**	**Probability**	**Consequence**	**Risk**	**Probability**	**Consequence**	**Risk**	**Probability**	**Consequence**	**Risk**	**Probability**	**Consequence**	**Risk**	**Probability**	**Consequence**	**Risk**
				1-5	**1-5**	**1-24414**	**1-5**	**1-5**	**1-24414**	**1-5**	**1-5**	**1-24414**	**1-5**	**1-5**	**1-24414**	**1-5**	**1-5**	**1-24414**
1	**Propulsion Motors (Z-drives or L-drives)**																	
1.1	Failure - Replace Component	Any number of components can fail	Propulsion not available for short period	4	2	78.13	4	2	78.13	4	2	78.13	4	2	78.13	4	2	78.13
1.2	Failure - Rebuild	Any number of components can fail - requires rebuilding	Propulsion not available for extended period	3	4	781.25	2	4	312.50	2	4	312.50	2	4	312.50	2	4	312.50
1.3	Failure - Replace	Armature/housing failure	Propulsion replacement	1	5	625.00	1	4	125.00	1	5	625.00	1	5	625.00	1	5	625.00
2	**Propulsion Drives**																	
2.1	Power Electronics Failure	SCR or IGBT failure	Loss of propulsion motor	0	0	0	1	4	125.00	1	4	125.00	1	4	125.00	1	4	125.00
3	**Propulsion Engines**																	
3.1	Failure - Replace Component	Any number of components can fail	Engine not available	5	3	976.56	5	2	195.31	5	2	195.31	5	2	195.31	0	0	0
3.2	Failure - Rebuild	Any number of components can fail - requires major disassembly	Engine not available extended period	3	4	781.25	3	3	156.25	3	4	781.25	3	3	156.25	0	0	0
3.3	Failure - Replace	Block failure	Engine requires replacement	1	5	625.00	1	5	625.00	1	5	625.00	1	3	25.00	0	0	0
4	**Battery Bank**																	
4.1	Failure - Battery Cell	Any number of components can fail	Battery bank voltage drops	0	0	0	0	0	0	2	1	2.50	2	1	2.50	2	1	2.50
4.2	Failure - Battery Module/String	Any number of components can fail	Power available reduced	0	0	0	0	0	0	1	3	25.00	1	2	5.00	1	3	25.00
4.3	Failure - Battery Bank	Any number of components can fail	Power available reduced	0	0	0	0	0	0	1	3	25.00	1	3	25.00	1	5	625.00
5	**Ship Service Power Converters (Inverters and Rectifiers for Batteries)**																	
5.1	Power Electronics Failure	SCR or IGBT failure	Loss of propulsion motor	0	0	0	0	0	0	1	2	5.00	1	2	5.00	1	4	125.00
6	**Switchboard**																	
6.1	Propulsion Circuit Breaker	Component failure	Install spare, replace	0	0	0	1	3	25.00	1	3	25.00	1	3	25.00	1	3	25.00
6.2	Major Failure	Short circuit	Lose bus	1	4	125.00	1	5	625.00	1	5	625.00	1	5	625.00	1	5	625.00
7	**Female Plug Assembly**																	
7.1	Power Electronics Failure	Component failure	Loss of charging	0	0	0	0	0	0	0	0	0	2	4	312.50	2	4	312.50
8	**Male Plug Assembly (APS)**																	
8.1	Power Electronics Failure	Cable, plug, or control electronics failure	Loss of charging	0	0	0	0	0	0	0	0	0	2	4	312.50	2	5	1562.50
8.2	Tower Mechanical Failure	Motor/plug track/tower aparatus general failure	Loss of charging	0	0	0	0	0	0	0	0	0	2	4	312.50	2	4	312.50
9	**Shore Backup Generator**																	
9.1	Failure - Replace Component	Any number of components can fail	Engine not available	0	0	0	0	0	0	0	0	0	0	0	0	4	1	15.63
9.2	Failure - Rebuild	Any number of components can fail - requires major disassembly	Engine not available extended period	0	0	0	0	0	0	0	0	0	0	0	0	2	2	12.50
9.3	Failure - Replace	Block failure	Engine requires replacement	0	0	0	0	0	0	0	0	0	0	0	0	1	2	5.00
10	**Battery Bank**																	
10.1	Failure - Battery Cell	Any number of components can fail	Battery bank voltage drops	0	0	0	0	0	0	0	0	0	2	1	2.50	2	1	2.50
10.2	Failure - Battery String	Any number of components can fail	Power available reduced	0	0	0	0	0	0	0	0	0	1	2	5.00	1	2	5.00
10.3	Failure - Battery Bank	Any number of components can fail	Ship charge rate reduced	0	0	0	0	0	0	0	0	0	1	5	625.00	1	5	625.00
11	**Battery Bank Inverter**																	
11.1	Power Electronics Failure	SCR or IGBT failure	Ship charge rate reduced	0	0	0	0	0	0	0	0	0	2	2	12.50	2	2	12.50
12	**Utility**																	
12.1	Failure - Brown-out	Utility loss upstream of equipment	Emergency generator brought online	0	0	0	0	0	0	0	0	0	3	3	156.25	3	4	781.25
13	**Utility AC/DC Transformer/Rectifier**																	
13.1	Power Electronics Failure	Any number of components can fail	Ship charge rate reduced	0	0	0	0	0	0	0	0	0	1	5	625.00	1	5	625.00

Risk Analysis		Project	Skagit County Ferry	**Propulsion Configuration Options**														
		Job no.	17097															
Identified hazard				**Geared Diesel**			**Diesel Electric**			**Series Hybrid**			**Plug-In Hybrid**			**All-Electric**		
Risk ID	**Activity**	**Significant hazard**	**Consequence**	**Probability**	**Consequence**	**Risk**	**Probability**	**Consequence**	**Risk**	**Probability**	**Consequence**	**Risk**	**Probability**	**Consequence**	**Risk**	**Probability**	**Consequence**	**Risk**
				1-5	**1-5**	**1-24414**	**1-5**	**1-5**	**1-24414**	**1-5**	**1-5**	**1-24414**	**1-5**	**1-5**	**1-24414**	**1-5**	**1-5**	**1-24414**
14	**MV Drawing Switchgear**																	
14.1	Utility Circuit Breaker	Component failure	Install spare, replace	0	0	0	0	0	0	0	0	0	1	3	25.00	1	4	125.00
14.2	Generator Circuit Breaker	Component failure	Install spare, replace	0	0	0	0	0	0	0	0	0	0	0	0	1	2	5.00
14.3	Major Failure	Short circuit	Lose bus	0	0	0	0	0	0	0	0	0	1	5	625.00	1	5	625.00
15	**DC Switchgear**																	
15.1	Plug Breaker Failure	Component failure	Install spare, replace	0	0	0	0	0	0	0	0	0	1	4	125.00	1	4	125.00
15.2	Battery Breaker Failure	Component failure	Install spare, replace	0	0	0	0	0	0	0	0	0	1	3	25.00	1	4	125.00
15.3	Major Failure	Short circuit	Lose bus	0	0	0	0	0	0	0	0	0	1	5	625.00	1	5	625.00
Total Risk						**3992.19**			**2267.19**			**3449.69**			**5993.44**			**8470.00**