Vessel Energy Analysis Tool
Model Documentation

Fishing Vessel Energy Efficiency Project

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NOAA FISHERIES
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Alaska Longline
FISHERMEN'S ASSOCIATION

AFDF
Alaska Fisheries Development Foundation, Inc.

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Nomenclature

Abbreviations

AC Alternating current

BSFC Brake Specific Fuel Consumption

DC Direct current

ECM Energy Conservation Measure

ft Feet

FVEEP Fishing Vessel Energy Efficiency Project

gal Gallon

hp Horsepower

hr Hour

kt Knots

kW Kilowatt

kWh Kilowatt-hours

PQA Power quality analyzer

RMS Root mean squared

RSW Refrigerated sea water

VEAT Vessel Energy Analysis Tool

Symbols

α Engine overhead fuel consumption rate (gal/hr)

β Marginal BSFC for an engine (gal/kWh)

η_{alt} Alternator efficiency

η_{batt} Battery efficiency

η_{PF} Electrical power factor

ϕ_s Stabilizer propulsion power correction factor

ϕ_t Hold mass propulsion power correction factor

ρ Duty cycle

B Vessel beam (ft)

C A cost ($)

c A VEAT constant determined using information in the database

C_{oil} Cost of an oil change ($)

$C_{rebuild}$ Cost of rebuilding an engine ($)

D Pump displacement per revolution (m^3)

D_0 Maximum displacement of a pressure compensating hydraulic pump (m^3)

DC Set of DC loads

E Energy (kWh)

F Fuel consumption (gal)

f_s Fraction of time with stabilizers deployed

f_t Fraction of time tanked

f_{circ} Ratio of time that a circulation pump runs to time that a compressor runs

f_{comp} Fraction of time that a compressor runs

f_{ijkm} Load allocation array

h Hours in a particular propulsion mode

h_{oil} Time between oil changes (hrs)

$h_{rebuild}$ Time between engine rebuilds (hrs)

I Electrical current (amps)

L Vessel length (ft)

N Rate of rotation (Hz)

$N_{aux-eng}$ Number of auxiliary engines on a vessel

$N_{prop-eng}$ Number of propulsion engines on a vessel

P Power (kW)

p Pressure (Pa)

p_{max} Maximum pressure at which the displacement is greater than zero in a pressure compensating hydraulic pump

p_{min} Minimum pressure at which the displacement is less than the maximum in a pressure compensating hydraulic pump

Q Fuel flow (gal/hr)

R An engine rating (hp)

s Speed over ground (kt)

V Voltage

Subscripts

circ Relating to a circulation pump

comp Relating to a compressor

i Index of an engine

j Index of an operating mode

k An index specifying a particular load class

l Index of a particular load

m An index specifying a particular propulsion mode

tot Indicates a total

Sets

$engines$ Set of engines on a vessel

$loads$ Set of load classes

$op\ modes$ Set of operating modes

$prop\ modes$ Set of propulsion modes

1 Introduction

1.1 The Fishing Vessel Energy Efficiency Project

The Fishing Vessel Energy Efficiency Project (FVEEP) identified, quantified and implemented energy conservation measures (ECM) to reduce fuel consumption by fishing vessels in Alaska and created tools that will help fishermen develop future ECMs. Energy audits have been performed on 30 vessels, and 19 vessels provided additional data without receiving an audit. The data provide a baseline measure of fuel consumption.

Quantifying the impact of ECMs requires a model of how fuel is used on vessels. Simply comparing fuel consumption before and after implementing an ECM is inadequate because of variability in the operating conditions on vessels. For example, a vessel may install a bulbous bow to reduce vessel drag at transit speeds in between fishing seasons. The bulb may reduce the fuel consumption rate at transit by 5%, but if the skipper chooses to travel 0.3 knots faster, fuel consumption will increase even if fuel efficiency improves. A fuel consumption model allows for meaningful estimates of the fuel saved due to an ECM when uncontrolled variables affect the total fuel consumption.

A fuel consumption model also provides a means for predicting the impact of ECMs. The model shows what fraction of vessel fuel consumption can be attributed to different loads and quantifies the impact of reducing any particular load. The model can help fishermen identify impactful ECMs and motivate implementation.

The Vessel Energy Analysis Tool (VEAT) calculates the fuel that a vessel will consume given a set of loads. The VEAT approximates an engine's fuel consumption rate as a linear function of engine load. The various loads that may exist on a vessel are summed together and applied to the linear engine model to calculate a fuel consumption rate, and the amount of time that each operating condition persists in a season is used to calculate the total annual fuel consumption. The VEAT includes default values for all common vessel loads to enable a reasonable estimate of fuel consumption in the absence of complete data on a particular vessel's loads. The VEAT summarizes fuel consumption by the various loads and operating modes on the vessel to deliver a useful description of how vessels consume fuel.

The following sections present the structure of the VEAT, explain the motivation for each of its components and justify the default values. The Python implementation of this model which powers the online VEAT follows the structure presented here. However, the Python implementation uses descriptive names for variables, while this document uses more concise variable names and subscripts. The constants (c_i) defined here can be looked up directly in the Python implementation's default values, but all other variables have somewhat different names. This document uses the term "array" to refer to all data structures in VEAT, although the Python implementation uses a variety of objects to store information. More detailed notes on the Python computer code must be read from comments within the program itself.

1.2 Model structure

The structure of the data model is described by Figure 1. The output from the model is a four dimensional array F. The first dimension, denoted with the subscript i, has an entry for each engine on the vessel. For example, a vessel might have a starboard propulsion engine, a port propulsion engine and an auxiliary generator all included in the set *engines*.

The second dimension, denoted by subscript j, spans the set of operating modes that the vessel uses. The set of operating modes is denoted as *op modes*. Trolling, long line, and deer hunting are examples of operating modes.

The third dimension, denoted by subscript k, spans the set of load classes. The set of load classes is defined as *loads*. The model supports six load classes: Propulsion, Refrigeration, Hydraulics, AC, DC and engine overhead. Some or all of the load classes may apply to any particular vessel, but no loads are supported that do not fit into one of the classes.

The fourth and final dimension is the set of propulsion modes denoted by subscript m. The set of propulsion modes is defined as *prop modes*. The model supports three propulsion modes: Transit, Fishing, and Anchor. Some or all of the propulsion modes may apply to any particular vessel, but all of the vessel's operating hours must be classified in one of the three supported categories.

The output from the model can be interpreted by summing along any combination of dimensions. For example, summing across the first three dimensions (*engines*, *op modes* and *loads*) yields the total fuel consumption in each propulsion mode.

The calculation used to produce F is separated into modules for each load class. Each module has a set of default values associated with it. The default values may depend on the operating mode, propulsion mode or engine in addition to the load class. The default values are retrieved from a database, but can be changed to customize the results. To make the application more user friendly, many of the default values are not exposed to the casual user. These values are referred to as 'constants.'

All of the equations and their relationships are shown in Figure 1. The variables and equations are defined and discussed in the following sections. Although many of the equations apply to every index of the *engines*, *op modes*, *loads* and *prop modes* sets, the indexes are suppressed in the text to simplify the equations.

1.3 Supported operating modes

The model supports seven operating modes: seine, troll, long line, gill net, tender, pot cod, and other. Each mode includes unique default values for input variables including transit speed, fishing speed, deck hydraulic loads and refrigeration systems. Table 1 shows the default number of active days in each mode, the fraction of time spent fishing, transiting and at anchor during active days, and the number of sets per active day when relevant.

Operating mode	Default values				
	Active Days	Fishing Fraction	Transit Fraction	Anchor Fraction	Sets per active day
Seine	56	0.47	0.33	0.20	11.3
Troll	52	0.67	0.13	0.20	-
Longline	20	0.49	0.31	0.20	1.05
Pot	20	0.49	0.31	0.20	1.05
Gill net	58	0.64	0.16	0.20	12.9
Tender	79	0.18	0.62	0.20	-
Other	52	0.64	0.16	0.20	-

Table 1: Default values for supported operating modes

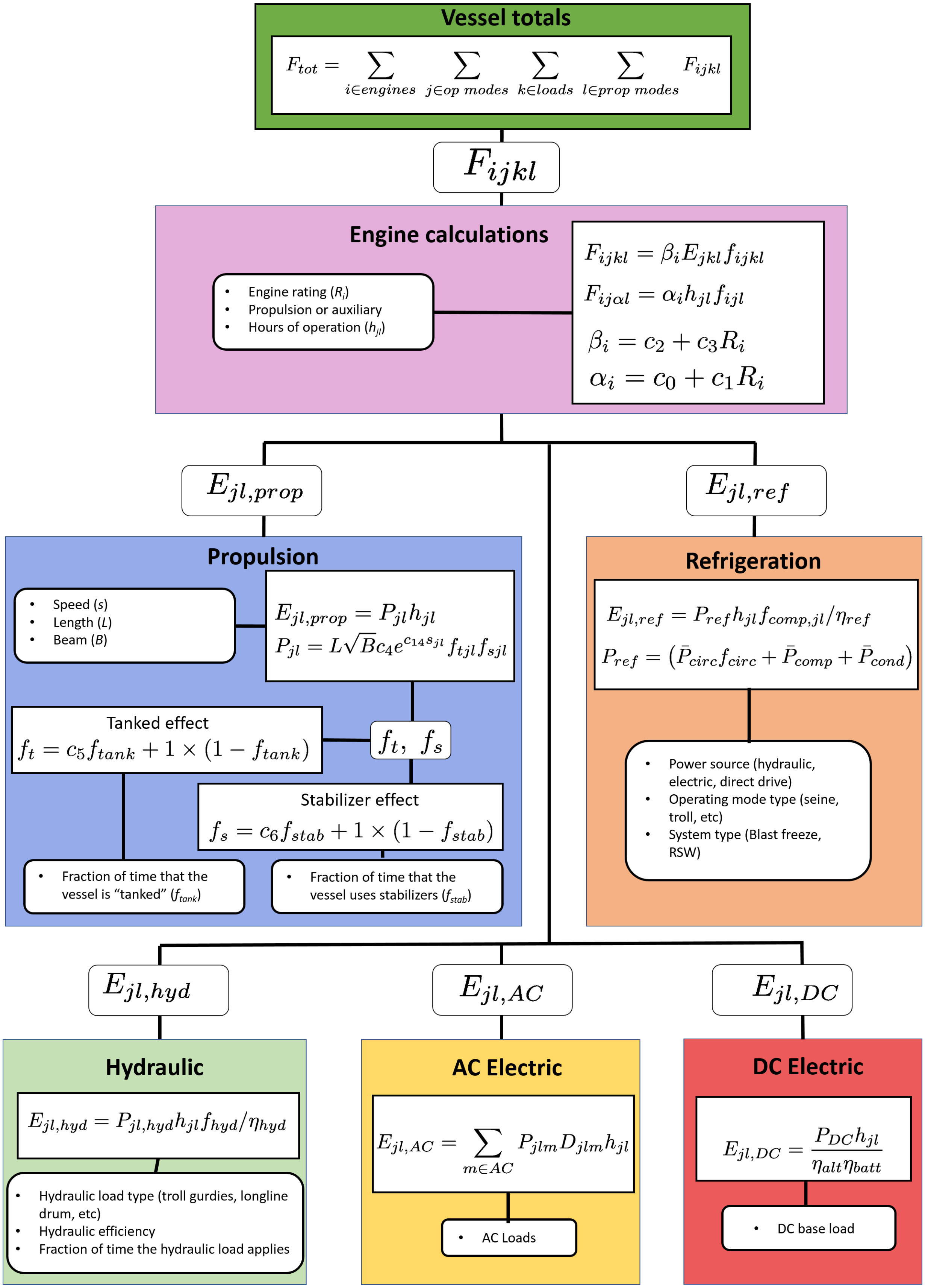

Figure 1: VEAT model structure

2 Module summaries

This section gives a succinct explanation of each module shown in Figure 1. The equations and constants associated with each module are defined. Supporting data, operating mode specific default values, measurement methods and expected accuracy of the modules are addressed in subsequent sections.

2.1 Engine module

VEAT models the fuel consumption rate as a linear function of engine load. The slope and intercept of the model depend on the engine application and engine rating. In the absence of those data default values are used. The equations used by VEAT to calculate fuel consumption are shown below.

$$F = \alpha h + \beta E \tag{1}$$

$$\alpha = c_0 + c_1 R \tag{2}$$

$$\beta = c_2 + c_3 R \tag{3}$$

The relevant variables are defined in Table 2. In the absence of an engine rating (R), α and β are set directly with no reference to Equations 2 and 3. The values of the c_n depend on the engine application as shown in Table 3.

Variable	Description	Units	Value
F	fuel consumption	gal	-
R	engine rating	hp	-
α	idle fuel consumption	gal/hr	0.49
β	marginal Brake Specific Fuel Consumption (BSFC) rate	gal/kWh	0.070
c_0	α zero-order coefficient	gal/hr	-
c_1	α first-order coefficient	gal/hr-hp	-
c_2	β zero-order coefficient	gal/kWh	-
c_3	β first-order coefficient	gal/kWh-hp	-

Table 2: Engine module variables

Engine Application	c_0 gal/hr	c_1 gal/hr-hp	c_2 gal/kWh	c_3 gal/kWh-hp
Propulsion	0.26	8.1×10^{-4}	0.080	-2.1×10^{-5}
Genset	0.45	0	0.061	0

Table 3: Engine module values dependent on engine application

2.2 Propulsion module

VEAT uses a cubic equation to calculate propulsion power requirements based on vessel speed for speeds below three knots (kt), and an exponential equation for speeds above three kt. The coefficients of the model depend on the vessel length and beam. The model is summarized by Equations 4-6. ϕ_s and ϕ_t correct the power estimate for vessels that often operate with a hold full of water (tanked) or with stabilizers deployed.

$$E = \begin{cases} L\sqrt{B}c_4 e^{c_{14}s}\phi_t\phi_s h, & \text{for } s > 3 \\ \left(\frac{s}{3}\right)^3 L\sqrt{B}c_4 e^{c_{14}3}\phi_t\phi_s h, & \text{for } s \leq 3 \end{cases} \tag{4}$$

$$\phi_t = c_5 f_t + 1 - f_t \tag{5}$$

$$\phi_s = c_6 f_s + 1 - f_s \tag{6}$$

The variables are defined in Table 4. The values of variables that do not depend on user input in the VEAT are shown. Default values for other variables are shown in Table 9.

Variable	Description	Units	VEAT value
E	Energy consumed for propulsion	kWh	-
L	Vessel length	ft	-
B	Vessel beam	ft	-
c_4	Exponential fit first coefficient	kW / ft$^{1.5}$	3.6×10^{-3}
c_{14}	Exponential fit second coefficient	1 / kt	0.57
s	Speed	kt	-
ϕ_t	Full fish hold drag correction factor	ratio	-
ϕ_s	Stabilizer drag correction factor	ratio	-
c_5	Ratio full hold power to empty hold power	ratio	1.27
c_6	Ratio of power with stabilizers to without stabilizers	ratio	1.64

Table 4: Propulsion model variables

2.3 Refrigeration module

Unlike the propulsion and engine modules, every variable in the refrigeration module depends on user input. The model is shown in Equations 7 and 8, and the relevant variables are defined in Table 5. Default values for all of the variables in Equations 19 and 8 are provided by operating mode and propulsion mode in Section 5.

Variable	Description	Units
$\bar{P}_{comp}$	Average compressor power	kW
$\bar{P}_{circ}$	Average circ pump or fan power	kW
$\bar{P}_{cond}$	Average condenser pump power	kW
f_{circ}	Ratio of circ pump or fan run time to compressor run time	-
η_{ref}	Power source (hydraulic, electric or direct drive) efficiency factor	-
f_{comp}	Compressor duty cycle	-
E	Energy consumed for refrigeration	kWh
$\bar{P}_{tot}$	Average total power	kW

Table 5: Propulsion model variables

$$\bar{P}_{tot} = \left(\bar{P}_{circ} f_{circ} + \bar{P}_{comp} + \bar{P}_{cond}\right) / \eta_{ref} \tag{7}$$

$$E = \bar{P}_{tot} h f_{comp} \tag{8}$$

2.4 Hydraulics module

Hydraulic energy consumption is calculated according to Equation 9. P_{deck} is the engine load due to a hydraulic deck load, ρ is the duty cycle of that load, and h_{fish} is the number of hours in the "fishing" propulsion mode. The user must select the deck load that applies to each of their operating modes from a library provided by the VEAT. Once selected, the VEAT provides the appropriate P_{deck} and ρ values. Hydraulic loads during the "anchor" and "transit" propulsion modes are approximated as zero. The deck load library is provided in Section 6. η_{hyd} is an efficiency factor that is equal to one for an average vessel's hydraulic system and greater or less than one for more or less efficient systems, respectively.

$$E = \rho P_{deck} h_{fish} / \eta_{hyd} \tag{9}$$

Variable	Description	Units
P_{deck}	Hydraulic deck load power	kW
ρ	Duty cycle of the deck load	-
h_{fish}	Time in the fishing operating mode	hrs
η_{hyd}	Hydraulic system efficiency factor	-
E	Energy consumed by the hydraulic system	kWh

Table 6: Hydraulic module variables

2.5 AC module

The AC loads model allows for an AC base load, lighting loads and electric heating loads. The baseload is set to a default value of 0.56 kW by the FVEAT, while the lighting and electric loads may be entered by the user. Equation 10 shows how the electrical energy demand is calculated, and Table 7 gives a definition of each variable.

$$E = \sum_{l \in AC} P_l \rho_l h \tag{10}$$

Variable	Description	Units
AC	The set of all AC loads	-
l	Index of a specific AC load	-
P	Power demanded by an AC load when it is on	kW
ρ	Duty cycle of an AC load	-
h	Time in a particular operating and propulsion mode	hrs

Table 7: AC model variables

2.6 DC module

The DC module simply assumes a constant DC baseload that applies to all operating hours. The value is exposed to the user directly for customization. The model is described by Equation 11, and the relevant variables are defined in Table 8.

$$E = \frac{P_{DC} h}{\eta_{batt} \eta_{alt}} \tag{11}$$

Variable	Description	Units	Default value
P_{DC}	DC base load	kW	0.3
h	Time in a particular operating and propulsion mode	hrs	-
η_{batt}	Battery efficiency	-	0.8
η_{alt}	Alternator efficiency	-	0.6

Table 8: DC model variables

3 Engine fuel consumption model

The engine fuel consumption model calculates a fuel consumption rate (gal/hr) based on the engine load (kW). The model is defined by Equation 12, where P is the engine load, and α and β are coefficients that must be estimated based on engine parameters. Equation 12 shows that the fuel consumption rate increases linearly with engine load.

$$Q = \alpha + \beta P \tag{12}$$

Integrating Equation 12 over a period of time h yields Equation 13, where E is the total energy demanded during the time period (kWh).

$$F = \alpha h + \beta E \tag{13}$$

The linear model shown in Equations 12 and 13 is supported by sea trial data as well as manufacturers' engine specifications. The following subsections describe the expected accuracy of the model, the method the VEAT uses to estimate α and β for a particular engine, and the default values assumed by VEAT in the absence of user input.

3.1 Available data

The engine fuel consumption model is based on sea trial data collected for the FVEEP in 22 vessel audits that included simultaneous fuel flow and power measurements. Maretron fuel flow meters were installed in the fuel supply and return lines of the engines and used to measure fuel consumption throughout the sea trials. Strain gages were also installed on the propeller shaft(s) to record the propeller shaft power, and in the case of auxiliary generators the electrical power output was measured with a power quality analyzer (PQA).

During sea trials, the vessels set a straight course and increased the engine speed in steps of 200 RPM. At each engine speed, the propeller shaft power and fuel consumption rate were recorded once the values stabilized. After reaching the maximum speed in the trial, the vessels turned 180^o and returned by the opposite course. The fuel consumption and power data were accumulated in a data base and used to identify the best model of fuel consumption based on engine load.

The accuracy of the measurements was limited by the flow sensors and strain gages. The flow sensors are rated to an accuracy of 0.25% of the total flow [1]. Since the relevant fuel measurement is the difference between supply and return, the accuracy of the fuel consumption measurement depends on the ratio of fuel consumption to fuel supply. Figure 2 shows the rated accuracy of the flow sensors as a function of the fraction of supply fuel consumed by the engine. Measurements were taken across the full range of the x-axis: at one extreme, a Detroit Diesel 6-71 engine was observed to supply 20 gallons of fuel while consuming less than 0.5 gal/hr at idle (a fuel consumption ratio of 0.025), while an Isuzu 3KC1 auxiliary engine consumed well over 99% of the fuel supplied while at idle. In most cases, only the fuel consumption rate was recorded rather than recording the supply and return fuel flows separately. As a result, the rated accuracy of the flow sensors can not be determined for each individual measurement. In the absence of that data, 2% is considered a reasonable estimate of the typical fuel consumption measurement error across the range of loads placed on the engine during sea trials.

The CEA series strain gauges used for the project are extremely precise, but uncertainty in the shaft diameter and modulus of elasticity limit the expected accuracy [2]. The shaft diameter was typically measured and rounded to the nearest half inch (since the shafts were generally made in the US to standard diameters), and the modulus of elasticity was based on the nominal value for stainless steel, steel, or aquamet depending on the composition of the shaft. The diameter and modulus estimates are expected to introduce an error of up to 3%. The root-mean-squared (RMS) error due to the fuel flow and strain measurement uncertainties is expected to be approximately 4%.

Several factors can cause much larger errors in actual installations. One of the most common problems encountered in fuel flow measurements was air in the return fuel which affected the apparent fuel consumption rate. In the case of strain gauges, the glue fastening the strain gauge to the shaft occasionally failed. Data from these and similar cases were omitted from the database due to obvious measurement errors.

In addition to the measurements made as part of FVEEP, manufacturers' data specify engine fuel consumption under various loads in laboratory conditions. The manufacturers' data provide a useful indication of expected engine performance, but the measured data are preferred because they capture the performance of the engines as they exist in the fishing fleet. The engines may not operate on the design propeller curve, may be exposed to phantom loads that increase fuel consumption, or may be poorly maintained. The VEAT uses measured data exclusively to inform the fuel consumption model. The result is a moderately higher fuel consumption rate than the manufacturers' data would suggest.

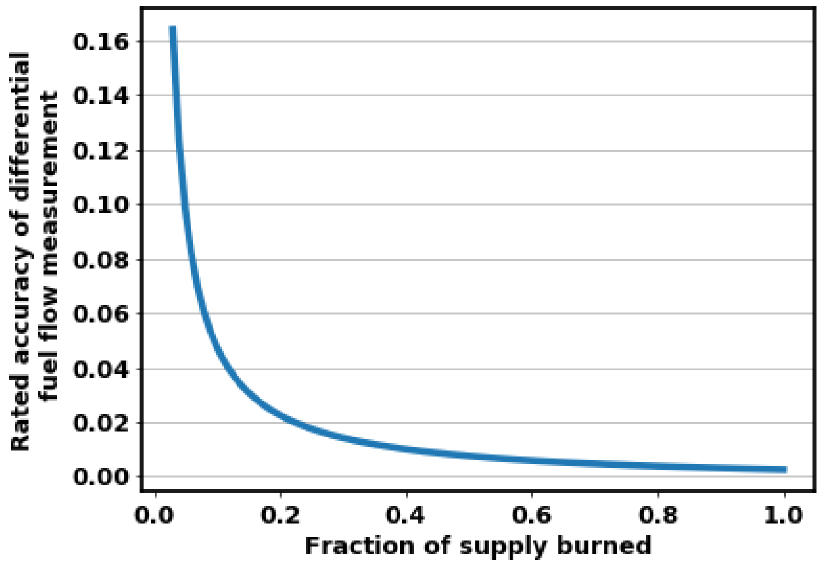

Figure 2: Fuel flow sensor accuracy expressed as a fraction of fuel consumption

3.2 Model accuracy

The accuracy of the model shown in Equation 12 has two components: the linearity of engine fuel consumption and the accuracy of α and β estimates. The linearity of fuel consumption is a measure of how well a linear model can predict engine fuel consumption, given optimal values for α and β. Linearity is important because it implies that the total fuel consumption is independent of how loads are distributed throughout the season. For example, in a linear model it makes no difference whether a freezer and a gurdy run at the same time or different times, they consume the same amount of fuel either way. If fuel consumption could not be predicted with a linear model, then the VEAT would need to be significantly more complex.

The accuracy of α and β estimates depends on the data that are available for an engine. The VEAT includes a default value if no information is available, as well as a more accurate estimate if the user specifies an engine application and power rating. In principle, the VEAT could also accommodate manufacturer's fuel consumption specifications at a range of powers or even measured fuel consumption curves from sea trial data to achieve increasingly accurate fuel consumption estimates, but those features are omitted from the VEAT for simplicity.

3.2.1 Linearity of engine fuel consumption

A linear model fits the fuel consumption patterns of most engines well. Out of 22 engines examined in this analysis, all but one had R^2 values greater than 0.96 when compared with an optimal linear model. The remaining engine had an R^2 value of 0.70, likely due to the fuel consumption measurement error shown in Figure 2 in two measurements at low engine load. The RMS relative difference between the linear model of each engine and the measured fuel consumption was 5.1%, and the median error across all engines was 0.7%. Given that the measurement error is expected to be 4%, the linear model appears to be as accurate as the data can support. More accurate and precise measurements would be required to identify a more accurate model.

3.2.2 Accuracy of α and β estimates

In the absence of any engine-specific data, the VEAT is forced to assume the average α and β values observed for all engines in the FVEEP. These values are $\alpha = 0.49$ gal/hr and $\beta = 0.070$ gal/kWh, and the associated RMS and median errors observed in the dataset are 14 and 9.1%, respectively.

The best method for improving the α and β estimates using basic engine specifications readily available from fishermen uses the engine application (propulsion or auxiliary) and engine rating (continuous horsepower [hp]). The models built using these variables are shown in Equations 14 and 15, where R is the engine rating (hp) and the c_n are coefficients determined based on the database of measurements that depend on the engine application.

$$\alpha = c_0 + c_1 R \tag{14}$$

$$\beta = c_2 + c_3 R \tag{15}$$

Using the equations presented above to calculate α and β for each vessel yields RMS and median errors of 11% and 6.5%, respectively. The c_n coefficients for propulsion engines show a gradual increase in α with engine rating, and a gradual decrease in BSFC. These trends are expected: all other variables being equal, larger engines require more fuel to overcome internal resistance, but tend to have a lower BSFC when fully loaded. Measurements from 5 auxiliary gensets were available, and they did not support a trend based on rated power production. Therefore, c_3 is set to zero for auxiliary engines.

In addition to the model presented here, models based on the engine aspiration method, number of cycles and number of cylinders were also considered. They were found to yield equal or worse accuracy. Details on the performance of these models are presented in Section 12.1.

4 Propulsion model

The propulsion power model generates an estimate of the total energy required from the engine for propulsion. The estimate is based on up to six user inputs: hours of operation (h), vessel speed (s [kt]), length (L [ft]), beam (B [ft]), fraction of time tanked (f_t) and fraction of time with stabilizers deployed (f_s). The model is summarized by Equations 16 17.

$$E = \begin{cases} L\sqrt{B} c_4 e^{c_{14} s} \phi_t \phi_s h, & \text{for } s > 3 \\ \left(\frac{s}{3}\right)^3 L\sqrt{B} c_4 e^{c_{14} 3} \phi_t \phi_s h, & \text{for } s \leq 3 \end{cases} \tag{16}$$

$$\phi_t = c_5 f_t + 1 - f_t \tag{17}$$

$$\phi_s = c_6 f_s + 1 - f_s \tag{18}$$

Numerous peer reviewed studies describe predictive models of vessel drag that could be coupled with existing models of propeller efficiency to estimate propulsion energy requirements (for example, see [9], [13], [14], [15], [16]). A custom model was developed for the VEAT based on sea trials conducted on 29 vessels in the fishing fleet. The custom model was chosen over the published models for the following reasons:

- Most published models are designed for larger vessels
- All published models require more information than the custom model
- The custom model achieves a lower RMS error for vessels in the FVEEP than the most comparable published model

The published models referenced above are generally based on a much larger sample of vessels than is available to the VEAT. As a result, the published models are expected to be more accurate over a broader range of hulls than the VEAT model if all of the required input parameters are provided accurately. However, given that hull design parameters required by the models are often unknown for fishing vessels and that the dataset used to train VEAT is a sample of vessels from the intended user population, the custom model of propulsion power is best suited to the VEAT.

4.1 Available data

The propulsion power model uses data from same sea trials similar to those described in Section 3 but with speed over ground recorded in addition to or instead of fuel flow. In addition to the uncertainty in the strain measurements discussed previously, the GPS measurements introduced error in the speed measurements. Speed was measured using a variety of GPS units, so there is no single specification for their associated error. However, all of the GPS units displayed speed to a precision of 0.1 kt and rarely deviated by more than that under constant conditions. Therefore, a speed measurement error of 0.1 kt (1-3% depending on the vessel speed) is reasonable.

In addition to the two measurement errors described above, innumerable factors can affect hull resistance that the propulsion power model makes no attempt to capture. A discussion of some of these effects, including hull cleanliness, trim and propeller design, is presented in Appendix 12.3. Each effect is expected to introduce a correction to hull resistance on the order of 10%. Since there are many such factors, achieving an accuracy better than 20% without quantifying these hull details is unlikely.

Two particularly important and easily obtained factors are considered by the model. These are the fraction of time that the hold is full of water, and the fraction of time that stabilizers are deployed. Three power measurements were made on vessels in both the full and empty condition (one seine vessel, one troll vessel and one tender). The constant c_5 is simply set equal to the mean ratio of fully loaded power to empty hold power across the three vessels at speeds from 5 to 8 kt (1.27).

Data are available with and without stabilizers for four vessels, all of which participate in troll fisheries. Similar to the tanked factor, c_6 is set equal to the mean ratio of power with stabilizers to power without stabilizers at speeds from 4 to 7 kt (1.64). The speed range is somewhat lower for vessels with stabilizers, because vessels cannot travel as fast with stabilizers deployed.

Finally, the accuracy of the measurements was affected by wind and current. The model interprets the average power and speed measurements from opposite courses to be equivalent to measurements taken in neutral conditions. However, currents perpendicular to the course and nonlinear drag forces affect the accuracy of this assumption. In general, sea trials were conducted parallel to shore in fair conditions to minimize this source of error but no attempt has been made to quantify it.

In addition to the various measurements outlined above, data are available from fishermen surveys. These data are useful for determining default values for the input variables to the model.

4.2 Model accuracy

An exponential model of propulsion power fit the data for each vessel very well: the lowest R^2 value out of all the sea trials was 0.92, and the average R^2 value was 0.99. However, predicting the coefficients without sea trial data is difficult. Several methods were tested before arriving at Equation 16.

The RMS error in the power estimate at transit speeds for vessels without stabilizers and empty holds using the model defined by Equation 16 is 28%, with $c_4 = 4.8 \times 10^{-3}$ hp/ft$^{1.5}$, $c_{14} = 0.57$ kt^{-1}. Transit speeds are defined here as 6.5-7.5, 7.5-8.5, 8-9 and 9-10 kt for 30-40, 40-50, 50-60 and 60-75 ft vessels, respectively.

The model is trained on displacement hulls that typically achieve speeds over water of three to 10 kt. The model interpolates power at speeds between zero and three kt using a cubic equation as shown in Equation 16. Using the exponential model to extrapolate to speeds over ten kt may result in errors, and will be inaccurate for planing hulls.

The correction factors for tanked vessels range from 1.05 to 1.6 depending on the speed and hull of the vessel. The correction factors for stabilizers range from 1.3 to 1.9. Although the data are too sparse to develop meaningful estimates of the population standard deviation, the range of ratios for the few vessels that have been tested suggest an increase in uncertainty of an additional 30% when vessels have stabilizers deployed or are fully loaded with water.

There are eight default values to define: speed while in transit, speed while fishing, vessel length, vessel beam, hours in transit, hours fishing, fraction of time with a full hold and fraction of time with stabilizers deployed. The default value for each variable is simply defined as the average value for vessels in each fishery, except for the fraction of time with stabilizers and a full hold. Those data were not collected during surveys. The default values are based on anecdotal evidence and will be updated as fishermen provide more information to the VEAT in the future. The average values are shown in Table 9. The RMS differences between the averages and the values reported in fishermen surveys are also shown to give an indication of the default values' precision.

Anchor hours were not recorded in fishermen surveys. Anchor hours are estimated based on long term recordings and conversations with fishermen. The anchor hours are important for vessels that maintain loads overnight when they are neither fishing nor in transit. Refrigeration systems are the most prominent load that applies during anchor hours, but some vessels may also maintain DC or other loads. The anchor hours are estimated based on long term recordings from three vessels that have refrigeration systems. These include two seine vessels and one troll vessel. 'Anchor hours' were identified as times when the vessel consumed more than 0.5 gal/hr of fuel, but maintained an average speed of less than 0.15 kt for two hours. The average fraction of time that met this condition was 0.22. That fraction was used to calculate the default anchor hours given the default fishing and transit hours for all operating modes. The value reported in the STD (standard deviation) column of Table 9 is the standard deviation of the anchor hour fraction observed in the data set multiplied by the default total hours.

Category	Default Value	STD (% of mean)	Default Value	STD (% of mean)
	Seine		Troll	
Transit speed (kt)	7.9	4.8	6.7	8.3
Fishing Speed (kt)	5.2	25.6	2.8	17.1
Length (ft)	49.5	4.6	44.0	11.3
Beam (ft)	14.8	2.9	13.5	7.6
Fraction of time tanked	0.75	-	0.2	-
Fraction of time with stabilizers	0	-	0.3	-
	Longline		Tender	
Transit speed (kt)	7.1	9.1	7.1	15.5
Fishing Speed (kt)	2.0	49.2	0.0	0.0
Length (ft)	49.0	13.1	65.0	7.7
Beam (ft)	14.8	1.1	22.0	0.0
Fraction of time tanked	0	-	0.5	-
Fraction of time with stabilizers	0	-	0	-
	Gill net		Pot fishing for black cod[1]	
Transit speed (kt)	8.3	25.8	8.3	25.8
Fishing Speed (kt)	2.9	45.0	2.0	45.0
Length (ft)	37.2	6.9	37.2	6.9
Beam (ft)	11.0	0.0	14.0	-
Fraction of time tanked	0.5	-	0	-
Fraction of time with stabilizers	0	-	0	-
	Other[2]			
Transit speed (kt)	8.0	-		
Fishing Speed (kt)	3	-		
Length (ft)	45	-		
Beam (ft)	13	-		
Fraction of time tanked	0.5	-		
Fraction of time with stabilizers	0	-		

Table 9: Default values for the propulsion model

5 Refrigeration model

The method used to calculate the refrigeration load is shown in Equations 19 and 20. $\bar{P}$ denotes the power of a refrigeration system component averaged over its operating hours and the subscripts *tot*, *circ*, *comp*, and *cond* denote total, circulation pump or fan, compressor and condenser pump, respectively. f_{circ} is the ratio of time that the circulation pump runs to time the compressor runs, and f_{comp} is the fraction of total hours in a particular operating and propulsion mode that the compressor runs. h is the total hours in a particular mode. η_{ref} is an estimate of the refrigeration power source efficiency factor, defined as the ratio of the engine load of a direct drive system to the engine load with the specified power source (hydraulic, electric or direct drive).

$$\bar{P}_{tot} = \left(\bar{P}_{circ} f_{circ} + \bar{P}_{comp} + \bar{P}_{cond}\right) / \eta_{ref} \tag{19}$$

$$E = \bar{P}_{tot} h f_{comp} \tag{20}$$

[1] No data were available for the pot fishery. The default values were assumed to match the long line fishery, with a 30% increase in beam.

[2] The "other" fishing mode uses arbitrary default values that are in the range of values observed in the available data.

All refrigeration systems are modeled using Equations 19 and 20. P_{circ} may be the power required by a fan in a blast freeze system or a pump in a refrigerated sea water system. In a plate freeze system, P_{circ} is simply set equal to zero.

The default values for the variables in Equation 19 depend on three factors: the operating mode, refrigeration system type (refrigerated sea water (RSW), blast freeze, or plate freeze), and power source (electric, hydraulic or direct drive). The hour fraction values are determined by the operating mode exclusively. The refrigeration system type and operating mode in combination determine the default power demanded by the system. Finally, an efficiency factor is applied to the power values based on the power source.

5.1 Available data

FVEEP has measured the load due to refrigeration systems during short term trials on 8 vessels. During these trials, the refrigeration system was turned on at the dock, and the load due to various components of the refrigeration system was recorded for less than one hour. These measurements provide meaningful estimates of average power for constant loads like circulation pumps, fans and condenser pumps that do not use a variable frequency drive. They do not provide an accurate estimate of compressor load under typical operating conditions. The system power demand changes dramatically as the hold temperature declines, and compressor units cycle off periodically. These two factors make it impractical to use the short term recordings to estimate average long term compressor loads.

FVEEP has measured long term refrigeration loads on five troll vessels, three seine vessels and two tenders. Two of the troll vessels used a hydraulic refrigeration system while the others used electric systems. The power requirements of the electric systems were recorded using a clamp-meter measuring the current in a single phase of the compressor or the total generator load and in some cases auxiliary refrigeration loads (including circulation pumps, condenser pumps and fans).

The power associated with the measured current was calculated according to Equation 21, where P is the calculated power, I is the measured RMS current in a single phase, V is the RMS line-to-line voltage, and η_{PF} is the power factor. The power factor associated with the load and the system voltage were measured before the fishing season began and assumed constant throughout the long term recordings.

$$P = \sqrt{3} I V \eta_{PF} \tag{21}$$

Auxiliary refrigeration loads (such as condenser pumps, circulation pumps and fans) that were not included in long term recordings were either measured during short term recordings (six vessels) or assumed equal to the auxiliary refrigeration loads measured on similar vessels (four vessels). In either case, when auxiliary refrigeration loads were not recorded, they were assumed constant throughout the long term recording period when the compressor was running.

The hydraulic freezer systems used load sensing pumps. The pumps are designed to deliver the same flow independent of pump speed, within limits. On one of the vessels, the pump was generally fully loaded and operating at maximum displacement. In that case, the hydraulic power was calculated according to Equation 22. In Equation 22, p is the fluid pressure (Pascal), N is the pump rate of rotation (Hz) and D is the pump displacement per revolution (m^3). On the other vessel, flow was measured and then assumed constant throughout the recording period. In that case, the hydraulic power was simply equal to $p \times f$, where f is the measured flow.

$$P = pND \tag{22}$$

5.2 Model accuracy

The default values for each variable in Equations 19 and 20 are shown in Tables 10 through 12, along with their ranges[3]. The defaults for each mode are set equal to the mean of the measurements described in the previous section. The hours in each propulsion mode were defined in Section 4, and are omitted here.

[3] Ranges marked with a dagger (†), are based on one measurement. The value reported is simply from one-half to double the original measurement.

5.2.1 Operating time fractions

Estimating the amount of time that the compressor ran in each mode required additional analysis of the existing data. When available, tachometer or speed recordings were used to classify times as anchor, fishing, or transit. For seine vessels, any time that the vessel maintained a speed above 6 kt for 20 minutes was classified as transit. Any 40 minute period in which the vessel achieved a speed above 1 kt and was not in transit was classified as fishing time. On troll vessels with an auxiliary generator, times when the propulsion engine ran were classified as transit or fishing based on the engine speed, and times with the propulsion engine off but the auxiliary running were classified as times at anchor.

No simultaneous speed or tachometer and refrigeration recordings were available for the tender operating mode, so the operating time fraction was assumed to be equal across all propulsion modes. The compressor operating fraction was estimated as the run time divided by the total recording period, and assumed to be constant across all propulsion modes.

Parameter	Prop. Mode	Default Value	Range
Seine			
f_{circ}	All	1.4	0.3
f_{comp}	Transit	0.35	0.26
f_{comp}	Fishing	0.70	0.11
f_{comp}	Anchor	0.27	0.19
Troll			
f_{circ}	All	1	0.1†
f_{comp}	Transit	0.75	0.21
f_{comp}	Fishing	0.96	0.21
f_{comp}	Anchor	0.92	0.21
Tender			
f_{circ}	All	1	-
f_{comp}	All	0.42	0.22
Other			
f_{circ}	All	1	-
f_{comp}	Transit	0.35	-
f_{comp}	Fishing	0.70	-
f_{comp}	Anchor	0.27	-

Table 10: Refrigeration operation time fractions

5.2.2 Compressor, circulation and condenser power

The power consumed by the compressor circulation pump or fan and condenser pump are shown in Table 11. The values shown are the average across all of the measured loads, along with the measured ranges. The loads shown are the estimated loads for a direct drive refrigeration system although no direct drive systems were included in the study. The direct drive loads were estimated by dividing the measured electrical loads by the electric system efficiency (see the following subsection).

5.2.3 Power system efficiency

Although the model estimates that all refrigeration systems use the power defined in Table 11, the associated load on the engine depends on how power is delivered to the compressor. Three types of power systems exist in the fleet: direct drive, electric and hydraulic. The power required by electric and hydraulic systems was measured directly, and the direct drive system was assigned an efficiency factor of 1. The electric motor driving the compressor and the electric motor in the generator were both assumed to operate at 90% efficiency[4], for an overall efficiency of 0.81. Hydraulic system efficiency was estimated based on the ratio of freezer system power demand in a hydraulic system to a similar capacity electric system.

[4] Motor efficiency depends on the load and design of the motor, but 0.9 is within the typical range for standard motors [3]

Parameter	Default Value	Range	Default Value	Range	Default Value	Range
System type: RSW						
Operating Mode:	Seine		Tender		Other	
P_{circ}	3.7	3.0	5.9	9	4	-
P_{cond}	1.4	1.1	1.9	3.0	1	-
P_{comp}	9.5	1.9	16.0	5.9	10	-
System type: Blast Freeze						
Operating Mode:	Troll		Other			
P_{circ}	0.66	1.0†	0.66	-	-	-
P_{cond}	0.67	1.0†	0.67	-	-	-
P_{comp}	5.8	1.1	5.8	-	-	-
System Type: Plate Freeze						
Operating Mode:	Troll		Other			
P_{circ}	0	0†	0	0	-	-
P_{cond}	0.67	1.0†	0.67	1.0†	-	-
P_{comp}	3.9	5.9†	3.9	5.9	-	-

Table 11: Default power (kW) for various refrigeration systems

Power source	Efficiency factor
Direct drive	1
Electric drive	0.81
Hydraulic drive	0.55

Table 12: Efficiency of drive systems

6 Hydraulics model

The hydraulic model consists of deck equipment engine loads and their associated duty cycles while the vessel is fishing. The default loads are stored in the database in units of kW. The following sections present the available data, then discuss each deck load for which default values are provided and their expected accuracy.

6.1 Available data

Hydraulic power was recorded by measuring the pressure a few feet from the hydraulic pump and measuring the rate of rotation of the pump. For positive displacement pumps, the displacement per revolution was obtained from the manufacturer. The power was then estimated according to Equation 22, as described in Section 5.

In the case of pressure compensating pumps, the displacement was calculated according to Equation 23[5]. In Eq. 23, D_0 is the displacement at zero pressure, p_{min} is the minimum pressure at which D begins to change, and p_{max} is the pressure at which $D = 0$.

$$D = \begin{cases} D_0, & \text{if P} \leq P_{min} \\ D_0 \frac{P_{max} - P}{P_{max} - P_{min}}, & \text{if } P_{min} \leq P \leq P_{max} \end{cases} \tag{23}$$

Load sensing hydraulic pumps maintain a constant flow independent of pump speed and pressure. For load sensing pumps, the increased fuel consumption by an engine due to the pump was measured during a sea trial and used to back calculate the pump flow. The flow was then assumed constant during long term recordings. No such indirect flow measurement was available for a deck hydraulic pump on one troll vessel,

[5]For further discussion, see Profile for Hybrid Design by Chandler Kemp, Mike Gaffney and Dan Falvey.

and in that case the pump was assumed to act as a pressure compensating pump typically operating at approximately one-half its rated displacement.

Since the fluid flow for positive displacement pumps and pressure compensating pumps was calculated based on the pump displacement without any allowance for back-flow through the pump, calculated power differs from the produced power by the volumetric efficiency of the pump. The volumetric efficiency is defined as the ratio of actual flow to theoretical flow.

The power calculated using Equation 22 also differs from the engine load due to the pump. The calculated power must be divided by the mechanical efficiency of the pump in order to estimate the engine load. The mechanical efficiency is defined as the ratio of theoretical torque to work against the measured pressure p and the actual torque on the pump shaft. Frictional forces within the pump cause the mechanical efficiency to be less than one.

The VEAT uses an estimate of mechanical efficiency to calculate the engine load due to hydraulic pumps. This report does not consider the volumetric efficiency or calculate the power produced by the pump. The mechanical efficiency is estimated based on data from Vickers (a common manufacturer of hydraulic pumps used in the fishing fleet) [22]. Vickers provides the typical input power required to produce rated flow at maximum pressure for its pumps. Dividing the theoretical power calculated for the rated displacement, pressure and pump speed by the typical input power yields the mechanical efficiency. For example, the Vickers 25VQ 21 US gallon per minute (gpm) pump has a theoretical power output of 58.2 kW (the product of displacement, maximum speed, and maximum pressure) and a typical input power of 61.9 kW. The implied mechanical efficiency is 58.2/61.9=96%. Similarly, the "shaft end" 42 US gpm pump in the Vickers 4520 VQ double pump has a mechanical efficiency of 94%. A value of 95% is used throughout the analysis in reported hydraulic power requirements.

6.2 Transit and anchor hydraulics

By default, the hydraulic load while a vessel is in transit or at anchor is set to 0 kW. There may be occasional deck loads applied during these times, but none have been observed to contribute significantly to total fuel consumption.

6.3 Deck equipment library

The hydraulic deck equipment library is summarized by Table 13. The table shows default values and likely ranges for deck equipment typically associated with the seine, troll, gill net and long line fisheries. Tender vessels must enter deck loads in the 'other' category, because they are difficult to predict.

Hydraulic deck load	Default power	Range	Duty Cycle	Range
Seine winch AND power block	35	16	0.2	0.04
Gurdies	3.7	0.5	1	-
Gill net drum	3.5	0.2	0.15	0.11
Gill net drum AND power roller	5.2	0.8	0.15	0.11
Autoline haul system	7.4	11	0.48	0.36
Longline Sheave OR drum	2.3	3	0.48	0.36
Longline sheave AND drum	2.8	3.5	0.48	0.36
Large pot hauler	8	-	0.48	-
Small pot hauler	4	-	0.48	-
Other (cranes, etc)	1	-	1	-

Table 13: Deck equipment library

6.3.1 Seine hydraulics

Season long recordings from two seine vessels were used to calculate the average value for the seine winch and power block loads.

6.3.2 Troll hydraulics

The average power demand while fishing is estimated as the average hydraulic load from long term recordings on two vessels. The value is 3.7 kW, and the range between measurements for the two vessels is 0.5 kW.

6.3.3 Gill net hydraulics

The gill net parameters were estimated based season-long recordings on one vessel, day long recordings from a second vessel and short term recordings from a third vessel. The day long and season long recordings were used to estimate the hydraulic duty cycle. Both the day long and short term recordings were used with equal weight to estimate the average power when the hydraulics were engaged. Power measurements on the season-long recording were anomalously low and omitted from this analysis pending corroboration from another gill net system.

6.3.4 Long line

The average power while hauling can take one of three values, depending on if the vessel uses an auto line system, a drum and a sheave, or either a drum or a sheave. No hydraulic power measurements are available for an autoline system so the model is based on manufacturer's data. Specifically, the autoline model is based on the Mustad MA-HV-100 hauler and the MA-HS-500 Hook Separator [18]. The devices are rated to 43 and 16 Liters/minute, respectively. The model assumes that the systems typically operate at 800 PSI and three-quarter speed, and a line loss estimate of 2 kW is applied. The reported range is simply from 1/2 of the estimated value to 2 times the estimated value. As more data are collected, the default value and the expected range will become more meaningful.

The average power for the other hauling arrangements are based on measurements taken on two vessels with a long line hauler and sheave, and two vessels with either a hauler or a sheave but not both. Since the long line hydraulic measurements were measured at the load rather than the pump, the model includes a line loss estimate of 2 kW for them as well.

In addition to the long term recordings referenced above, the Electronic Monitoring (EM) program has analyzed the duration of 423 hauls spread over 16 vessels. The model uses data from four vessels in this set that have haul tachometer recordings for a total of 61 hauls to inform the duty cycle and power estimates of hydraulic long line deck equipment.

6.4 Hydraulic efficiency variability

The efficiency of hydraulic systems varied dramatically in some vessels. In the most extreme case a long line vessel used 6 times the average power to turn its long line drum. The hydraulic efficiency variable provides a means for fishermen to capture some of this variability. Selecting "Low" efficiency doubles the power demand of all hydraulic loads, while selecting "High" reduces the power demand by 25%.

7 AC model

The alternating current (AC) model estimates the total energy required for AC loads, excluding refrigeration systems. The model is described by Equation 24, where AC is the set of modeled AC loads, l is the index of a specific load, P_l is the power associated with load index l, ρ_l is the duty cycle, and h is the hours in a particular propulsion mode.

$$E = \sum_{l \in AC} P_l \rho_l h \tag{24}$$

An analysis of measured AC loads and survey responses was used to identify the most significant AC loads. Lighting and electric heaters were identified as common, significant and variable AC loads and the model includes fields to specify those loads directly. Loads that are powered by an inverter connected to a battery bank are classified as DC loads.

7.1 Available data

AC load measurements are available from 11 vessels, and survey data are available from a different set of 11 vessels that specifically listed their AC loads. AC loads were generally measured using a PQA on site, although a few loads were also recorded over longer time periods using clamp meters to measure current in a single phase, as described in Section 5. The PQA is rated to an accuracy of approximately 1% (with the clamp meters used by FVEEP and typical power factors observed on vessels). The duty cycle estimates provided in surveys are almost certainly a larger source of error although there are no measurements to compare those estimates to in order to quantify their accuracy.

7.2 Model accuracy

Default values for each category are shown in Table 14, along with the range in observed or reported values. The duty cycles shown should apply to all propulsion modes. The duty cycle ranges that are set to one indicate loads that some fishermen reported using less than 5% of the time, while others reported using them more than 95% of the time.

Load class	Default power (kW)	Range	Default duty cycle	Range
Lighting	1.9	2.3	0.26	1.0
Space heating	0.6	0.3	2	1.0†
Hot water	1.8	1.3	0.2	0.3†
Other	0.2	1	1.6	-

Table 14: Default values for the AC model

The ‘other’ category is set to default to the average unaccounted for load observed on vessels.

7.3 Power source specification

AC loads are divided evenly among any auxiliary engines present on the vessel. If no auxiliary engines are present, then the load is attributed to the propulsion engines. With no generator, AC loads must be carried by an inverter powered by an alternator or batter bank. In practice, the inverter and alternator introduce an additional efficiency factor, but it is not included in the model for simplicity.

8 DC model

The direct current (DC) model estimates the total energy required for DC loads. The model allows for one constant “baseload” P that applies for all hours h and assumes batteries with charge/discharge efficiency of η_{batt} and an alternator with efficiency η_{alt}.

$$E = \frac{Ph}{\eta_{batt}\eta_{alt}} \tag{25}$$

An analysis of measured DC loads and survey responses was used to determine the average DC load. The user can enter a custom, total average DC load to override the default values.

8.1 Available data

DC loads were measured using either instantaneous measurements or long term recordings. A multimeter was used for instantaneous measurements. First, the voltage at the battery bank or an electronic control panel was measured. Then the current supplied by the battery or to the control panel was measured as loads were switched on and off one at a time. Loads that have transient behavior after they are switched on were allowed to ‘warm up’ until the current stabilized. The current measurements were typically repeatable to within 1 Amp (approximately 13 Watts), and this is taken as the accuracy of the DC load measurements. The instantaneous measurements were used to develop the library of DC loads referenced in later sections.

During long term recordings, the total current to a panel or from a battery was recorded periodically over an extended period of time. The voltage was typically measured once at the beginning of the recording period and assumed to be constant for the duration of the recording. These long term recordings were used to check the average loads estimated based on the DC load library, but ultimately did not affect the values used by the model.

In addition, 17 skippers estimated the duty cycle for all of their DC loads while in transit and fishing for each fishery that they participate in. These duty cycle estimates were used in combination with the multimeter measurements described above to estimate the average power consumed while the vessels are in operation.

8.2 Model accuracy

The default values and the expected ranges on working vessels are shown in Table 15. The default power values are the average measurement across all vessels audited where that load was measured. The range is the difference between the maximum and minimum non-zero values observed in the fleet. The duty cycle averages and ranges are based on survey data provided by fishermen. The "other loads" power value and range are also based on the survey data rather than measurements. The Excel VEAT did not provide a "Flood light" category, so the duty cycle value and range were assumed to match the "Deck lights" category. The duty cycle default values shown should apply to all fishing and transit hours. Only the 'other loads' should apply during anchor hours.

Load class	P (kW)	Power range (kW)	D Duty cycle	Duty cycle range
Flood light	0.26	0.18	0.14	0.49
Deck lights	0.06	0.03	0.14	0.49
Wash down pump	0.17	0.15	0.17	0.59
Autopilot	0.05	0.07	0.88	0.9
Cabin fridge	0.1	0.04	0.24	0.05
Cabin lights	0.04	0.05	0.15	0.35
Engine room lights	0.07	0.08	0.14	0.70
Running lights	0.04	0.09	0.27	0.95
Other loads	0.14	0.33	1	-
Alternator efficiency	0.6	0.3	-	-
Battery efficiency	0.8	0.2	-	-

Table 15: Default values for the DC model

The round trip efficiency of lead acid batteries (η_{batt}) varies from around 70% to around 90% depending on the depth of discharge, type of battery and other factors [19]. A default value of 80% is used in the model.

The alternator efficiency is partly included in the engine model, because the engine model is based on measurements taken when the alternator was connected to the engine. There is no measurement of DC power production by the alternator during the sea trials, so the effect cannot be quantified. The model works under the assumption that the DC power production was low during most sea trials, which could lead to a modest overestimate of fuel consumption. In a worst case scenario, the fuel consumption of the DC loads would be counted twice: once as DC fuel consumption, and once as part of the "Engine overhead" fuel consumption. Alternator efficiency varies from around 40% to 70% under typical operating conditions [20], [21]. A default value of 60% is used by the model.

9 Load allocation

Sections 4-8 explain how the energy for each load is calculated and Section 3 explains how to calculate fuel consumption for an engine to produce a specified amount of energy. This section explains how to allocate the energy calculated for each load among the engines on the vessel.

The energy requirements are allocated to each engine based on load class. Equation 26 shows how the loads are divided. The indexes are shown to emphasize the relationship between the energy and fuel requirements, and the load allocation factor f_{ijkm}.

$$F_{ijkm} = \beta_i f_{ijkm} E_{jkm} \text{ for } k \neq \text{engine overhead} \tag{26}$$

Recall from Section 1.2 that E_{jkm} specifies the energy required by propulsion mode m and load class k during operating mode j. f_{ijkm} is then the fraction of E_{jkm} that applies to engine i. Since f has four dimensions, it requires many values to populate. For example, if a vessel has three engines, four operating modes, five load classes and three propulsion modes, f contains $3 \times 4 \times 5 \times 3 = 180$ values. The user can not be expected to enter all of that information, so the model relies on a set of rules to define values for f_{ijkm}. The rules are explained in the following subsections.

9.1 Propulsion load allocation

Propulsion loads are allocated according Equation 27, where $N_{prop-eng}$ is the number of propulsion engines.

$$f_{ij,k=propulsion,m} = \begin{cases} 1/N_{prop-eng} & \text{if engine } i \text{ is a propulsion engine} \\ 0 & \text{otherwise} \end{cases} \tag{27}$$

9.2 Refrigeration load allocation

The refrigeration load default allocation depends on the type of refrigeration system being used and the propulsion mode. Electrical refrigeration system loads are allocated in the same way as all other AC electric loads. The allocation process is described by Equation 30 in Subsection 9.4. For a hydraulic refrigeration system, loads are allocated in the same way as all other hydraulic loads. The allocation process is defined by Equations 28 and 29 in Subsection 9.3.

9.3 Hydraulic load allocation

Hydraulic loads are allocated to the propulsion engines while in transit or fishing, and the auxiliary engines while at anchor. If there are zero auxiliary engines, then the hydraulic load while at anchor is also attributed to the main engine.

$$f_{ij,k=refrigeration,m\neq anchor} = \begin{cases} 1/N_{prop-eng} & \text{if engine } i \text{ is a propulsion engine} \\ 0 & \text{otherwise} \end{cases} \tag{28}$$

$$f_{ij,k=refrigeration,m=anchor} = \begin{cases} 1/N_{prop-eng} & \text{if there are zero auxiliary engines} \\ 1/N_{aux-eng} & \text{if engine } i \text{ is an auxiliary engine} \\ 0 & \text{otherwise} \end{cases} \tag{29}$$

9.4 AC loads

AC loads are allocated to the auxiliary engines if they exist, and to the propulsion engines otherwise.

$$f_{ij,k=refrigeration,m} = \begin{cases} 1/N_{prop-eng} & \text{if there are zero auxiliary engines} \\ 1/N_{aux-eng} & \text{if engine } i \text{ is an auxiliary engine} \\ 0 & \text{otherwise} \end{cases} \tag{30}$$

9.5 DC loads

DC loads are all allocated to the propulsion engines, as shown in Equation 31.

$$f_{ij,k=DC,m} = \begin{cases} 1/N_{prop-eng} & \text{if engine } i \text{ is a propulsion engine} \\ 0 & \text{otherwise} \end{cases} \tag{31}$$

9.6 Load allocation accuracy

The effect of using the default load allocation on the accuracy of fuel consumption estimates is expected to be much less than other sources of error in the model for three reasons. First, the rules outlined above are expected to match a large majority of the vessels using the VEAT. Second, the most common errors are expected to be between engines in similar application classes and sizes. For example, a twin screw vessel may have an alternator on one propulsion engine to supply DC loads. The model would allocate that load equally to both propulsion engines. However, if the two engines are rated to the same power, the model would give them the same β value, and there would be no effect on the overall result. Finally, the loads that are likely to be mis-allocated tend to be small. Propulsion loads are highly unlikely to be carried by a non-propulsion engine. No electric refrigeration loads have been observed to violate the rules above, and hydraulic refrigeration loads have been observed to follow the rules over 95% of the time. AC and DC loads may be mis-allocated more often, but are generally smaller than the propulsion and refrigeration loads. An upper bound on the error due to load allocation can be estimated by assuming hydraulic, AC, and DC loads account for 20% of the total vessel load, are mis-allocated 50% of the time to an engine that has a β value that differs from the correct engine by 40%. The resulting error in fuel consumption estimate is 4%. The general accuracy of the allocation rules, coupled with small changes in β between similar engines and the consistency of how large loads are allocated within the fleet make the load allocation algorithm a small source of error overall.

10 Monetary cost model

The cost model estimates fuel and engine maintenance expenses for each operating mode. The maintenance model has not been implemented in the online tool, but the mathematical model is included here as a foundation for future work. The cost of operating an engine in a particular operating mode is given by Equation 32, where C, C_{oil}, $C_{rebuild}$ and C_{fuel} are the total cost, oil change cost, rebuild cost and the cost of one gallon of fuel, respectively. h, h_{oil}, and $h_{rebuild}$ are the hours in a particular operating mode, the engine hours per oil change and the engine hours per rebuild, respectively. F is the fuel consumption estimate returned by the fuel consumption model for the relevant operating mode.

$$C = \begin{cases} h\left(\frac{C_{oil}}{h_{oil}} + \frac{C_{rebuild}}{h_{rebuild}}\right) + FC_{fuel} & \text{for engine overhead costs} \\ FC_{fuel} & \text{for other load classes} \end{cases} \tag{32}$$

10.1 Available data

Fishermen provided estimated maintenance cost data for 46 engines. The estimates included the cost per oil change, average hours between oil changes, the cost to rebuild an engine[6] and the average hours between engine rebuilds. The rated power of the engines were recorded as well.

10.2 Model accuracy

The cost model simulates the fuel, oil change and rebuild costs of running an engine, but does not include miscellaneous maintenance items. A user may achieve more accurate results for their vessel by entering information for their specific situation. However, if users rely on the default values there will be broad uncertainty in the results.

The default values were calculated as the average values from the survey data described in the previous subsection. The engines were classified as ‘small’ (rated to less than 150 hp) or ‘large’ (rated to 150 or more hp). The classification roughly corresponds to engines with 3 or 4 cylinders and engines with 6 or more cylinders. The default values, along with the standard deviation in the data, are shown in Table 16. The standard deviation data give an indication of the range of costs and operating practices present in the fishing fleet.

[6] For engines that fishermen did not expect to rebuild, the replacement cost was used.

Variable	Default Value	Range
Engines <150 hp		
Rebuild cost ($)	12600	6240
Oil change cost ($)	99	103
Rebuild interval (hours)	23100	9090
Oil change interval (hours)	354	259
Engines ≥150 hp		
Rebuild cost ($)	20200	13300
Oil change cost ($)	164	116
Rebuild interval (hours)	28000	12300
Oil change interval (hours)	334	263

Table 16: Default values for the cost model

Variable	Description	Units
C_{eng}	The cost of running an engine	$
h	Time in a particular operating and propulsion mode	hrs
C_{oil}	Cost per oil change	$
h_{oil}	Average interval between oil changes	hrs
C_{fuel}	Cost of fuel	$/gal
F	Fuel demanded by a particular load class	gal
$h_{rebuild}$	Average time between engine rebuilds	hours

Table 17: Cost model variables

10.3 Fuel cost

Fuel costs, as well as taxes and fees, vary throughout the state. The Pacific Sates Marine Fisheries Commission maintains a database of fuel dock prices before taxes and fees in all regions of Alaska [24]. The default fuel cost value used by the VEAT is based on the average cost in this database plus taxes and fees. The base, average fuel rate for fishing communities in Alaska in 2016 and 2017 was $2.55/gallon. Federal and state taxes apply to fuel, in addition to any local sales tax [25], [26]. In addition to the federal and state taxes, a sales tax rate of 6% was assumed to calculate a total cost of $3.01/gallon.

10.4 Summary

The cost model calculates the cost of maintaining and running all engines on board a vessel. The model is described by Equation 33, and the variables are defined in Table 17. Default values are shown in Table 16.

$$C_{eng} = \begin{cases} h\left(\frac{C_{oil}}{h_{oil}} + \frac{C_{rebuild}}{h_{rebuild}}\right) + FC_{fuel} & \text{for engine overhead costs} \\ FC_{fuel} & \text{for other load classes} \end{cases} \tag{33}$$

11 Conclusion

The VEAT provides a comprehensive model of fishing vessel fuel consumption that can be used to explore how six load categories contribute to total fuel consumption, to estimate how modifications to the vessel will affect fuel consumption, and to guide investment in energy conservation measures. The model is a compromise between accuracy and simplicity: the fuel consumption estimates could be made more accurate by requiring more information from users, but each question would add to the work load of the users. The model captures the trends and variability that are present in the 50 vessels that contributed data to the FVEEP, but will be less accurate for vessels that have different hulls or participate in different fisheries. Many vessels in the Alaskan fishing fleet and beyond are similar enough to vessels surveyed for the FVEEP that the model will provide useful fuel consumption estimates. However, the default values will not be accurate for planing hulls, vessels more than 100' or less than 30' in length, or vessels that have large hydraulic loads that were not measured in the FVEEP.

With customized default values, any vessel that uses diesel engines and has loads that fit into the propulsion, refrigeration, hydraulic, AC, DC and engine overhead categories can be simulated using the mathematical model and Python implementation developed for the VEAT. In addition to the values exposed in the online tool, novel vessels would require adjusting the variables described in this document that cannot be changed by online users. The VEAT provides a convenient method for analyzing Alaskan fishing vessel fuel consumption and a foundation for developing a model of fuel consumption for a much broader set of vessels.

12 Appendix

12.1 Alternative engine models

In addition to the engine application (generator or propulsion) and engine rating, the aspiration system, number of cycles per revolution, and number of cylinders were recorded for each engine analyzed in the FVEEP. Table 18 summarizes the significance of each parameter in determining the α and β values.

Category	α (gal/hr)	β (gal/hp-hr)	Max. fuel error (%)
Parameters considered: sea trial data			
All vessels	-	-	20.2
RMS error	-	-	4.5
Parameters considered: none (average values applied to all vessels)			
All vessels	0.49	5.2×10^{-2}	47.2
RMS error	-	-	13.6
Parameters considered: engine application			
Genset	0.47	$4.58\ \times10^{-2}$	38.9
Propulsion	0.50	$5.51\ \times10^{-2}$	20.6
RMS error	-	-	12.7
Parameters considered: engine application, # of cylinders			
Genset	†	†	35.9
Propulsion	†	†	21.1
RMS error	-	-	12.1
Parameters considered: power rating (R), engine application			
Genset	$0.51 + \text{-}8.3\ \times10^{-4}R$	$0.033 + 2.83\times10^{-4}R$	34.3
Propulsion	$0.26 + 8.1\ \times10^{-4}R$	$0.060 \text{ - } 1.56\times10^{-5}R$	18.6
RMS error	-	-	11.1
Parameters considered: aspiration method, power rating (R), engine application			
Turbo propulsion	$0.13 + 1.09 \times 10^{-3}R$	$0.066 - 2.94 \times 10^{-5}R$	11.5
Naturally aspirated propulsion	$-0.21 + 4.41 \times 10^{-3}R$	$0.057 - 2.04 \times 10^{-6}R$	10.6
Turbo genset	0.47	0.059	1.1
Naturally aspirated genset	$0.72 - 7.32 \times 10^{-3}R$	$0.014 + 8.58 \times 10^{-4}R$	35.0
RMS error	-	-	11.0
Parameters considered: cycles per revolution, power rating (R), engine application			
Four cycle propulsion	$0.16 + 1.03 \times 10^{-3}R$	$0.060 - 1.61 \times 10^{-5}R$	15.3
Two cycle propulsion	$-0.34 + 6.00 \times 10^{-3}R$	$0.049 + 6.85 \times 10^{-5}R$	9.1
Four cycle genset	0.37	0.062	1.1
Two cycle genset	$0.38 + 4.74 \times 10^{-3}R$	$0.036 + 1.49 \times 10^{-4}R$	40.1
RMS error	-	-	11.0

† Depends on number of cylinders

Table 18: Impact of various parameters on model accuracy

The average BSFC of turbo charged engines and four cycle engines is better than their naturally aspirated and two cycle counterparts. However, engine rating, aspiration, and cycles per revolution are correlated variables. In the data that has been collected for FVEEP, accounting for the observed trend toward greater efficiency in larger engines adequately accounts for the improvement in energy efficiency due to adding a turbo or changing from a two cycle to a four cycle engine. If changing the engine style is proposed as an ECM, the expected savings could not be estimated accurately with the data included in this analysis because there are not enough engines that have the same rating but different aspiration or number of cycles to produce a statistically significant result. Instead, the efficiency of the new engine should be estimated based on manufacturer's data and compared to measurements on board the existing vessel.

12.2 Engine energy conservation measures

Purchasing an engine that runs efficiently under the operating conditions on board each vessel is the best way to minimize BSFC. There are a few general patterns discussed below that can help narrow the search for an efficient engine, but there is no replacement for comparing the fuel consumption specifications of specific engines that meet the requirements for a vessel. In a survey of 20 marine diesels manufactured by Lugger, Caterpillar, Cummins and Detroit Diesel, the rated BSFC was found to range from 205 to 265 gram/kWh–a variation of over 25%. Over a 30 year service life, a 25% efficiency improvement on 150 hp engine in a troll vessel would save $30,000-$60,000 depending on the hours spent fishing and the price of fuel.

12.2.1 Turbochargers

Turbo chargers are very effective at increasing the power density of engines, and they generally improve engine efficiency as well. In a survey of 7 pairs of marine diesels with and without turbo chargers, the average BSFC improvement was 7% according to manufacturer's data. However, the Cummins 2001 6B showed a 2% increase in BSFC when turbo charged; the engine specifications must be checked to verify that a turbo model provides a better BSFC than its naturally aspirated counterpart.

12.2.2 Four cycle versus two cycle

Two cycle marine diesels are increasingly rare. However, the Detroit Diesel 71 series remains common in the fishing fleet. These engines have fairly high BSFC ratings: 235 g/kWh for the turbo charged 6V71, for example, and 257 g/kWh for the naturally aspirated 6V71. For comparison, the average BSFC in the 20 engines surved was 230 g/kWh. Many new engines have BSFC ratings under 210 g/kWh.

12.3 Hull drag factors

The condition of the hull and propeller are known to affect vessel power requirements. Skippers surveyed for FVEEP referenced a rule of thumb that their speed at transit RPM increases by approximately 1/2 knot after their hull is cleaned. FVEEP measured power requirements before and after a hull and propeller cleaning on three vessels and observed a reduction in power demand at cruising speed of 10-30%. This result is corroborated by Lamb, who predicts an increase in resistance of 10% if the hull becomes rough [7].

12.3.1 Trim

Adjusting the vessel's "longitudinal center of buoyancy" can reduce vessel resistance by over 10% according to Lamb [7]. FVEEP has not made measurements to determine how relevant this is to the fishing fleet, but it could be a significant source of error.

12.3.2 Bulbous bow

A bulbous bow can reduce vessel resistance in transit by 20% [7]. One vessel in FVEEP was audited before and after a bulbous bow was installed, and a 25% decrease in power consumption at 7 kt was observed. However, the other two vessels with bulbous bows included in the FVEEP were found to consume more fuel for their size than vessels without a bulb during the sea trial. Several complicating factors affect the impact of the bulb on vessel performance, including the shape and position of the bulb. In general, the bulb can reduce drag at cruising speeds when wave-making wake is the dominant source of drag, but will increase drag at lower speeds when friction is the dominant source of drag.

12.3.3 Keel coolers

Many fishing vessels audited in FVEEP have external keel coolers, but their presence or absence was not noted for most vessels. Adding an external keel cooler to an otherwise smooth keel can increase vessel resistance by 13% [7].

12.3.4 Propeller design

FVEEP has not recorded data on the propeller model used in vessel's surveyed (in many cases, this information may not be available). However, [7] indicates that installing an optimal propeller can reduce fuel consumption by 10%.

References

[1] FFM100 Fuel Flow Monitor User's Manual, Maretron, 2015. [Online]. Available: https://www.maretron.com/support/manuals/FFM100UM_1.4.html. [Accessed: 02-Feb-2018].

[2] B. Holden, CEA series accuracy, Binsfeld Engineering Inc, 06-Jun-2017.

[3] United States, Department of Energy, Energy Efficiency and Renewable Energy. Continuous Energy Improvement in Motor Driven Systems. 2014.

[4] Helmore, P. Update on ovan Oortmerssen's Resistance Prediction. 2000.

[5] Molland, A., S. Turnock, D. Hudson. Ship Resistance and Propulsion. Cambridge University Press: 2011.

[6] Tupper, E. Introduction to Naval Architecture Fourth Edition. 2004.

[7] Lamb, T. Measuring Fishing Vessel Efficiency and Ways to Improve It. SNAME: 1981.

[8] Froude, W. The Resistance of Ships. Washington: Government Printing Office: 1888.

[9] Holtrop, J. "Statistical Analysis of Performance Test Results." International Shipbuilding Progress 24.270 (1977): 23-28.

[10] Yamagata, Masao. "Model Experiments of the Combined Effect of Breadth of Hull and Propeller Revolutions upon the Propulsive Economy of Single-Screw Ships." Journal of Zosen Kiokai 62 (1938): 7-50. Web. 4 July 2017.

[11] Taylor, David. The Speed and Power of Ships. Vol. I. New York: John Wiley & Sons, 1910. Print.

[12] International Towing Tank Conference. ITTC Recommended Procedures and Guidelines: Resistance Test. N.p.: n.p., 2011.

[13] The Specialist Committee on Powering Performance Prediction. Proc. of 24th International Towing Tank Conference, Edinburgh. ITTC, 2005. Web. 5 July 2017.

[14] Sabit, A.S. Regression analysis of the resistance results of the BSRA series. International Shipbuilding Progress, Vol. 18, No. 197, January 1971, pp. 3-17.

[15] Oortmerssen, G. A power prediction method and its application to small ships. International Shipbuilding Progress, Vol. 18, No. 207, 1971, pp. 397-412.

[16] Robinson, J.L. Performance prediction of chine and round bilge hull forms. International Conference: Hydrodynamics of High Speed Craft. Royal Institu- tion of Naval Architects, London, November 1999.

[17] Tupper, E. Introduction to Naval Architecture. Elsevier: 2013.

[18] Mustad Autoline Coastal System, Mustad Autoline, 2018. [Online]. Available: https://mustadautoline.com/products/coastal-system. [Accessed: 26-Jan-2018].

[19] Jung, Joey. Fundamentals of Lead-Acid Rechargeable Batteries. *Lead-Acid Battery Technologies*, Taylor & Francis, 2016, pp. 166.

[20] R. Ivankovic, J. Cros, M. Kakhki, C. Martins, and Pseine hours transitseine hours transit. Viarouge, Power Electronic Solutions to Improve the Performance of Lundell Automotive Alternators, in New Advances in Vehicular Technology and Automotive Engineering, InTech, 2012.

[21] M. Bradfield, Improving Alternator Efficiency Measurably Reduces Fuel Costs, Delco Remy, rep., 2008.

[22] Vane Pump & Motor Design Guide For Mobile Equipment. Vickers. 1998.

[23] 6000 watt pure sine inverter charger. The Inverter Store. Accessed Jan. 19, 2018. https://theinverterstore.com/product/6000-watt-pure-sine-inverter-charger/

[24] Alaska Fuel Prices, 2018. Pacific States Marine Fisheries Commision. www.psmfc.org/efin/data/fuel.html#AKFUEL_TOP.

[25] State Motor Fuel Taxes. American Petroleum Institute. 2017. Accessed Dec. 6, 2017. http://cdn.api.org/pdf/state-taxes/alaska.pdf

[26] Motor Fuel Tax. Alaska Department of Revenue - Tax Division. 2017. Accessed Dec. 6, 2017. http://www.tax.alaska.gov/programs/programs/index.aspx?60210

[27] City and Borough of Sitka. 2017. Accessed Dec. 6, 2017. http://www.cityofsitka.com/business/registration/index.html.