Computerized Fuel Management System for a Foss Tugboat

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A thesis
submitted in partial fulfillment
of the requirements for the degree of

Master of Science in Mechanical Engineering

University of Washington

2011

Program Authorized to Offer Degree:
Mechanical Engineering

University of Washington
Graduate School

This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
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Signature ____

Date ____

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ACKNOWLEDGEMENTS

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Garth Foss Crew

Mechanical Engineering Department: Bill Kuykendall, Huimin Guo, Maria Tovar Hopper, and Wanwisa Kisalang

DEDICATION

To my mother and father who provided support through any decision. To Grandma CC and Grandpa Don for making sure my sister and I had the best educational opportunities. To Grandma and Grandpa Hohn who were always loving, smart, and light-hearted.

1. Introduction

Marine towing is important today because of the vast amount of resources that must be shipped over water including items fabricated abroad, crude oil, and raw materials. Foss Maritime services oil and gas, container shipping, mining, fishing, and construction industries. Foss' tugboats are used by marine vessels to ensure safety, reliability, and efficiency[3].

Fuel efficiency is an important issue for environmental and economic reasons. Foss Maritime is taking steps to become more environmentally conscious by attempting to reduce the amount of fuel burnt and emissions released to the atmosphere. In addition, rising fuel costs will become increasingly economically burdensome to Foss Maritime. Foss Maritime recognizes that there is potential for their fleet to be more fuel efficient, but most of its tugboats do not have sufficient instrumentation or data to fulfill that potential.

The Garth Foss is a tractor tug that assists the largest ships. The Garth is hired to assist oil tankers in the endeavour ship class, which can hold up to one million gallons of oil, and bulk cargo carriers, which can hold up to 360,000 deadweight tonnage of cargo[6]. The Garth consumes up to 430 gallons per hour. Consequently, the Garth potentially could save thousands of gallons per year with modest piloting adjustments and small improvements of fuel efficiency.

The Computerized Fuel Management System proposed in this paper is to provide insight into the fuel efficiency of the Garth Foss. The Computer Fuel Management System refers to a combined system of hardware, to measure and transfer important data about the Garth Foss to a laptop, and software, to record and present the information. Through development and implementation, the Computerized Fuel Management System will record data that allows for greater understanding of how the Garth Foss functions, such as how it is piloted and the characteristics of its drive system. The final implementation of the Computerized Fuel Management System will provide insightful recommendations, based on the data collected, to the crew of the Garth Foss to enable them to reduce fuel consumption.

1.1 Research Objectives

The objective is to create and deploy a Computerized Fuel Management System on-board the Garth Foss, which will provide information to the crew to help pilot the tugboat in a more fuel efficient manner.

The objective of the project, as defined in the *Project Proposal* [2], has been:

> "To complete the initial phase of the development of a computerized fuel management system for Foss Maritime. The resulting system (resulting from this phase) will operate on a Foss tug. It will be comprised of sensors that measure (1) the fuel consumption rate, (2) the RPM of the main engines, and (3) the position of the vessel (longitude and latitude, from GPS measurements) and an algorithm that processes those signals, so as to display, in the pilothouse, in real-time, the current fuel efficiency (e.g., gallons per nautical mile over ground) and, for the ongoing operation, the total amount of fuel consumed to the present time. In addition, by utilizing other data, such as, for the ongoing operation, the destination and the intended completion time, and historical data, such as the average fuel efficiency for this specific vessel under similar conditions, the system will also estimate and display changes in the total amount of fuel required to complete the ongoing operation and changes in the time required to complete the ongoing operation, both versus changes in the RPM of the main engines."

1.2 Research Plan

The following research plan outlines the main steps to implement the Fuel Management System:

1. Install the required hardware components to measure the Garth's position, vessel speed, engine speed (rpm), and fuel consumption.

2. Develop the initial software components of the Computerized Fuel Management System to store and present real-time and historical data. Deploy the first realization of

the Computerized Fuel Management System and collect data for an extended period of time.

3. Analyze the fuel consumption data collected to see how fuel is utilized over various trips. Identify scenarios of potential ways to save fuel. (Results are presented in Chapter 4. Current Piloting Methodology)

4. Establish new fuel consumption curves that illustrate the relationships of the engine configuration and the resulting vessel speed. (Results are presented in Chapter 5. Fuel Consumption Curves)

5. Create a simplified estimation method to estimate the total fuel consumed during a “trip” or “job.” Verify the accuracy with recorded trips. As well, predict total time of travel and fuel consumed at alternative engine speed (RPM) values. (Results are presented in Chapter 6. Simple Estimation and Prediction Capabilities)

6. Design and program a new realization of the software application component of the Computerized Fuel Management System to use the simple prediction method in real-time. The new realization will need to include a way to know the route it is traversing, without adding significant burden to the crew. Design the application to provide information to the crew to show the total predicted fuel that will be consumed to accomplish the current trip with the current engine configuration. (Results are presented in Chapter 7. New Realization of Application)

7. Launch the second realization of the Computerized Fuel Management System, and collect more data for future analysis. Show crew how to use the new software application.

2. Background

This section will describe the background of the test bed, the preliminary fuel consumption study, and limitations of the instrumentation on-board. First, the test platform, the Garth Foss, will be described. The preliminary study will be described, and the implications it had on our project. Next, the types of controls and indicators for systems and measurements that are used on-board will be described.

2.1 Garth Foss

The Garth Foss is a 350 ton tractor tug that can burn up to 450 gallons per hour. Table 1in Appendix A: Garth Foss Properties list other characteristics of the Garth Foss. The Garth is different than most ships, and even most tugboats, because of the unique Voith Schneider Propeller and Drive System installed. The Voith Schneider Propeller and Drive System were first installed on tugboats in 1954 to generate “thrust steplessly, precisely, and fast into all directions”[1]. Unlike most traditional propeller systems, that have sets of gears that must be stepped through, Voith Drives have a single fixed set of gears between the engine and the axis of the set of Voith Propellers. Traditional propellers are usually fixed and provide thrust in only one direction. The complex system of Voith Propellers allow for variance of the magnitude and direction force, which enables superior maneuverability compared to traditional fixed drives or Z-drives.

The Voith Schneider Propellers are installed in a lateral configuration, one on the port side and one on the starboard side, in the front (bow) of the vessel. Voith Schneider Propellers, and the axis at which they rotate around, point straight down. They rotate in opposite directions to prevent large objects from being trapped between the drives when going forward. Tugboats equipped with Voith Drives do not require rudders, but have a fixed skeg for stabilization installed on the rear (stern) section of the keel. A view from the starboard side can be seen in Figure 1, which illustrates the Voith Schneider Drive on the bottom right side of the image and the skeg on the lower left side.

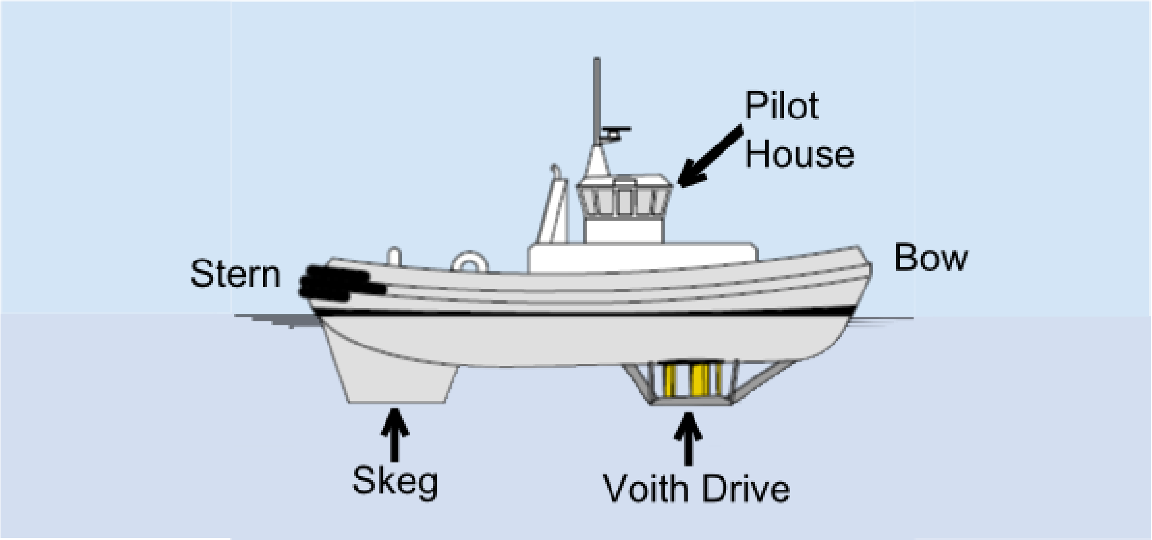


Figure 1: Illustration of starboard view of a tugboat with a pair of Voith Schneider Drives

The Voith Schneider Drive System uses a throttle and propeller pitch system that provides more variability than traditional drive systems, which only have a throttle. An in-depth description of both the throttle and the propeller pitch controls are presented in Appendix D: On-Board Controls. Because of the Voith Schneider Drive System, exceptional scenarios can be precisely executed. An in-depth description of the various scenarios and use of controls are presented in Appendix F: Voith Drive Scenarios.

2.2 Fuel Efficiency Pilot Study by Aspin, Kemp and Associates

In 2008, Foss Maritime commissioned Aspin, Kemp, and Associates (AKA) to quantify the general trends of fuel consumption for ships in the Foss Maritime fleet. Previous to the AKA study, the piloting methods of the Garth relied on preferences and intuition of the captain. The crew, previously, was not given a baseline suggestion to run the Garth on trips that did not have a tight time schedule. It is desirable for the crew to spend less time in transit, so they often travelled at higher speeds. When asked to be more fuel efficient, the ship’s captains set the engine speed (RPM) of the Garth to be near “sweet spots,” where the engines sounded like they were running efficiently.

The results presented by Aspin, Kemp, and Associates are shown in Figure 2, which plots effective power and fuel consumption rate, along the y-axis, over a range of engine speeds along the x-axis. Aspin, Kemp and Associates concludes that the higher speeds are less economical; their suggestion was that the “most economical” engine speed to operate the Garth Foss at is 650 RPM, which should result in a vessel speed of 10 Knots [5].

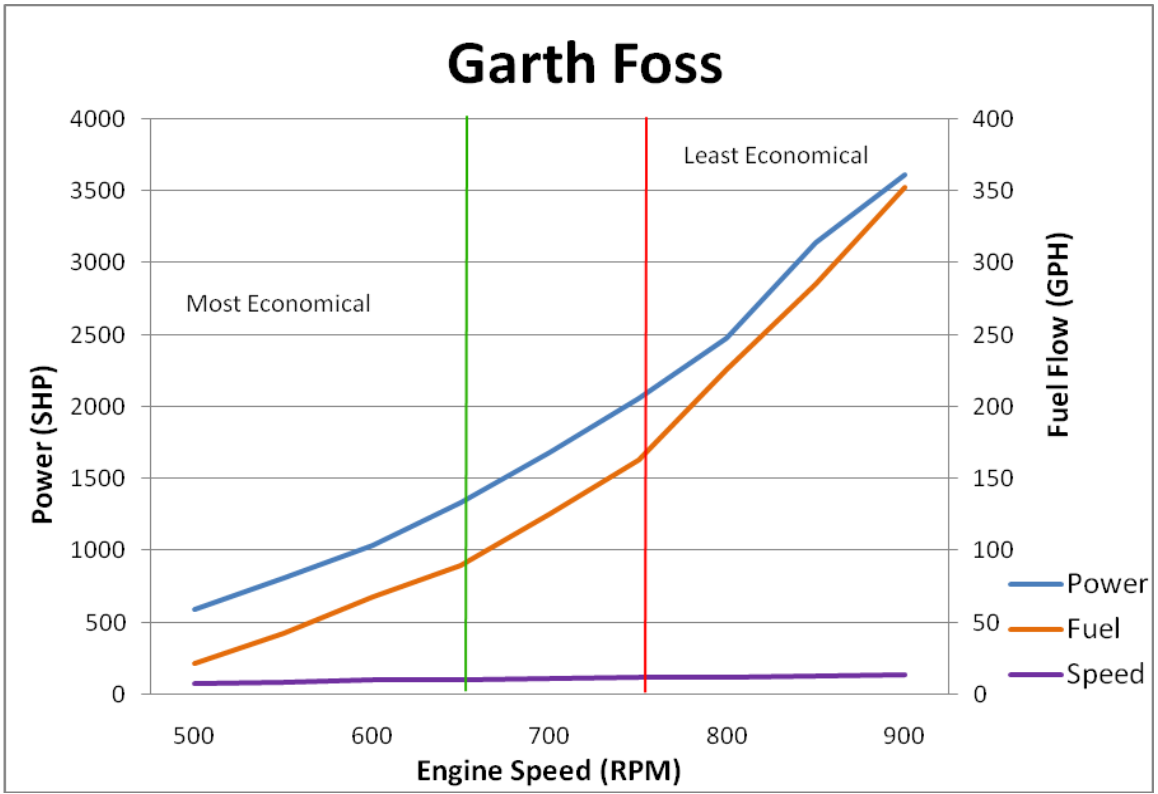


Figure 2: The results from the study performed by Aspin, Kemp and Associates [5]

However, the pilot study contained limitations. The fuel flow was measured using ultrasonic flow meters, which are noninvasive and have no temperature compensation. The Garth was only tested for one day and in one set of conditions. This limited the tidal current conditions faced by the Garth, and prevented the study from containing a large set of data to be able to compare the amount of fuel measured by the meters and the hand-recorded amount of fuel used. Finally, the trend line concluded by Aspin, Kemp and Associates does not take in account the variance of the propeller pitch angle described in Appendix F: Voith Drive Scenarios.

While the pilot study is not completely accurate, Figure 2 further validates the importance of having an accurate fuel consumption characterization. If the data in Figure 2 roughly captures the trend of fuel consumption, there is a large potential for improvements to the fuel economy of the Garth Foss by reducing the engine speed. New fuel meters that will be installed on the Garth will enable for a more accurate fuel characterization curve, which be proven to be more accurate by comparing the amount of fuel measured by the meters to the known amount of fuel loaded on-board over months of time, instead of just a single day. The results and conclusions using the new meters are presented in Chapter 5. Fuel Consumption Curves.

3. Deployed Computerized Fuel Management System

The instrumentation on-board the Garth, previous to this project, functioned only as real-time indicators. The engine speed, current GPS coordinates, and current speed were displayed in the pilot house, but none of these values were recorded. Consequently, quantitative analyses of fuel efficiency and methods to reduce fuel consumption were not possible. The first realization of our Computerized Fuel Management System enables data to be saved for real-time or historical analysis.

The Computerized Fuel Management System consists of a data collection system and a graphical user interface (GUI). The data collection system refers to the hardware used to sense the data, the methods used to transfer the data, and software used to store the data. The GUI refers to the portion of the software application that takes input from the user and displays processed information to the user.

Figure 3 shows a simplified version of the logic within the Computerized Fuel Management System. This realization of the Computerized Fuel Management System works to achieve the first set of goals from the *Project Proposal* [2]:

> “The resulting system (resulting from this phase) will operate on a Foss tug. It will be comprised of sensors that measure (1) the fuel consumption rate, (2) the RPM of the main engines, and (3) the position of the vessel (longitude and latitude, from GPS measurements) and an algorithm that processes those signals, so as to display, in the pilothouse, in real-time, the current fuel efficiency (e.g., gallons per nautical mile over ground)” and, for the ongoing operation, the total amount of fuel consumed to the present time.”

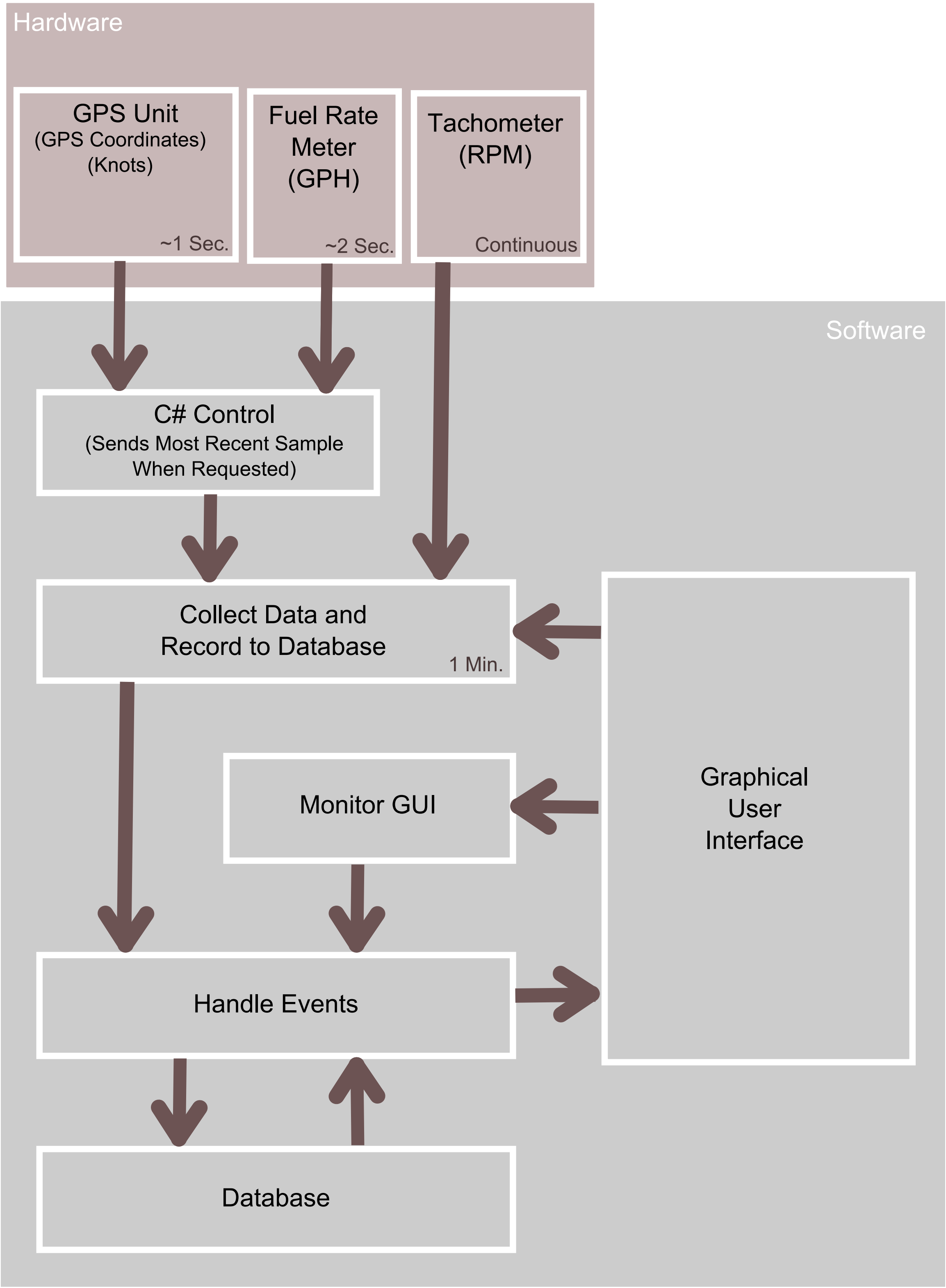


Figure 3: Simplified block diagram of the logic behind the Computerized Fuel Management System. If a block executes at a regular time, it is indicated in the lower right corner of that block.

Data Collection System

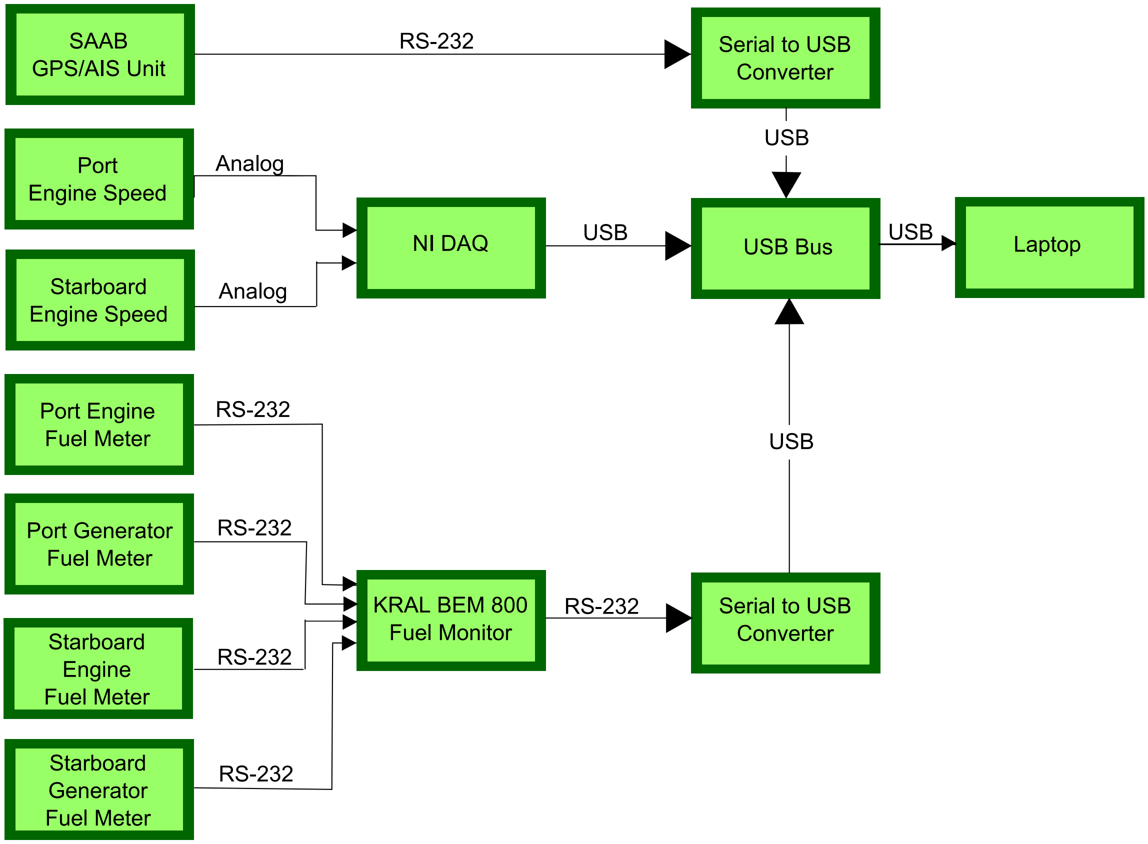
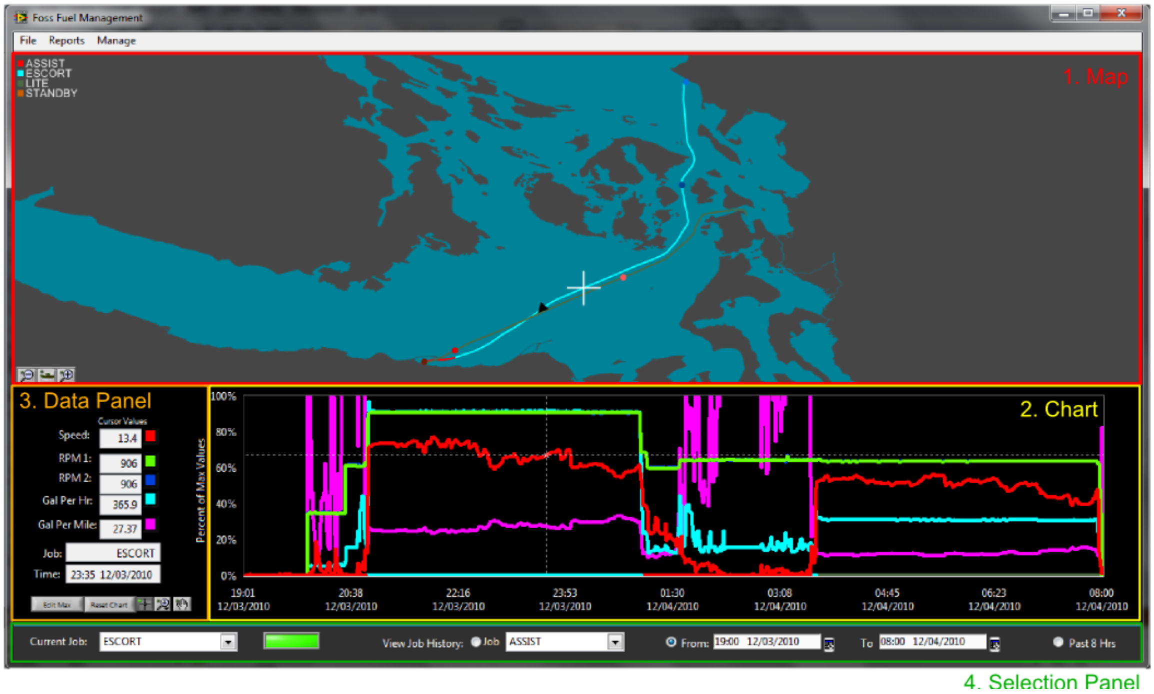


Figure 4: Diagram of data flow from the indicators to the Computerized Fuel Management System

Figure 4 illustrates how the indicators are connected to the laptop. The instruments send data at various rates, which are continuously monitored by the Computerized Fuel Management System. At the end of each minute, the most recent values are recorded, along with the time and the current job. The database can be accessed through the GUI or by using Microsoft Access.

Graphical User Interface

The graphic user interface (GUI) provides functionality to display real time and historical data for on-board real-time and historical data analysis. The GUI has four main graphical components, 1) Map, 2) Chart, 3) Data Panel, and 4) Selection Panel. These sections are shown in Figure 5. These components work together to give a complete picture over a set of data and at each data point. Each part will be expanded on separately in this chapter.



Speed: 13.4 🟥
RPM 1: 906 🟩
RPM 2: 906 🟦
Gal Per Hr: 365.9 ■
Gal Per Mile: 27.37 ■
Job: ESCORT
Time: 23:35 12/03/2010

Current Job: ESCORT
View Job History: ● Job ASSIST ◉ From: 19:00 12/03/2010 To 08:00 12/04/2010 ● Past 8 Hrs

Figure 5: GUI with labels of four main sections

3.1 Map

The Map depicts the land, in gray, and the water, in blue, for geographical reference to the engine conditions shown in the Chart and Data Panel. For any set of data, the Map and Chart contain the same data set. Certain tools are specific to the Map including the job list, route, map cursor, direction indicator, and map controls.

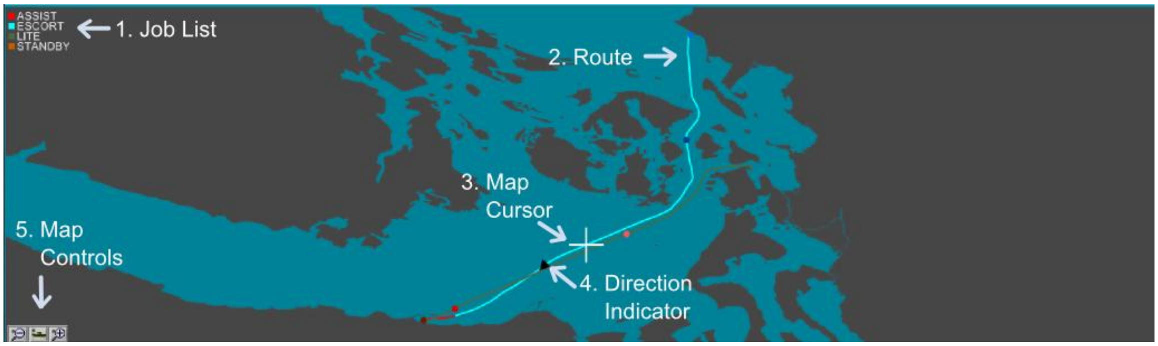


Figure 6: Map with labels of features

Job List

The job list contains a list of every type of job that is currently plotted on the Map. The color box next to each job expresses the color in the Route and on the Chart.

Route

The route connects all of the historical GPS coordinates. A break appears where there is a gap in time of the dataset. The color of the route indicates the type of job, which is listed in the Job List.

Map Cursor

The map cursor snaps to the closest GPS coordinate in the route when a point on the Map is double clicked. The data at that point is shown in the Data Panel and the Chart Cursor is moved to the corresponding point on the Chart.

Direction Indicator

A direction indicator is placed on the Route to show which direction the Garth was travelling at noon and midnight. A black arrow corresponds to midnight, and a white arrow corresponds to noon. The direction indicators are useful when large sets of data are being analyzed. Every three hours, a color marker is placed on the route to show how far the Garth has travelled over that time and where it was at certain times of the day.

Map Controls

There are three buttons that are a part of the Map Controls. From the left, there is a zoom-out button, a “follow boat” button, and a zoom-in button. Zoom-out and zoom-in buttons are self-explanatory. The “follow boat” button continuously pans and rotates the map to have the Garth at the center of the screen on the map and travelling in a vertical direction on the screen. The “follow boat” function is only available when the Garth is collecting live data and the “Past 8 Hours” option is selected in the Selection Panel.

3.2 Chart

The Chart displays data over a set of time. It plots the date and time, along the x-axis, and “Percent of Max Values,” along the y-axis. The chart contains solid-color lines, which match the color boxes in the Data Panel, representing speed, two main engine speeds, gallons per hour (GPH), and gallons per nautical mile (GPM). Both GPH and GPM are calculated using the data over a single data point. To make all of the lines fit on a single axis, they are each scaled according their own “Max Value,” which is edited in the Data Panel. This enables the user to make all of the lines remain in the plotted area.

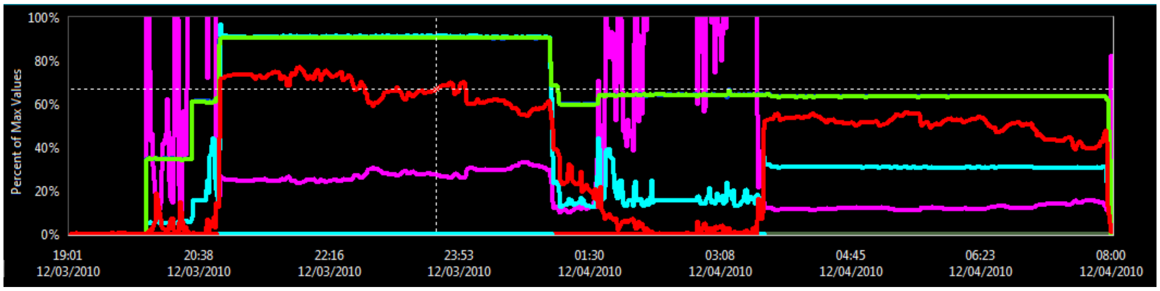


Figure 7: Close-up of the Chart

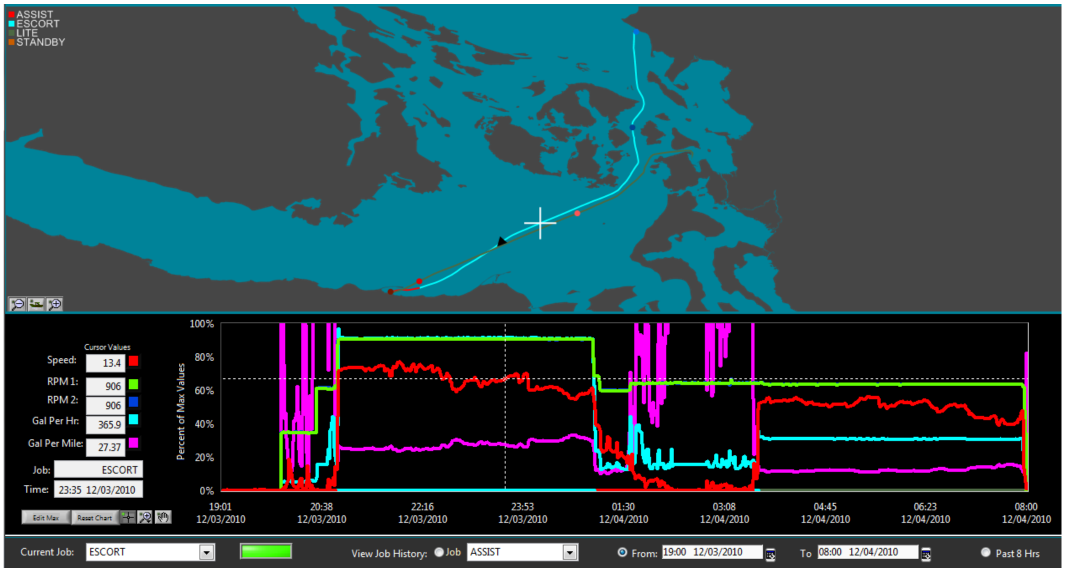
Along the bottom is a variable color line that represents the type of job, which is not scaled because jobs do not have a numerical value. The color of the job line matches the color of the route on the Map. Finally, any point on the Chart can be chosen using the chart cursor. The chart cursor snaps to a single line, and all of the data at that time point is shown in the Data Panel. The map cursor also snaps to the corresponding point on the route.

3.3 Data Panel

The Data Panel is able to show the details of any point in the chosen dataset and the maximum values used to plot the data fields. In both modes, which will be called Cursor Mode and Edit Max Mode, a color box next to each data field control or indicator signifies which color on the chart is represented. The color boxes also allow the user to turn off any data field on the Chart by clicking on the color box. The color box will then turn black, and the data field line will not be drawn on the chart. The next sections will describe the qualities that are unique to the Cursor Mode and Edit Max Mode.

3.3.1 Cursor Mode

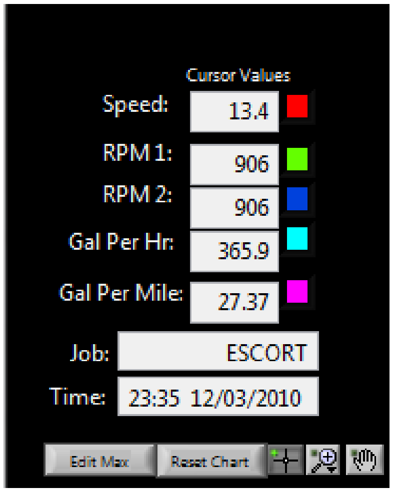
In Cursor Mode, single points in the dataset, which are shown on the chart and the map, can be chosen. The exact values are shown in the data boxes on the left. The vessel speed (Knots), engine speed (RPM) of each main engine, fuel consumption rate over time (GPH), fuel consumption rate over distance (gallons per nautical mile), time and date, and type of job are listed in the indicators corresponding to the data point chosen by the cursor.



Speed: 13.4 🟥
RPM 1: 906 🟩
RPM 2: 906 🟦
Gal Per Hr: 365.9 🟦
Gal Per Mile: 27.37 🟪
Job: ESCORT
Time: 23:35 12/03/2010

Current Job: ESCORT
View Job History: ● Job ASSIST
○ From: 19:00 12/03/2010
To 08:00 12/04/2010
● Past 8 Hrs

Figure 8: Whole GUI in Cursor Mode

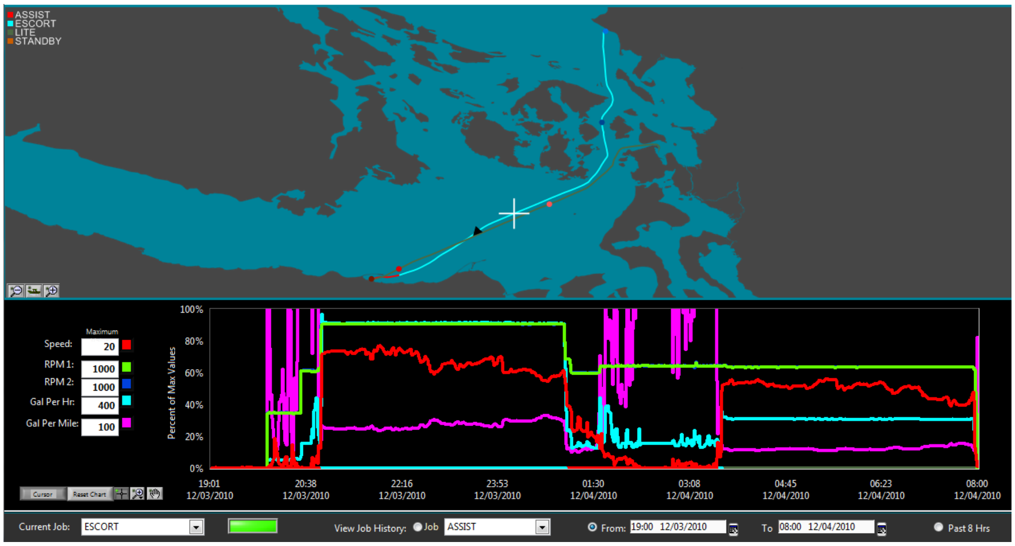


Speed: 13.4 🟥
RPM 1: 906 🟩
RPM 2: 906 🟦
Gal Per Hr: 365.9 🟦
Gal Per Mile: 27.37 🟪
Job: ESCORT
Time: 23:35 12/03/2010

Figure 9: Close-up of Data Panel in Cursor Mode

3.3.2 Edit Max Mode

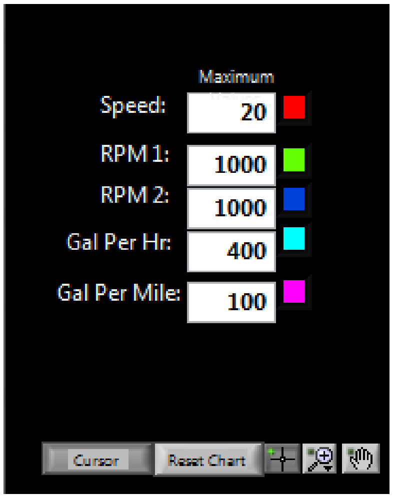
In Edit Max Mode, the data boxes turn into controls. The user can either see or change the max values, which determine the scale used in the chart. Because the job and time do not have maximum amounts, they disappear in Edit Max Mode. The cursor on the Chart also disappears, because the controls in the Data Panel do not represent a single point when in Edit Max Mode. If the maximum is changed for a data field, the corresponding line changes to reflect the dataset's proportion to the new maximum value.



Speed: 20
RPM 1: 1000
RPM 2: 1000
Gal Per Hr: 400
Gal Per Mile: 100

Current Job: ESCORT
View Job History: ○ Job ASSIST
● From: 19:00 12/03/2010 To 08:00 12/04/2010
○ Past 8 Hrs

Figure 10: Whole GUI in Edit Max Mode



Speed: 20
RPM 1: 1000
RPM 2: 1000
Gal Per Hr: 400
Gal Per Mile: 100

Figure 11: Close-up of Data Panel in Edit Max Mode

3.4 Selection Panel

The Selection Panel is the area of the chart which controls the current job selection and the dataset plotted. It also contains the “Fuel Efficiency Indicator.”

Current Job: ESCORT
View Job History: ○ Job ASSIST
● From: 19:00 12/03/2010 To 08:00 12/04/2010
○ Past 8 Hrs

Figure 12: GUI Selection Panel

Current Job Control

The first dropdown control lets the user indicate the current type of job the Garth is running. When live data is being collected, the type of job chosen is saved in the database along with the other parameters.

Fuel Efficiency Indicator

The “Fuel Efficiency Indicator” is a color box that changes between green and red when the system is collecting live data. Currently, it remains green unless the engines are running “in the red,” which is set to be above 650 RPM. This engine speed is chosen, because the AKA study suggested that it becomes less efficient to run the Garth above 650 RPM.

View Job History Controls

The next three “View Job History” radio button controls decide which type of data is going to be shown on the Map and Chart. The “Job” option allows for a single type of job to be chosen. All of the historical data designated as the selected job is then shown. The next radio button allows the user to choose a start and end point in time. All of the data collected between the two points will be shown on the Map and Chart. Finally, the last option, “Last 8 Hours,” shows all of the live data up to the past eight hours. If only data for less than eight hours is available, only that data is shown. As live data is collected, the Map, Chart, and Data Panel update to reflect the latest sample.

4. Current Piloting Methodology

There are many different types of "jobs" that are performed by the crew. A job is defined as the period of time that the Garth is executing a certain assignment. The type of job influences how the pilot will control the Garth, due to physical interactions or dependence of position and speed with other vessels. Understanding the different kinds of jobs is important when analyzing the data collected and this is the subject of Chapter 5. Fuel Consumption Curves.

There are over fifty types of jobs defined by Foss Maritime, but 95% of the time the Garth is running a lite, escort, or assist job. Many of the other job types are similar to the three main types of jobs. Figure 13 shows the three main types of jobs. Each type can be differentiated based on the mixture of location, fuel consumption rate, engine speed, and effective vessel speed (i.e. gallons per nautical mile). The reasons for which they can be differentiated are described in the following sections and illustrated in the data in Chapter 5. Fuel Consumption Curves. In addition, this chapter describes how the pilot controls the ship during each job and each job's potential for reduction of fuel consumption.

Speed: 0.18
RPM 1: 0
RPM 2: 0
Gal Per Hr: 0
Gal Per Mile: 0
Job: LITE
Time: 01:09 12/03/2010

Current Job: ESCORT
View Job History: ○ Job STANDBY
● From: 20:20 12/02/2010
To 01:10 12/03/2010
○ Past 8 Hrs

Figure 13: Screenshot of three jobs combined into a single trip on 2-3 December 2010

4.1 Lite

When the Garth is running “Lite,” it is travelling, from one destination to another, on the crew’s own time schedule. (Although, sometimes the schedule will dictate that the Garth needs to be at a destination at a certain time that requires the Garth to travel quicker.) The engine speed of lite trips is usually 620-690 RPM.

Previous to the AKA study, pilots ran the engines at higher speeds to increase the speed and reduce the time of the trip. It was felt that the faster the vessel travelled, the sooner it would reach its destination, and hence could turn off its engines sooner. The pilots often chose an engine speed that was faster, but below the threshold at which the Garth’s engines become exceedingly loud and motion becomes very turbulent. (It should be noted that running the Garth below this threshold is beneficial to the living conditions of the crew not currently on shift.)

There is a standard procedure that characterizes most lite trips. The route is selected on the navigation program either immediately preceding or following launch. The engine speed is set to the desired engine speed (RPM), and the Voith Drives’ pitch angles are set to full pitch. Even slight adjustment of the engine’s throttle and Voith Drives’ pitch angle controls are typically not required through the duration of the trip. Rare adjustments to the throttle only occur when there are unpredicted changes of the tidal currents or schedule.

The wheel is used to set the bearing of the Garth towards to first point in the planned route. The navigation program conveniently displays the bearing required. The autopilot is then turned on. The autopilot maintains a specified bearing by mechanically controlling the wheel. It however does not have control of going towards a specific point. It is not aware of side-to-side drift, and the crew must adjust the bearing periodically if there is significant drift. Otherwise, the bearing is left alone until the next route point is reached. As the Garth transitions from one leg of the route to the next, the bearing is usually adjusted one to three times to round out a turn. In comparison to the length of the trips, the distance from the preplanned route is never very far. The Garth is usually within half a mile of a preplanned route.

Lite trips have the most potential for fuel savings and have been identified by Foss Maritime as the type of job that we should focus on. These trips are able to conserve fuel, because the vessel speed, time of trip, time of launch, and engine settings are variables that can be adjusted, within the limits of the schedule and energy of the crew, to save fuel. Initial fuel savings have already been observed due to the installation of the KRAL fuel monitor in the pilothouse. The pilots often check the current fuel consumption rate and try to keep it under a certain level. However, when travelling into a current that is reducing the speed over ground, the engine speed is often increased even though a certain time of arrival is not required. The same logic as to using higher engine speeds, such as the 800 RPMs before the meters were installed, were used to explain why the throttle is raised in a tidal current that reduces the vessel speed of the Garth.

4.2 Escort

Escort trips are characterized by the Garth leading, flanking, or following another vessel. The speed is determined by the escorted ship. There are two ways the pilot may adjust the Garth's controls. One is to set a higher engine speed to maintain for the whole trip, and adjust the Voith Drive pitch angles as necessary to maintain a steady position in relation to the ship. Or the pilot can set the controls to full pitch and adjust the throttle as needed. Setting the Garth at a higher engine speed and staying below full pitch allows for a quick application of thrust as the pitch angles can be quickly changed to full pitch. Otherwise, if the throttle must be adjusted to obtain more thrust, the time it takes for the thrust to be applied is longer. When the main vessel desires to keep a higher speed, the Garth runs at full throttle and full pitch.

These trips are potentially a source of some fuel savings. Fuel cannot be saved by lowering the vessel speed, because the position from the escorted vessel is necessary to maintain. However, there are possibly methods that can balance the engine speed and the magnitude of the pitch angles, while lowering fuel consumption and maintaining the required vessel speed.

4.3 Assist

An assist job requires the tugboat to help the ship approach or keep the ship near the dock through applied force. Force towards or away from the ship is applied by using the stern of the ship or with a tether line connected to the ship. The tug can be positioned on one of the sides or on the stern of the ship being assisted. Assist jobs are usually at the beginning and/or end of an escort job. Although, more tugs may be required for the assist job than the escort job.

An assist job requires large amounts of thrust applied quickly in different directions. To satisfy this requirement, the engine speed is kept at high RPMs. A large force can then be quickly applied towards or away from the assisted ship.

This type of job is purely functional, and requires the steadfast concentration of the pilot. These jobs also only account for a small percentage of the total fuel consumed. Therefore, trying to reduce fuel consumption during assist jobs is not practical.

5. Fuel Consumption Curves

The previous study performed to characterize the ship performance by Aspin Kemp & Associates[5] (AKA) is beneficial in multiple facets. The fuel curves obtained have given the crew on board a better understanding at which points the fuel efficiency degrades in performance. As well, the data has given us a baseline to compare the recorded data when our new fuel management system was installed. The new fuel management system includes more accurate fuel meters than the AKA study. Therefore, it is important to use the data collected to verify and update the previously accepted characterizations of the Garth. The main sets of data compared in Figure 14, Figure 17, and Figure 18 are Fuel Consumption Rate (GPH) vs. Engine Speed (RPM), Vessel Speed (Knots) vs. Engine Speed (RPM), and Vessel Speed (Knots) vs. Fuel Consumption Rate (GPH).

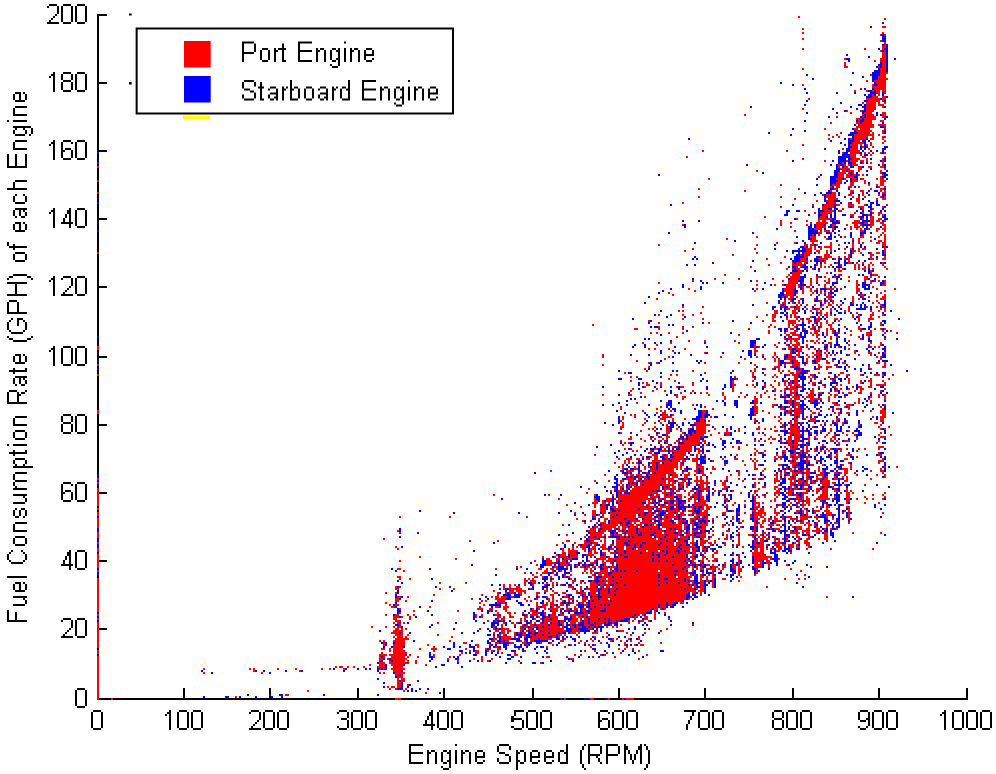


Figure 14: Fuel Consumption Rate (GPH) of Each Engine vs. the Engine Speed (RPM) data collected August 11, 2010 - January 27, 2011

5.1 Full Dataset

As illustrated by Figure 14, Figure 17, and Figure 18, the relations between engine speed, fuel consumption rate, and vessel speed are influenced by several variables that complicate the relations. To identify the relationships that are the most important, the data when the Voith Drive pitch angles are at “full pitch” should be isolated from the rest of the data.

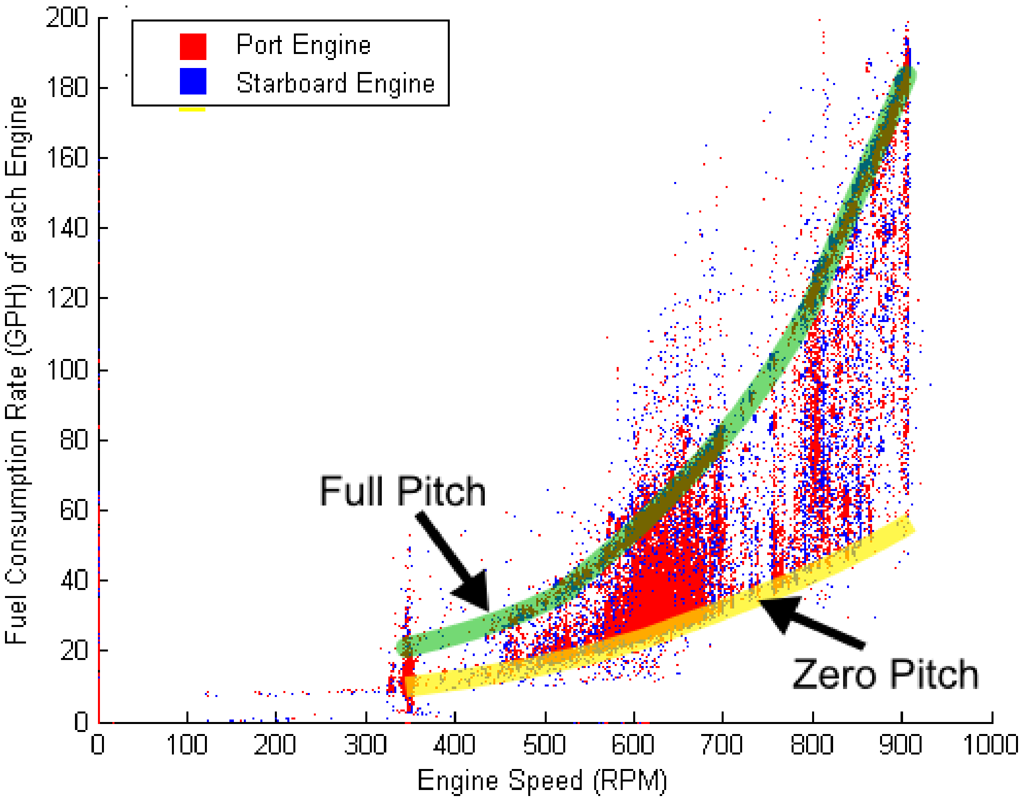


Figure 15: Fuel Consumption Rate (GPH) of Each Engine vs. the Engine Speed (RPM) data collected August 11, 2010 - January 27, 2011

Figure 15 is a plot of the fuel consumption rate (GPH) vs. the engine speed (RPM), which illustrates a range of fuel consumption rates (GPH) for each engine speed (RPM). This range is the presumed trend between the way the pitch angles are applied and the resulting relation of engine speed to fuel consumption rate of each engine. (For now, this is only a presumption, because the pitch angles are not being recorded. Further discussion is presented in section 8.2 Voith Drive Pitch Angle Sensor.) When the propellers are at “zero pitch,” the engines burn the minimum amount of fuel to accomplish the engine speed controlled by the throttle. As the propeller pitch angle is increased, a force is output to the water and a resulting load is applied from the propellers back to the engine. To overcome the resulting force, the fuel consumption rate is increased so that the engine speed is not affected. The same logic would conclude that "full pitch" would generate the most force and require the highest fuel consumption at every engine speed. The fuel consumption values in between represent the propeller pitch angle values between zero pitch and full pitch.

The data that lies outside of the zero pitch and full pitch trend lines can be attributed to the discretization of fuel consumption data. While most of the data being recorded represents the state within a two second range, the fuel consumption data recorded is the total amount of fuel burnt over the entire minute, as can be seen in Equation 1.

$$Fuel\ Consumption\ Rate\ (t) = \frac{Total\ Fuel\ (t) - Total\ Fuel\ (t-1)}{Time\ (t) - Time\ (t-1)} \quad [1]$$

Consequently, the recorded fuel rate values are imprecise, because the state at the beginning of the minute may be vastly different than the final state for other data fields. For example, the Garth often is at an approximate cruise speed with the engine running at 900 RPM, a fuel consumption rate at 300 GPH, and a vessel speed of 15 knots. The Garth's throttle may then be adjusted so that the engine's speed is 600 RPM. The change of engine speed occurs almost instantly. The vessel speed may take a half minute to three minutes to adjust. While the correct data should approximately show 600 RPM, 120 GPH, and 10 knots, the actual data recorded may show 600 RPM, 250 GPH, and 11 knots. Therefore, during the transition period, the fuel consumption rate to engine speed relation and vessel speed is not accurately reflected by the data collected.

Figure 16 highlights the areas that have fuel consumption rates that do not accurately portray the relation from the engine speed to fuel consumption rate of each engine. Highlighted area A includes data points that were recorded right after the throttle was drastically reduced in speed. Highlighted area B includes data points that were recorded right after the engines were turned on or the throttle was dramatically increased.

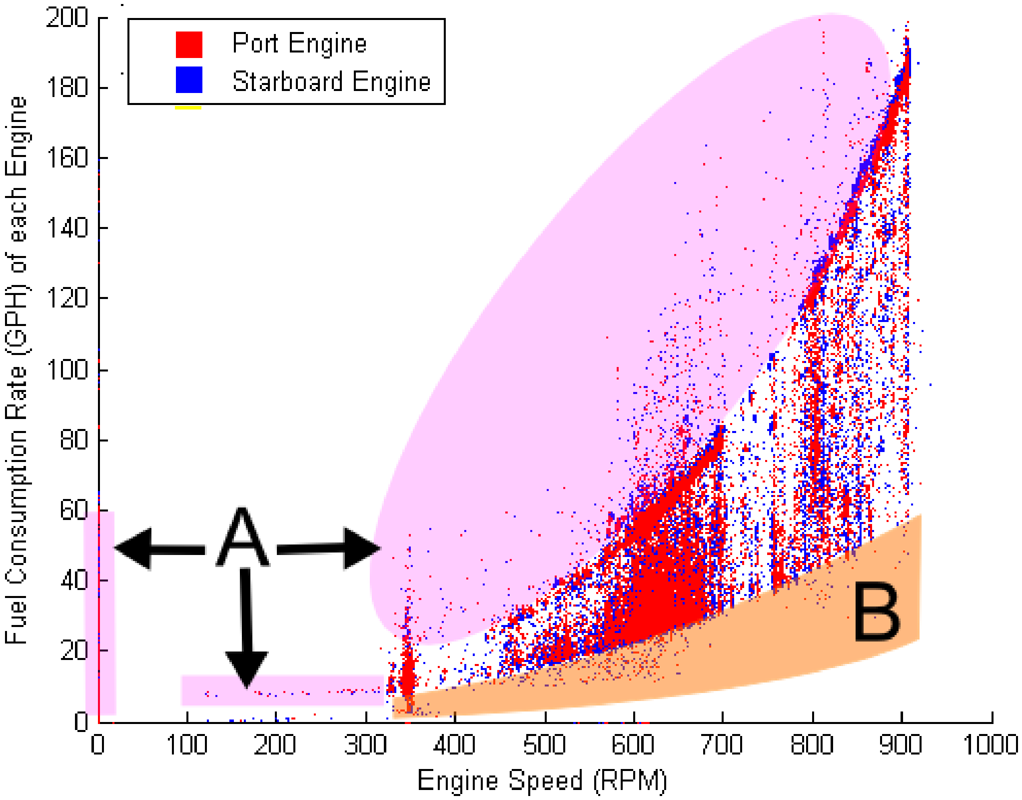


Figure 16: Fuel Consumption Rate (GPH) of Each Engine vs. the Engine Speed (RPM) data collected August 11, 2010 - January 27, 2011

The other relations, vessel speed (Knots) vs. engine speed (RPM), and vessel speed (Knots) vs. fuel consumption rate (GPH), are plotted in Figure 17 and Figure 18. (Note: Even though the two engines are fixed to maintain nearly the same engine speed, the Starboard Engine has a tendency to be slightly faster and therefore will consume more fuel at the same speed. This effect is exaggerated at higher engine speeds.) Both of these figures are subject to the same errors caused by the data collection methods, as previously described.

Both Figure 17 and Figure 18 are also prone to vessel speed deviation due to external influences on vessel speed. One such outside force is local currents. While in transit, the tidal currents can produce a local current that increases or decreases the vessel speed of the Garth. Therefore, corresponding to a single fuel consumption rate and engine speed, a range is produced of vessel speed values. This effect creates horizontal blotches of data in Figure 17 and vertical blotches of data in Figure 18.

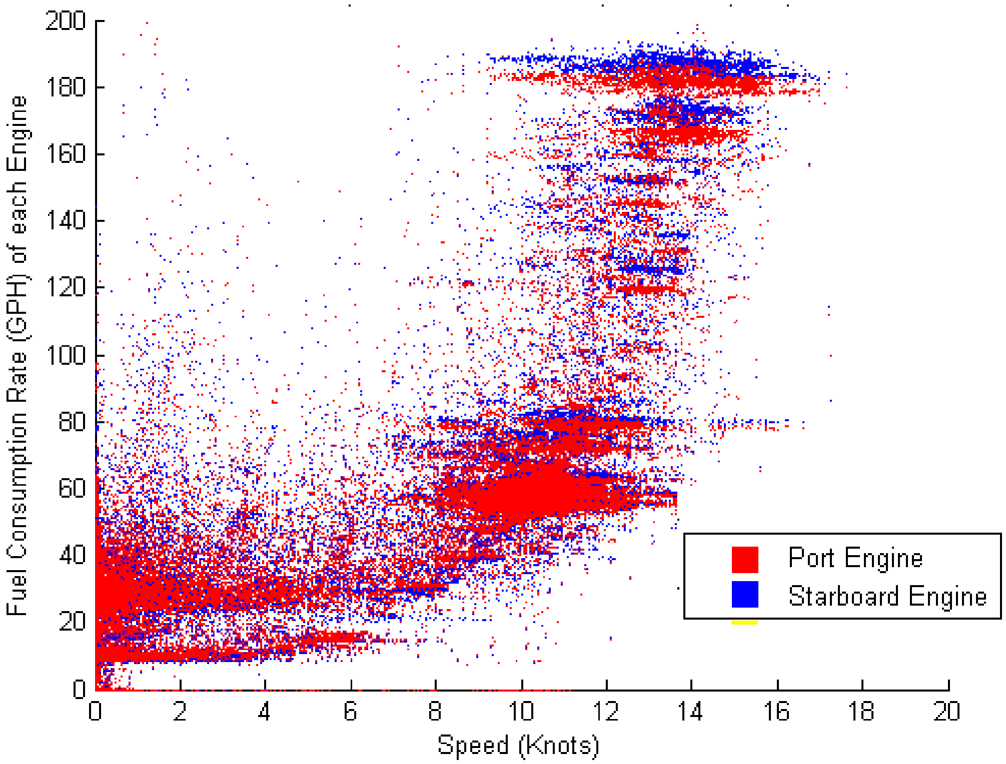


Figure 17: Fuel Consumption Rate (GPH) of Each Engine vs. the Vessel Speed (Knots) data collected August 11, 2010 - January 27, 2011.

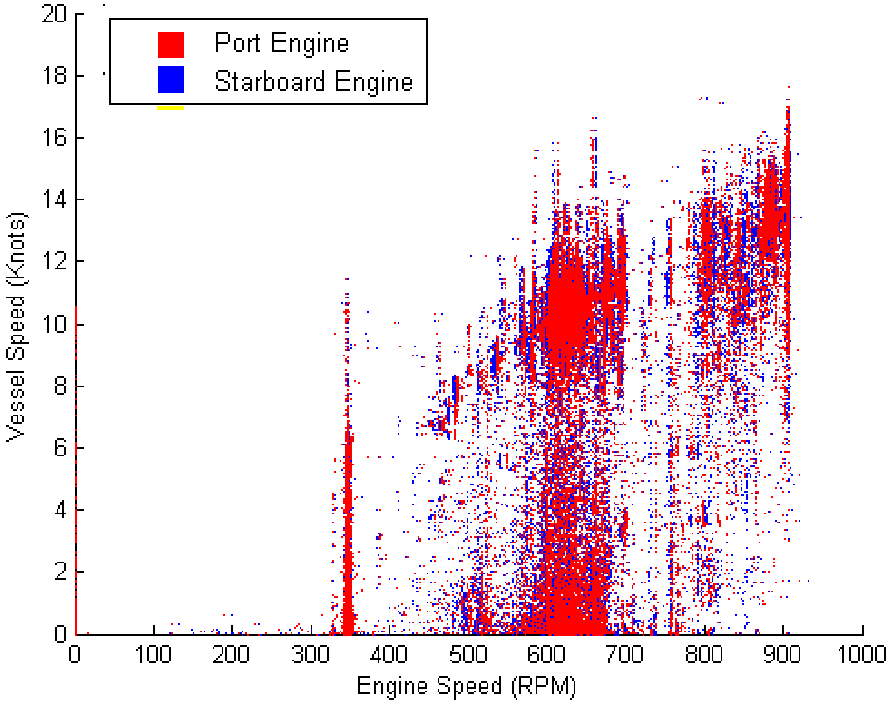


Figure 18: Vessel Speed (Knots) vs. the Engine Speed (RPM) data collected between August 11 and January 27.

The other external force that alters the data is the counterforce applied by the assisted ship. The thrust being generated by the Voith Drives translates into force applied to the assisted ship, rather than in realization of the expected vessel speed. Therefore, the areas highlighted in Figure 19 and Figure 20 correlate with assist job scenarios described in Section 4.3 Assist.

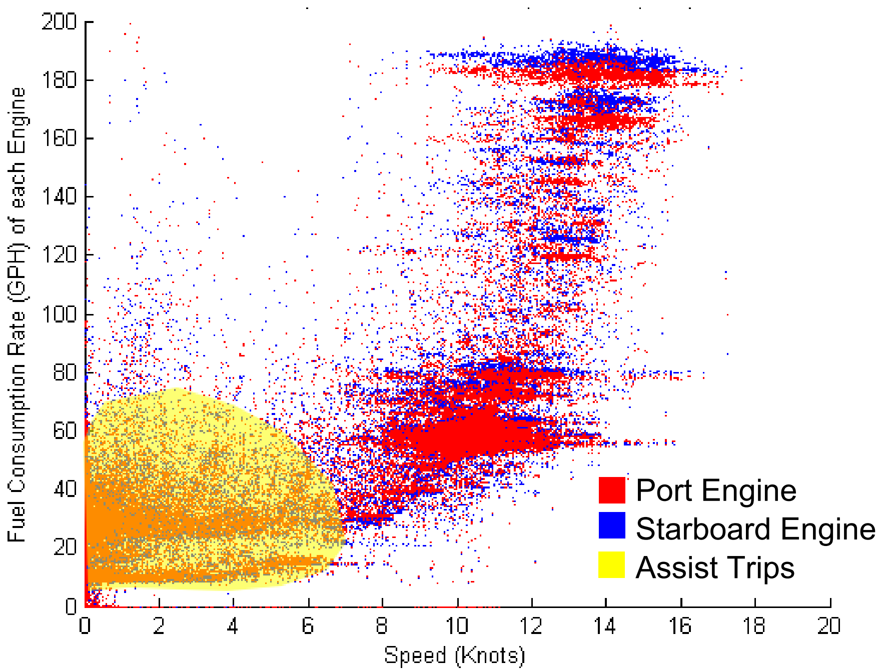


Figure 19: Fuel Consumption Rate (GPH) of Each Engine vs. the Vessel Speed (Knots) data collected August 11, 2010 - January 27, 2011. The assumed Assist trips are indicated in yellow.

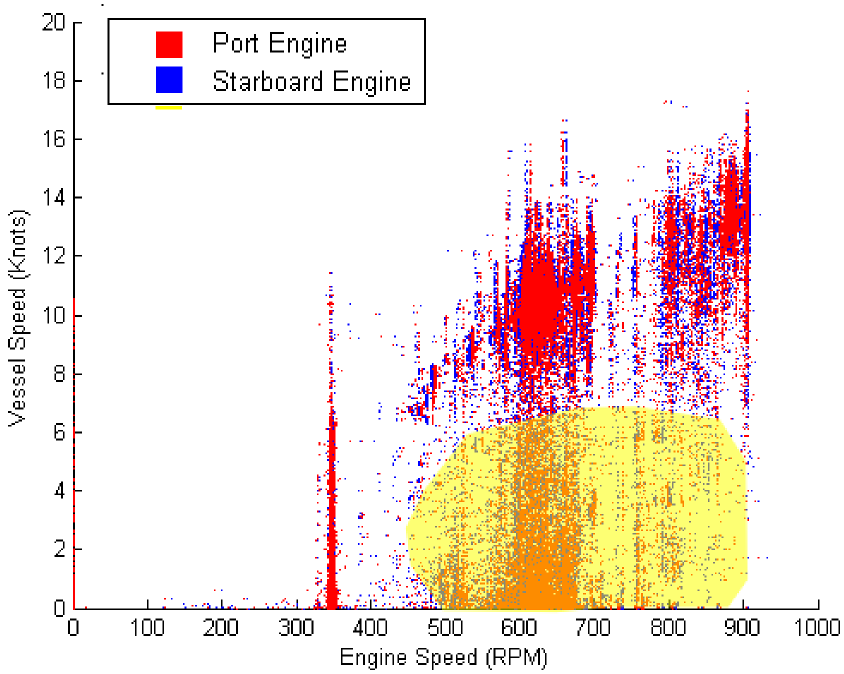


Figure 20: Vessel Speed (Knots) vs. the Engine Speed (RPM) data collected between August 11 and January 27. The assumed Assist trips are indicated in yellow.

5.2 Full Pitch Dataset

As per the previous discussion, it is necessary to identify the full pitch data points. As described in Section 4.1 Lite, data points corresponding to when the Garth is running at full pitch are the most important. The combination of a lite job and full pitch is where the fuel consumption rate should be optimized to burn the least amount of fuel to accomplish the lite job. Using the method described in Appendix B: Isolating the “Full Pitch” Dataset, the resulting fuel characterization curves are plotted in Figure 21, Figure 22, and Figure 23.

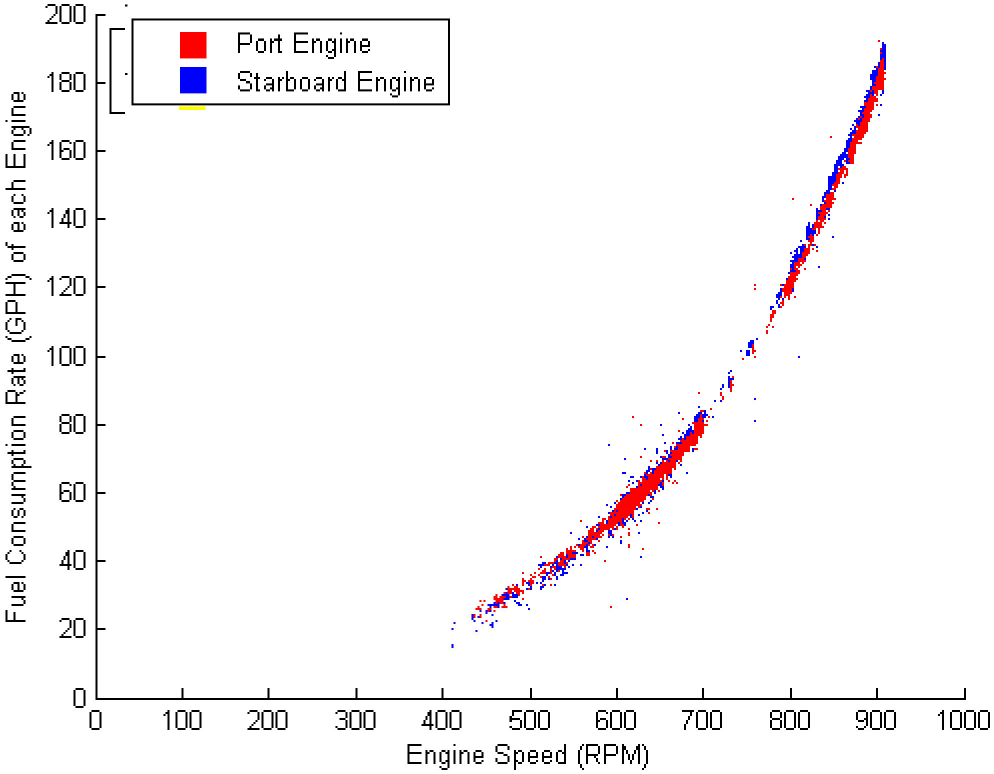


Figure 21: Fuel Consumption Rate (GPH) of Each Engine vs. the Engine Speed (RPM) of the full pitch data collected August 11, 2010 - January 27, 2011

In Figure 22 and Figure 23, the noise, which correlates to the data recorded during assist jobs, is mostly discarded in the procedure to isolate full pitch data. Some stray points remain, because occasionally the Garth is required to operate at full pitch during an assist job to generate the required thrust. The correlations including vessel speed contain some of the previous noise characteristics due to natural forces, which are from current, wind, or waves.

With the full pitch dataset, trend lines are calculated using a least squares third-order best fit algorithm. The corresponding trend lines and equations are presented in Appendix C: Final Trend Lines and Equations. These trend lines are used in Chapter 6. Simple Estimation and Prediction Capabilities and Chapter 7. New Realization of Application to make estimations at different engine speeds.

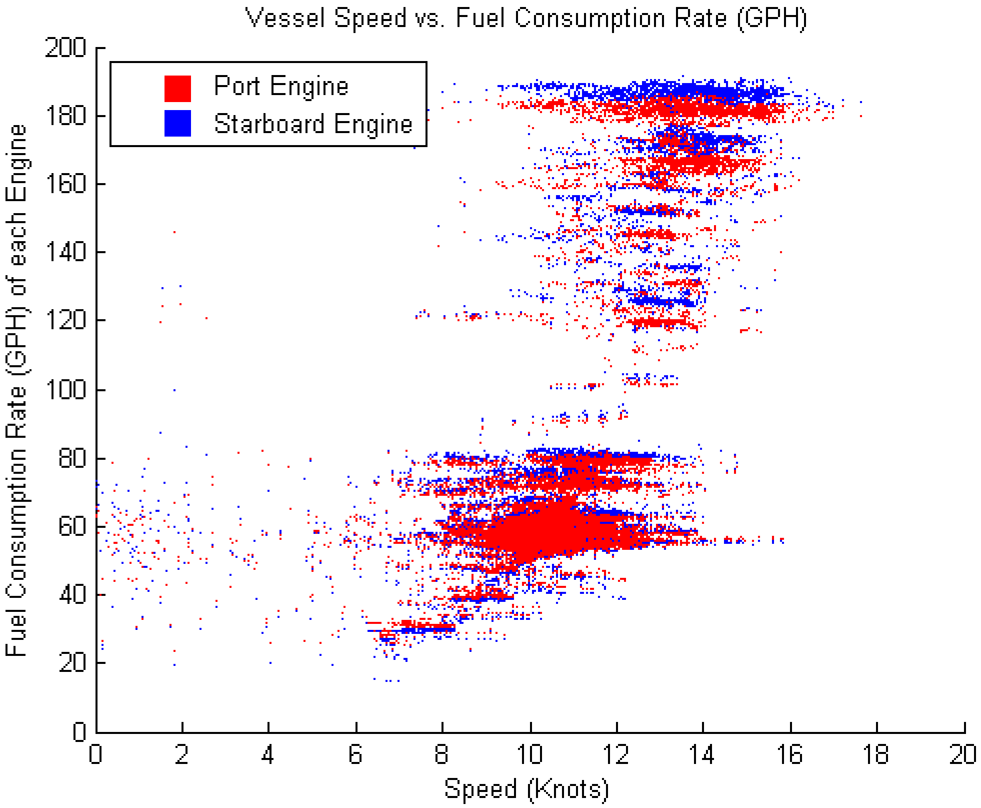


Figure 22: Consumption Rate (GPH) of Each Engine vs. the Vessel Speed (Knots) of the assumed full pitch data collected August 11, 2010 - January 27, 2011

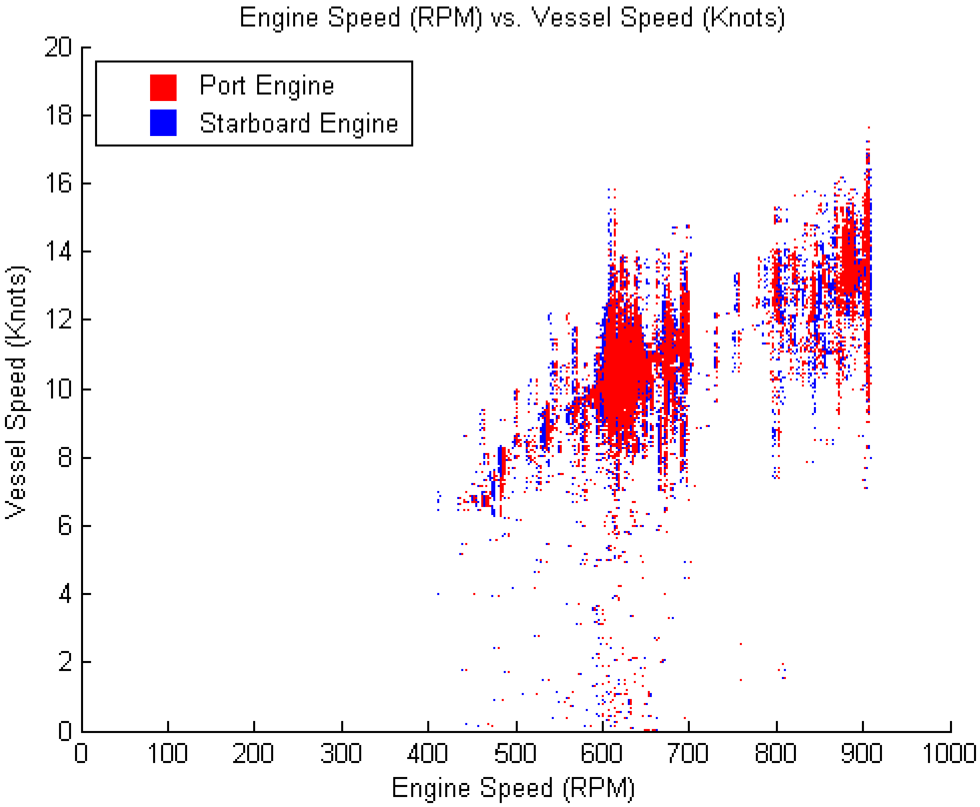


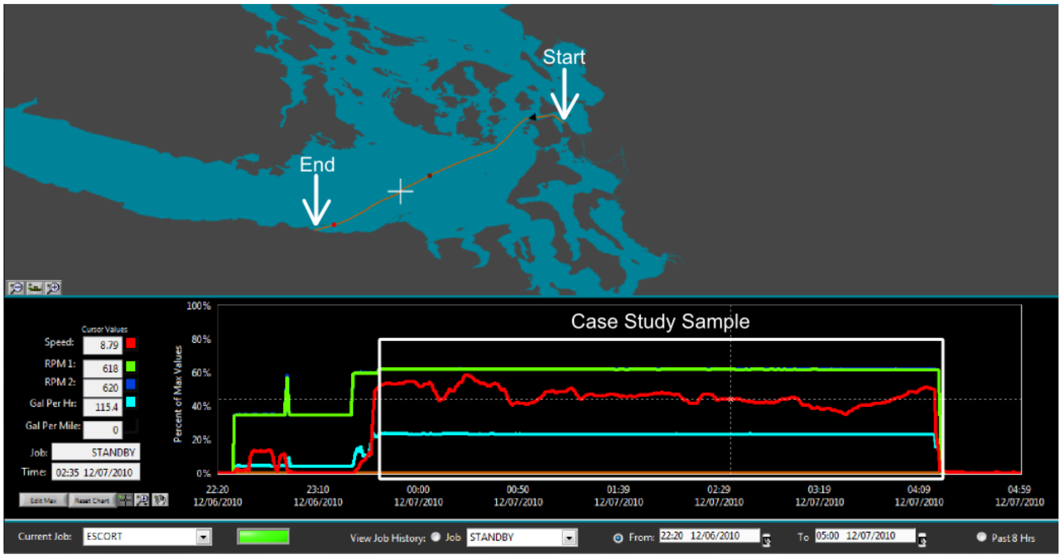
Figure 23: Vessel Speed (Knots) vs. the Engine Speed (RPM) of the assumed full pitch data collected August 11, 2010 - January 27, 2011

6. Simple Estimation and Prediction Capabilities

With the trend line equations listed in Appendix C: Final Trend Lines and Equations, algorithms can be implemented to estimate how long a trip will take and how much fuel will be burned. Figure 25 shows how, using a given engine speed and distance, total time and fuel consumed values can be calculated. Given the strong external influences on the vessel speed, the following sections will examine the simple estimation capabilities with and without the influence of external forces. The estimation procedure will then be used to predict future values. The accuracy of prediction will then be analyzed.

6.1 Description of Case Study

The simple algorithm case study will be for a portion of a trip shown in Figure 24. The portion examined for the case study is from 11:37 PM on 6 December 2010 until 4:19 AM on 7 December 2010, which is a total of 4 hours and 42 minutes. This portion is identified as a lite job, with the engines continuously set at full pitch. As can be seen in Figure 24, the Garth travels from Anacortes to Port Angeles. For the duration of the trip of interest, the Garth is running at a nominal 618 RPM and 115 GPH. The distance of this trip is found to be 37.56 Nautical Miles.



Speed: 8.79 🟥
RPM 1: 618 🟩
RPM 2: 620 🟦
Gal Per Hr: 115.4 🟦
Gal Per Mile: 0
Job: STANDBY
Time: 02:35 12/07/2010

Current Job: ESCORT

View Job History: ○ Job STANDBY ● From: 22:20 12/06/2010 To 05:00 12/07/2010 ○ Past 8 Hrs

Figure 24: Application screenshot of simple estimation and prediction capability case study

6.2 Estimation without Speed Correction

The purpose of being able to accurately estimate the resulting fuel consumption rate and vessel speed allows for a prediction of how much time and fuel will be spent to reach the destination. The logic used for the simple estimation procedure is presented in Figure 25. The diamond boxes represent an input provided by the user. The rectangles represent equations of trend lines of the fuel consumption curves. The circles represent the output estimate values.

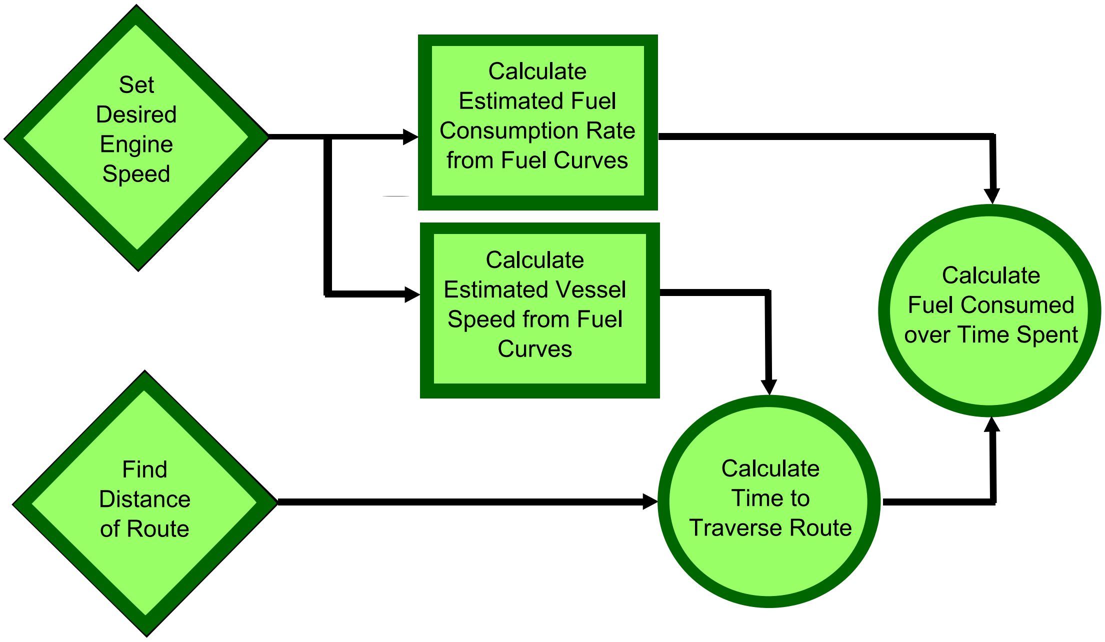


Figure 25: Diagram of the calculation used to estimate values at various engine speeds

6.2.1 Comparison with Nominal Engine Speed

First, by using the nominal engine speed to see if the estimation procedure accurately calculates the resulting fuel consumption rate and vessel speed, we later assume that the estimation procedure could accurately calculate the resulting fuel consumption rate and vessel speed at a different engine speed (RPM). To demonstrate the accuracy of the simple estimation method, the nominal engine speed is input to the equations in Appendix C: Final Trend Lines and Equations to see if the output matches the actual results of the trip. The results are presented in Figure 26.

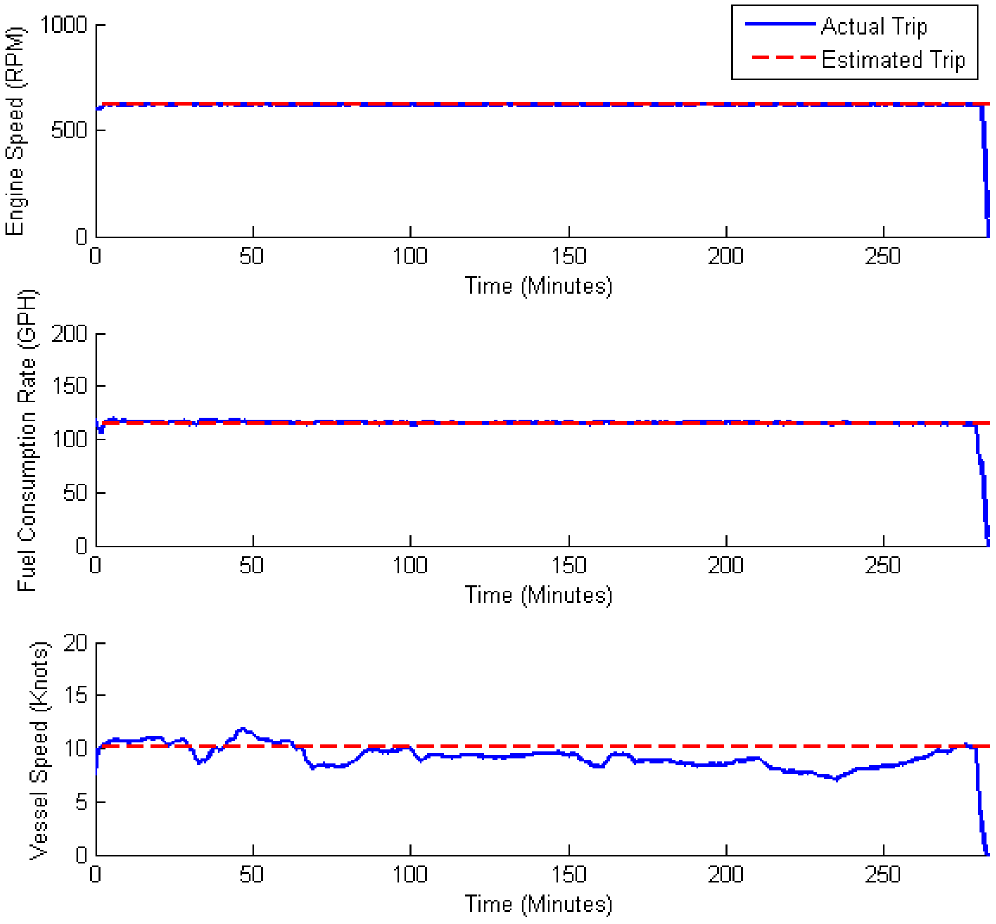


Figure 26: Results of the simple estimation algorithm at the nominal engine speed of 619 RPM

Figure 26, starting at the top plot, shows that the actual values and the values in the estimation procedure of the "desired" engine speed and the resulting estimates of fuel consumption rate and vessel speed. The top plot shows that the input, or "desired," engine speed is approximately the same as the actual engine speed. Shown in the middle plot, the calculated fuel consumption rate is almost the same as the actual fuel consumption rate through the entirety of the trip. The bottom graph shows that the vessel speed is not very accurate. For some portions of the trip, the vessel speed is up to two knots above the predicted vessel speed. The actual average vessel speed, of the entire trip, is about one knot below the calculated vessel speed. The poor accuracy of vessel speed estimation, due to tidal currents as described in Section 5.2 Full Pitch Dataset, limits the accuracy of the estimated amount of time added to the trip.

In many cases, experimental data with an error of 10% is not a problem. However, if the average value for approximate vessel speed is 10% off, the predicted amount of time to reach the destination, calculated at each moment of time, could be much higher than 10%. (This is shown later in Section 6.4 Prediction Capabilities.) Therefore, it is important to minimize the error between the estimated vessel speed and the actual vessel speed.

6.2.2 Comparison with Lower Engine Speed

One of the goals of the Computerized Fuel Management System is to present the corresponding result at different engine speeds. The result of using the same calculation, but with a lower desired engine speed value of 560 RPM is presented in Figure 27. As expected, there is a lower fuel consumption rate during the trip. This case is subject to the same vessel speed errors. Because the estimated vessel speed is, in this case, about the same as the actual vessel speed, the algorithm falsely indicates that the trip should take about the same time as the actual time recorded for this trip, while having a lower engine speed and fuel consumption rate. Under lower engine speed conditions, the trip should take longer. This example shows that without external influences to speed used in the estimation, errors will tend to be systemic in the simple estimation algorithm.

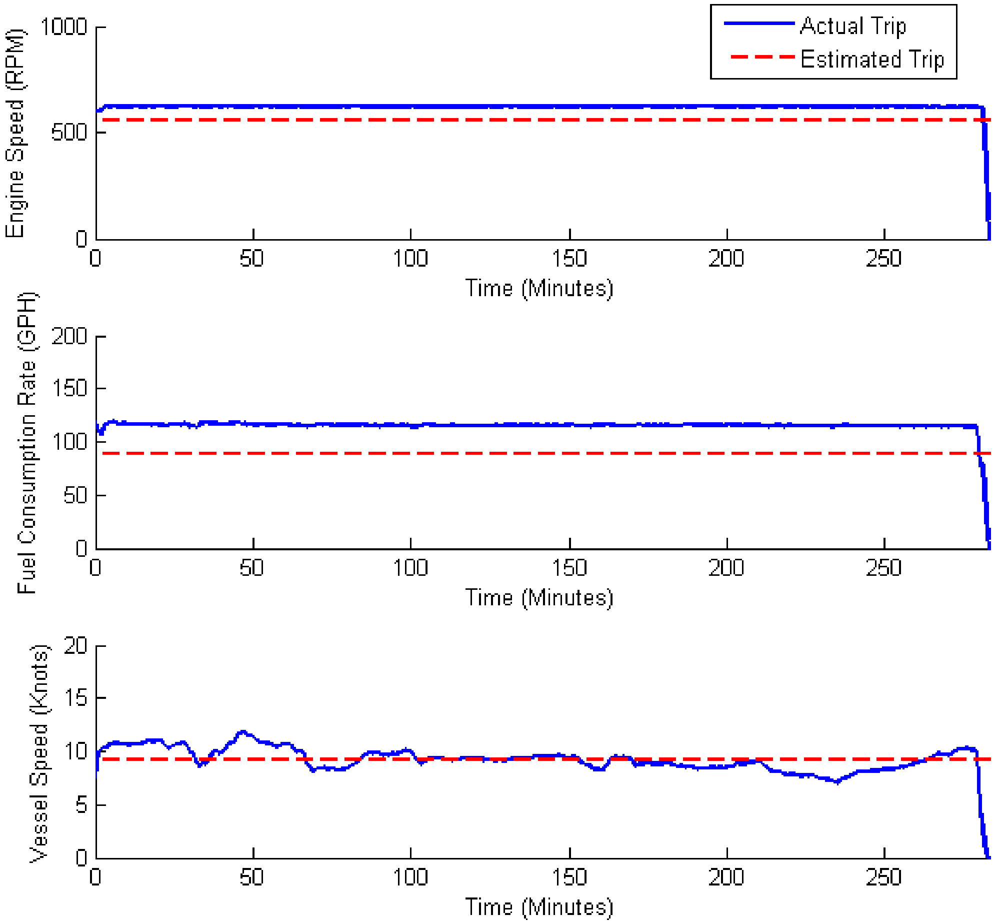


Figure 27: Results of the simple estimation algorithm at the lower engine speed of 560 RPM

6.2.3 Comparison with a Range of Engine Speeds

If the analysis example just presented for 560 RPM is repeated across a range of engine speeds, the time difference and fuel consumption difference can be more fully illustrated. Figure 28 shows that with increasing engine speed, it will take less time to reach the destination, but will cost more fuel exponentially. The nominal engine speed is also marked at 619 RPM.

The effect of not using accurate vessel speed estimation distorts the amount of time that is calculated to reach a destination. Because, during this particular trip, a significant amount of the trip was spent going against a tidal current, the estimated velocity is greater than the actual velocity over the duration of the trip. Therefore, the calculated amount of time at the nominal engine speed is calculated to be less than the actual time that it takes. Such discrepancies highlight the desirability of taking into account, in the estimations, the modulations of the vessel's speed due to external influences.

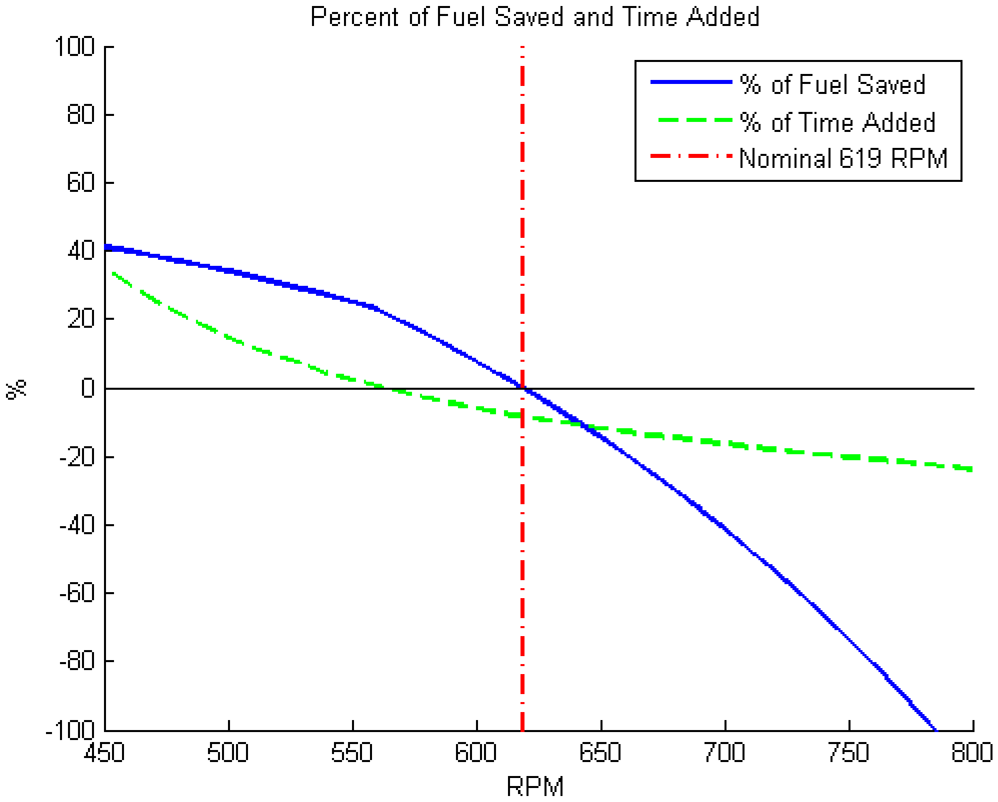


Figure 28: Results of the simple estimation algorithm over a range of engine speeds of 450-800 RPM

6.3 Estimation with Speed Correction

Next, the real-time filtered vessel speed is used in the calculation to estimate how fast the ship would travel at various engine speeds to account for modulations in vessel speed due to external forces. (This is different than before which used only the vessel speed calculated using the fuel consumption curve equations.) By using the information from the fuel consumption curves, an approximate vessel speed can be calculated, but then we calculate a presumed more accurate vessel speed estimate at the current engine speed by subtracting the difference in between the actual and expected vessel speed at the nominal value. A flow chart of this logic is shown in Figure 29. The filter, used to smooth out extreme vessel speeds, is represented by an octagon. Arithmetical operations have also been represented with hexagons. The results of the case study, using this method and the same tests as the previous section, are shown in the following sections.

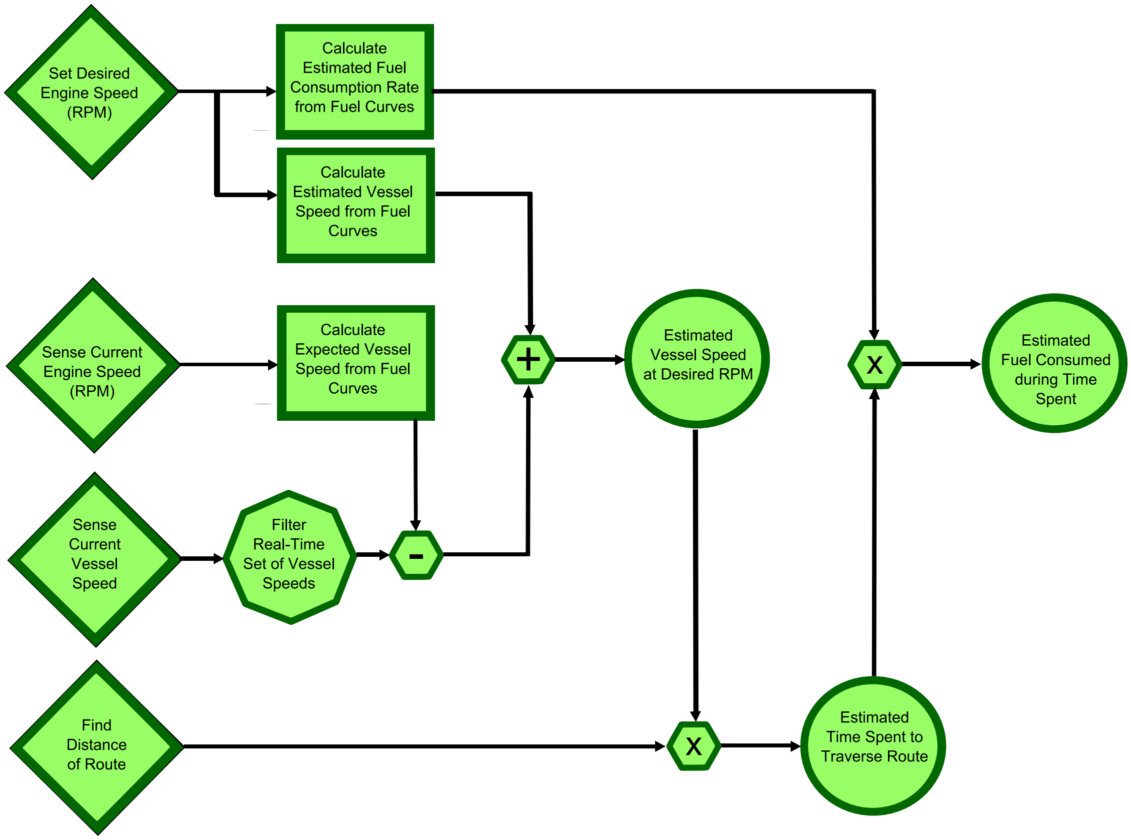


Figure 29: Diagram of algorithm used to estimate final values at various engine speeds with external influence on vessel speed

6.3.1 Comparison with Nominal Engine Speed

A nominal engine speed test, such as the one presented earlier, is shown in Figure 30. In this case, a filter using a running average of the past thirty minutes of data was used. (More filter scenarios and results are presented in Section 6.4 Prediction Capabilities.) The top and middle plots, showing “desired” engine speed and resulting fuel consumption rate, are the same as in Figure 26 in the previous analysis, but the bottom plot, resulting vessel speed, has a varying value and accuracy throughout the trip, as compared to the actual vessel speed. The varying speed is much closer throughout the trip and the average of the estimated vessel speed is much closer to the average of the actual vessel speed. Because of the filter, smaller jumps in speed do not heavily influence the estimated vessel speed. This should be helpful when predicting future values, because the prediction is made with a moderated value, instead of the statistically rarer, outlying value. It is concluded that this method is preferred to the previous method, because, at the nominal engine speed, the resulting calculated vessel speed is closer to the actual vessel speed.

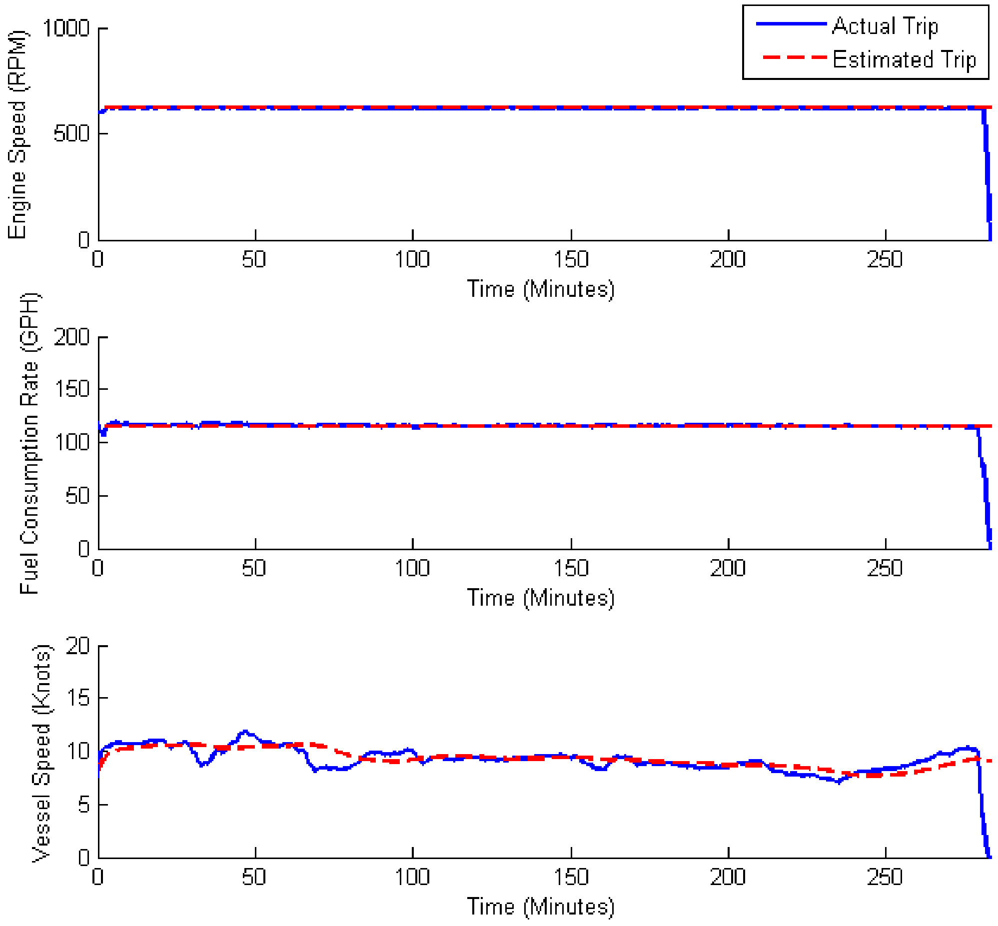


Figure 30: Results of the simple estimation algorithm with vessel speed correction at the nominal engine speed of 619 RPM

6.3.2 Comparison with Lower Engine Speed

Next, a lower engine speed of 560 RPM is used in the simple estimation algorithm. The results are shown in Figure 31. Looking immediately at the bottom plot, the profile of the actual vessel speed is added onto the profile of the expected vessel speed at the desired engine speed. This is assumed to create a more accurate vessel speed profile that would take into account the external influences. Because the external influence is taken into account, the algorithm realizes that it will take longer to reach the destination. Therefore, time is added onto the end of the estimated trip to make up for the distance lost with a lower vessel speed. Unfortunately, the predicted vessel speed, at the engine speed of 560 RPM, is still theoretical, and since the Garth cannot traverse the same exact route with the same exact conditions, it remains unproven whether this is actually more accurate.

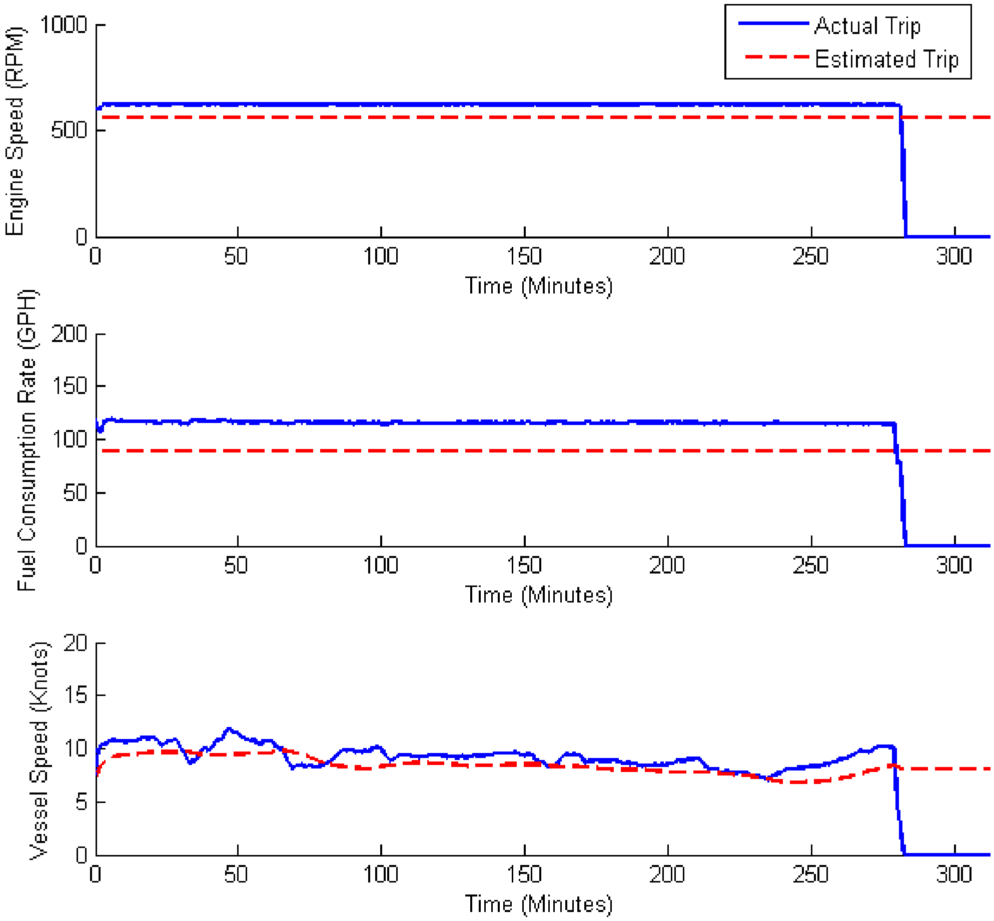


Figure 31: Results of the simple estimation algorithm with vessel speed correction at the lower engine speed of 560 RPM

Now that there is a theoretically more accurate predicted time value, the resulting fuel used over the trip is presumably more accurate. Because the time is theoretically accurate, a total fuel consumed figure will be theoretically more accurate. Figure 32 shows the theoretical amount of saved fuel at a lower engine speed. The actual trip line and the theoretical trip line represent the compounded amount of fuel burnt up to that point of the trip. The theoretical saved fuel line represents how much cumulative fuel was saved or spent up to that minute by adjusting the engine speed.

Figure 32 shows that the cumulative actual fuel consumed value stops increasing when the actual trip ended. Because the estimated trip is slower, the estimated trip must burn fuel for longer to account for the distance lost, due to travelling at a slower vessel speed. At this point, the total amount of fuel saved begins to decrease. If the amount of time to arrive at the destination is significantly longer than the original trip, the Garth would end up using more fuel to make up the lost distance than the original trip. However, in this example, there is a positive value for the amount of fuel saved, which is theoretically 50 gallons or 10% of the fuel consumed during the actual trip.

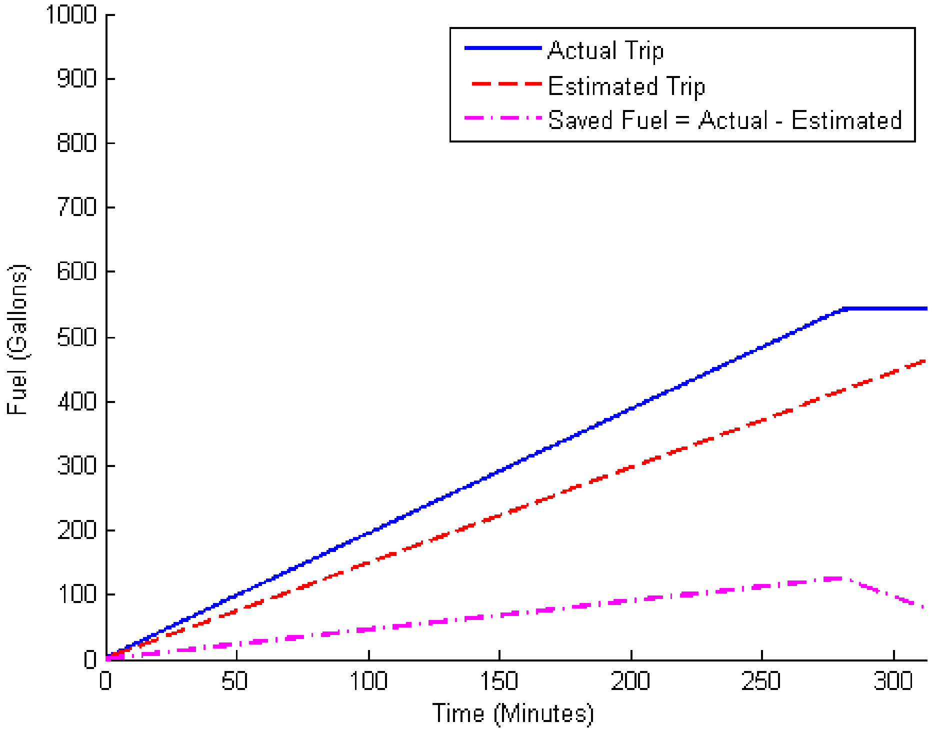


Figure 32: Comparison of the actual fuel consumed over the trip and the theoretical amount of fuel consumed at a lower engine speed of 560 RPM

6.3.3 Comparison with a Range of Theoretical Engine Speeds

Using the same method to find the theoretical time spent in transit and the fuel consumed over that time as Figure 31and Figure 32, Figure 33 shows the theoretical results of prediction of the total time of travel and fuel consumed over a range of desired engine speeds, from 450 RPM to 800 RPM. As an indication of the accuracy of the provided method, both the fuel saved and time added lines crossover at the nominal engine speed of 619 RPM. The results show that for engine speeds below the theoretical nominal engine speed, the predicted time added increases exponentially, but the amount of fuel saved approaches a maximum amount. For higher engine speeds, only a small amount of time is saved, but the amount of extra fuel burnt diverges. For example, the results show that if the trip was done at 700 RPM instead of 619 RPM, the Garth would have only arrived about 10% sooner, but would have burnt 50% more fuel. So while the crew would have saved 40 minutes, Foss Maritime would be responsible for 250 more gallons of fuel.

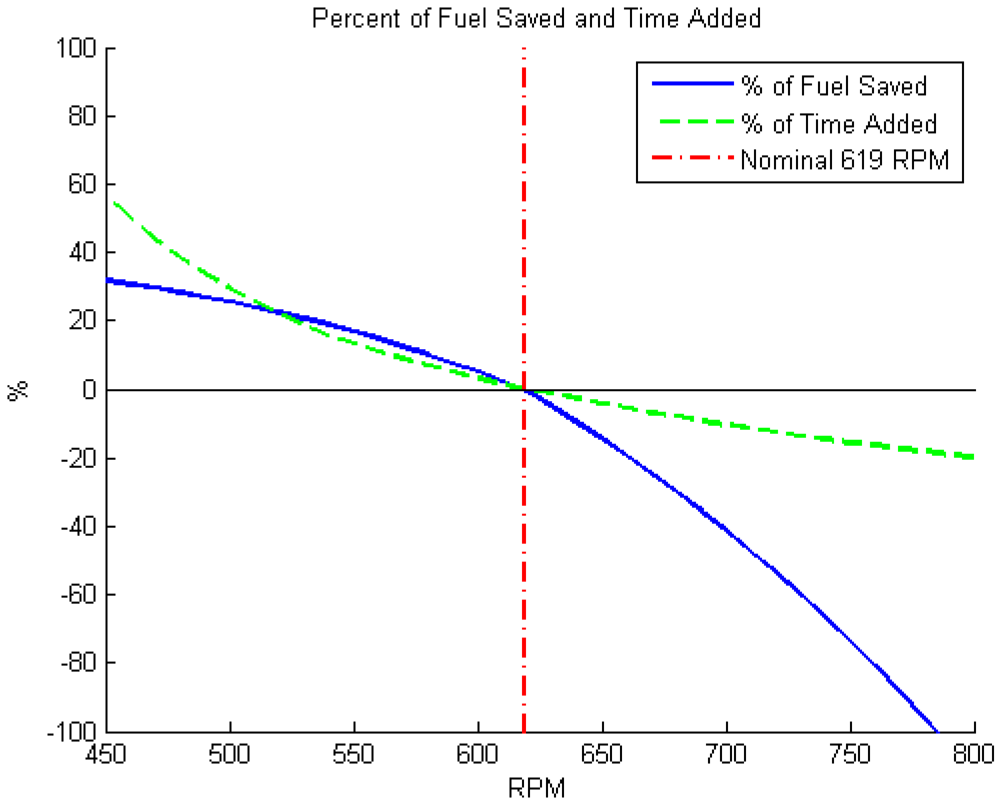


Figure 33: Results of the simple estimation algorithm with vessel speed correction over a range of engine speeds of 450-800 RPM

6.4 Prediction Capabilities

Previously using the fuel consumption curve relations and a set of filtered data, a post-processed estimation of total time and total fuel used could be calculated. To improve upon the first realization, the system needs to predict future values. Figure 34 shows the results of predicting the final time using the methods illustrated in Figure 25 and Figure 29 to calculate the time taken to complete a trip at the nominal engine speed during the case study trip. Along the x-axis is the time of the trip of the case study. Along the y-axis of the top plot, each curve shows the predicted amount of time left at that moment of time. The middle plot shows the error in total minutes between the predict amount of time and the actual amount of time remaining. The bottom plot shows the percent difference between the actual amount of time left and the predict amount of time left over the total actual time to accomplish the trip.

$$Percent\ Error = \frac{Time\ Remaining_{actual}(t) - \ Time\ Remaining_{predicted}(t)}{Total\ Time} \times 100 \qquad [2]$$

Figure 34 shows that all of the different types of prediction with the actual vessel speed, with vessel speed correction, and without vessel speed correction have significant error. Prediction using the fuel consumption curves without any vessel speed correction has the highest average error. The actual vessel speed with no moving average filter has the highest error of any of the methods near the 50 minute time; therefore, it is important to use a moving average filter to moderate the largest deviations of external influence.

In between the prediction using the actual vessel speed and the theoretical vessel speed are the results using a mixture of the fuel consumption curve solution and a moving average filter. As more samples are used in the moving average filter, the results approach the same result as when only the fuel consumption curves are used to predict the final values. All scenarios perform about the same for the second half of the trip, because the actual vessel speed is fairly consistent through this portion of the trip. The reason that there is significant error is that the average vessel speed for the second half of the trip is much lower than the first half. Consequently, the prediction algorithm expects a significantly shorter time to travel. These results show that to have accurate prediction, the Computerized Fuel

Management System must be able to predict the drop in the vessel speed for the second half of the trip.

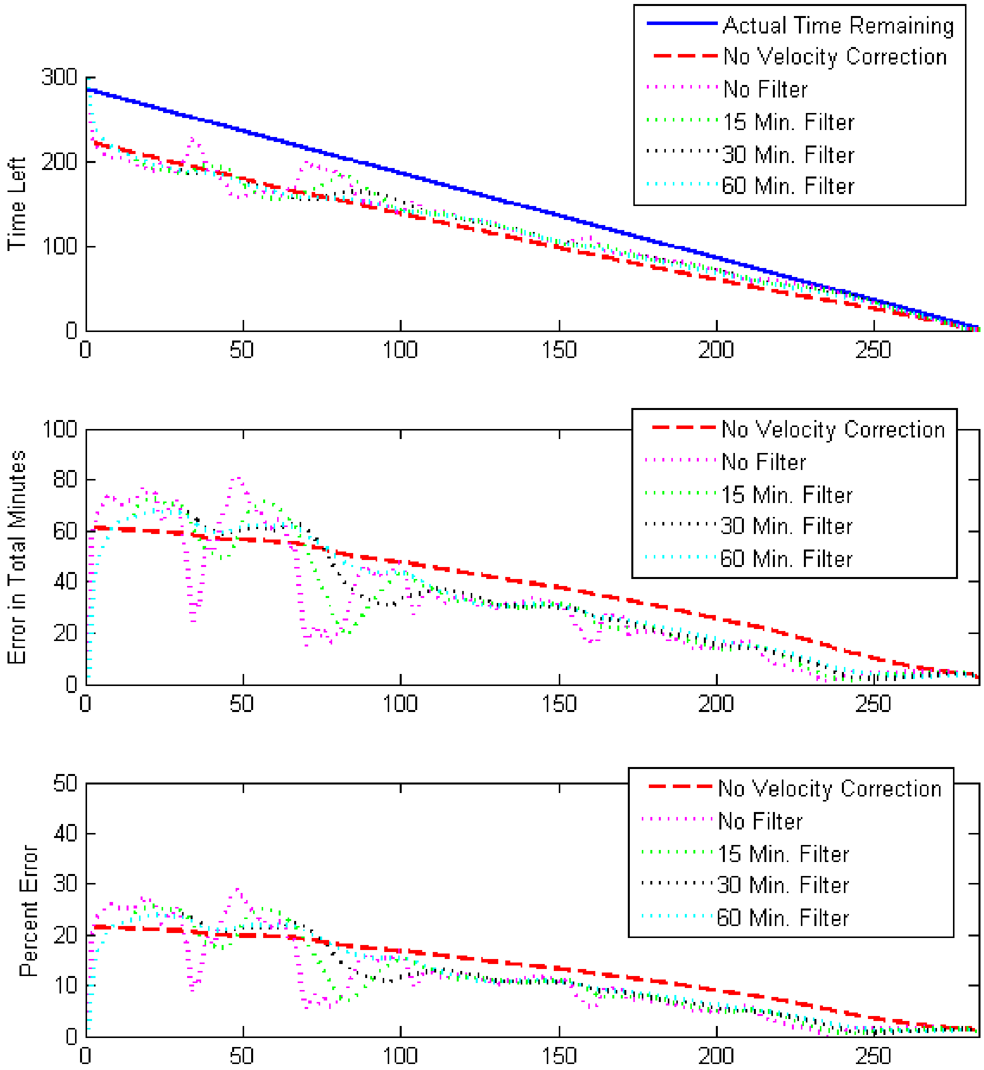


Figure 34: Results of prediction of final arrival time using the algorithms for the same case study trip at the actual engine speed at every minute through the trip.

7. New Realization of Application

As stipulated in the *Project Proposal*, the Computerized Fuel Management System will display:

> “. . . for the ongoing operation, the total amount of fuel consumed to the present time. In addition, by utilizing other data, such as, for the ongoing operation, the destination and the intended completion time, and historical data, such as the average fuel efficiency for this specific vessel under similar conditions, the system will also estimate and display changes in the total amount of fuel required to complete the ongoing operation and changes in the time required to complete the ongoing operation, both versus changes in the RPM of the main engines [2].”

Using the prediction method formulated in the previous chapters, a new realization that presents the information to the crew has been designed and implemented. There are two tabs titled “Historical and Real-Time Data” and “Prediction and Estimation.” The Historical and Real-Time Data section contains the chart, data panel, and selection panel in the original software application. When either tab is chosen, all of the data collection functions of the first realization of the GUI work the same. Figure 35, Figure 36, and Figure 37 show the new realization with the Prediction and Estimation tab selected. Figure 35 shows the GUI before a trip has been started. Figure 36 shows the GUI while the user is being prompted about their destination. Figure 37 shows the GUI after a trip is started. The new section can be useful to the crew, because now the Computerized Fuel Management System shows a predicted final value of fuel to be spent and theoretical changes to the final values at different engine speeds (RPMs) without changing the actual configuration of the Garth.

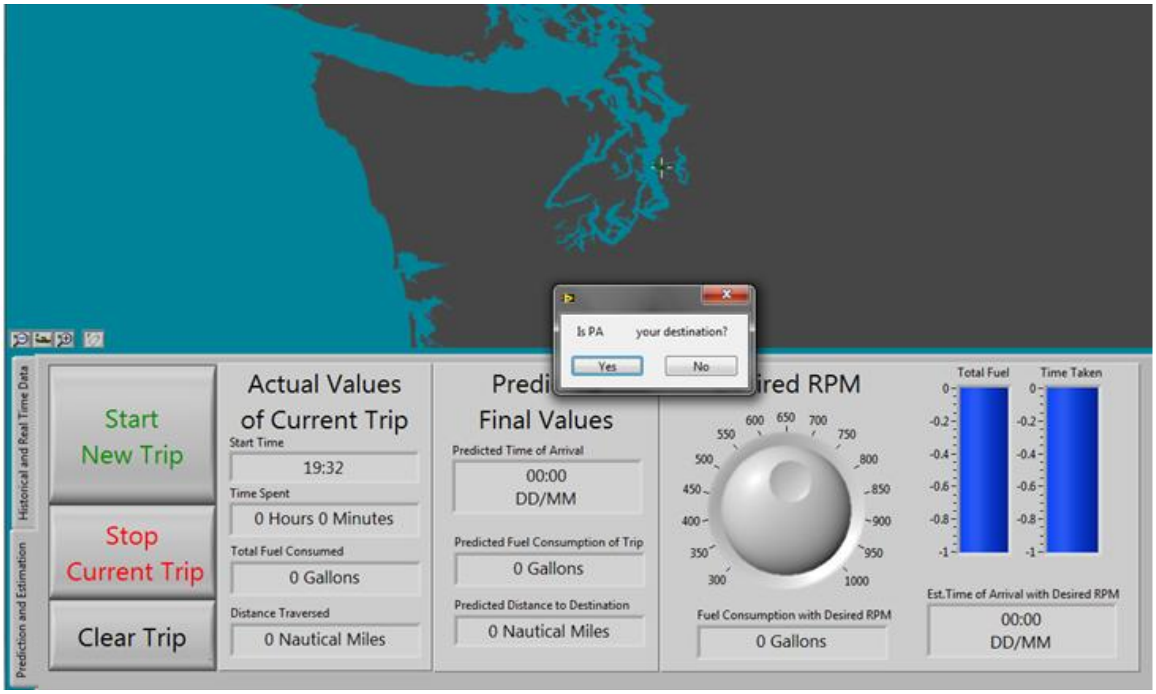
Pre-Planned Route

As described in Appendix E: On-Board Indicators, the Garth’s Navigation System uses a database of pre-planned routes to help the crew pilot the Garth safely. This database has been integrated into the database used to record the fuel consumption data. It is used by the new realization of the Computerized Fuel Management System to calculate how far the Garth must travel to the destination. Because the Garth rarely significantly deviates from the pre-planned routes, the so-determined total distance to travel is reasonably accurate. When starting a trip, using the database of possible routes from the current GPS location, the program prompts the user for the destination for the current trip. This reduces the work required by the crew to start a trip. Utilizing the pre-planned routes, as few as two clicks can start a trip.

Start Button

No indicators are shown until the start button is pressed and a trip is initialized. When the Start Button is pressed, a box prompts the user for a possible destination. More destinations are presented until the user chooses one. If all options are exhausted, no trip is started. Once a destination is chosen, the route appears on the map. The total distance to the destination is continuously updated with each new sample. The total distance is calculated from the current position through each waypoint of the pre-planned route. As the Garth passes waypoints, they will disappear from the route.

Figure 35: Screenshot of the new section of the GUI before a trip is started. The indicators are invisible until a "Start New Trip" is pressed.



Is PA your destination?

Start Time
19:32

Time Spent
0 Hours 0 Minutes

Total Fuel Consumed
0 Gallons

Distance Traversed
0 Nautical Miles

Predicted Time of Arrival
00:00
DD/MM

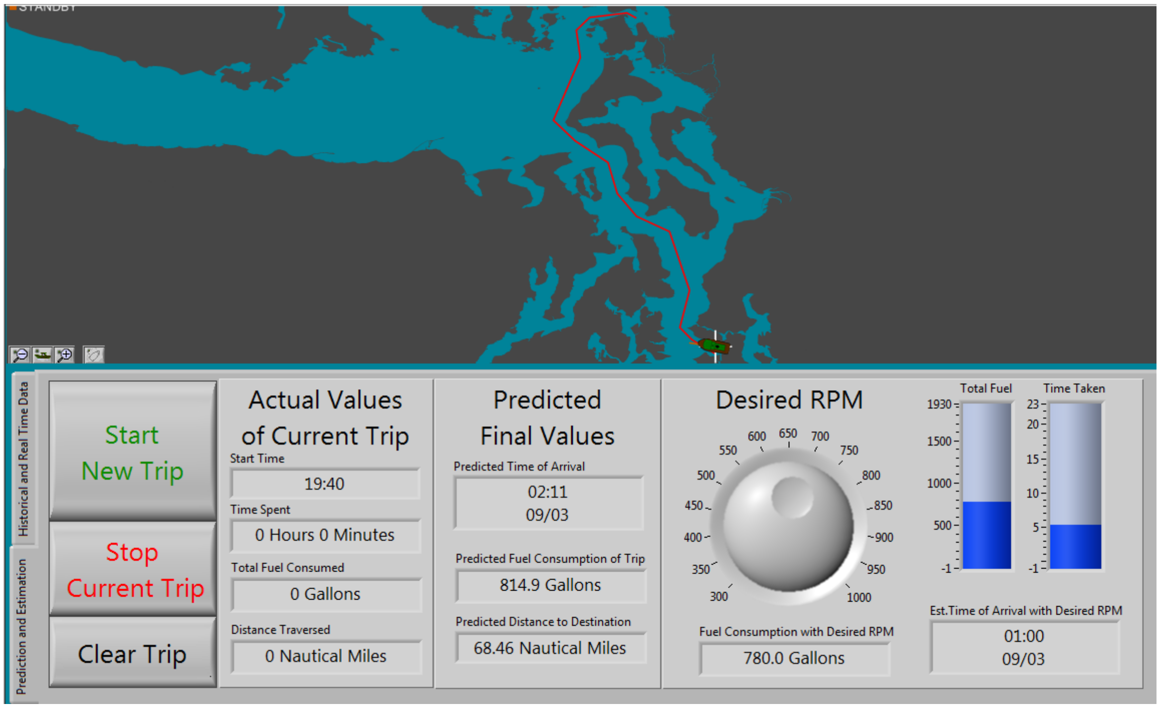
Predicted Fuel Consumption of Trip
0 Gallons

Predicted Distance to Destination
0 Nautical Miles

Fuel Consumption with Desired RPM
0 Gallons

Est.Time of Arrival with Desired RPM
00:00
DD/MM

Figure 36: The user is being asked if Port Angeles is the correct destination using the name in the database. When "Yes" is clicked, the pre-planned route will appear. If "No" is chosen, another possible destination is prompted.



Start Time
19:40

Time Spent
0 Hours 0 Minutes

Total Fuel Consumed
0 Gallons

Distance Traversed
0 Nautical Miles

Predicted Time of Arrival
02:11
09/03

Predicted Fuel Consumption of Trip
814.9 Gallons

Predicted Distance to Destination
68.46 Nautical Miles

Fuel Consumption with Desired RPM
780.0 Gallons

Est.Time of Arrival with Desired RPM
01:00
09/03

Figure 37: The user has chosen "March Point" to be the destination, and the pre-planned route is be drawn on the map. As well, the "Predicted Final Values" and the values at the "Desired RPM" are shown in the indicators.

Stop Button

The Stop Button clears the route from the map and the information in the indicators. The cumulative data is cleared from memory. The indicators also disappear until a new trip is started.

Clear Button

The Clear Button re-initializes the cumulative data in the Actual Values of Current Trip indicators and from the memory. The route and the rest of the prediction data remains the same. A new start time is recorded, and the cumulative data will begin to grow with each new sample from the new initialization point.

Actual Values of Current Trip

The Actual Values of Current Trip section displays the cumulative data since the beginning of the trip. The cumulative or historical values of the current trip shown are total time spent, total fuel consumed, and total distance traveled. The start time is also shown.

Predicted Final Values

The Predicted Final Values section displays how far the trip will be, how long it will take, and how much fuel will be consumed using the current conditions of the Garth. The distance to the destination is calculated using the current position and the remaining portion of the pre-planned route. Using the prediction algorithm presented in Section 6.3 Estimation with Speed Correction, the indicators in the Predicted Final Values section display the predicted time of arrival and amount of fuel that will be consumed.

Desired RPM

The Desired RPM section allows the user to see the predicted total fuel and total time required to complete the current trip for different engine speed (rpm) values. The RPM knob control allows the user to put in a theoretical RPM value. The predicted time of arrival and fuel consumed are shown in boxes under the knob. To the right of the Desired RPM control, two indicators show the scaled predicted total time required and total fuel consumed for the current trip based upon the entered theoretical engine speed (RPM) value. The scaling is implemented as follow: 1) The maximum time taken is set by using the time taken to reach destination at 450 RPM, and 2) the maximum fuel consumed is set by using the fuel consumed to reach destination at 900 RPM.

8. Future Work

The project has so far consisted of data collection, engine/drive characterization, and projection of current conditions. Many issues arose that can be further investigated to produce a more useful system. To create an accurate system that will create helpful predictions and achieve greater efficiency, the system must be aware of more variables that effect the speed, fuel efficiency, workload on the crew, suitability of the ride, and wear on the components. This section addresses the main issues that should be further researched.

8.1 Tidal Current and Weather Affects

Critical decisions related to departure time and anchor location are based on the schedule, time of day, tidal current, and weather. These factors affect the desired vessel speed, fuel efficiency, and suitability of living conditions.

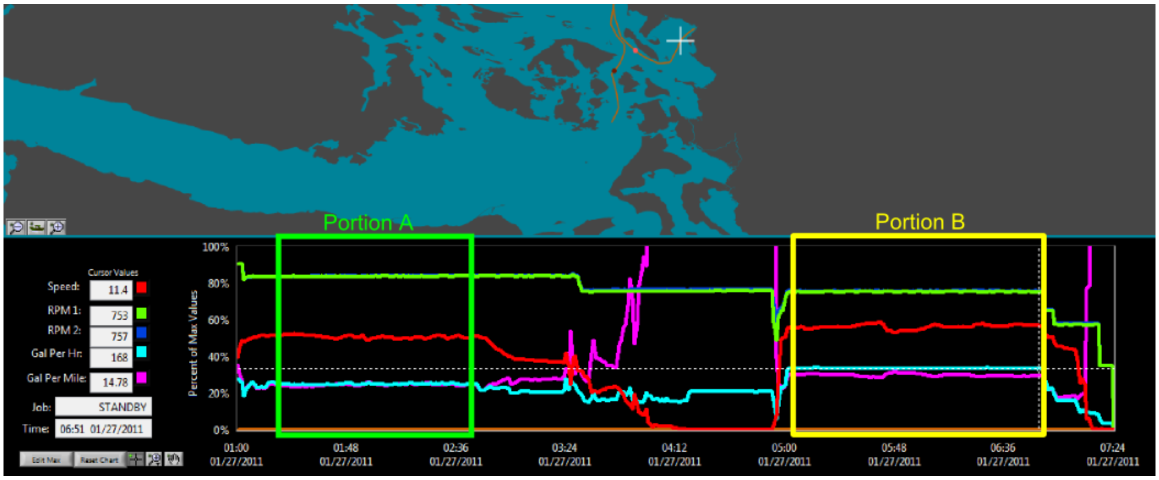
Tidal effects contribute significant speed loss and gain. These effects are exacerbated in Puget Sound, where geology on the floor of the sound and local currents can add or detract up to six knots of the vessel’s speed. Currents can be localized, and as a vessel enters a strong local current, speed loss can occur quickly. Tidal currents have been witnessed to slow down the Garth over a knot within a few minutes. Through experience, the Garth’s captains have a strong knowledge of local current patterns. General tidal current information is also available from NOAA, and this information is consistently referenced by the crew.

Bad weather can slow down the vessel and create significant motion in the yaw and roll directions. When the Garth encounters large waves in the bow, energy is dissipated and the speed is decreased. Oscillations in the yaw and roll directions can grow depending on the frequency, size, and direction of the waves. Strong winds can also contribute to a decrease or increase of the vessel speed. Lateral winds also increase the amount of motion in the roll direction. Large oscillations in the roll direction decrease the suitability of the living environment for the crew, which encourages the pilot to reach the destination faster. Therefore, choosing a time of departure to avoid bad weather will decrease the desire of the pilot to sacrifice fuel efficiency for time savings.

8.2 Voith Drive Pitch Angle Sensor

Currently, "full pitch" is determined using the assumption that the fuel consumption rate at an engine speed must be within a range of values to be identified as consistent with full pitch operation. The accuracy of this method is at best questionable. Foss Maritime recognizes that pitch angle sensors must be installed to verify the full pitch data presented in Section 5.2 Full Pitch Dataset.

Measurement of the pitch angles will enable a better characterization to be determined of the engine and Voith Drives across many pitch angles. It has been assumed that the most efficient pitch value is "full pitch." Using the two variables of engine speed and propeller pitch angle, a wider range of outcomes could be analyzed. It is, for example, possible that 600 RPM at "full pitch" is less efficient than 800 RPM at "half pitch."



Cursor Values
Speed: 11.4 🟥
RPM 1: 753 🟩
RPM 2: 757 🟦
Gal Per Hr: 168
Gal Per Mile: 14.78
Job: STANDBY
Time: 06:51 01/27/2011

Figure 38: Example of a scenario with medium pitch applied

For example, Figure 38 and Figure 39 show a scenario at which the Garth, during an escort job, is running at two different pitch angles. The Garth, while running at the lower engine speed, is travelling faster than the higher engine speed. This is assumed to be caused by a lower pitch angle. It is also interesting to note that the higher engine speed with lower pitch angle burns less fuel to travel at almost the same vessel speed. This example is not conclusive to show that full pitch is not an optimal way to run the Garth, but it shows that comparable vessel speeds are achievable with various engine configurations. With further research, conclusive evidence presumably could be obtained to convincingly demonstrate whether or not full pitch is the most efficient engine configuration.

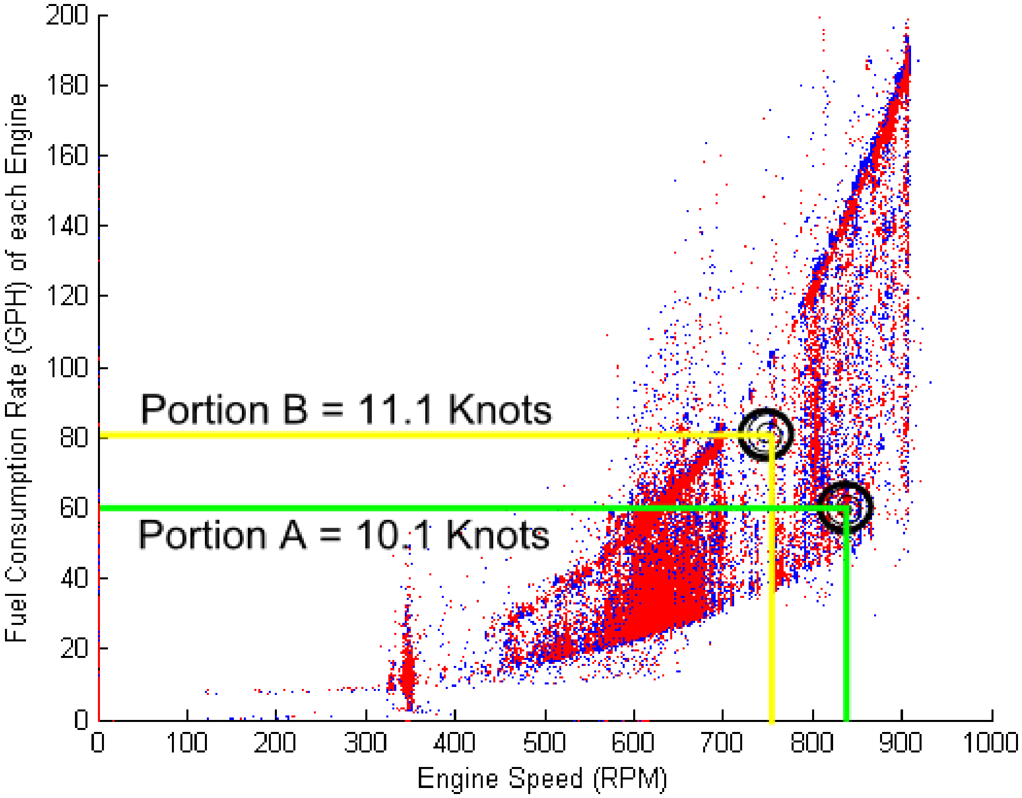


Figure 39: Partial pitch scenarios in relation to the fuel consumption rate vs. engine speed (RPM)

8.3 Generator Fuel Usage

This study has only taken into account the fuel usage of the two main engines. The generators on each side are each used intermittently and rotated between, presumably to share the wear on each. Their fuel consumption does not seem to vary greatly between driving patterns, and each generator can only burn up to 8 GPH. The generators provide energy to other parts of the Garth while the main engines are off. There may or not be potential to reduce the fuel consumption of the generators, since the crew already makes a point of turning off components when they are not required.

8.4 Life Cycle Cost of Equipment

A system can be determined to be fuel efficient by showing that less fuel is being burnt. However, a system may not be overall efficient, in terms of cost on the crew, wear on parts, and costs of maintenance. The study up to this point has focused on minimization of fuel costs, but in the future, other costs must be further understood and calculated to provide better overall system efficiency.

An example of a balance of cost savings is the use of lower engine speeds. It is observed that lower engine speeds can be both beneficial and detrimental to overall cost and efficiency. Engines are often assumed to require maintenance and replacement after a certain number of revolutions, due to mechanical wear. By accomplishing fewer revolutions per minute, the engines should be able to run for a longer time period until the estimated number of cycles is met. However, it has been observed by the crew that the fuel lines, engine, and smoke stack become increasingly dirty when the Garth is only run at lower engine speeds. This may cause lower emission quality and increased costs to maintain the fuel lines and the engine. Therefore, issues such as the effects of lower engine speeds should be further examined and assessed.

Furthermore, as mentioned in Section 8.2 Voith Drive Pitch Angle Sensor, it may be possible to accomplish the same vessel speed at various engine configurations. Thus, when factors such as engine emissions and wear are considered, it is entirely conceivable that operation of the main engines at higher RPM is more efficient than it otherwise would be. So, further insight about the ability of different engine configurations and the needs of the equipment could be important to increasing overall efficiency.

9. Conclusion

Sensors have been installed on-board the Garth Foss to measure fuel consumption rate, GPS coordinates, vessel speed, and engine speed. The installation of the fuel consumption meters immediately showed that with increased knowledge of the engine conditions, the crew would adapt to more fuel efficient piloting methods.

An initial realization of our Computerized Fuel Management System was launched on the Garth that collected data for months. The data gave information about the piloting methods and characteristics of jobs performed. In addition, fuel consumption curves were determined from the data and trend lines were calculated to estimate theoretical fuel consumption rates and vessel speeds at various desired engine speeds. Analysis of the accuracy of the theoretical values at the nominal engine speed was performed with and without vessel speed correction. It was found that both the current fuel consumption rate and vessel speed could be estimated. However, calculating results outside of the nominal value provides only theoretical results. Furthermore, predicting future values in all cases could be systemically erroneous without further knowledge of future external effects, such as tidal currents.

A new realization of the Computerized Fuel Management System with an additional prediction component has been developed. The new prediction component adds predictions based on current measured conditions. It also uses the fuel consumption curves to predict how much fuel could be saved by reducing the engine speed (RPM). This system requires minimal crew interaction, through use of the same preplanned routes as those already programmed into the Garth’s Navigation System, but, unlike the Navigation System, allows for the crew to experiment with different engine speeds (RPMs). This new Computerized Fuel Management System will operate on the Garth Foss and provide a new tool to the crew.

References

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2. Berg, Martin and Mason, Greg. Project Proposal: A Computerized Fuel Management System for Foss Maritime.

3. Foss Maritime Company. Services. http://foss.com/services.html (15 February 2011).

4. Marine Traffic. Garth Foss. http://www.marinetraffic.com/ais/shipdetails.aspx?mmsi=366767140 (19 January 2011).

5.Mink, Kurtis. Foss Maritime: Fuel Efficiency Study. Aspin, Kemp, and Associates, Pacific Coast, USA, December, 2008. Foss Document Ref: 090602-FSR-FOSS-1971[FuelEfficiencyStudy].doc.

6. Munro,Guillermo Polar Tankers. Seattle Post-Intelligencer 22 March 2003.

Appendix A: Garth Foss Properties

Table 1 shows the properties of the Garth Foss. The Garth's sister tug, the Lindsey Foss, was manufactured at the same time and has the similar properties. They are some of the largest and most powerful tugboats. They often work together on assist jobs in Puget Sound.

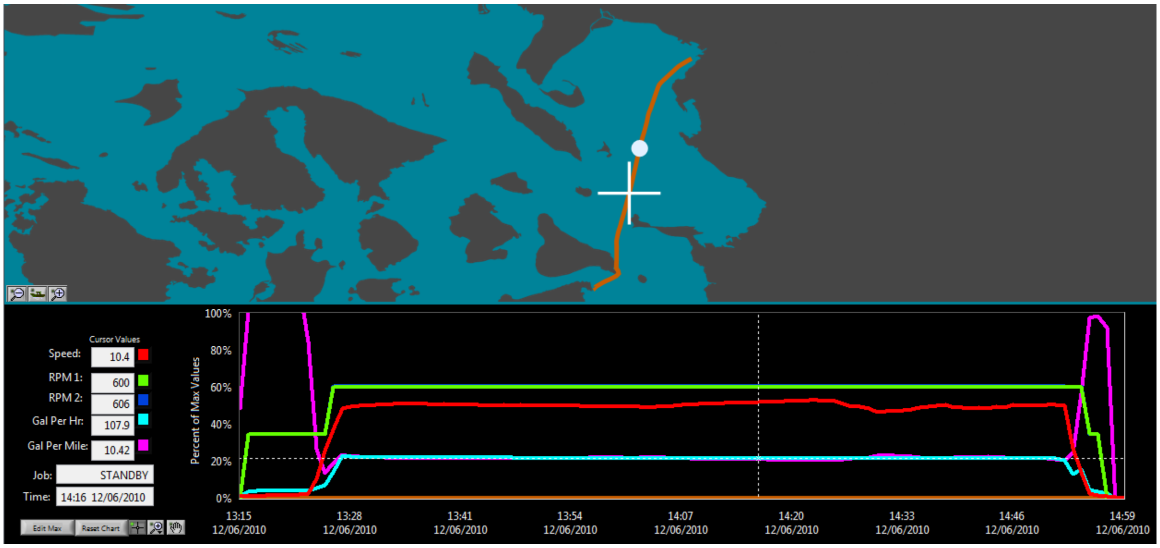
Table 1: The characteristics of the Garth Foss[5]

Type:	Enhanced Tractor Tug
Engines:	2 Voith Drives
Max Speed:	13.7 Knots
Average Speed:	10.2 Knots
Dead Weight:	350 Tons
Length:	47 Meters
Breadth:	14 Meters
Home Area:	Pacific North
Year Built:	1994
Ave. Crew Size:	5 People

Appendix B: Isolating the “Full Pitch” Dataset

Approximate Fuel Consumption Rate vs. Engine Speed “Full Pitch” Trend Line

The first rough characterization of the Garth’s engines took place by hand picking stable sets of trips from 23 July to 10 August 2010. The trips were chosen that had steady state engine speed and fuel consumption rate values. An example of the handpicked data is shown in Figure 40. Because the engine speed and fuel consumption rate are steady for a long period of time, the data at the cursor would be recorded as a full pitch point to be used in the handpicked full pitch dataset. The resulting data is listed in Table 2. The plotted points and resulting trend line using a second-order curve fit are in Figure 41.



Cursor Values
Speed: 10.4 🟥
RPM 1: 600 🟩
RPM 2: 606 🟦
Gal Per Hr: 107.9
Gal Per Mile: 10.42
Job: STANDBY
Time: 14:16 12/06/2010

Figure 40: Full Pitch “Lite” trip on 6 December 2010.

Table 2: List of handpicked data points used to approximate the full pitch engine speed (RPM) to fuel consumption rate (GPH) relation

Data Point	Engine Speed (RPM)	Fuel (Gallon/Hour)	Vessel Speed (Knots)
1	900	180.00	15.0
2	615	55.49	10.5
3	647	64.17	10.9
4	701	80.57	10.7
5	630	60.00	10.1
6	596	51.01	9.5
7	653	66.75	10.6

8	628	59.15	8.5
9	501	33.78	6.8
10	900	180.00	13.5
11	636	60.28	10.7
12	690	78.11	11.3
13	660	67.46	11.7
14	907	181.40	12.8
15	634	60.77	10.7
16	627	58.06	10.4
17	617	57.57	9.3
18	630	59.53	11.2
19	487	31.90	8.3
20	614	55.32	10.1
21	472	30.68	7.8
22	655	67.53	10.7
23	636	61.35	10.9
24	649	64.36	10.9
25	664	68.45	11.6
26	543	40.88	8.8
27	557	45.04	8.8
28	614	57.00	10.1
29	905	184.80	12.9
30	906	183.00	14.2
31	607	55.68	10.8
32	557	45.66	9.0
33	638	62.40	10.6
34	585	51.00	9.8
35	905	183.60	14.8
36	810	132.60	13.5
37	903	184.20	14.5
38	658	66.66	11.5
39	825	142.20	15.1
40	505	35.40	8.4
41	561	46.20	9.3
42	641	63.00	10.6
43	905	183.00	15.2
44	660	67.20	11.9

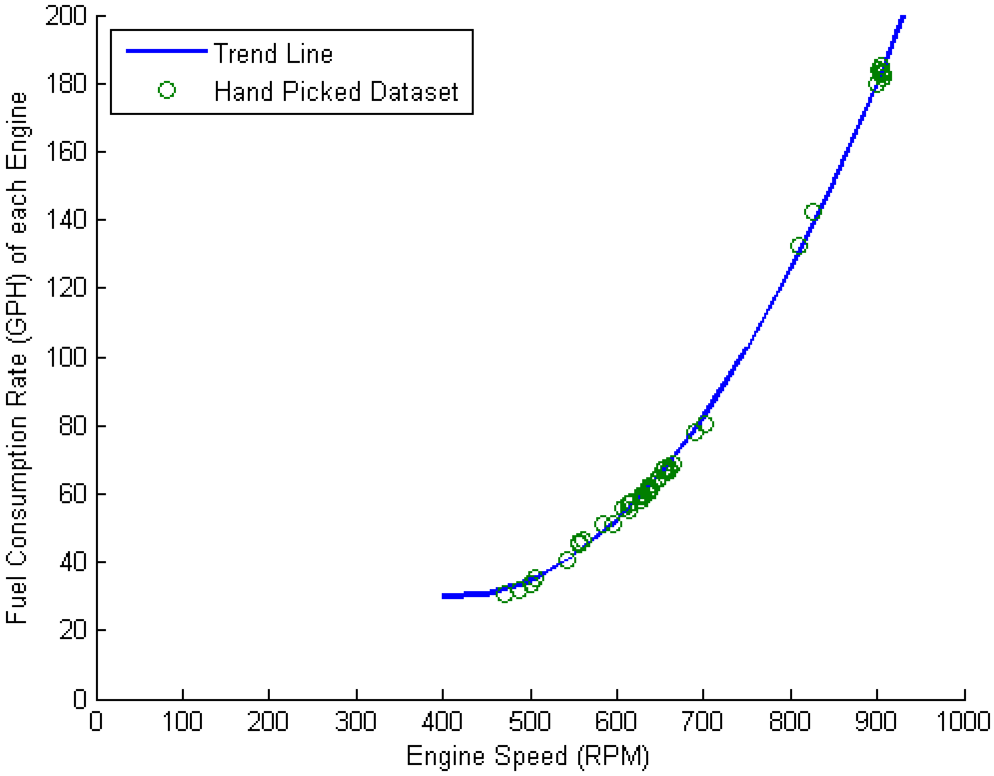


Figure 41: Handpicked “full pitch” data points 23 July to 10 August 2010.

Isolate an Approximate “Full Pitch” Dataset

The full pitch data points can be isolated from the full set of data, by only saving the data points that are within a specified window of the engine speed to fuel consumption rate relation. Figure 42 shows the trend line calculated from the handpicked dataset with data isolated within +/- 10 GPH of the expected relation. The initial window of +/- 10 GPH was chosen because it seemed to contain a majority of the full pitch data without including the large batches of the partial pitch data that would significantly distort the trend line. As the data is isolated, the vessel speed, corresponding to each engine speed and fuel consumption rate value, is saved to be plotted after isolation.

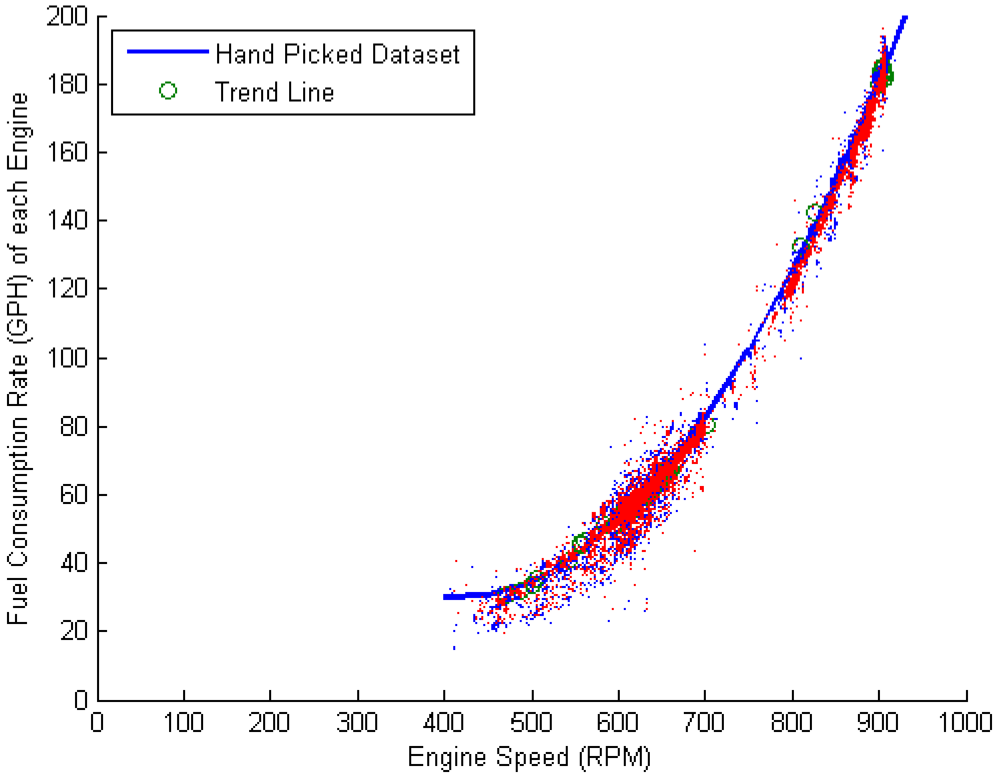


Figure 42: The full dataset Fuel Consumption Rate (GPH) of each engine vs. the Engine Speed (RPM) with +/- 10 GPH of the handpicked dataset trend line relation

Recalculate Trend Line of "Full Pitch" Data and Tighten Isolation

Now that the general relationship has been identified, a more accurate trend line is calculated from the larger set of full pitch data points. The new trend line is more accurate using the already isolated data, because the +/- 10 GPH window provides thousands of data points from which the trend line is now calculated. The partial data still included in the +/- 10 GPH window is insignificant relative to the number of full pitch data points. This is because the captain usually operates the engines at full pitch rather than at "almost" full pitch. Figure 43 shows the previous dataset with a new second-order-fit trend line. Figure 44, presented in Appendix C: Final Trend Lines and Equations, shows the final set of data +/- 5 GPH with the new trend line.

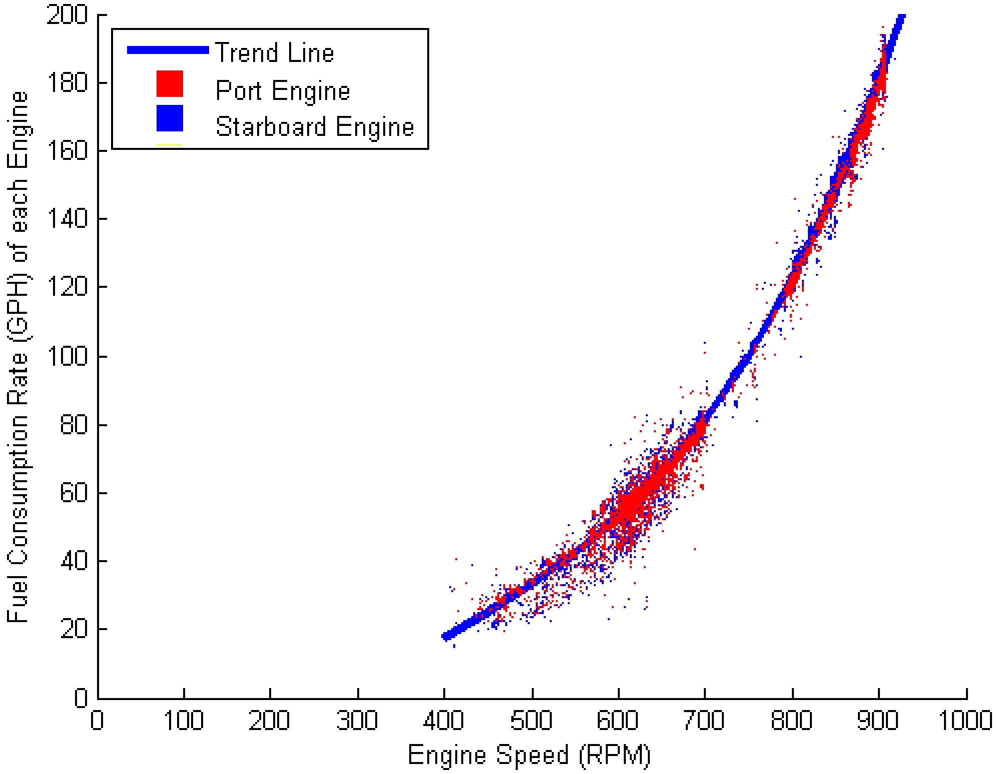


Figure 43: Isolated data with +/- 10 GPH of the handpicked dataset trend line relation, with newly calculated trend line

Appendix C: Final Trend Lines and Equations

Figure 44 and Figure 45 show the final full pitch dataset with the final trend line and resulting third-order best fit trend line. Figure 44 is not split, because each engine has a fuel consumption rate at a specified engine speed regardless of whether the other engine is running and regardless of whether the ship is moving. They also both tightly follow the same trend at each engine speed. Therefore, the port engine running at one speed correlates to a single fuel consumption rate. Although, at that point in time the starboard engine speed is slightly higher, the fuel consumption rate is also slightly higher. If both engines were lowered so that the starboard engine was going the same speed that the port engine used to be going, then the starboard engine would have the same fuel consumption rate that the port engine used to have.

Conversely, Figure 45 splits the data for each engine, because the vessel speed is a function of the effort accomplished by the work of both engines combined. Therefore, one port engine speed and a different starboard engine speed combine to accomplish one vessel speed. But if they were both lowered, the resulting vessel speed would also be lower.

The resulting fuel consumption rate trend line equations are also shown in Equation 3, Equation 4, and Equation 5. These equations are used in Chapter 6. Simple Estimation and Prediction Capabilities and Chapter 7. New Realization of Application to estimate current values, predict future values, and calculate theoretical values at a desired engine speed.

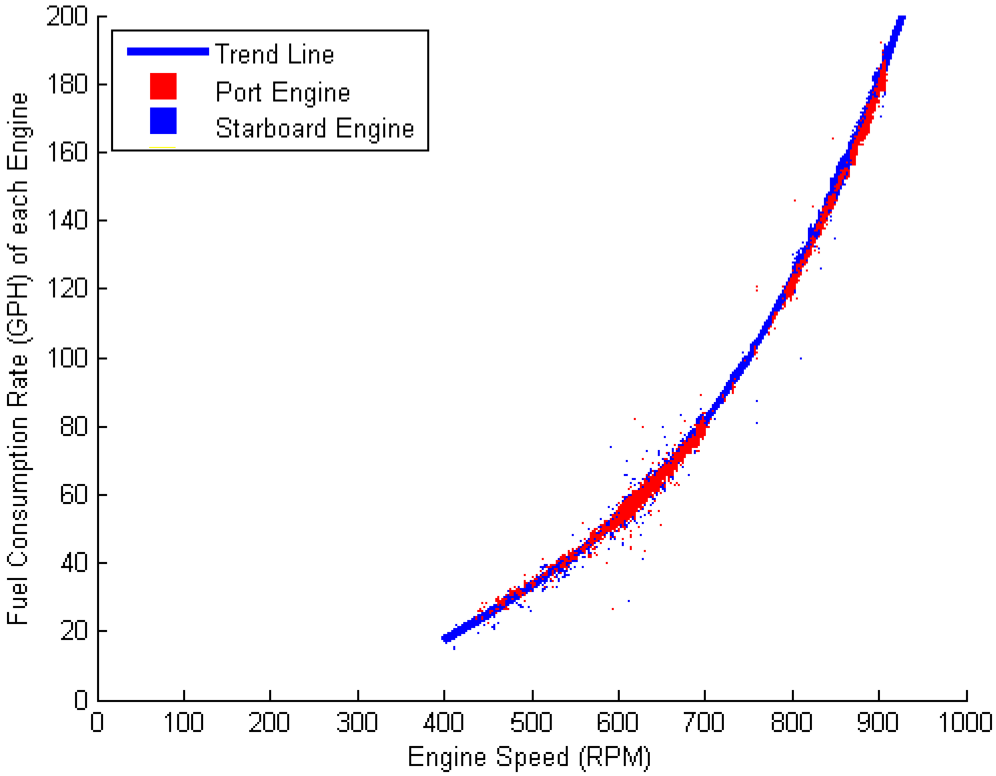


Figure 44: Isolated full pitch data with +/- 5 GPH of final trend line

Fuel Consumption Rate Using Average RPM of the two Engines:

$$GPH = 7.181 \times 10^{-7} \times RPM^3 - 8.726 \times 10^{-4} \times RPM^2 + 0.504 \times RPM - 90.608 \qquad [3]$$

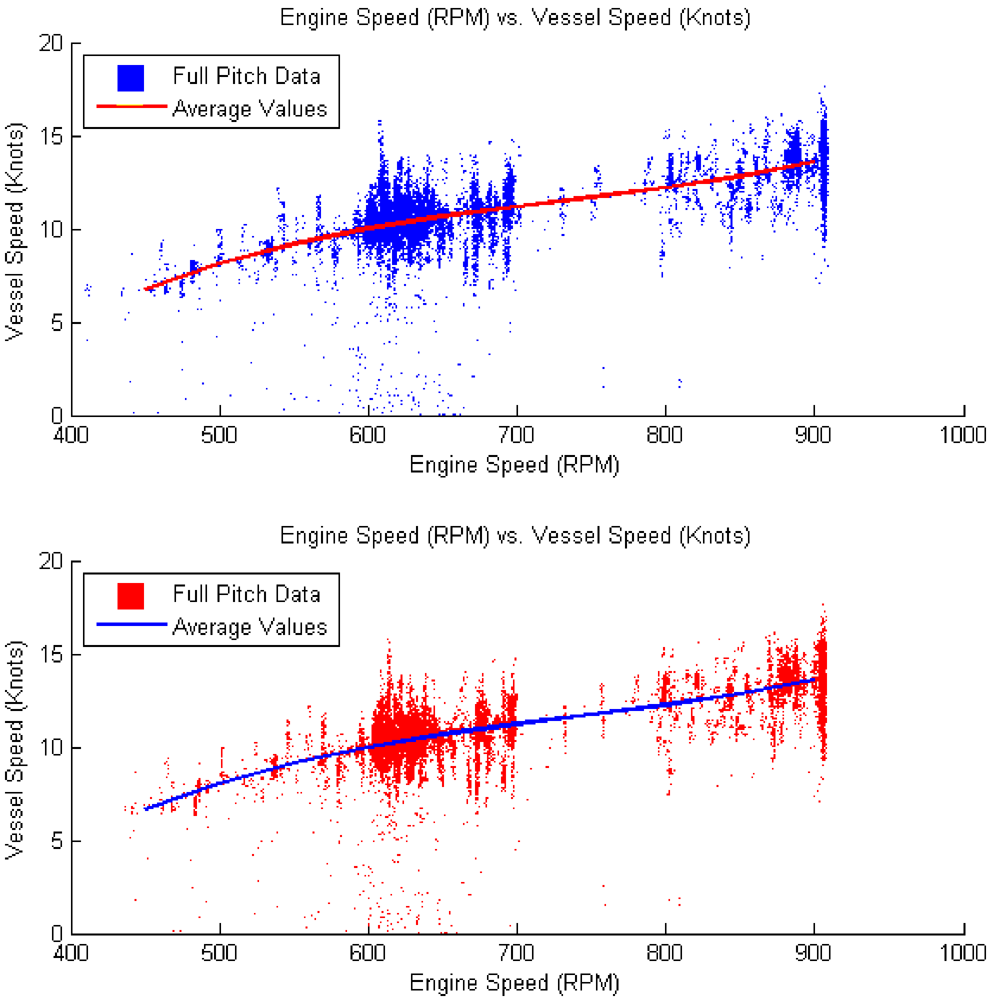


Figure 45: Full pitch dataset and trend line of vessel speed (Knots) vs engine speed (RPM) of each engine

Port Engine:

$$Knots = 6.561 \times 10^{-8} \times RPM^{3} - 1.454 \times 10^{-4} \times RPM^{2} + 0.118 \times RPM - 22.855 \qquad [4]$$

Starboard Engine:

$$Knots = 9.455 \times 10^{-8} \times RPM^{3} - 2.064 \times 10^{-4} \times RPM^{2} + 0.160 \times RPM - 32.459 \qquad [5]$$

Appendix D: On-Board Controls

This section names and describes the pertinent controls used by the crew to adjust the running conditions of the Garth.

Throttle

The throttle controls the rotational speed of the Voith Drives. The throttle has one lever for each engine, which ranges from 0-10 and roughly corresponds to 300-950 RPM when the Garth is running. The tachometer indicates the resulting engine speed. It is important to note that increasing the throttle will not move the Garth without pitch adjustments. The engine can speed up to higher RPM values while the propellers are travelling through the water without applying force in any direction.

Figure 46: Throttle control in pilothouse of the Garth Foss

Direction and Pitch Controls

The controls for the direction of the thrust consist of the wheel and two independent levers. There are three sets of these controls that are the identical: one set on the front (bow) and two sets on the back (stern). All three sets are mechanically connected, and the corresponding control will move in all three sets. The levers control the magnitude of the pitch, between 0 to

10, of the port and starboard engines toward the front (bow) or the back (stern). The Garth can go "full pitch" in either the forward or the backward direction. The direction of this force is then rotated in accordance to the rotation of the wheel control as described in the scenarios presented in Appendix F: Voith Drive Scenarios.

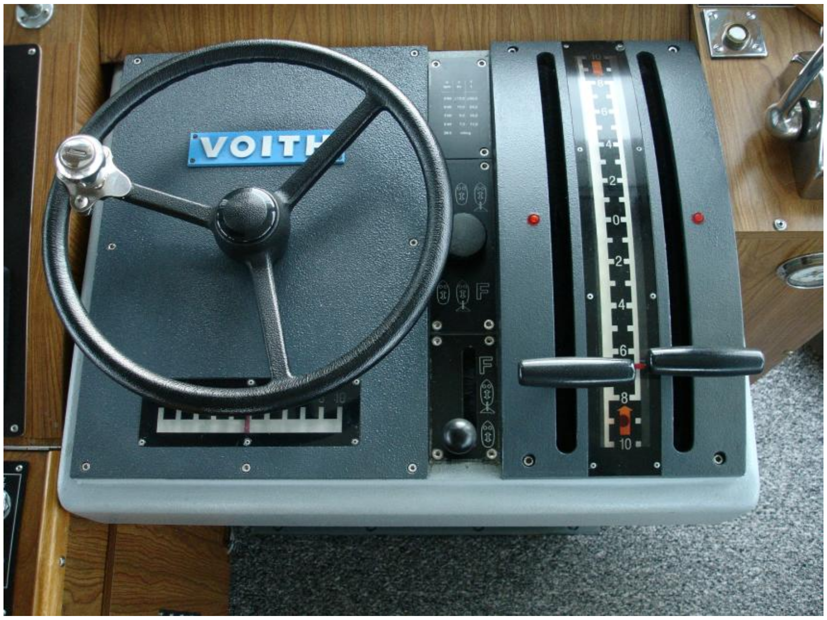


Figure 47: Direction and pitch controls in the pilothouse of the Garth Foss

Autopilot System

The autopilot system is used during long trips. The only variable it is able to control is the bearing. It cannot aim for a certain GPS coordinate. The bearing is set to match the route to the next point in the route. While heading to a destination, the bearing sometimes needs to be adjusted, because sideways drift is not recognized by the autopilot system. Once the next point in the route is reached, the bearing will then be adjusted to aim towards the subsequent point in the route. This is repeated until the final destination.

Figure 48: Autopilot system controls and indicators

Appendix E: On-Board Indicators

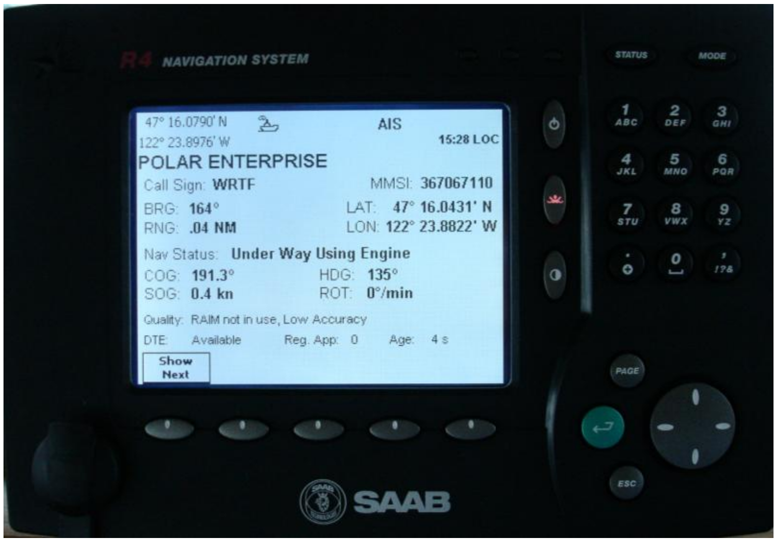
This section names and describes the pertinent indicators used by the crew to monitor conditions of the Garth.

Tachometer

The speeds of each of the Voith Drives are shown on digital readout panels in the pilothouse. A continuous analog signal for each engine is sent through an analog-to-digital data acquisition device to the Computerized Fuel Management System and is saved in the database, every minute.

GPS Unit

The GPS unit is a Saab R4 Electronics On-Board Vessel Tracking (AIS) System. The GPS calculates the GPS coordinates, speed, and bearing of the Garth. It also is capable of calculating the GPS coordinates, speeds, and bearings of other ships in the Puget Sound. All of this information is sent via a serial signal to the Navigation System and the Computerized Fuel Management System. The GPS coordinate and speed are then recorded by the Computerized Fuel Management System every minute.



47° 16.0790' N
122° 23.8976' W
AIS
15:28 LOC
POLAR ENTERPRISE
Call Sign: WRTF
MMSI: 367067110
BRG: 164°
RNG: .04 NM
LAT: 47° 16.0431' N
LON: 122° 23.8822' W
Nav Status: Under Way Using Engine
COG: 191.3°
SOG: 0.4 kn
HDG: 135°
ROT: 0°/min
Quality: RAIM not in use, Low Accuracy
DTE: Available
Reg. App: 0
Age: 4 s

Figure 49: GPS display in the pilothouse of the Garth Foss

Fuel Consumption Meter

Four sets of KRAL BEM 500 fuel flow meters, one for the main engine and one for the generator for each of the port and starboard sides, are installed in the engine room. They are wired to the KRAL BEM 800 in the pilothouse, which displays the current fuel consumption data. The data is sent to the Fuel Management System using a serial signal.

Figure 50: Front panel of the KRAL BEM 800 Fuel Meter

Navigation System

The navigation system allows the crew to choose preplanned routes to follow. By going through the database that they have compiled, the crew can choose the trip with the correct start and end points. The points of these routes have been carefully chosen to guide the Garth through accepted traffic lanes in the Puget Sound. The Navigation System displays the Garth’s current speed, current position, current bearing, preplanned route, and estimated time of arrival. It also shows the positions and speeds of other vessels. The routes are followed with the assistance of Autopilot System described in the next section. This Navigation System is not connected to the Computerized Fuel Management System, but the route database utilized by the Navigation System is used in the second version of the Computer Fuel Management System.

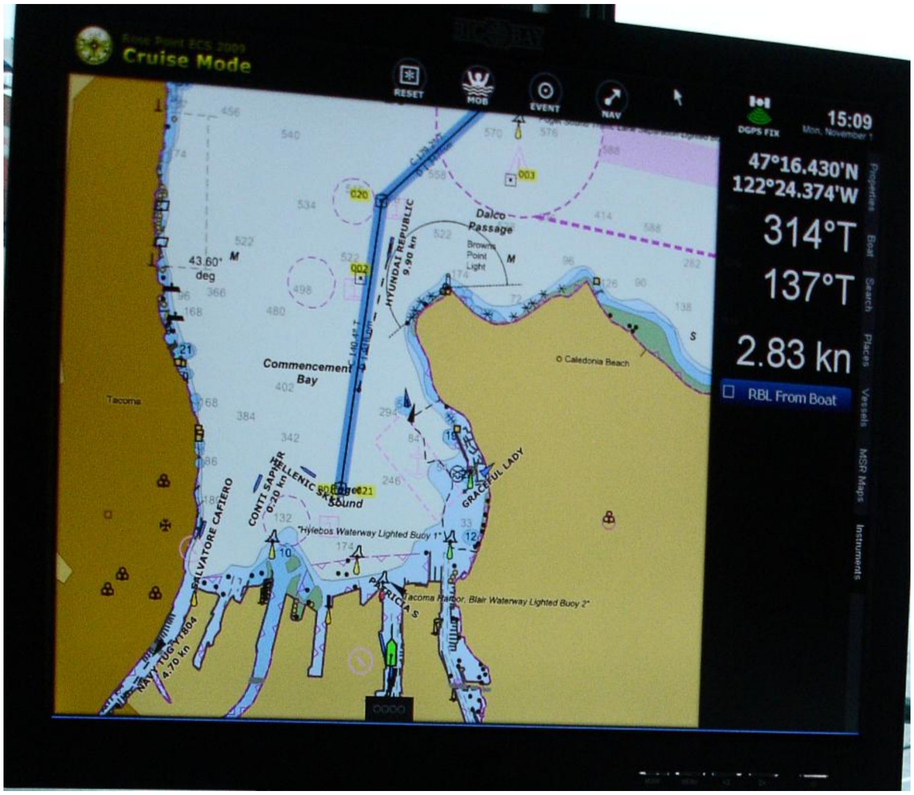


Figure 51: Navigation System on the bow-side in the pilothouse on the Garth Foss

Appendix F: Voith Drive Scenarios

This section gives examples of how various pitch angle configurations create the thrust and motion of the Garth Foss.

Scenario #1: Zero Pitch

Voith Schneider Propellers have variable pitch propellers. Therefore, the amount of thrust applied to the water is determined by the pitch of the propellers. The controls utilize a combination of an independent lever for each drive and a single directional wheel, which controls both drives simultaneously. When the pitch is set to zero, the engines and drives rotate, but no thrust is created. This scenario is illustrated in Figure 52, which shows that the propellers cut through the water in a circle without displacing water and creating thrust.

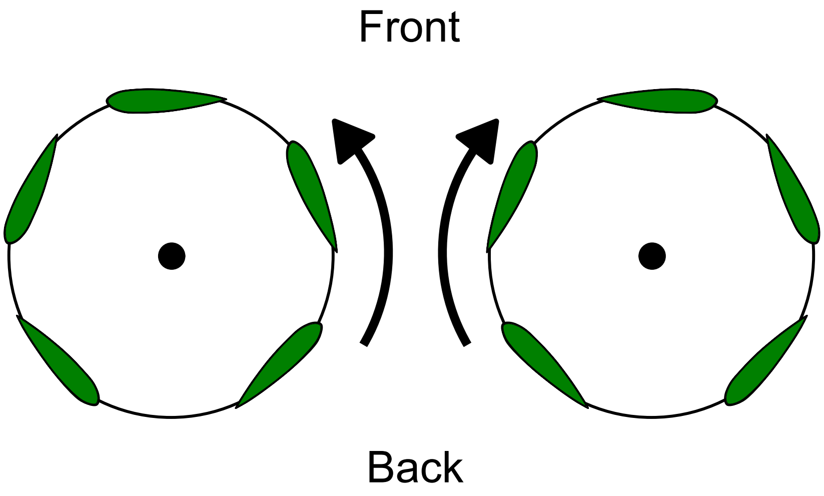


Figure 52: Diagram of the Voith Schneider Propeller system rotating at zero pitch

Scenario #2: Full Pitch

When the pitch angles of the propellers are increased, along one side of the rotation, the propellers slice into the rotation and then push outwards to create thrust. For the rest of the rotation, the propellers cut through the water without displacing water. In Figure 53, the motion of a single propeller at six stages is illustrated, for each drive.

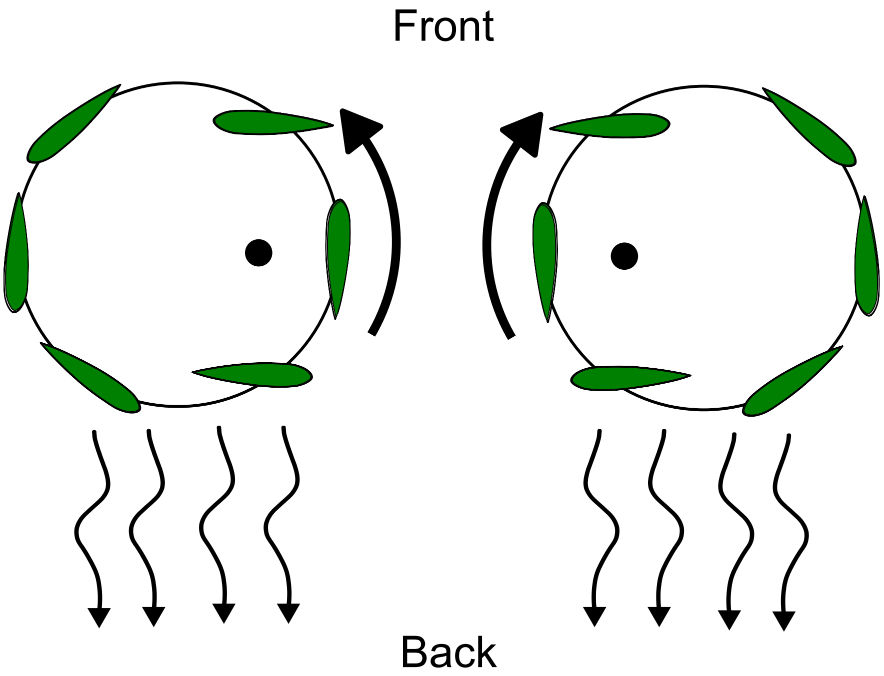


Figure 53: Diagram of a single Voith Schneider Propeller rotating at full pitch in the forward direction with no wheel adjustment

Scenario #3: Full Pitch and Full Wheel Direction Adjustment

The direction of the thrust is also adjusted by the wheel. The thrust is applied in the opposite direction of the direction the wheel is turned. For example, in a full pitch scenario, if the wheel is turned all the way to the left, the propellers push the water to the right and the ships moves laterally to the left. This scenario is shown in Figure 54.

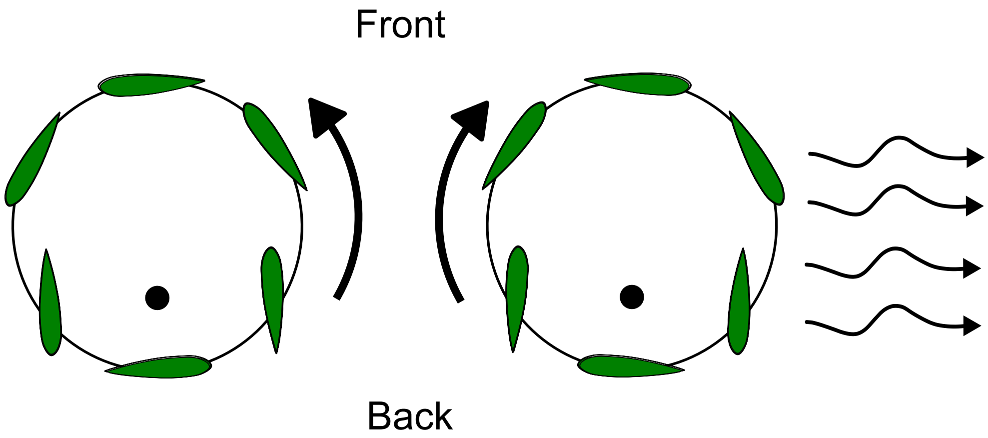


Figure 54: Diagram of a single Voith Schneider Propeller rotating at full pitch of both levers in the forward direction and the wheel turned all the way to the left, so that all of the force is applied towards the right.

Conclusion

The Garth Foss is often at Scenario #1, when idling, or Scenario #2, when travelling. Extreme scenarios, such as Scenario #3, occur less frequently and only for a short amount of time. There are an infinite numbers of configurations, which include extreme scenarios such as full pitch angles in opposite directions to spin the vessel in place, but most of the time the engines are configured with partial pitch and some wheel direction applied.