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OTTER: AN OPTIMIZED TRANSIT TOOL AND EASY REFERENCE

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ABSTRACT

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Ships’ commanding officers use fuel-usage curves to determine the most efficient propulsion-plant speed. Fuel efficiency is typically gauged by maintaining a consistent optimal speed. Often there are combinations of speeds that are more efficient than a constant speed. The transit fuel planner, developed in the Naval Postgraduate School’s operations research department by Brown, Kline, Rosenthal, and Washburn in 2007, calculates speed combinations to achieve fuel savings for a given single ship. This thesis adds additional capacities based upon common principles.

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<tr>
<td>BOSC</td>
<td>Battlegroup Optimum Speed Calculator</td>
</tr>
<tr>
<td>CBG</td>
<td>carrier battle group</td>
</tr>
<tr>
<td>CG</td>
<td>guided missile cruiser</td>
</tr>
<tr>
<td>CO</td>
<td>commanding officer</td>
</tr>
<tr>
<td>DDG</td>
<td>guided missile destroyer</td>
</tr>
<tr>
<td>DFM</td>
<td>diesel fuel, marine</td>
</tr>
<tr>
<td>DOD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>FFG</td>
<td>guided missile frigate</td>
</tr>
<tr>
<td>FY</td>
<td>fiscal year</td>
</tr>
<tr>
<td>GAO</td>
<td>Government Accountability Office</td>
</tr>
<tr>
<td>GPH</td>
<td>gallons per hour</td>
</tr>
<tr>
<td>GPNM</td>
<td>gallons per nautical mile</td>
</tr>
<tr>
<td>HR</td>
<td>hour</td>
</tr>
<tr>
<td>kts</td>
<td>knots or nautical miles per hour</td>
</tr>
<tr>
<td>LCS</td>
<td>littoral combat ship</td>
</tr>
<tr>
<td>LHA</td>
<td>landing-helicopter assault</td>
</tr>
<tr>
<td>LHD</td>
<td>landing-helicopter dock</td>
</tr>
<tr>
<td>LP</td>
<td>linear program</td>
</tr>
<tr>
<td>LPD</td>
<td>landing-platform dock</td>
</tr>
<tr>
<td>LSD</td>
<td>dock landing ship</td>
</tr>
<tr>
<td>NM</td>
<td>nautical miles</td>
</tr>
<tr>
<td>NPS</td>
<td>Naval Postgraduate School</td>
</tr>
<tr>
<td>OOD</td>
<td>officer of the deck</td>
</tr>
<tr>
<td>OTTER</td>
<td>Optimized Transit Tool and Easy Reference</td>
</tr>
<tr>
<td>PIM</td>
<td>plan of intended movement</td>
</tr>
<tr>
<td>RASP</td>
<td>replenishment-at-sea planner</td>
</tr>
<tr>
<td>SAG</td>
<td>surface-action group</td>
</tr>
<tr>
<td>TFP</td>
<td>transit fuel planner</td>
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<tr>
<td>TTSC</td>
<td>time to speed change</td>
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EXECUTIVE SUMMARY

This thesis describes a fuel-saving tool that may be used in daily shipboard operations, at the fleet level, and in planning offices. The transit fuel planner (TFP) developed in the Naval Postgraduate School’s Operations Research department by Brown, Kline, Rosenthal, and Washburn in 2007, calculates speed combinations to achieve fuel savings for a given single ship; this thesis adds additional capacities based upon common principles by expanding the optimization to multiple ships and events. This research develops a decision aide that is easy to use and distribute to military operators and planners.

Our optimization tool is dubbed the Optimized Transit Tool and its Easy Reference (OTTER). OTTER is made up of two components. “Dynamic OTTER” enables planners at the ship and group levels to factor in variables such as drills and evolutions (e.g., flight operations and man-overboard exercises) when calculating optimal speed combinations for travel. For example, suppose the Littoral Combat Ship, USS Freedom (LCS1) is required to transit at 19 knots (kts) average speed for 24 hours. The commanding officer (CO) may operate at any speed, so long as the ship stays inside a moving operating window. To meet training requirements, COs often run drills at slow speed and then catch up with the operating window. If a CO runs a four-hour drill at five kts and then accelerates to meet the expected arrival time, the combined speeds will yield extremely high burn rates. Sacrificing drills in this situation would save significant fuel, but this may not be an option. Dynamic OTTER optimally builds drills and evolutions into a schedule while allowing the user to update shaft-limit changes and fuel-curve data.

Dynamic OTTER can also produce a standalone reference sheet of optimal speed combinations for each class of ship, based on known fuel-consumption rates. This reference sheet, “Static OTTER,” could be added to CO standing orders for use by the officer of the deck (OOD).

Our results show significant fuel savings at high speeds for cruisers and destroyers, although savings of less than 1% are seen at normal transit speeds of 14 to 20
kts. In contrast, LCS-class ships see enormous savings under the same average transit speeds, adding significant time on station to the fleet at no additional cost. OTTER, using fuel curves for the first LCS class ship, could gain an 18% increase in fuel saved, equating to 10,368 gallons or an additional 57 hours on station at 8 kts. Figure A shows significant improvement in fuel economy both with and without scheduled drills.

Figure A. USS Freedom (LCS1) hours earned on station from 24 hour transit

<table>
<thead>
<tr>
<th>Speed profile</th>
<th>Avg burned (GPH)</th>
<th>48 hour transit total (gal)</th>
<th>Additional Time on station at 8 kts (hrs)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/o Drills</td>
<td>19 kts</td>
<td>2,428</td>
<td>116,544</td>
<td>0</td>
</tr>
<tr>
<td>W/o Drills</td>
<td>15 kts / 35 kts</td>
<td>1,996</td>
<td>95,827</td>
<td>113</td>
</tr>
<tr>
<td>W/ Drills</td>
<td>5 kts / 22 kts</td>
<td>2,537</td>
<td>121,753</td>
<td>0</td>
</tr>
<tr>
<td>W/ Drills</td>
<td>5 kts / 15 kts / 35 kts</td>
<td>2,221</td>
<td>106,611</td>
<td>83</td>
</tr>
</tbody>
</table>

USS Freedom (LCS1), with an average speed requirement of 19 kts, can earn 113 hours on station by using speed combinations recommended in OTTER with no drills or 83 hours on station with 4 hours of drills at 5 kts.
ACKNOWLEDGMENTS

I would like first to acknowledge my dear companion in this mission of life, Lani Blackburn, who has been my greatest support for 18 years. Lani, I fall in love with you more each day. I hope our children, Weston, Connor, and Emily, will someday find a best friend as I have in you.

There are a few NPS professors I will always remember. Professor Emily Craparo opened my mind to the complexities of linear and non-linear optimization with a smile. Professor, your promise was fulfilled—I lived through it. I would like also to thank Connor McLemore, who skillfully taught powerful, complex ideas using simple tools. Alan Howard and Dan Nussbaum from the Energy Academic Group provided travel funding to San Diego for me to compete in the Athena Conference (and take a first-place award). Brandon Naylor was a talented man that turned out to be a great friend and associate. I would pick you on my team anytime. Finally, I thank the professors and staff in the Operations Research Department for their professionalism and the knowledge they imparted to me.
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I. INTRODUCTION

A. BACKGROUND

Over the past 15 years, U.S. naval ships have consumed an annual average of nearly 500 million gallons of marine diesel fuel (DFM) at an estimated annual cost of $2 billion (Pehlivan 2015). In 2009, the Navy established aggressive goals for reducing consumption of energy at sea (DODLIVE 2015). Since that announcement, ships have consumed approximately 20% less fuel, with fiscal year (FY) 2013 consumption at the lowest, totaling 345 million gallons (Pehlivan 2015). Figure 1 depicts average underway barrels and hours per ship.

Figure 1. Average underway barrels of oil and time (hours) per ship

Total underway fuel consumption rates for FY 1999 through 2013. The overall decrease in fuel consumption per ship reflects conservation measures, despite a concurrent increase in underway hours per ship. Source: Hasan P (2015) Email message to the author, June 19.

Steam and gas turbine U.S. Navy ships are powered by multiple engines. The term “engineering configuration” refers to a ship-specific available combination of engines. A ship with four General Electric LM2500 gas turbines, for example, may be
operated in three different engineering configurations: one, two, or four engines online, with each additional engine adding to the available horsepower and fuel burn rate of the ship (Schrady et al. 1996). For a ship to reach higher speeds, more horsepower and often more engines are required. Ship speed limits may be imposed upon each engine configuration because of safety concerns determined by engineers (Ibid). Ships record fuel burn rates at each engineering configuration during performance trials; this thesis refers to the resulting fuel burn data as “fuel curves.”

Fuel usage aboard naval ships has steadily decreased since 2009 due to conservation measures. Simultaneously, ships are being removed from the fleet due to budget cuts, thereby increasing average underway time per ship. Figure 2 depicts this trend, as well as an increase in underburn, defined as the fuel saved annually on a specific ship, as compared with a baseline three-year average (FY 1999–2001). Fleet efficiency is imperative if the Navy is to sustain its mission and reduce fuel consumption.

Fuel-saving measures needing structural modifications require a significant investment of money in the beginning of the program, ideally earning back the money invested within a few years of implementation. Software improvements can also provide fuel savings, but they require managers that maintain support for the software development and application. Each of these technologies adds to the efficiency of the fleet. As RADM Thomas Eccles said, “No single technology will enable the Navy to achieve its energy goals” (McCoy 2012).
Figure 2.  Average barrels per ship and percent underburn annually

Annual average underburn per ship and percent underburn for FY 1999 through 2012. Underburn is defined as the amount of fuel saved compared to a baseline established from FY 1999—FY 2001, inclusive. Note the overall increase in fuel saved per ship due to conservation. Source: Hasan P (2015) Email message to the author, June 19.

While a number of fuel-saving measures have been implemented in recent years, improvements in operational transit speeds have been limited. Commanding officers do use fuel curves to configure ship’s propulsion plants for optimal efficiency at given constant speeds. If time or distance constraints demand a speed that is less than optimal, COs often apply common sense speed alternatives to save fuel; for example, a ship may drive at higher speeds for a time and then switch to a slower, more economical speed while maintaining a satisfactory position from a mission perspective. Figure 3 shows fuel-burn rates in gallons per nautical mile (GPNM) vs. ship speed in knots (kts) for a guided-missile cruiser (CG). Driving at the minimum point of the lowest curve (15.5 kts at trail shaft in Figure 3) at constant speed would return the absolute minimal burn rate
for a given vessel. Fuel curves for each ship analyzed in this thesis are included in Appendix A.

**Figure 3.** CG47 class total-ship fuel consumption GPNM vs. speed (with stern flap)

United States naval ships often operate within established moving boundaries called *plan of intended movement (PIM) boundaries* (NAVDORM 2012). A *PIM window* is an operating window that moves at a constant transit speed; its boundaries are typically four hours to the front and rear of the average speed point (see Figure 4). Traveling at a constant speed at the center of a PIM window is generally impossible due to conflicts with operational tasking and training requirements. To meet these requirements, evolutions are run at lower speed down the intended track, causing the ship to lag within
the PIM window and requiring it to “catch up” with other ships after the drill is complete. Such training requirements complicate the problem of optimizing transit speed to minimize fuel consumption. Often, a ship will travel at a combination of higher and lower speeds to accommodate training requirements. There exist optimal combinations of burn rates for several constant required speeds that are more efficient than the original burn rate, depending on specific ship configurations and respective burn rates.

Figure 4. PIM window example

![PIM window example](image)

PIM window is based upon a four-hour allowance forward and behind of the allowed average speed determined by higher authority.

B. LITERATURE REVIEW

The transit fuel planner (TFP) developed in the Department of Operations Research at the Naval Postgraduate School (NPS) prescribes optimal transit speeds to minimize fuel consumption based on the propulsion-plant configuration for a single ship (Brown et al. 2007). This thesis introduces the Optimized Transit Tool and Easy Reference (OTTER), which uses the concepts derived in the TFP to find optimal speeds and implement them in a useful manner (Brown, et al. 2011).

NPS student S. Fonte compares several fuel-saving techniques in his 2009 thesis, as shown in Table 1. The technique with the highest savings per year across his analysis was based upon efficient engineering configuration. Fonte noted that after the introduction of the TFP, follow up work was “waiting to be explored” (Fonte 2009). In 2014, NPS student Dustin K. Crawford proposed follow-up work to modify the TFP,
citing a need to analyze ships traveling together in a carrier battle group (CBG) or surface-action group (SAG).

Table 1. Fuel saving techniques and their estimated savings

<table>
<thead>
<tr>
<th>Technique</th>
<th>Savings/yr/ship ($K)</th>
<th>Savings/yr/SD Fleet ($K)</th>
<th>10-yr Savings at 0% disc ($K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practice Single Generator Ops</td>
<td>881</td>
<td>9,690</td>
<td>96,895</td>
</tr>
<tr>
<td>Modify Plant Status During RMD</td>
<td>44</td>
<td>920</td>
<td>9,200</td>
</tr>
<tr>
<td>Reduce Use of Prairie/Masker Air</td>
<td>38</td>
<td>789</td>
<td>7,886</td>
</tr>
<tr>
<td>Employ Duty Radar w/ 2 Aegis Ships</td>
<td>12</td>
<td>256</td>
<td>2,555</td>
</tr>
<tr>
<td>Allow for a Flexible C3F OAPERA</td>
<td>7</td>
<td>139</td>
<td>1,389</td>
</tr>
<tr>
<td>Use Auto-Pilot During Long Transit</td>
<td>6</td>
<td>86</td>
<td>860</td>
</tr>
</tbody>
</table>

As clearly seen, operating configuration has the most effect by far on fuel savings. Source: Fonte S (2009).

In 2015, Naval Systems Command (NAVSEA) 05Z created a tool that could be used onboard ships that optimize SAG or CBG transits that are required to maintain a steady state throughout the transit. This tool is called the Battlegroup Optimum Speed Calculator (BOSC). The limiting assumptions to this model are that the ships must maintain a constant speed throughout the transit and stay within a constant distance from each other. BOSC adds up the fuel burn rates for the different ships and returns the best fuel burn rate for the given group. For example, if a CG SAG was required to transit at 19 kts average speed, the calculator would tell you that 16 kts would be more efficient, given more time was available. BOSC, helps planners to schedule transits at a more optimal average speed (Pehlivan 2015). BOSC does not incorporate operational requirements such as drills and evolutions, constraining the ships to maintain a steady state speed throughout the transit. Additionally, it does not take into account the potential savings the TFP offers for ships if the SAG cannot travel at the optimal speed throughout the transit.

Naval Postgraduate School’s Energy Academic Group in 2015 commissioned a research project to determine the effect of ship configuration on fuel usage for a CBG on station (Naylor 2015). It was noted during the study that ships often operated with all
engines running during certain evolutions in order to be prepared for quicker response. Operating at an optimal engine configuration, CG and DDG class ships would spend between 50 and 100 percent more time conducting operations before needing to refuel. This study recommended coordination between CBG components in order to relax the requirements upon the CG and DDG escort ships in order to increase their operational capability.

The LCS is the newest class ships added to the Navy fleet and has as of today received little analysis with regards to fuel usage. In 2014, the Government Accountability Office (GAO) reported that “Fleet users said LCS fuel constraints contributed to a low average transit speed that, coupled with the very long distances ships have to travel within the 7th Fleet theater, make it hard for LCS to easily or efficiently get around the theater” (Government Accountability Office [GAO] 14-749 2014).

In the summer of 2014, the Navy conducted an experiment directing USS Sampson (DDG 102) to travel to Hawaii and back at a PIM speed of 15.5 kts, the minimum point on Sampson’s fuel curve. This is the ship’s most efficient speed, if maintained constantly. The ship was outfitted with a monitoring system that recorded fuel-burn rate and speed at 10-minute intervals throughout the transit. As shown in Figure 5, several factors contributed to decreased efficiency. Less than three hours was spent at optimal speed. Two-thirds of the time was spent at trail-shaft configuration, while the other third was spent at either full power or split plant (SURFPAC 2015). Maintaining an optimal transit speed of 15.5 kts could have saved 20,334 gallons of fuel, or 12.2%, equating to an additional 30 hours at 8 kts on station. The experiment demonstrated that a ship maintaining a constant speed of 15.5 kts for a seven-day transit is unrealistic, given the training and operational requirements a commander must fulfill. A primary objective of this thesis is to provide a decision tool that promotes awareness of fuel consumption while accounting for the operational realities inherent in naval operations.
Recent fuel-saving measures that have been implemented on board Navy ships include:

- Solid-state light-emitting diodes (LEDs), which save 50% to 80% on energy-related fuel requirements but cost 40 times that of the existing fluorescent bulbs at $158 per bulb. Each bulb has an expected 10 year life span, which is long enough to recoup the setup cost when compared to traditional bulb replacements (U.S. Navy 2014).

- A real-time monitoring program (the Shipboard Energy Dashboard), which shows how power requirements can be reduced while maintaining system performance and reliability requirements. This was developed by NAVSEA and is a decision tool that enables the user to modify operating behavior to save fuel. It is estimated to save less than one percent of fuel on average (DODLIVE 2015).

- Stern flaps installed on new ships and retrofitted on many existing ships modifying the water flow under the ship’s hull reduce drag and turbulence, thereby reducing overall hull resistance. Savings are estimated to be between 2 and 7%, recouping installation costs within the first 2 years of use (Ibid).
The Smart Voyage Planning Decision Aid is a computer software module that uses a ship’s Electronic Chart Display and Information System and information from meteorologists to determine an efficient and optimized route accounting for currents, waves and weather (Ibid). Fleet adoption of this system is in the initial stages.

C. OBJECTIVES

We develop a mathematical model incorporated in an Optimized Transit Tool and its Easy Reference dubbed “OTTER.” A major objective of this thesis is to determine the potential fuel savings of multiple ships moving together in convoy, as well as the operational requirements involved in keeping all such ships within a prescribed PIM window.

OTTER is made up of two components. “Dynamic OTTER” enables planners at the ship and group levels to factor in drills and evolutions, which occur typically at slow speeds (5 kts), when calculating optimal speed combinations for travel. For example, the USS Freedom (LCS1) is required to transit at 19 knots (kts) average speed for 24 hours. The commanding officer (CO) may operate at any speed, so long as he or she stays inside a moving operating window. To meet training requirements, COs often run drills at slow speed and then catch up with the operating window. If a CO runs a four-hour drill at five kts and then accelerates to 22 kts meet the expected arrival time, the combined speeds will yield extremely poor burn rates when averaged. Sacrificing drills in this situation would save significant fuel, but this may not be an option. Dynamic OTTER optimally builds drills and evolutions into a schedule while allowing the user to update shaft-limit changes and fuel-curve data.

Dynamic OTTER can also produce a standalone reference sheet of optimal speed combinations for each class of ship, based on known fuel-consumption rates. This reference sheet, “Static OTTER,” would be a valuable addition to CO standing orders for use by the officer of the deck (OOD).

In the analysis section of this thesis, we calculate the average and 90th percentile distances between ships traveling inside a common PIM window. Additionally, we calculate and analyze the time required until a CO must change speeds in order to stay
within the PIM window for various situations. These two values give the CO knowledge to support maneuvering decisions in transit routes.

D. SCOPE, LIMITATIONS AND ASSUMPTIONS

This thesis focuses on United States Navy surface-fleet, fossil-fuel ships. This flexible tool can serve as a basis for additional, comprehensive planning tools. While this thesis discusses a particular set of ships, further study of fuel optimization may be applied to any engineering platform with multiple fuel/distance curves.

Oceanic winds and currents affect ship speed during transit. To employ the static reference sheet, the OOD must determine the effect of current and wind using existing methodology before applying results from OTTER. If, for example, the required ship speed over ground is 12 kts, but there is a 2-kts current pushing back, the OOD adjusts the speed through water to 14 kts. We assume basic seamanship skills for simple navigation calculations using speed and direction manually entered into the calculation using Dynamic OTTER.

While Dynamic OTTER allows for the scheduling of drills in the short term, Static OTTER requires that the user calculate the new speed of advance after drills are complete. This new average speed can be used with the Static OTTER reference sheet to determine the most efficient speed combinations for the remaining transit.

E. CONTRIBUTIONS AND OUTLINE

The main contributions of this research are the proving and application of simple linear optimization of fuel curves across engineering configurations and the development of OTTER as a tool to implement this research in the fleet. The mathematics behind the linear programming model and how it was implemented are demonstrated in Chapter II. Static and Dynamic OTTER description and implementation tools are described in Chapter III. After providing examples and analysis results in Chapter IV, this thesis concludes with recommendations for implementation and potential future work.
II. MODEL

OTTER solves a linear program (LP) similar to the TFP in order to determine the optimal combination of speeds for each of the ships in a convoy, subject to the constraints that each ship arrive at the desired destination at a prescribed time while performing any required drills. The time and distance values used in the formulation account for requested drills, ocean current, starting and ending distance from the center of PIM, and the overall effect of the scheduled drills upon forward progress in reference to center of PIM. Although the relative positioning of the ships during transit is an important practical consideration, the LP does not explicitly calculate or prescribe individual ships’ positions as a function of time. Rather, after performing the optimization, OTTER determines a schedule of speed changes to guarantee that each ship remains within the PIM window.

Dynamic OTTER applies the faster of the two speeds first, putting the ship toward the forward half of the window. This models the current CO behavior and is most realistic. Drills are scheduled according to specified user input times. The schedule is broken down into time increments in number of minutes specified by the user.

The linear optimization model is shown next, followed by an explanation of the variables and constraints. This model simply calculates the most efficient speeds to travel at for a specified time and distance and is modified from the TFP model (Brown et al. 2007). The schedule builder is described in great detail in Chapter III.
A. TRANSIT FUEL PLANNER LINEAR PROGRAM (TFP-LP)

Indices and sets:
\[ v \in V = \text{Vessels} \{\text{CG, DDG1, DDG2, LCS1, LCS2, LHA1, LHA6, LHD1, LHD8, LPD4, LSD41, FFG7}\} \]
\[ s \in S = \text{Speed levels} \{1, 2, 3...40\} \]

Data [units]:
- \( Distance \): Required transit distance [nautical miles]
- \( Speed_{v,s} \): Speed of level \( s \) for vessel \( v \) [kts]
- \( BurnRate_{v,s} \): Fuel burn rate for vessel \( v \) operating at the most efficient plant configuration at speed level \( s \) [gallons per hour]
- \( AlTime \): Allotted time to complete transit [hours]

Decision variables [units]:
- \( Time_{v,s} \): Time for vessel \( v \) to spend at speed level \( s \) [hours]

Formulation:

\[
\text{Min} \sum_{v,s} Time_{v,s} \times BurnRate_{v,s}
\]

s.t.

\[
\sum_{s\in S} Speed_{v,s} \times Time_{v,s} \geq Distance \quad \forall v \tag{1}
\]

\[
\sum_{s\in S} Time_{v,s} = AlTime \quad \forall v \tag{2}
\]

\[
Time_{v,s} \geq 0 \quad \forall v, s \tag{3}
\]

B. DISCUSSION

For each ship, the model determines the optimal amount of time the ship should spend in each of a set of speed levels. The objective is to minimize the total fuel consumed by all ships. Constraint set (1) ensures that each vessel covers at least the required distance. Constraint set (2) ensures that the sum of the suggested times are equal to the allotted time constraint. Constraint set (3) ensures that the ship times at each speed
are non-negative. Each ship has unique speed profiles and fuel burn rates. Speeds chosen for a specific transit are only chosen from the specific ship’s profile ensuring feasibility.

For a SAG with 10 vessels, the optimization model contains 300 decision variables and 320 constraints. It solves in 0.5 seconds on an Intel 2.4GHz, 32-bit laptop with 4GB RAM.

Figure 6 walks through an example of how this optimization works using the LCS1 class ship. The states listed in the figure are the various engineering modes available to the LCS1. The straight line on connecting state 4 and 8 is the fuel burn rate possible if the ship travels at combinations of 15 kts and 35 kts. We present the following example:

- IF: a speed of 22 kts is ordered to be maintained, on average,
- THEN: 65% of the time should be spent at 15 kts in “state 4” mode
- AND: 35% of the time should be spent at 35 kts in “state 8” mode,
- RESULTING: in a savings of 468 gallons per hour (GPH) or 43 GPNM.
An example of an optimized speed combination of 15 kts and 35 kts. LCS1 fuel burn rate displayed in gallons per nautical mile (GPNM) vs. ship speed (kts). The OTTER solution at 22-kts average speed returns 102 GPNM instead of the 145 GPNM in state 8 only. Adapted from Pehlivan H (2015).

It is important to note that in an optimal solution, each ship will spend a nonzero amount of time traveling at most two speeds, excluding drills. This principle can be proven by first assuming the negation. Assume there are three speeds that minimize the average fuel consumption for a given speed. These three speeds on Figure 6 would form a triangle. The minimum burn rate on this triangle would be found along the lowest edge which is a combination of exactly two points. Therefore, proving that as time segments become infinitesimally small, there will always exist at least one but at most two speeds that will be optimal.
III. THE USER INTERFACE

This chapter describes the user interfaces for Dynamic OTTER and Static OTTER.

A. DYNAMIC OTTER

Dynamic OTTER solves for the optimal speed combinations for the given engineering plant configurations, constrained by user-defined drill periods. The user sets the drill time, duration, and effect on forward progress down track as input, as seen in Figure 7. Dynamic OTTER is built in the Visual Basic for Applications (VBA) language in the Microsoft Excel framework.

Dynamic OTTER requests transit distance and time, start time, time interval and the effect of ocean current on the transit. The user can add two separate drill starting times, durations, and effects on transit.

Dynamic OTTER’s schedule builder output was inspired by the NPS CBG study done by Naylor (Naylor 2015). The study used a tool called the Fuel Usage Study Extended Demonstration (FUSED) which created a ship schedule by hour allowing the scheduler to analyze the fuel usage of the ships over time. OTTER’s schedule builder output allowed calculations such as distance traveled, distance between ships in the
group, and cumulative fuel used. It also enables the scheduling of drills and optimization of the remaining time and distance values. A pictorial representation of an output schedule that could be built using Dynamic OTTER can be seen on Figure 8.

Figure 8. Schedule builder timeline

Timeline for a 48-hour transit scheduled into one-hour time increments (TI) with two four-hour drills (DN) scheduled. The drill event is annotated by a start time \( (D_{SI,v,dn}) \), drill speed \( (D_{SI,v,dn}) \) and a duration \( (D_{DI,v,dn}) \) for each vessel.

1. Dynamic OTTER Schedule Builder Pseudocode

Sets:
- Ships (CG, DDG, etc.) \( V \)
- Drill numbers (1, 2) \( DN \)
- Time intervals (1, 2, 3...) \( TI \)
- Speed options (1, 2) \( SP \)

Input:
- Distance to travel (nm) \( D \)
- Time for transit to be complete (hrs) \( T \)
- Transit start time for ship \( v \) (mm/dd/yy hh:mm) \( TS \)
- Transit time interval size (min) \( M \)
- Ocean current relative to PIM (kts) \( OC \)
- Drill start time for ship \( v \) and drill number \( dn \) (mm/dd/yy hh:mm) \( D_{SI,v,dn} \)
- Drill duration for ship \( v \) and drill number \( dn \) (hrs) \( D_{DI,v,dn} \)
• Forward progress for ship $v$ during drill number $dn$ (nm) $DP_{v,dn}$

• Drill speed for ship $v$ during drill number $dn$ (kts) $DSP_{v,dn}$

• Start offset for ship $v$ (nm) $SO_v$

• Ending offset for ship $v$ (nm) $EO_v$

**Compute values:**

• Current progress of vessel $v$ at time interval $ti$ (nm) $CP_{v,ti}$

• Front boundary of PIM window at time interval $ti$ $FB_{ti}$

• Back boundary of PIM window at time interval $ti$ $BB_{ti}$

• Time intervals in transit (integer) $TI = \frac{T \times 60}{M}$

• Travel time at interval $ti$ (mm/dd/yy hh:mm) $TT = \frac{ti \times M}{60}$

• Final distance for ship $v$ after drills (nm)

\[
FD_v = D - \sum_{dn} DP_{v,dn} + EO_v - SO_v \quad \forall v \in V
\]

• Remaining time for ship $v$ drills (min)

\[
RT_v = TI - \sum_{dn} DDI_{v,dn} \quad \forall v \in V
\]

• PIM speed (kts) $PIMSP = \frac{D}{T}$

• PIM window center progress (nm) $PIM = PIMSP \times TT$

• Drill number $dn$ start intervals for ship $v$ (integer)

\[
DSI_{v,dn} = \frac{DS_{v,dn} - TS_v}{M} \quad \forall v \in V, \, dn \in DN
\]

• Drill number $dn$ duration intervals for ship $v$ (integer)

\[
DDI_{v,dn} = \frac{DD_{v,dn} \times 60}{M} \quad \forall v \in V, \, dn \in DN
\]
• Run TFP-LP\(^1\) Optimization uses \(FD_v, RT_v \forall v \in V\) and returns:
  
  • 2 optimal speeds (high/low speeds) for vessel \(v\) (kts)

\[
OSP_{hi,v}, OSP_{lo,v}
\]

• 2 sets (high/low speeds) of remaining time intervals for vessel \(v\) (integer)

\[
SPI_{hi,v}, SPI_{lo,v}
\]

**Plan ship schedule:**

\[CP_{v,ti} = SO_v\]

For \(ti = 1\) to \(TI\)

For each \(v \in V\)

\(\text{did\_drill} = \text{false}\)

For each \(dn \in DN\)

If \(\text{ti} \geq DSI_{v, dn} \& \text{ti} < DSI_{v, dn} + DDI_{v, dn}\) then

\[
SP = DSP_{v, dn}
\]

\[
CP_{v, ti} = CP_{v, ti} + \frac{DP_{v, dn}}{DD_{v, dn}} * \frac{M}{60}
\]

\(\text{did\_drill} = \text{true}\)

End if

End for

If not did\_drill then

If \(SPI_{hi,v} > 0 \& CP_v \leq (PIM + 4*PIMSP)\) then

\[
SP = OSP_{hi,v}
\]

If \(CP_{v,ti} \geq (PIM + 4*PIMSP)\)

\[
FB_{ti} = CP_{v, ti}^2
\]

---

\(^1\) Optimization method explained in Chapter II

\(^2\) Front and Back boundary calculations described in Chapter II, Section B, Subsection 2
The Dynamic OTTER schedule builder pseudocode builds the arrays and user specified values that will be used to include the ship types used, offset and drill parameters, new and old fuel burned variables. The interval size $M$ is chosen from a drop down cell of values that are factors of 60. This ensures that $M$ is always an integer. After clearing the old schedule, it updates the schedule headers for each ship chosen on the planner with the appropriate ship types.

The code then loops through the entire range of time intervals scheduled and determines whether to plan a drill, high speed value or low speed value. The modeler sends the ship to the forward half of the operating window by using the faster of the two speeds first. If the chosen time interval is large (60 min), the processing time will be nearly instantaneous.

Now that the schedule builder has calculated the current position $CP_{v,ti}$ for each vessel $v$ and time interval $ti$, and we have the PIM window center position $PIM$ over each time interval $ti$, we can plot these two for position comparison on the transit. As seen in Figure 9, the OTTER plan maintains a close position to PIM center even with the scheduled drills.
Figure 9. OTTER transit vs. PIM center

Transit distance relative to average speed (PIM center) using Dynamic OTTER schedule builder. This is a DDG Flt 1 48 hour transit at 24 kts average speed with 2 four hour drills scheduled during the transit. Fuel saved during this transit was 70,646 gal or 96 hours of additional time on station compared to typical ship behavior.

After the schedule has been built, the comparative burn rates are calculated based upon a surge speed that is defined by user settings. This surge speed is sub optimum and representative of actual CO behavior during sprint and drift operations. These old burn rates are compiled and compared to the new total fuel burned and values are output as fuel saved. This is also converted to extra time on station by using the ship’s average burn rate at 8 kts. Actual VBA code for Dynamic OTTER can be found in Appendix D.

The OTTER schedule builder runs extremely quickly. It requires approximately 1.0 second to plan a 48-hour transit in 5-minute increments for a SAG with 10 ships. The resulting file size is 671 KB, making it easy to share via email or download.

2. Time Until Speed Change

Another valuable capability this thesis describes is a method of calculating PIM boundaries. The time until speed change (TTSC) is defined as the time (in hours) until a ship is required to change speed to stay within the PIM window. Normally the ship CO must determine when to change speeds in order to stay within the PIM window boundaries. Assuming the ship starts a transit at the center of an authorized PIM window,
the time to change speed can be calculated for both the front and back of the PIM window.

In the pseudocode, the front boundary $FB_i$ and the back boundary $BB_i$ were saved, recording the time at which a forward or back boundary was reached. These moving boundaries in time are not to be crossed, so they serve as a guide in Static OTTER as well as in our analysis Chapter as TTSC.

3. **Dynamic OTTER Output**

Dynamic OTTER returns a schedule indicating the PIM center, each ship position, engineering configuration, and speed in each time step. The fuel burned, saved, and equivalent time on station is shown for each ship. The “largest spread” value reported in the header is the greatest difference between ship positions at any point in time. Each ship will stay within the PIM window during the transit. Figure 10 shows the output from Dynamic OTTER, a schedule broken down into time increments for each ship modeled.
OTTER output returns a schedule broken down by time intervals and start-time specified for each ship, showing the optimal speed and engineering mode to be used.

4. **Dynamic OTTER Settings**

To update ship parameters such as shaft limits or maximum speed, the user completes an interactive form for each engineering configuration, as depicted in Figure 11. This is required when engineering limits are imposed due to engineering casualties, or as higher authority directs. The fuel curves can also be updated after ship performance trials. New fuel-curve data may result in significant changes in the findings for optimal speed.
User-defined settings enable the user to update shaft limits for each engineering configuration used. It also enables constraints for time intervals between speed and mode changes.

Users also have the ability to add new ship types (Figure 12) through the settings tab. Users must have ship configuration data such as burn rates and propulsion limits for each mode. When the user inputs this data, the spreadsheet parameters are updated allowing for validation and implementation into both Dynamic and Static OTTER calculations.

When ship types are no longer needed, users can delete the ship from the database through the user-defined settings for that particular ship. This permanent removal deletes the worksheet and all associations to that worksheet in the name manager.

The CO may decide that changing engineering modes impacts the personnel on the ship and therefore wants to limit the frequency. The settings page has parameters such as the minimum time between mode or speed changes to allow for these customizations.
Figure 12. Create a new ship type

New ship type input form from Dynamic OTTER settings page. User may input propulsion limits which will be saved on a new worksheet in OTTER for new optimal transits and Static worksheet creation.

B. STATIC OTTER

The interface of Static OTTER, depicted in Figure 13, is a user-friendly reference sheet customized to specific ship parameters. Once the proper fuel curves and shaft limits have been verified for a ship, this reference sheet is available for printing. Static OTTER has a speed combination for several requested average speeds. It also gives the percentage of time a user should spend at each of the two speeds. It shows the time until a PIM boundary is met based upon a 4 hour PIM operating window and the ship starting point is from the middle of PIM. Because of these assumptions, operators should always note their position inside the PIM window and ensure boundaries are not violated.

The reference sheet contains detailed instructions and examples. More static tools can be found in Appendix B. Additional sheets can be made and printed from Dynamic OTTER. The spreadsheet also notes the source of the fuel-curve data; this note can be updated by the user through Dynamic OTTER when changes are made to the baseline fuel burn rates.

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Static OTTER can be used to minimize fuel consumption by combining two ship speeds instead of maintaining a single constant speed.
IV. RESULTS

We now demonstrate the benefits of applying linear optimization to fuel curves in the following example. Suppose LCS1 is in a 48-hour transit and is required to maintain an average speed of 19 kts. Using a standard approach, if the CO decided to run a four-hour drill at five kts and then adjusted the ship’s speed to catch up to the expected arrival time (5 kts/21 kts), less-efficient burn rates would be achieved. However, if after running drills the more efficient speed combinations were used (5 kts/15 kts/35 kts), significant fuel would be saved (see Table 2). A CO need not sacrifice drills to save fuel and extend on-station endurance. Dynamic OTTER optimally builds the drill into the schedule at the time specified by the user.

Table 2. USS Freedom (LCS1) with average speed requirement of 19 kts

<table>
<thead>
<tr>
<th>Speed profile</th>
<th>Avg burned (GPH)</th>
<th>48 hour transit total (gal)</th>
<th>Additional Time on station at 8 kts (hrs)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/o Drills 19 kts</td>
<td>2,428</td>
<td>116,544</td>
<td>0</td>
<td>Constant speed</td>
</tr>
<tr>
<td>W/o Drills 15 kts / 35 kts</td>
<td>1,996</td>
<td>95,827</td>
<td>113</td>
<td>With OTTER</td>
</tr>
<tr>
<td>W/ Drills 5 kts / 22 kts</td>
<td>2,537</td>
<td>121,753</td>
<td>0</td>
<td>Catch up</td>
</tr>
<tr>
<td>W/ Drills 5 kts / 15 kts / 35 kts</td>
<td>2,221</td>
<td>106,611</td>
<td>83</td>
<td>With OTTER</td>
</tr>
</tbody>
</table>

USS Freedom reduction in fuel burn rates when OTTER is used, earning many more hours on station before refueling is required.

A. DATA COLLECTION

For our computational experiments, we used ship performance data collected by Naval Surface Warfare Center, Carderock Division, in West Bethesda, Maryland, during initial sea trials of the lead ship in a class (Pehlivan 2015). Users can update fuel usage data in OTTER as needed accounting for the slight changes in fuel burn as equipment ages.

In order to apply realistic ship transits to the model, we used data collected by Commander Naval Surface Force, U.S. Pacific Fleet Energy Office in 2014 from the USS
Sampson during transit from San Diego to Hawaii and back (Richards 2015). Speed and configuration profile data were collected every 10 minutes for the duration of the transit. This data shows the real transit habits of COs at sea. While a constant transit speed is most convenient to model, it is often unrealistic. Fuel savings were substantially greater using OTTER than using a conservative constant-speed model.

Because burn rates are not stochastic, simulations or trial runs were not required to validate the model. We ran the optimization model over the entire speed range for each ship to produce Static OTTER reference sheets. These new burn rates are independent of other ship transits. Groups of ships could still use reference sheets independently if their constraints are only to remain inside the PIM window. Closer grouping requirements will be addressed in the next section.

B. MAXIMUM SPREAD BETWEEN SHIPS

When a group of ships travels in a SAG, higher authority will dictate the maximum distance between ships during the transit for force protection or logistical reasons. Transiting as a group requires daily planning coordination between COs to ensure these boundaries are not violated. OTTER considers the four hour ahead and behind of the PIM window center as acceptable boundaries for planning. Figure 14 depicts the spread in distance during an example 48-hour transit that a CG and DDG1 would experience following the Dynamic OTTER “Short Term Schedule” recommendations.

With a simple evaluation by the CO or OOD, the spreads could be reduced significantly with no impact on fuel savings. The deviation from the proposed transit plan might be to alternate speeds more frequently than otherwise proposed. Dynamic OTTER has the ability to constrain the spread distance to a specified parameter. This feature does not affect the fuel savings; rather, the effect is seen through more frequent speed or mode changes.
Figure 14. Spread among ships during a group transit of CG and DDG1

Distance between a CG and DDG1 with an average transit speed of 14 kts. These spread distances are due to the differences in proposed transit speeds. The CG travels at 15 kts and then 10 kts while the DDG1 travels at constant 14 kts. The maximum spread between the ships is 37 nm with no additional constraints applied.

Changing some engine configurations may require significant effort for some ships. Intuitively, the larger the spread allowed, the less frequently the ship will have to change engineering modes. If the optimal speeds are followed in their respective ratios as provided by Static OTTER, the fuel savings will be the same, regardless of the frequency of mode changes. In short, the cost of earning a small spread between ships is more frequent engine configuration changes.

Following the recommended OTTER solution with no spread minimization, Table 3 shows the average spread between two ships traveling in a SAG. For example, if a CG and a DDG1 transit in a SAG together, they will, on average be 11 NM apart. Table 4 shows the 90th percentile of the data. Similarly, a CG and DDG1 traveling together would be less than 30 NM apart 90% of the time.
Table 3. Average spread among ships using Dynamic OTTER

<table>
<thead>
<tr>
<th></th>
<th>CG</th>
<th>DDG1</th>
<th>DDG2A</th>
<th>LCS1</th>
<th>LCS2</th>
<th>LHA1</th>
<th>LHD1</th>
<th>LSD41</th>
<th>LPD4</th>
<th>FFG7</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG</td>
<td>NA</td>
<td>11</td>
<td>6</td>
<td>30</td>
<td>8</td>
<td>7</td>
<td>14</td>
<td>11</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>DDG1</td>
<td>NA</td>
<td>7</td>
<td>34</td>
<td>10</td>
<td>4</td>
<td>12</td>
<td>10</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DDG2A</td>
<td>NA</td>
<td>29</td>
<td>7</td>
<td>3</td>
<td>12</td>
<td>7</td>
<td>11</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCS1</td>
<td>NA</td>
<td>29</td>
<td>22</td>
<td>19</td>
<td>24</td>
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<td></td>
</tr>
<tr>
<td>LCS2</td>
<td>NA</td>
<td>9</td>
<td>12</td>
<td>10</td>
<td>11</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHA1</td>
<td>NA</td>
<td>14</td>
<td>4</td>
<td>11</td>
<td>4</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>LHD1</td>
<td>NA</td>
<td>13</td>
<td>5</td>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSD41</td>
<td>NA</td>
<td>10</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPD4</td>
<td>NA</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFG7</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With a four-hour PIM window established, the average distance between two ships is shown. This average was calculated over the speed range (1-30 kts for CG) of the slower of the two ships analyzed.

Table 4. 90% of time spread—using Dynamic OTTER

<table>
<thead>
<tr>
<th></th>
<th>CG</th>
<th>DDG1</th>
<th>DDG2A</th>
<th>LCS1</th>
<th>LCS2</th>
<th>LHA1</th>
<th>LHD1</th>
<th>LSD41</th>
<th>LPD4</th>
<th>FFG7</th>
</tr>
</thead>
<tbody>
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With a four-hour PIM window established, 90% of the time the distance between ships will be less than the expressed value.

From each of the combinations in Tables 3 and 4, we created a histogram to represent the number of times during a 48 hour transit (broken down into five minute intervals), that one of the \( \left(\binom{10}{2}=45\right) \) 45 ship pairs shown on the y axis, across all common speed ranges, would be a particular distance apart. This is a good way of quickly visually portraying the ship pair separation distances. Figure 15 compiles these
48 histograms together into a three dimensional graph. By design the ships are constrained to the common PIM window. This design keeps their spread distances to a minimum, and as one can see from the figure, the majority of the time is spent with very minor distances between them.

![Figure 15. Spread values for all ship pairs analyzed](image)

Spread distances (x axis) between ship pairs (y axis) and the frequency (z axis) that particular spread distance occurs.

C. **TIME TO SPEED CHANGE**

As described in Chapter III, the TTSC values are a measure of the frequency of mode shifts. A low TTSC value means that these shifts occur at higher frequency, likely adding some burden on the engineering crew. TTSC results could be considered highly reasonable with no times less than one hour, and only 3% of situations require a time of one hour. A cumulative summary of TTSC is shown in Figure 16. The TTSC are usually greater than 100 hours which is typically negligible. Individual ship TTSC for the ships analyzed are included in Appendix C.
Figure 16. Frequency of TTSC across all ships modeled

These are TTSC (x axis) vs. number of occurrences (y axis) accumulated over CG, DDG1, DDG2A, LCS1, LCS2, LHA1, LHD1, LSD41, LPD4, LSD49 and FFG7 ships.

Another metric to represent the additional engineering burden required to stay within a PIM window is a quantity we denote as \( \text{big } T \). Big T represents the PIM window size in nm divided by the percentage of time spent at one of two optimal speeds. To calculate these values we assume that the ships are operating in a standard four hour window with no drills and there is time to complete the transit. The same variables and definitions from Chapter III are used, with the addition of \( PT_{lo,v} \) which is defined as the optimal percentage of time for vessel \( v \) to spend at \( lo \) speed or its counterpart \( hi \) speed. These values are output from the TFP optimizer. Big T can be defined as the following:

\[
\text{Big } T = \frac{PIMSP*4hrs}{(OSP_{hi,v} - PIMSP)*PT_{hi,v}} = \frac{PIMSP*4hrs}{(PIMSP - OSP_{hi,v})* PT_{lo,v}}
\]

Figure 17 is a graph of every big T value for the range of average speeds for different ship types. It is observable that on average, at lower speeds big T values are lower, meaning that the impactful mode changes would be experienced at average speeds under 10 kts. The outlier to this trend is the LCS1 (shown in purple), where lower big T values
exist at higher transit speeds, owing to the unique engineering plant on that ship that allows greater savings at higher average speeds.

Figure 17. Big T (average speed vs. big T)

Big T times are expressed as the time until a ship is forced to change speeds in order to stay inside of the standard operating envelope using OTTER. This figure shows a standard 4 hour PIM operating window. For example: At 25 kts average speed, LCS1 will have to change speeds at intervals of (20 hours * 50%) = 10 hours. In order to stay inside the PIM operating window. Twenty hours came from the y-axis and the fraction is an output of the TFP optimization.

D. ANALYZING MULTI-SPEED FUEL OPTIMIZATION

In practice, COs currently tend to operate in the forward region of their moving PIM window. This allows the CO more flexibility to perform drills and evolutions such as flight operations as needed. Keeping this in mind, Dynamic OTTER models the base-case ship fuel usage as a forward operating ship. It surges the ship to the forward edge of the window using a user-defined surge speed established on the settings page (27 kts for a CG) and then operates at the forward edge until a drill is run or the destination is reached on time.
OTTER then creates a schedule using the optimal speed combinations to position the ship in the forward part of the window, as the CO would desire. The key difference between the base case and the OTTER solution is the use of the inefficient surge speed in the base case. Surging forward is done so frequently for operational reasons that it has been adopted as a common practice called “sprint and drift” (Friedman 2014). The concept is sound, but without knowing the optimal speeds to sprint and drift, the sprint and drift solution is sub-optimal and therefore, unnecessarily wasteful.

We compared the base case with the Dynamic OTTER solution over 48 hour transits in Figure 18. We assumed no drills were scheduled with a 5 minute incremental resolution. The spread constraint was set at 40 nm and the on station speed was assumed to be 8 kts. For average transit speeds of 15–20 kts, on average a ship could earn 20–35 hours on station. The base case modeled typical CO transit behavior. A more comprehensive graph for each ship is included in Figure 19.

Figure 18.  Average hours earned at various average speeds

![Average hours earned at various average speeds](image)

Additional average hours earned by following OTTER recommendations for a sample of ships traveling in a SAG for a range of average speeds. For example, with a PIM of 15 kts, the ships capable of traveling 15 kts earn about 20 hours of on station time at 8 kts per 48-hour transit, on average.
E. CONFIGURATION MATTERS

Ships do not always operate under the most efficient configurations. This may be due to readiness conditions required for an exercise or possibly engineering restrictions. Operating under the optimal engineering-plant configuration and speed are vital components in an efficient transit. For the LCS1 example in Table 2, OTTER proposes a combination of 15 kts and 35 kts at the optimal configuration without drills, resulting in an additional 113 hours on station (at 8 kts) compared to a constant speed. If the user decides to operate under a less efficient engineering mode at the same durations (state 9 vs. state 6/7), the fuel saved will be reduced significantly—from an earned 113 hours on station to 87 hours.

Not all engineering plants are created equal. Boiler plants with only two modes of operation—single or dual boiler mode—do not experience an improvement at all in the majority of their speed ranges (see Appendix B). In contrast, LCS1, has a total of nine engineering configuration modes of operation, allowing for optimization between each
mode giving the LCS class ships enormous opportunity gains in fuel efficiency because of the plant configuration modes.

Applying OTTER to the transit shown in Figure 5 would save 3,329 gallons, which equates to an additional five hours on station at 8 kts—a 1.5% improvement in efficiency. The improvement on the CG and DDG are significant, but not extraordinary. The LCS1-class ship however, could have earned 14% improvement, equating to 37,703 gallons, or an additional 206 hours on station at 8 kts.
V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis provides a tool that optimizes fuel usage across a group of ships in an impactful way. Benefits of its use are displayed in units of earned time on station to show the operational impact of fuel savings.

B. IMPLEMENTATION CHALLENGES

Designing an intuitive and easily distributable tool for routine use by fleet and shipboard commanders was the goal of this research. Walt DeGrange, a developer of the Replenishment-at-Sea Planner (RASP), laments the indifference that operations-research analyst’s typical experience:

[We] spend months developing the perfect optimal scheduling model by defining the problem, collecting the data, refining the model, enhancing the user interface and including customer feedback and then finally deploying the model. After all this work the customer does not use the model and reverts to legacy practices. What went wrong? (DeGrange 2012)

This thesis faced these challenges of implementation through direct fleet involvement. Briefs were given to the Fleet Forces Command, Commander, Surface Forces, Commander Destroyer Squadron 31 (to include an operational trial in April 2016), Rand Corporation, Office of Naval Research and the Office of the Chief of Naval Operations—Joint Logistics Engagement. OTTER has been tested and distributed with a reference point of contact at Naval Postgraduate School for technical support in the Energy Academic Group.

Implementation of this tool could have taken many different forms, but because we wanted a model that would be directly applicable and used in the fleet, we chose to use Microsoft Excel with no add-ins or external required software. This stand-alone file can be used on Navy computers afloat and ashore. This feature is potentially the most valuable of all.
C. FUTURE WORK

A few modeling variants could yield additional insight. This thesis models speed changes as instantaneous time points. Further modeling of speed ups and slowdowns during these speed changes may result in meaningful results. Another variant of the schedule might build it using closed form calculations for times to speed change, thus eliminating the need to iterate over discrete time periods. Alternatively, a more comprehensive optimization model could simultaneously determine optimal speeds and build a schedule for the battle group.

Application toward other engineering platforms such as train transport or aviation could be explored. Any multi-modal engineering platform with different burn rates could benefit from linear optimization. Implementation of OTTER toward Navy oilers and supply support ships may provide additional fuel savings that are worth investigation.
APPENDIX A. FUEL CURVES

This appendix contains fuel curves for CG, DDG flight 1, DDG flight 2A, LCS1, LCS2, LHA, LHD, LSD, LPD, and FFG7 class ships.

Figure 20.  CG 47 class total ship fuel consumption (with stern flap) (GPNM)

Adapted from: Hasan P (2015)
Figure 21. DDG51 FLT 1 and II class total ship fuel consumption (with stern flap) (GPNM)

Figure 22. DDG51 FLT IIA class total ship fuel consumption (with stern flap) (GPNM)

Figure 23. LCS1 total ship fuel consumption (GPNM)

Figure 24. LCS2 total ship fuel consumption (GPNM)

Figure 25.  FFG7 class total ship fuel consumption (with stern flap) (GPNM)

Figure 26. LSD41 class total ship fuel consumption (GPNM)

Figure 27. LSD49 class total ship fuel consumption (GPNM)

Figure 28. LHD8 class total ship fuel consumption (GPNM)

Adapted from Pehlivan H (2015)
This appendix contains OTTER static tools for CG, DDG flight 1, DDG flight 2A, LCS1, LCS2, LHA, LHD1, LHD8, LSD, LPD, and FFG7 class ships. Reference sheets are to be used independently with no required assumptions. Fuel performance dates for each class ship are annotated on the sheet.
**Figure 29. CG Static OTTER**

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**CG 47 CLASS TOTAL SHIP FUEL CONSUMPTION**

*With Stern Flag*

**Source:** USS Vinson (CG 49) Performance and Special Trials Preliminary Results Dated January 1986

**Source:** USS Vinson (CG 49) Fuel Performance Trials Final Report. Project PM 5586 Dated November 1985

**Displacement = 9,545 LT from report Dated November 1985**

**For displacement changes modify SHP by +/- 0.5% per +/- 100 LT change**

**Average 24-Hour Load = 2,200 kW [888 GPM] from Fuel Performance Trials Final Report**

**For kW changes modify GPM by +/- 8 GPM per +/- 100 kW change**

**No Bleed Air**

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always
Figure 30. DDG1 Static OTTER
Figure 31. DDG2 Static OTTER

**DDG2A OTTER V1.2 Speed Table**

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**DDG2A OTTER V1.2**

**DDG2A**

**OTTER V1.2**

**Supplemental Info**

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. Hrs to cross PIM boundary column is based upon starting at middle of PIM window - always
Figure 32. LCS1 Static OTTER

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LCS1 CLASS TOTAL SHIP FUEL CONSUMPTION

SOURCE: NSWCDD-S3-TR-2012-018, "USS Freedom (LCS 1) Performance and Special Trials Results Volume 1."

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drifts.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. Nt indicates PIM boundary column is based upon starting at middle of PIM window - always

Most efficient speed (gallons per mile)

Speed vs Fuel Usage (GPM/mi)

Minimum Burn
OTTER Burn

Fuel Usage (gpm)

Average Speed (kts)
Figure 33. LCS2 Static OTTER

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### LCS2 CLS2 CLASS TOTAL SHIP FUEL CONSUMPTION

- For displacement differences, modify SHP by +/- 3.4% per +/- 100 LT change
- Average 24 Hour Electric Load Fuel Consumption: 64 GPM
- Includes 10% factor for adverse sea conditions and hull fouling
- Includes 5% factor for plant deterioration
- Shaft alignments not included - G201 tested at 29 knots and fuel consumption was greater than G210

*Fuel burn rate for speeds below 5kts extrapolated from available data

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. Has to cross PIM boundary column is based upon starting at middle of PIM window - always

### Speed vs Fuel Usage (GPM/M)

- Most efficient speed (gallons per min)
- Minimum Burn
- OTTER Burn

### Fuel Usage (gpm)

- Average Speed (kts)

54
Figure 34. LHA1 Static OTTER

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LHA 1 CLASS TOTAL SHIP FUEL CONSUMPTION

Source [1]: Naval Ship Research and Development Center Report # 77-00081 "Standardization and Preliminary Fuel Economy Trials of USS Tarawa (LHA 1): Donald H. Drazin, Dated January 1977
Source [2]: NAVSEA Project 8-1635 "USS Tarawa (LHA-1) NAVSEA Performance and Special Trials Fuel Economy Trials Report" Dated 5 May 1977
- Trial displacement: 33,000 tons corrected to 38,500 tons F.L.D.
- For displacement differences, modify SHP by 1/2; 0.4% per +/- 100 LT change
- Total installed SHP = 76,000 HP
- All alignments are at 100% design pitch

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drift planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. Hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

Speed vs Fuel Usage (GPMN)

- Most efficient speed (gallons per mile)
- Minimum Burn
- OTTER Burn

Fuel Usage (gpmn)

Average Speed (kts)
Figure 35. LHD1 Static OTTER

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LHD1 CLASS TOTAL SHIP FUEL CONSUMPTION
Source: NAVSEA IFINCON SEACAT XL Version 1.2 Class Trial Data (From LHD 2 USS ESSEX)
- Ship Displacement: 17 = 81,950
- Average 24 Hour Electric Load: 3350 kW
- All alignments are at 100% design pitch
- SBECoc = single boiler economic
- 2BECoc = 2 boiler economic
- 28Fw = 2 boiler full power
* Fuel burn rate for speeds below 5 kts extrapolated from available data

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always

Graph: Speed vs Fuel Usage (GPNM)
- Minimum Burn
- OTTER Burn

Average Speed (kts): 5 10 15 20 25
Fuel Usage (gpm): 0 50 100 150 200
Most efficient speed (gpm) per unit

56
Figure 36. LPD4 Static OTTER

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**LPD 4 CLASS TOTAL SHIP FUEL CONSUMPTION**

Source: NAVSEA ENCON SECAT II Version 1.2 Class Trial Data (from LPD 9 USS DENVER)

- Ship Displacement, LT = 15,060
- Average 24 Hour Electric Load: 8000 kW
- All alignments are at 100% design pitch
- SEICon + single boiler economic
- 2SEICon = 2 boiler economic
- 2BBull = 2 boilers full power
*Fuel burn rate for speeds below 5kts extrapolated from available data

1. GPM saved based on maintaining average speed for transit.
2. GPM saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window - always
### LSD41 Static OTTER

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**LSD 41 CLASS TOTAL SHIP FUEL CONSUMPTION**


- Full Load Displacement 15,590 tons
- For displacement differences, modify SHP by +/- 1.7% per +/- 100kW change
- Average 24 Hour Electric Load Fuel Consumption = 173kW (139 GPH)
- For kW differences, adjust GPH by +/- 8 GPH per +/- 100 kW change
- Total Installed SHP = 50,000 HP
- All alignments are at 100% design pitch

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM with this sheet.
4. hrs to cross PIM boundary column is based upon starting at middle of PIM window always.

#### Speed vs Fuel Usage (GPH/NM)

- **Minimum Burn**
- **OTTER Burn**

#### Average Speed (kts)

- 0 to 7
- 7 to 10
- 10 to 15
- 15 to 20
- 20 to 25
- 25 to 30
- 30 to 35
- 35 to 40

#### Fuel Usage (gpm)

- 0 to 16
- 16 to 40
- 40 to 75
- 75 to 100

[Graph showing speed vs fuel usage]
Figure 38. LSD49 Static OTTER
Figure 39. LHD8 Static OTTER

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Source: LHD8 performance analysis conducted July-September 2009 recorded by chief engineer.

- Speeds were calculated using the following:
  - Average 24 Hour Electric Load Consumption: 2500kW for >7000 kW
  - APM = Auxiliary Propulsion Motor
  - GT = Gas Turbine
  - TS = Trail shaft
  - 2G = 2 SGSG on line to support >7000 kW loading
  - 3G = 3 SGSGs on line to support >7000 kW loading
  - Fuel burn rate for speeds below 50kts extrapolated from available data

1. GPH saved based on maintaining average speed for transit.
2. GPH saved rate is much greater when compared to sprint and drift operations inside PIM window for drills.
3. For drill planning use Short Term Planner, or determine new required average speed to stay in PIM window with this sheet.
4. Hit to cross PIM boundary column is based upon starting at middle of PIM window - always

**Speed vs Fuel Usage (GPNM)**

- Minimum Burn
- OTTER Burn

**Fuel Usage (gpm)**

- Minimum Burn
- OTTER Burn

*Figures extrapolated from available data.*
APPENDIX C. TTSC ANALYSIS

This appendix contains histograms of the frequency and duration of TTSC of analyzed ships. Each figure contains the range of TTSC across the entire speed range of the ship. Figure 40 for example shows TTSC calculated for a CG from 1 kts average speed to 30 kts average speed in units of hours. In most instances, the CG could operate for more than 100 hours before requiring to change speed or mode. For example, a CG in transit with an average speed of 21 kts would reach the front of the operating window in

- \((\text{Big} T^* P T_{lo,v}) = \text{TTSC}\)

- \((126 \text{hrs} \times 0.67) = 84 \text{ hrs}\)

Figure 40. CG TTSC
Figure 41. DDG1 TTSC

Figure 42. DDG2A TTSC
Figure 43. FFG7 TTSC

FFG7

Figure 44. LCS1 TTSC

LCS1
Figure 45. LCS2 TTSC

Figure 46. LHA1 TTSC
Figure 47. LHD1 TTSC

LHD1

Figure 48. LPD4 TTSC

LPD4
Figure 49. LSD41 TTSC

LSD41

Time to speed change (hrs)

Number of occurrences

Figure 50. LSD49 TTSC

LSD49

Time to speed change (hrs)

Number of occurrences
APPENDIX D. DYNAMIC OTTER VBA CODE

'groups try to stay at front of window, so instead of spread constraint, have groups constrained such that 'every speed change must last at least an hour and groups try to be at front of window for drills 'any speed change must last at least an hour. Large changes cause engine config change, small changes insignificant 'assuming drill times of < 4 hours and no drills with negative forward progress, spread will be at most 4 hours. 'assume that in all other cases groups will be moving as a single (combined) unit

Public startTime As Date 'time and date at start of model Public intervalSize As Integer 'time interval size in minutes Public intervalCount As Integer 'total number of intervals Public currentInterval As Integer 'current time interval in the schedule Public currentSpeeds() As Integer Public targetDistance As Double Public PIMDistance As Double Public averageSpeed As Double Public oceanSpeed As Double Public Const maxSpeed = 40 Public minSpeedDuration As Integer 'minimum number of time intervals between speed changes Public Const scheduleStartRow = 6 'first row of schedule for speeds, with ship header row as row 1 Public Const headerStartRow = 10 Public bShips() As battleShip 'holds the battleships Public shipNames() As String 'holds the name of each ship type Public maxSpread As Double 'maximum spread between two ships at any time Public maxSpreadAllowed As Integer 'max spread allowed by user Public countDrillsInSpread As Boolean Public Type battleShip 'count As Integer 'number of type of ship shipType As String 'Type of ship distance As Double 'distance traveled thus far finalOffset As Double 'final offset from PIM window center at end of travel initialOffset As Double 'initial offset from PIM window center at start of travel drillStarts(2) As Integer 'time intervals when this ship starts a drill drillDurations(2) As Integer 'duration of drills in time intervals drillSpeeds(2) As Integer 'speed during drill drillFP(2) As Double 'forward progress made by each drill per time interval speedIntervals(maxSpeed) As Integer 'array containing how many time intervals to spend at each speed (index) fuelBurned As Double 'fuel burned under given schedule fuelBurnedOld As Double 'fuel burned under old practices, extrapolated from daily average 'engineConfig(maxSpeed) As String 'array of engine configurations with speed as index offset As Double 'distance from center of PIM window highSpeed As Integer 'fastest travel speed lowSpeed As Integer 'slowest travel speed biggestLeap As Double 'biggest possible speed change multiplied by interval. Used to determine impossible spread lastSpeedChangeTime As Integer 'time interval where last speed change took place lastModeChangeTime As Integer 'time interval where last mode change took place lastSpeed As Integer 'speed at which ship was traveling during last interval index As Integer 'position in bShips array
minSpeedTime As Integer ‘minimum number of intervals required before changing speeds (same engine config)
minModeTime As Integer ‘minimum number of intervals required before changing engine configs
RushSpeed As Integer ‘speed at which to rush to front of PIM window
rushing As Boolean ‘whether or not ship is rushing to catch up
countInSpread As Boolean ‘determines whether or not to include ship in spread.
needNewSpeeds As Boolean
’targetDist As Double ‘target distance to be at at a a certain time
’targetTime As Integer ‘time interval pertaining to targetDist

End Type

Sub buildSchedule()
‘master subroutine that calls all subs/functions needed to build and present the schedule
countDrillsInSpread = False
currentInterval = 0
With ThisWorkbook.Sheets(“Short Term Planner”)
’set startTime, intervalSize, and currentInterval
startTime = .Range(“PlannerStartTime”).Value
targetDistance = .Range(“PlannerDistance”).Value
intervalSize = .Range(“PlannerTimeInterval”).Value
intervalCount = .Range(“PlannerDuration”).Value * 60 / intervalSize
’change this to accommodate different ship limits
minSpeedDuration = 60 / intervalSize
’reset PIM and average Speed
PIMDistance = 0
averageSpeed = .Range(“PlannerAverageSpeedLand”).Value
oceanSpeed = .Range(“PlannerOceanCurrent”).Value
maxSpreadAllowed = .Range(“PlannerMaxSpread”).Value
End With

maxSpread = 0
’create ships and populate arrays
Call buildArrays
’clear old schedule and update the headers on the Schedule sheet
Call clearSchedule
Call updateHeaders
'label timeline
Call labelTimeline
'plan ship schedules
Call planShipSchedules
Call getOldBurnRate
Call recordFuelSaved
ThisWorkbook.Sheets(“Short Term Schedule”).Select
Application.Calculation = xlCalculationAutomatic
End Sub

Sub planShipSchedules()
‘for each ship, iterates through each time interval to place speeds and drills
Dim ship As battleShip
For currentInterval = 0 To intervalCount - 1
‘check spread status
For j = 0 To UBound(bShips)
ship = bShips(j)
Call checkSpreadAfterDrills(ship)
Next j
‘get this interval’s speeds
For j = 0 To UBound(bShips)
ship = bShips(j)
If currentInterval < ship.drillStarts(1) Then
‘before drill 1
currentSpeeds(j) = getIntervalSpeed(ship, False)
ElseIf currentInterval >= ship.drillStarts(1) And currentInterval < ship.drillStarts(1) +
ship.drillDurations(1) Then
‘drill 1
ElseIf currentInterval < ship.drillStarts(2) Then
‘after drill 1, before drill 2
currentSpeeds(j) = getIntervalSpeed(ship, False)
ElseIf currentInterval >= ship.drillStarts(2) And currentInterval < ship.drillStarts(2) +
ship.drillDurations(2) Then
‘drill 2
Else
‘after drill 2
currentSpeeds(j) = getIntervalSpeed(ship, False)
End If
Next j
‘record this interval’s speeds
For j = 0 To UBound(bShips)
ship = bShips(j)
If currentInterval < ship.drillStarts(1) Then
‘before drill 1
Call recordSpeed(ship, currentSpeeds(j))
ElseIf currentInterval >= ship.drillStarts(1) And currentInterval < ship.drillStarts(1) +
ship.drillDurations(1) Then
‘drill 1
Call recordDrill(ship, currentInterval)
ElseIf currentInterval < ship.drillStarts(2) Then
‘after drill 1, before drill 2
Call recordSpeed(ship, currentSpeeds(j))
ElseIf currentInterval >= ship.drillStarts(2) And currentInterval < ship.drillStarts(2) +
ship.drillDurations(2) Then
‘drill 2
Call recordDrill(ship, currentInterval)
Else
‘after drill 2
Call recordSpeed(ship, currentSpeeds(j))
End If
Next j
If findSpread() > maxSpread Then
maxSpread = findSpread()
End If
If findSpread() > maxSpreadAllowed Then
With ThisWorkbook.Sheets(“Short Term Schedule”)
For i = (1) To 44 Step 3
‘go to correct row
row = scheduleStartRow + currentInterval
' record speed and current distance
.Range(“ShipHeaders”).Cells(row, i + 1).Interior.ColorIndex = 54
.Range(“ShipHeaders”).Cells(row, i + 2).Interior.ColorIndex = 54
Next i
End If
Next currentInterval
If maxSpread > maxSpreadAllowed Then
MsgBox (“Broke Spread”)
End If
ThisWorkbook.Sheets(“Short Term Schedule”).Range(“ScheduleLargestSpread”).Cells(1, 1).Value = maxSpread
End Sub
Sub getOldBurnRate()
' get old fuel burn for comparison
' uses same daily burn calculation as TFP
Dim ship As battleShip
Dim fuel As Double
Dim days As Double
Dim drillHoursPerDay As Integer
Dim avgSpeed As Double ' average speed after accounting for PIM position
days = intervalCount * (intervalSize / 60) / 24
For j = 0 To UBound(bShips)
ship = bShips(j)
With ThisWorkbook.Sheets(“Short Term Schedule”)  
Call getOldFuelWithPIM(ship)
End With
With ThisWorkbook.Sheets(“Comparison Schedule”)  
End With
Next j
End Sub
Sub updateHeaders()
' update the headers/boxes on the schedule page to reflect the ship names and transit parameters
With ThisWorkbook.Sheets(“Short Term Schedule”)  
' clear previous ship headers
.Range(“ShipHeaders”).Value = “”
' write in new ship headers
i = 1
For s = 0 To UBound(bShips)
.Range(“ShipHeaders”).Cells(1, i).Value = “Ship ” & s + 1 & “: “ & bShips(s).shipType ‘ ship names
.Range(“ShipHeaders”).Cells(5, i + 1).Value = “Dist (nm)” ‘ distance
Next s
End For
End With
Next i
End Sub
.Range("ShipHeaders").Cells(5, i + 2).Value = "Mode" 'engine config
i = i + 3
Next s
'populate transit summary boxes
.Range("ScheduleDistance").Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerDistance").Value
.Range("ScheduleDuration").Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerDuration").Value
.Range("ScheduleOceanCurrent").Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerOceanCurrent").Value
.Range("ScheduleTimeInterval").Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerTimeInterval").Value
.Range("ScheduleStartTime").Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerStartTime").Value
End With

With ThisWorkbook.Sheets("Comparison Schedule")
'clear previous ship headers
.ShipHeaders().Value = ""
'write in new ship headers
i = 1
For s = 0 To UBound(bShips)
.ShipHeaders().Cells(1, i).Value = "Ship " & s + 1 & ": " & bShips(s).shipType 'ship names
.ShipHeaders().Cells(4, i).Value = "Spd (kts)" 'ship names
.ShipHeaders().Cells(4, i + 1).Value = "Dist (nm)" 'distance
.ShipHeaders().Cells(4, i + 2).Value = "Mode" 'engine config
i = i + 3
Next s
'populate transit summary boxes
.ScheduleDistance().Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerDistance").Value
.ScheduleDuration().Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerDuration").Value
.ScheduleOceanCurrent().Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerOceanCurrent").Value
.ScheduleTimeInterval().Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerTimeInterval").Value
.ScheduleStartTime().Value = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerStartTime").Value
End With
End Sub

Sub clearSchedule()
'clears the schedule page
With ThisWorkbook.Sheets("Short Term Schedule")
.Rows(scheduleStartRow + headerStartRow - 1 & ":" & .Rows.count).Delete
End With
With ThisWorkbook.Sheets("Comparison Schedule")
.Rows(scheduleStartRow + headerStartRow - 1 & ":" & .Rows.count).Delete
End With
End Sub

Sub labelTimeline()
'creates timeline on schedule sheet based on intervals

71
Dim dist As Double
Dim time As Date
With ThisWorkbook.Sheets("Short Term Schedule")
time = .Range("ScheduleStartTime").Value
dist = 0
While (i - 2) * intervalSize / 60 < .Range("ScheduleDuration").Value
 .Range("TimeHeader").Cells(i, 1).Value = DateAdd("n," (i - 2) * intervalSize, time)
 .Range("TimeHeader").Cells(i, 2).Value = dist
 i = i + 1
 dist = dist + (averageSpeed * (intervalSize / 60))
Wend
End With
End Sub

Sub buildArrays()
 ' populate the array of bShips and shipNames
 ' clear previous values from arrays and set to size 0
 ReDim shipNames(0)
 ReDim bShips(0)
 ReDim currentSpeeds(0)
 Dim tempSpeedArray(40) As Integer

 With ThisWorkbook.Sheets("Short Term Planner")
 ' count ship types used in this model
 Dim i As Integer
 i = -1
 For Each s In .Range("PlannerShipType").Cells
 If s.Text <> "none" Then
  i = i + 1
 End If
 Next s
 ' safety in case no bShips
 If i < 0 Then
 Exit Sub
 End If
 ' resize ship arrays
 ReDim shipNames(i) As String
 ReDim bShips(i) As battleShip
 ReDim currentSpeeds(i)
 ' populate ship arrays
 i = 0
 For s = 1 To .Range("PlannerShipType").Cells.count
If .Range("PlannerShipType").Cells(s, 1).Text <> "none" Then
    'add to shipNames
    shipNames(i) = .Range("PlannerShipType").Cells(s, 1).Text
    'create new battleship
    Dim bShip As battleShip
    bShip.shipType = shipNames(i)
    bShip.distance = .Range("PlannerStartingOffset").Cells(s, 1).Value
    bShip.initialOffset = .Range("PlannerStartingOffset").Cells(s, 1).Value
    bShip.finalOffset = .Range("PlannerFinalOffset").Cells(s, 1).Value
    bShip.drillStarts(1) = getInterval(CDate(.Range("Drill1StartTime").Cells(s, 1).Value))
    If bShip.drillStarts(1) > 0 Then
        bShip.drillDurations(1) = Round(.Range("Drill1Duration").Cells(s, 1).Value * 60 / intervalSize, 0)
        bShip.drillSpeeds(1) = .Range("Drill1Speed").Cells(s, 1).Value
        bShip.drillFP(1) = .Range("Drill1ForwardProgress").Cells(s, 1).Value / bShip.drillDurations(1) +
            (oceanSpeed * intervalSize / 60)
        Else
            bShip.drillDurations(1) = 0
            bShip.drillSpeeds(1) = 0
            bShip.drillFP(1) = 0
        End If
        bShip.drillStarts(2) = getInterval(CDate(.Range("Drill2StartTime").Cells(s, 1).Value))
        If bShip.drillStarts(2) > 0 Then
            bShip.drillDurations(2) = Round(.Range("Drill2Duration").Cells(s, 1).Value * 60 / intervalSize, 0)
            bShip.drillSpeeds(2) = .Range("Drill2Speed").Cells(s, 1).Value
            bShip.drillFP(2) = .Range("Drill2ForwardProgress").Cells(s, 1).Value / bShip.drillDurations(2) +
                (oceanSpeed * intervalSize / 60)
        Else
            bShip.drillDurations(2) = 0
            bShip.drillSpeeds(2) = 0
            bShip.drillFP(2) = 0
        End If
        bShip.countInSpread = True
        bShip.needNewSpeeds = False
        bShip.lastSpeed = 0
        bShip.rushing = False
        bShip.fuelBurned = 0
        bShip.fuelBurnedOld = 0
        'get slowest, fastest speeds, and biggest leap
        bShip.lowSpeed = getSlowestSpeed(bShip)
        bShip.highSpeed = getFastestSpeed(bShip)
        bShip.RushSpeed = ThisWorkbook.Sheets(UCase(bShip.shipType)).Range(LCase(bShip.shipType) &
            "RushSpeed").Cells(1, 1).Value
        'get # intervals spent at each speed
        Call getSpeedIntervalsArray(bShip, bShip.speedIntervals)
        'min speed and mode times
        bShip.minModeTime =
            Application.WorksheetFunction.RoundUp(ThisWorkbook.Sheets(UCase(bShip.shipType)).Range(LCase(b
            Ship.shipType) & "ModeMinTime").Cells(1, 1).Value / intervalSize, 0)
        bShip.minSpeedTime =
            Application.WorksheetFunction.RoundUp(ThisWorkbook.Sheets(UCase(bShip.shipType)).Range(LCase(b
            Ship.shipType) & "SpeedMinTime").Cells(1, 1).Value / intervalSize, 0)
        'initialize last change times
        bShip.lastSpeedChangeTime = -bShip.minSpeedTime 'set to -minSpeedtime so speed can change at time
        interval 0
    End If
bShip.lastModeChangeTime = -bShip.minModeTime 'set to -minModetime so speed can change at time interval 0
'record bship index
bShip.index = i
'add bShip to the bShips array
bShips(i) = bShip
i = i + 1
End If
Next s
End With
End Sub

Function getInterval(time As Date) As Integer
'updated for V2
'compares a given time to the transit start time and interval size to return the corresponding time interval
'define startTime, intervalSize if there isn't one defined
With ThisWorkbook.Sheets("Short Term Planner")
startTime = .Range("PlannerStartTime").Value
intervalSize = .Range("PlannerTimeInterval").Value
End With
If startTime > time Then
getInt = -1
Else
'get time difference in minutes
Dim minutesDiff As Integer
minutesDiff = DateDiff("n", startTime, time)
'convert to interval #, 0 indexed
getInt = Round(minutesDiff / intervalSize, 0)
End If
End Function

Function getSlowestSpeed(s As battleShip) As Integer
'returns the slowest speed remaining for a ship
For i = 0 To maxSpeed
If s.speedIntervals(i) > 0 Then
s.lowSpeed = i
getSlowestSpeed = i
Exit For
End If
Next i
End Function

Function getFastestSpeed(s As battleShip) As Integer
'returns the fastest speed remaining for a ship
For i = maxSpeed To 0 Step -1
If s.speedIntervals(i) > 0 Then
s.highSpeed = i
getFastestSpeed = i
Exit For
End If
Next i
End Function
Function findSpread() As Double
'returns the current spread of the group in nm
findSpread = bShips(findHead).distance - bShips(findTail).distance - (bShips(findHead).lastSpeed - bShips(findTail).lastSpeed) * intervalSize / 60
End Function

Function findHead() As Integer
'returns the bShips index of ship at front of pack
Dim maxDist As Double
maxDist = -9999
For s = 0 To UBound(bShips)
If maxDist < bShips(s).distance And bShips(s).countInSpread = True Then
maxDist = bShips(s).distance
findHead = s
End If
Next s
End Function

Function findTail() As Integer
'returns the bShips index of ship at back of pack
Dim minDist As Double
minDist = 9999
For s = 0 To UBound(bShips)
If minDist > bShips(s).distance And bShips(s).countInSpread = True Then
minDist = bShips(s).distance
findTail = s
End If
Next s
End Function

Function getPIMLeadAtTime(t As Integer) As Double
'returns the PIM leading edgedistance at given time interval
getPIMLeadAtTime = (4 + (t * intervalSize / 60)) * averageSpeed
End Function

Function getIntervalSpeed(ship As battleShip, bypass As Boolean) As Integer
'returns the speed at which the ship will travel for this interval
getIntervalSpeed = ship.lastSpeed 'hold current speed as default
Dim PIMGain As Double 'distance gained on PIM window by traveling at a speed
Dim dur As Integer 'min time intervals required to hold a speed
Dim speed As Integer 'only possibly change speeds if have been at current speed for long enough or no more time at last speed
'If currentInterval - ship.lastSpeedChangeTime >= minSpeedDuration Or ship.speedIntervals(ship.lastSpeed) = 0 Then
If ship.needNewSpeeds = True Then
Call getSpeedIntervalsArray(ship, ship.speedIntervals)
Call getSpeedIntervalsArray(bShips(ship.index), bShips(ship.index).speedIntervals)
End If
If currentInterval - ship.lastSpeedChangeTime >= ship.minSpeedTime Or ship.speedIntervals(ship.lastSpeed) = 0 Then
'iterate through possible speeds, highest speed 1st
For speed = maxSpeed To 0 Step -1
'only consider speeds that the ship will use
If ship.speedIntervals(speed) > 0 Then
  'only consider speeds in same mode unless minModeTime has passed since last mode change
  If StrComp(modeAtSpeed(ship, speed), modeAtSpeed(ship, ship.lastSpeed)) = 0 Or currentInterval - ship.lastModeChangeTime >= ship.minModeTime Or bypass = True Then
    'adjust min required duration
    If speed = ship.lastSpeed Then 'can hold current speed for an interval ok
dur = 1
    ElseIf ship.speedIntervals(speed) < ship.minSpeedTime Then 'Or ship.speedIntervals(speed) < ship.minModeTime Then 'if speed has fewer than minSpeedDuration intervals remaining
dur = ship.speedIntervals(speed)
    Else
      If StrComp(modeAtSpeed(ship, speed), modeAtSpeed(ship, ship.lastSpeed)) = 0 Then
        dur = ship.minSpeedTime
      Else
        dur = ship.minModeTime
      End If
    End If
  x = ship.index
  'choose speed if it won’t break PIM if held for min duration
  gain = (speed + oceanSpeed) * intervalSize * dur / 60 'min possible gain on PIM
  If ship.distance + gain <= getPIMLeadAtTime(currentInterval + dur) And checkSpread(ship, speed, dur) = True Then
    'ship can travel at this speed for the min required duration
    getIntervalSpeed = speed
    'prioritize high speeds
    'if set to rush after drills, and ship is recovering after drills
    If Sheets("Short Term Planner").RushAfterDrillsButton.Value = True And ship.countInSpread = False Then
      If ship.rushing = True Then
        'rush behavior overrides speed
        getIntervalSpeed = ship.RushSpeed
      End If
    End If
  Exit For
  Else
    x = 3
  End If
End If
End If
End If
End If
End Function

Sub recordSpeed(ship As battleShip, speed As Integer)
  'records the given speed for the given ship type into the schedule.
  'Also updates ship’s speed array and distance for the ship
  'ship.distance = ship.distance + speed * intervalSize / 60
bShips(ship.index).speedIntervals(speed) = ship.speedIntervals(speed) - 1
'find right column in header array
With ThisWorkbook.Sheets("Short Term Schedule")
i = 1 + 3 * ship.index
'go to correct row
row = scheduleStartRow + currentInterval
'record speed and current resulting distance
.Range("ShipHeaders").Cells(row, i).Value = speed
.Range("ShipHeaders").Cells(row, i + 1).Value = ship.distance
.Range("ShipHeaders").Cells(row, i + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed").Cells(speed + 1, 1).Value
'update speed change time if speed changed
If speed <> ship.lastSpeed Then
.Range("ShipHeaders").Cells(row, i).Interior.ColorIndex = 27
.Range("ShipHeaders").Cells(row, i + 1).Interior.ColorIndex = 27
.Range("ShipHeaders").Cells(row, i + 2).Interior.ColorIndex = 27
End If
If modeAtSpeed(ship, speed) <> modeAtSpeed(ship, ship.lastSpeed) Then
bShips(ship.index).lastModeChangeTime = currentInterval
.Range("ShipHeaders").Cells(row, i).Interior.ColorIndex = 45
.Range("ShipHeaders").Cells(row, i + 1).Interior.ColorIndex = 45
.Range("ShipHeaders").Cells(row, i + 2).Interior.ColorIndex = 45
End If
bShips(ship.index).lastSpeedChangeTime = currentInterval
bShips(ship.index).lastSpeed = speed
ElseIf ship.countInSpread = False Then
.Range("ShipHeaders").Cells(row, i).Interior.ColorIndex = 43
.Range("ShipHeaders").Cells(row, i + 1).Interior.ColorIndex = 43
.Range("ShipHeaders").Cells(row, i + 2).Interior.ColorIndex = 43
End If
bShips(ship.index).fuelBurned = bShips(ship.index).fuelBurned + CDbl(intervalSize / 60) * 
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & 
"BurnRateUsed").Cells(speed + 1, 1).Value 'burn fuel during transit
End With
bShips(ship.index).distance = bShips(ship.index).distance + CDbl((speed + oceanSpeed) * intervalSize / 60)
End Sub

Sub recordDrill(ByRef ship As battleShip, time As Integer)
'records the drills for the given ship into the schedule
'determine which drill
Dim drillNum As Integer
If time < ship.drillStarts(2) Or ship.drillStarts(2) < 0 Then
drillNum = 1
Else: drillNum = 2
End If
bShips(ship.index).countInSpread = False

With ThisWorkbook.Sheets("Short Term Schedule")
i = 1 + 3 * ship.index
'go to correct row
row = scheduleStartRow + currentInterval
'record speed and current distance
Sub getSpeedIntervalsArray(ByRef ship As battleShip, ByRef intervals() As Integer)
'populates the ships speedIntervals array.
'still needs to be tested.
'ReDim intervals(40)
'get required distance and time
Dim drillDist As Double
Dim drillTimeInterval As Integer
Dim dist As Double
Dim duration As Integer

ship.needNewSpeeds = False

drillDist = 0
drillTimeInterval = 0

If currentInterval <= ship.drillStarts(1) Then
    drillDist = drillDist + ship.drillDurations(1) * ship.drillFP(1) + (oceanSpeed * (ship.drillDurations(1)) * (intervalSize / 60))
    drillTimeInterval = drillTimeInterval + ship.drillDurations(1)
End If

If currentInterval <= ship.drillStarts(2) Then
    drillDist = drillDist + ship.drillDurations(2) * ship.drillFP(2) + (oceanSpeed * ship.drillDurations(2) * (intervalSize / 60))
    drillTimeInterval = drillTimeInterval + ship.drillDurations(2)
End If

'distance of transit - drill dist - starting position - (ocean speed * (time-drill time))
dist = targetDistance + ship.finalOffset - ship.distance - oceanSpeed * (intervalCount - currentInterval - drillTime) * (intervalSize / 60) - drillDist '+ (ship.lastSpeed * (intervalSize / 60))
duration = intervalCount - currentInterval - drillTimeInterval

Call solveShip(ship.shipType, dist, duration, intervalSize)

'populate speedIntervals, adjust for non-integers in solver
Dim temp As Double
Dim foundLow As Boolean
foundHigh = False
For i = 40 To 0 Step -1
    temp = ThisWorkbook.Sheets("Solver").Range("SolverIntervalRange").Cells(i + 1, 1).Value
    *update distance
    bShips(ship.index).distance = bShips(ship.index).distance + ship.drillFP(drillNum) * drillDist
    bShips(ship.index).fuelBurned = bShips(ship.index).fuelBurned + CDbl(intervalSize / 60) * drillDist
End If
If temp > 0.01 And foundHigh = False Then
    If temp - Application.WorksheetFunction.RoundDown(temp, 0) > 0.05 Then
        intervals(i) = Application.WorksheetFunction.RoundUp(temp, 0)
    Else
        intervals(i) = Application.WorksheetFunction.RoundDown(temp, 0)
    End If
    foundHigh = True
Else
    If temp - Application.WorksheetFunction.RoundDown(temp, 0) > 0.95 Then
        intervals(i) = Application.WorksheetFunction.RoundUp(temp, 0)
    Else
        intervals(i) = Application.WorksheetFunction.RoundDown(temp, 0)
    End If
End If
Next i
End Sub

Function modeAtSpeed(ship As battleShip, speed As Integer) As String
    'returns the mode for a given ship and speed
    modeAtSpeed = ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & 
    "ModeUsed").Cells(speed + 1, 1).Value
End Function

Sub getOldFuelWithPIM(ByRef ship As battleShip)
    'gets the total fuel used by given ship under old practices. Assumes ships will rush to 
    'front of pim window, and hold pim speed while at front. Each ship has its own rush speed
    
    'check that rush speed set for ship can complete transit on time
    'get distance to be traveled by non-drill transit
    distcheck = (averageSpeed * intervalCount * intervalSize / 60) - ship.drillFP(1) * ship.drillDurations(1) - 
    ship.drillFP(2) * ship.drillDurations(2) + ship.finalOffset - ThisWorkbook.Sheets("Short Term 
    Planner").Range("PlannerStartingOffset").Cells(ship.index + 1, 1).Value
    intervalCountTran = intervalCount - ship.drillDurations(1) - ship.drillDurations(2) 'get # intervals spent 
    transiting, not including drills
    
    If (ship.RushSpeed + oceanSpeed) * intervalCountTran * intervalSize / 60 < distcheck Then
        'rush speed too low, reset to highest possible speed
        MsgBox ("Ship " & ship.index & ", of type " & ship.shipType & ", rush speed is too low to complete transit 
        on time." & vbNewLine & 
        "Fuel comparison calculator will use a rush speed of " & getMaxSpeed(ship) & 
        "kts instead of the user-specified " & ship.RushSpeed & "kts." & vbNewLine & 
        "This has no impact on the generated schedule and will only affect the predicted fuel saved by using OTTER."))
        bShips(ship.index).RushSpeed = getMaxSpeed(ship)
        ship.RushSpeed = getMaxSpeed(ship)
        If (ship.RushSpeed + oceanSpeed) * intervalCountTran * intervalSize / 60 < distcheck Then
            'even max speed is too slow
            MsgBox ("Even the new rush speed is too slow. Brandon should build some checks into the start of the 
            scheduling process to make sure that this can’t happen")
        End If
        End If

    Dim time As Date
    Dim speed As Integer
    Dim dist As Double
    Dim pimDist As Double
Dim burn As Double

time = startTime
dist = ThisWorkbook.Sheets("Short Term Planner").Range("PlannerStartingOffset").Cells(ship.index + 1, 1).Value
pimDist = 0
'With ThisWorkbook.Sheets("ScheduleTesting")
With ThisWorkbook.Sheets("Comparison Schedule")
'record ship in test schedule
For i = 0 To intervalCount - 1
j = 1 + 3 * ship.index

'go to correct row
row = scheduleStartRow + i - 1

'until 1st drill
If i < ship.drillStarts(1) Then
'rush to front of window
If dist + ((ship.RushSpeed + oceanSpeed) * intervalSize / 60) <= pimDist + 4 * averageSpeed Then
speed = ship.RushSpeed
'hold pim speed
Else
speed = Application.WorksheetFunction.RoundDown(averageSpeed, 0) - oceanSpeed
End If
'record speed and current resulting distance
.Range("ShipHeaders").Cells(row, j).Value = speed
.Range("ShipHeaders").Cells(row, j + 1).Value = dist
.Range("ShipHeaders").Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed").Cells(speed + 1, 1).Value
burn = burn + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "BurnRateUsed").Cells(speed + 1, 1).Value 'burn fuel during transit
dist = dist + (speed + oceanSpeed) * intervalSize / 60
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd("n", intervalSize, time)

'do drill 1
ElseIf i >= ship.drillStarts(1) And i < ship.drillStarts(1) + ship.drillDurations(1) Then
speed = ship.drillSpeeds(1)
.Range("ShipHeaders").Cells(row, j).Value = speed
.Range("ShipHeaders").Cells(row, j + 1).Value = dist
.Range("ShipHeaders").Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed").Cells(speed + 1, 1).Value
.Range("ShipHeaders").Cells(row, j + 1).Interior.ColorIndex = 20
.Range("ShipHeaders").Cells(row, j + 2).Interior.ColorIndex = 20
burn = burn + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "BurnRateUsed").Cells(speed + 1, 1).Value 'burn fuel during transit
dist = dist + ship.drillFP(1)
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd("n," intervalSize, time)

' until 2nd drill
ElseIf i >= ship.drillStarts(1) + ship.drillDurations(1) And i < ship.drillStarts(2) Then
' rush to front of window
If dist + ((ship.RushSpeed + oceanSpeed) * intervalSize / 60) <= pimDist + 4 * averageSpeed Then
  speed = ship.RushSpeed
  ' hold pim speed
Else
  speed = Application.WorksheetFunction.RoundDown(averageSpeed, 0) - oceanSpeed
End If
.Range("ShipHeaders"),Cells(row, j).Value = speed
.Range("ShipHeaders"),Cells(row, j + 1).Value = dist
.Range("ShipHeaders"),Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed"),Cells(speed + 1, 1).Value

burn = burn + CDbl(intervalSize / 60) * 
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
"BurnRateUsed"),Cells(speed + 1, 1).Value ' burn fuel during transit
dist = dist + (speed + oceanSpeed) * intervalSize / 60
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd("n," intervalSize, time)

' do drill 2
ElseIf i >= ship.drillStarts(2) And i < ship.drillStarts(2) + ship.drillDurations(2) Then
  speed = ship.drillSpeeds(2)
  .Range("ShipHeaders"),Cells(row, j).Value = speed
  .Range("ShipHeaders"),Cells(row, j + 1).Value = dist
  .Range("ShipHeaders"),Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & "ModeUsed"),Cells(speed + 1, 1).Value
  .Range("ShipHeaders"),Cells(row, j).Interior.ColorIndex = 20
  .Range("ShipHeaders"),Cells(row, j + 1).Interior.ColorIndex = 20
  .Range("ShipHeaders"),Cells(row, j + 2).Interior.ColorIndex = 20

burn = burn + CDbl(intervalSize / 60) * 
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
"BurnRateUsed"),Cells(speed + 1, 1).Value ' burn fuel during transit
dist = dist + ship.drillFP(2)
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd("n," intervalSize, time)

' until destination
Else
  ' rush to front of window
  If dist + 4 * averageSpeed <= targetDistance + ship.finalOffset Then
    If dist + ((ship.RushSpeed + oceanSpeed) * intervalSize / 60) <= pimDist + 4 * averageSpeed Then
      speed = ship.RushSpeed
    Else
      speed = Application.WorksheetFunction.RoundDown(averageSpeed, 0)
End If
'hold pim speed
Else
'speed = Application.WorksheetFunction.RoundDown(averageSpeed, 0) - oceanSpeed
speed = Application.WorksheetFunction.RoundUp((targetDistance - dist + ship.finalOffset) / ((intervalCount - i) * intervalSize / 60), 0)
End If
.Range("ShipHeaders").Cells(row, j).Value = speed
.Range("ShipHeaders").Cells(row, j + 1).Value = dist
.Range("ShipHeaders").Cells(row, j + 2).Value =
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) & “ModeUsed”).Cells(speed + 1, 1).Value
burn = burn + CDbl(intervalSize / 60) *
ThisWorkbook.Sheets(UCase(ship.shipType)).Range(LCase(ship.shipType) &
  “BurnRateUsed”).Cells(speed + 1, 1).Value 'burn fuel during transit
dist = dist + (speed + oceanSpeed) * intervalSize / 60
pimDist = pimDist + averageSpeed * intervalSize / 60
time = DateAdd(“n,” intervalSize, time)
End If
If speed <> ship.lastSpeed Then
.Range("ShipHeaders").Cells(row, j).Interior.ColorIndex = 27
.Range("ShipHeaders").Cells(row, j + 1).Interior.ColorIndex = 27
.Range("ShipHeaders").Cells(row, j + 2).Interior.ColorIndex = 27
If modeAtSpeed(ship, speed) <> modeAtSpeed(ship, ship.lastSpeed) Then
.Range("ShipHeaders").Cells(row, j).Interior.ColorIndex = 45
.Range("ShipHeaders").Cells(row, j + 1).Interior.ColorIndex = 45
.Range("ShipHeaders").Cells(row, j + 2).Interior.ColorIndex = 45
End If
End If
ship.lastSpeed = speed
'exit condition
If dist >= targetDistance + ship.finalOffset Then
Exit For
End If
Next i
bShips(ship.index).fuelBurnedOld = burn
End With
End Sub

Function getMaxSpeed(ship As battleShip) As Integer
Dim s As String
s = ship.shipType
getMaxSpeed = Application.max(ThisWorkbook.Sheets(UCase(s)).Range(LCase(s) & “ModeMaxSpeed”))
End Function

Function checkSpread(ByRef ship As battleShip, speed As Integer, intervals As Integer) As Boolean
i = ship.index
Dim tempDist As Double
tempDist = ship.distance + speed * intervalSize / 60
Dim predictedSpread As Double
Dim maxPredictedSpread As Double
'check against ships that have already set their speeds for this interval
For j = 0 To i - 1
If bShips(j).countInSpread = True Then
predictedSpread = (ship.distance - bShips(j).distance) + CDbl((intervals) * intervalSize / 60) * CDbl(speed - currentSpeeds(j)) + speed * intervalSize / 60
If (Application.WorksheetFunction.max(predictedSpread, -predictedSpread)) > maxSpreadAllowed And ship.countInSpread = True Then 'And currentInterval <> 0 Then
checkSpread = False
Exit Function
End If
End If
Next j
'check against ships that still have to set speed (assume their speed = their lastSpeed)
For j = i + 1 To UBound(bShips)
If bShips(j).countInSpread = True Then
If currentInterval <> 0 Then
predictedSpread = (ship.distance - bShips(j).distance) + CDbl(intervals * intervalSize / 60) * CDbl(speed - bShips(j).lastSpeed)
Else
predictedSpread = (ship.distance - bShips(j).distance) + CDbl(intervals * intervalSize / 60) * CDbl(speed - getAssumedStartSpeed(bShips(j)))
End If
If (Application.WorksheetFunction.max(predictedSpread, -predictedSpread)) > maxSpreadAllowed And ship.countInSpread = True Then 'And currentInterval <> 0
checkSpread = False
Exit Function
End If
End If
Next j
checkSpread = True
End Function
Sub checkSpreadAfterDrills(ByVal ship As battleShip)
i = ship.index
Dim maxSpreadNow As Double
Dim sprd As Double
For j = 0 To i - 1
sprd = ship.distance - bShips(j).distance -(ship.lastSpeed - bShips(j).lastSpeed) * intervalSize / 60
maxSpreadNow = Application.WorksheetFunction.max(maxSpreadNow, sprd, -sprd)
Next j
For j = i + 1 To UBound(bShips)
sprd = ship.distance - bShips(j).distance -(ship.lastSpeed - bShips(j).lastSpeed) * intervalSize / 60
maxSpreadNow = Application.WorksheetFunction.max(maxSpreadNow, sprd, -sprd)
Next j
If maxSpreadNow < maxSpreadAllowed And ship.countInSpread = False Then
bShips(i).countInSpread = True
ship.countInSpread = True
If Sheets("Short Term Planner").RushAfterDrillsButton.Value = True Then
bShips(i).needNewSpeeds = True
ship.needNewSpeeds = True
bShips(i).rushing = False
ship.rushing = False
ship.countInSpread = True
End Function
bShips(i).countInSpread = True
End If
Else
If Sheets("Short Term Planner").RushAfterDrillsButton.Value = True Then
ship.rushing = True
bShips(i).rushing = True
End If
End If
End Sub
Function getAssumedStartSpeed(ship As battleShip) As Integer
getAssumedStartSpeed = 0
For i = 40 To 0 Step -1
If ship.speedIntervals(i) <> 0 Then
getAssumedStartSpeed = i
Exit For
End If
Next i
End Function
Sub recordFuelSaved()
fuel = 0
For s = 0 To UBound(bShips)
fuel = fuel + bShips(s).fuelBurnedOld - bShips(s).fuelBurned
Next s
ThisWorkbook.Sheets("Short Term Schedule").Range("ScheduleFuelSaved").Value = fuel
End Sub
LIST OF REFERENCES


NAVDORM (2012) COMNAVSURFOR/COMNAV AIRFOR Instruction 3530.4 Ch. 2.


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