Operational Profiling and Statistical Analysis of Arleigh Burke-Class Destroyers

by

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Submitted to the Department of Mechanical Engineering
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ABSTRACT

Ship operational profiles are a valuable tool for ship designers and engineers when analyzing potential designs and ship system selections. The most common is the speed-time profile, normally depicted as a histogram showing the percent of time spent at each speed. Many shortcomings exist in the current Arleigh Burke (DDG 51)-class operational profiles. The current speed-time profile is out of date, based on another ship class, and does not depict the profile in one-knot increments. Additional profile data, such as how the engineering plant is operated and a mission profile, do not exist. A thorough analysis of recent DDG 51 operations was conducted and new and improved profiles were developed. These profiles indicate the ships tend to operate at slower speeds than was previously predicted with 46% of the time spent at 8 knots and below as compared to the previous profile with 28% for the same speeds. Additionally, profiles were developed to show the amount of time spent in each engineering plant line-up (69% trail shaft, 24% split plant, 7% full power) and the time spent in different mission types (69% operations, 27% transit, 4% restricted maneuvering doctrine). A detailed statistical analysis was then conducted to better understand the data used in profile development and to create a region of likely speed-time profiles rather than just a point solution that is presented in the composite speed-time profile. This was accomplished through studying the underlying distributions of the data as well as the variance.

Thesis Supervisor: Franz Hover
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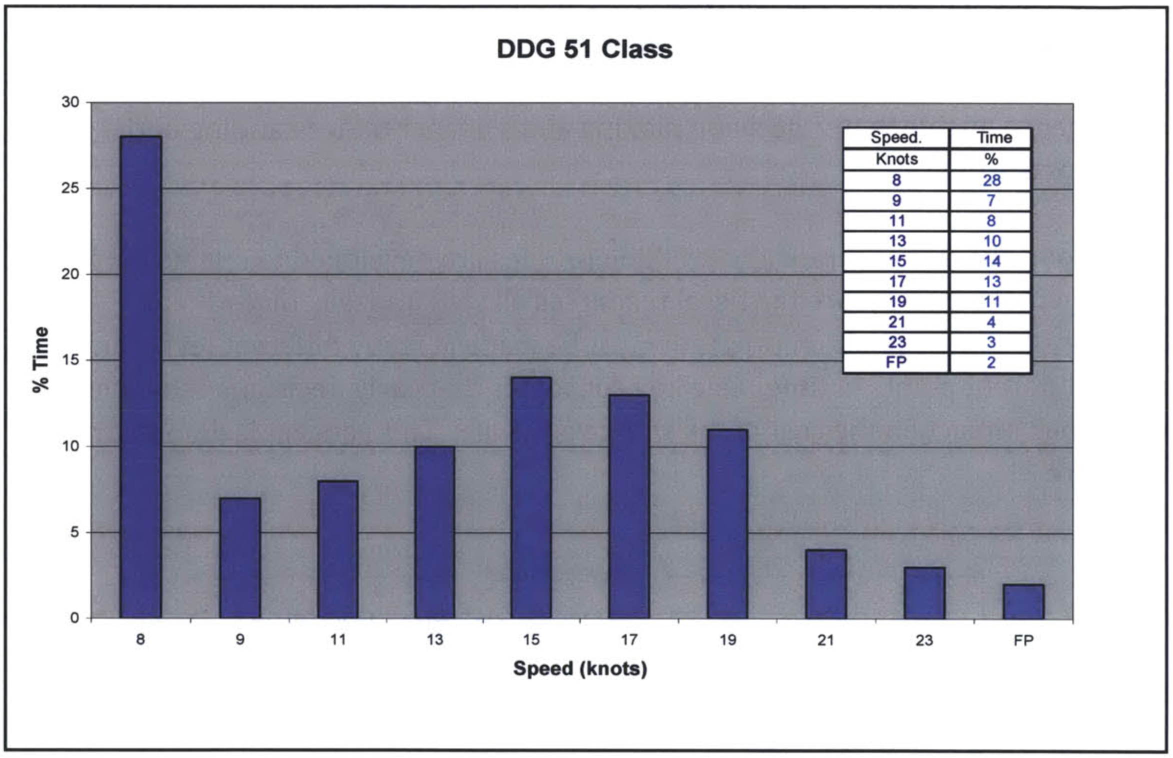
1 Introduction

Some of the first questions requirements setters and ship designers face pertain to how the ship is to be operated. How fast will the ship need to go? How far will it need to go? How much fuel should it carry? Does it go fast all the time, or just once in a while? The answers to these questions are usually laid out in the concept of operations (CONOPS). One key piece of the CONOPS is the speed-time profile. As the most common form of an operating profile, a speed-time profile is normally a histogram depicting the percentage of time a ship will spend at a given speed or group of speeds. An example of a speed-time profile for the Arleigh Burke (DDG 51) class of guided missile destroyers is shown in Figure 1.



Speed. Knots	Time %
8	28
9	7
11	8
13	10
15	14
17	13
19	11
21	4
23	3
FP	2

Figure 1: DDG 51 Class Speed-Time Profile (NAVSEA Code 05Z1 2003)

This profile provides information on how much time a nominal DDG 51-class ship will spend operating in each of the given groups of speeds. In this particular example, each grouping represents speeds from the previous group up to the label for that group (i.e., 0-8, 9, 10-11...). From this profile one could deduce that a DDG 51-class ship spends most of its time either at low speeds (≤ 8 kts) or in the upper teens (15-19 kts). These deductions then form the basis for many ship design decisions such as hull form selection, propulsion plant architecture, and engine and auxiliaries selection.

The decisions that are made, in part based on speed-time profiles, are significant and have long-lasting impact on the programs. With this in mind it is prudent to investigate the speed-time profile: What data is it based on? What is the variance of the data? Is the data that was used relevant to today's ships? Why are the speeds grouped as they are? Has the profile been validated or verified by any other means?

A detailed investigation of a speed-time profile will provide the foundation for this thesis. The DDG 51 profile, as shown in Figure 1, will provide the example to be used. There are two reasons the DDG 51 was chosen. First, the applicability of the current profile to a nominal ship in the class is in question because it is based on data from another ship class collected nearly 20 years ago. Second, a credible profile is needed now to make investment decisions on current DDGs as well as plan for future ships with the coming of the fourth iteration, the Flight III. The end result will be to demonstrate a method to collect, analyze, and present operational data in a manner to enable better decision making and a deeper understanding of the way the ships are operated.

It is important that accurate and credible profiles are developed to enable better decision making to ensure the fiscal resources all well utilized. Investment decisions for an acquisition program must be made at many different levels and at many different points in time. One key concept is that early decisions can have an enormous impact on the cost of the ship over its life. This concept is demonstrated in Figure 2.

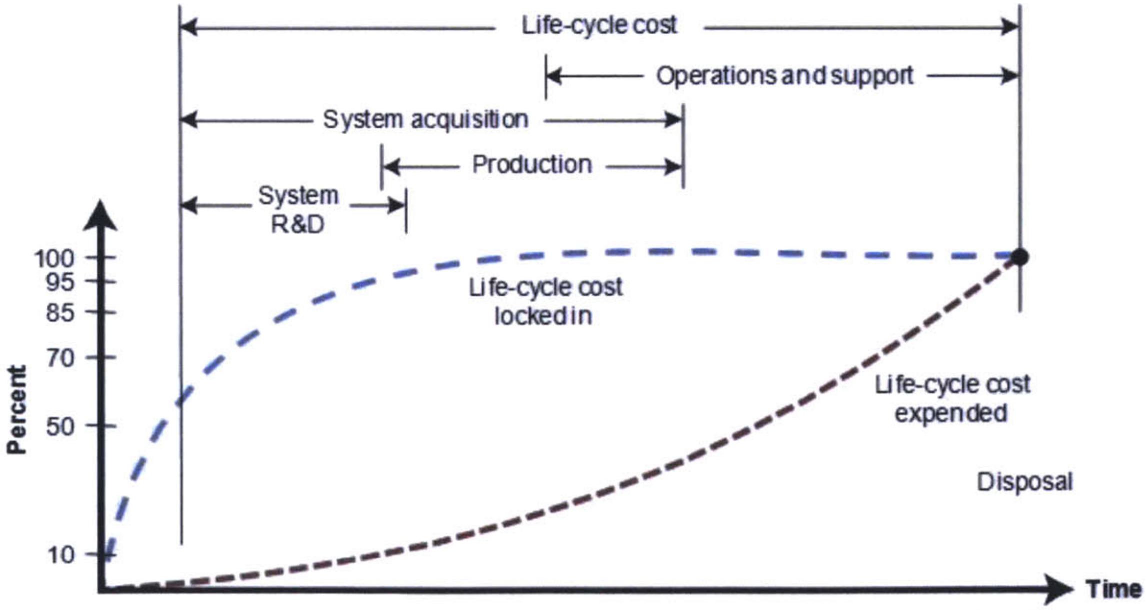


Figure 2: Relationship Between A Programs Expended Life-Cycle Cost and Locked-In Cost ("Design Effectiveness and DMSMS" 2013)

This concept is applicable to all stages and levels of an acquisition program. This diagram can be used to represent not only the overall shipbuilding program, but can also apply to sub-programs or modernizations and modifications made later in life. By having better knowledge earlier on in the program one can theoretically make decisions that can reduce the total lifecycle cost.

One of they key areas operational profiles can have an impact is fuel usage. The DDG 51-class is the largest single ship class in the Navy and consumes half of all the fuel used by US warships ("Navy Energy Use Reporting System Annual Reports" FY2012). Even fuel savings as modest as 5% equate to saving of nearly 220,000 barrels a year. Using fiscal year 2011 numbers as an example, at a fully burdened fuel cost of $140/barrel, the annual fuel bill can be reduced by nearly $31M (NAVSEA 2012). With 62 ships operating, 4 more under construction, and an unknown number of Flight III ships to be built it is clear that these decisions can have a large effect. Compound those reductions with a 40-year service life and there is the potential to make a real difference.

Much of the challenge in creating the operating profiles for a ship lies in the data. One of the most difficult parts of the process is just to obtain the records from which the needed data can be collected. Other challenges included determining how much, from where, and from whom the data should be collected. Once the data is collected and reviewed operating profiles can be created. These profiles must then be further studied to find a method to validate them, as well as to interpret the information the profiles provide.

1.1 Success Criteria

The goal of this thesis will be to fully define the operations of the DDG 51 class, document a methodology for said definition, and to analyze the results using statistical methods to gain a deeper understanding of what the profiles mean. This will be accomplished by first improving the currently utilized DDG 51 speed-time profile. The profile will be improved by using one-knot increments, collecting and using data from recent (previous 18 months) DDG 51 ship operations, and then validating that profile against a known metric. The new speed-time profile will be considered a success if it can validate to within a 3% margin.

In addition to the speed-time profile, additional operating profiles will be developed. A profile will be developed to characterize how the engineering plant (main engines) is utilized as well as a mission profile for the ships. These profiles will be developed in a manner similar to the speed-time profiles. The operating profiles will be successful if they can provide breakdowns of time for engineering plant configurations and mission types. Each engineering plant configuration and mission type must also have an individual speed-time profile.

When complete, this thesis should provide a documented, repeatable process for the development of operational profiles for any Naval vessel. Some aspects of the process are dependent on the type of ship being profiled. These aspects will be identified and the example of the DDG 51 will be used to expound upon how they affect the process. Areas for improvement will also be identified and possible solutions will be provided.

A detailed statistical analysis will be performed to better understand what the speed-time profile is telling us about the nominal DDG 51. Because the profile is based on a collection of data from many ships, it can be very useful to understand the variation of that data. This will enable one to better understand what the differences may be between the nominal DDG 51 and how a real ship is operated. Success is achieved by quantifying the variation in the data, explaining the variation, and comparing the profile to actual ship data.

1.2 Thesis Outline

This thesis is broken into a few main sections. Chapter 2 will discuss other related works, both in how they influenced this thesis as well as how they were improved or expounded upon. Detailed information about the Arleigh Burke class will be given in Chapter 3. This information is needed to understand how the process is specific to the DDG 51 and the rationale for decisions made throughout the process. Chapters 4 and 5 will present the data and the resulting profiles that were developed. Validation of the profile will be discussed and demonstrated in Chapter 6. Chapter 7 will provide the detailed statistical analysis used to gain insight into what the profiles are telling us. Chapter 8 will follow up with some examples of how the profiles can be used to make informed decisions followed by some conclusions.

2 Background and Related Work

The use of speed-time profiles to define how a class of ships is operated is by no means a new or novel concept. However, the amount of research and effort that has been put in to studying and creating these profiles is not on the same level as the impact the profiles have. This chapter is broken into three categories. The first includes some documents that helped to serve as motivation for this thesis. Second is a "state of the current practice". These are the documents from Naval Sea Systems Command (NAVSEA) that prescribe the current profiles. The final category covers the "state of the art". From these documents stems a discussion as to how the operating profiles developed for this thesis are an improvement.

2.1 Motivation

Much of the motivation for this work stems from common mistrust of the DDG 51 speed-time profile. It is a generally accepted sentiment that this profile is outdated and does not reflect how the ships are operated. This sentiment is clearly expressed and justified by Surko and Osborne in their article "Operating Speed Profiles and the Ship Design Cycle". In the article the authors clearly and succinctly lay out the need for improved speed-time profiles. One key point that motivated this work was, "...whole ship and shipboard machinery studies should be based on overall modal data as opposed to mean, since the modal data represent actual ship operations, whereas mean data may or may not represent actual operating points" (Surko and Osborne 2005).

Looking to the bigger picture, there is also other work that demonstrates how knowing a ship operating profile can improve the ship design process. One such work studies a ferry in the North Sea and correlates the operating profile to environmental data, while in particular looking at fuel efficiency and rudder cavitation (Greitsch, Eljardt, and Krueger 2009). Although some of the specifics of this paper do not completely transfer from commercial to Naval ship design, the concept of using actual ship operating profile data and the benefit it provides does. This work, as well as the work of Surko and Osborne, leads to the realization that a deeper understanding of the operating profiles is needed to aid the ship design process.

2.2 State of the Current Practice

NAVSEA serves as the leading technical authority for US Naval ship design. As the leading technical authority they also have cognizance over ship operating profiles. These profiles are published in the "Speed-Time Profile Guide for Surface Ships" (NAVSEA Code 05Z1 2003). The last set of speed-time profiles for surface ships were released in 2003 and the DDG 51 profiles was shown in Figure 1 and has changed little since first developed. This profile has been further promulgated for use in other NAVSEA documents such as DDS 200-2 (NAVSEA 2012). The use of the 2003 profiles in this 2012 document could easily be taken as an implicit approval that the profiles are accurate and represent current ship operations. Beyond just NAVSEA internal use, the profile has been accepted in open literature (Surko and Osborne 2005; S. P. Markle and Brown 1996; Rodeghiero et al. 1999; Cusanelli 2012). There is little doubt that the NAVSEA speed-time profiles are accepted and used throughout NAVSEA and the larger Naval ship community.

Because the profiles are so widely accepted and used it is imperative they accurately represent how the ships are operated and that any risk in the profiles is clearly conveyed. This is not the case for the most recently (i.e. 2003) released profiles. The first and most glaring shortcoming of the current profile for the DDG 51 is that it is based on a study of CG 47 operations from 1994 (Surko and Osborne 2005; NAVSEA Code 05Z1 2003). This means that not only is the profile based on operations from a different ship class, but also on how that ship class was operated nearly 20 years ago. The second shortcoming is that the speeds are grouped into large increments that limit the analysis that can be performed with the profile. Important details, such as when engineering plant modes are changed, is lost within the large grouping used.

2.3 State of the Art

Several pieces of literature were found that represented a departure from the "state of the current practice" methods. These can be broken into two categories. The first would be those that were created using actual paper ship logs (S. Markle 1994; Mayeaux 1995; Rodeghiero et al. 1999). The second category would be those that were created using electronically captured data (Gaffney et al. 2011; Greitsch, Eljardt, and Krueger 2009). The work done in both of these categories follows a similar path of using data collected from the same or similar ships to create the speed-time profiles. The main difference, as one would expect given the advances in technology during the time period, is that the more recent profiles are generated using electronically captured log data.

The work of Markle and Mayeaux used deck and engineering logs to create speed-time profiles that were then used in modeling engine emissions. Modeling of engine emissions was needed at the time because of the regulatory environment and proposed regulations that could impact the operation of Naval vessels. Because these impacts were only of interest in the regulatory zones the profiles that were created only reflected operation in those zones. The data collected and the resultant profiles provided the critical information needed in determining the cost of compliance alternatives. The work was also important because it provided a method for data collection and profile generation on one class of ships, Markle and the LSD 41, which could be repeated on another class of ships, Mayeaux and the MCM 1.

Rodeghiero et al. at the Center for Naval Analysis did the other work that used the paper logs from ships. The need for the updated profiles stemmed from a study on developing a business case analysis for installing a hybrid-electric drive on the DDG 51. An interesting aspect of this work was the use of an entire calendar year worth of data for each of the five ships studied.

The two profiles that were developed using electronic data were of great interest as this new method potentially offered the opportunity to create a profile with a similar level of fidelity in a greatly reduced amount of time. Although the work by Greitsch, Eljardt, and Krueger comes from an electronic source, there are not a lot of details about the data. Sampling frequency, a key variable to achieving the fidelity desired in the model, is not specifically defined in their work.

The most exciting of the "state of the art" is the article by Gaffney et al. The overall focus of the paper is on identifying ways by which surface ship fuel efficiency can be improved. One of the first tasks undertaken by the authors was to analyze ship operations and create a speed-time profile. The Integrated Condition Assessment System (ICAS) collected the data on engineering plant mode and an estimated speed for each hour. Again, for the fidelity desired in the model, the sampling frequency of one hour is insufficient as it is not on the same time scale as which the variable can change.

The key points gained from the related work are:

- There is a need for accurate operating profile information for the DDG 51
- The current profiles lack sufficient detail
- Methods exist to generate speed-time profiles from ship's logs
- Profiles have been generated using electronic logs, but fidelity is lacking

3 Arleigh Burke Class Destroyers

3.1 The Arleigh Burke Class

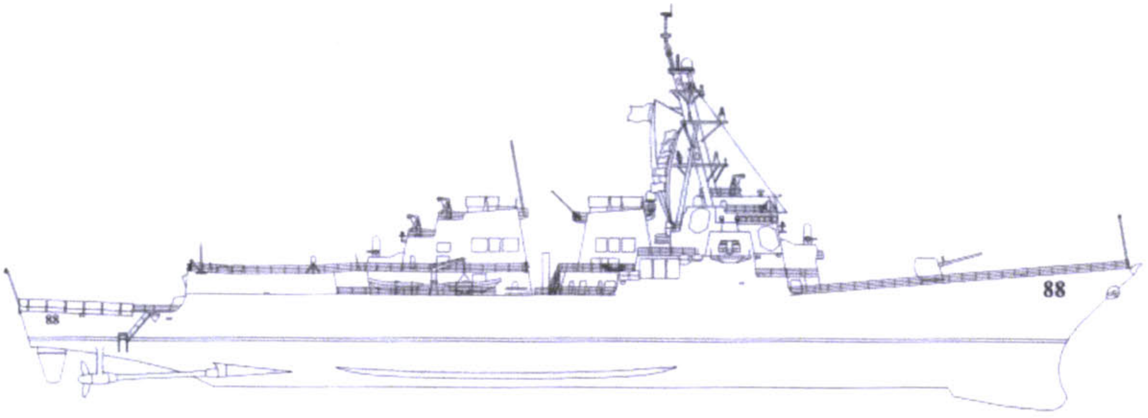
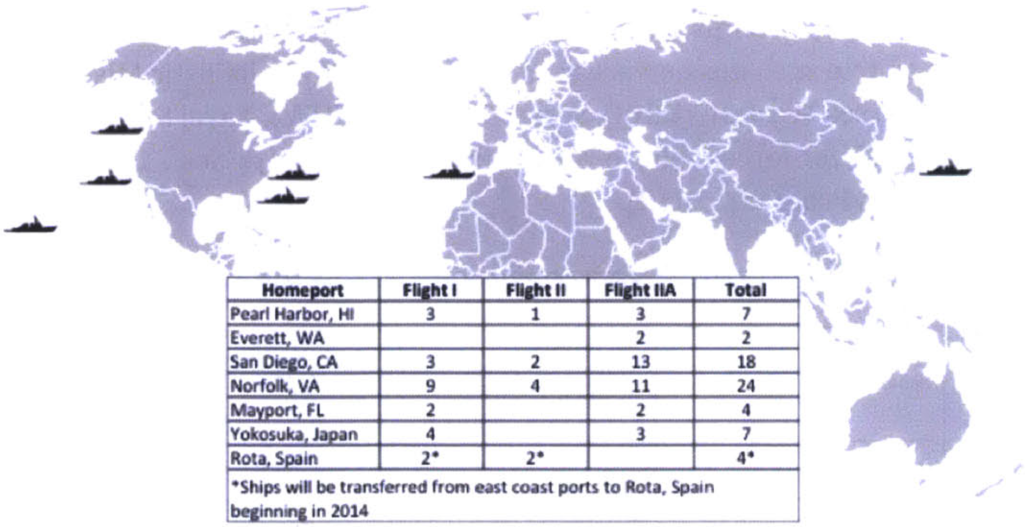


Figure 3: The USS Preble Flight IIA DDG ("USSPreble.org" 2013)

Arleigh Burke class guided missile destroyers, with an example shown in Figure 3, are multi-mission warships with offensive and defensive capability in multi-threat air, surface, and subsurface environments. The USS Arleigh Burke (DDG 51), the first ship and namesake of the class, was commissioned on July 4, 1991 ("Naval Vessel Register" 2013). Since then 61 more ships have been commissioned. The most recently commissioned ships are Flight IIA variants. There are three Flights, or variants, of the DDG in service today – Flight I, Flight II, and Flight IIA. Each Flight represents an evolutionary upgrade to the capability of the ship.

The ships are home ported on the east and west coasts, as well as in Pearl Harbor, HI, and Yokosuka, Japan. Homeport locations, as well as a breakdown of the number and Flight of ships assigned, are shown in Figure 4. An important aspect of this is the number of ships assigned to the Pacific, 34, is much greater than that assigned to the Atlantic, 28. Ships typically deploy such that they minimize the transit time to get to the operational area. This would indicate that the Pacific has more mission requirements than the Atlantic, consistent with the Department of Defense's strategic pivot to Asia. One must note, however, that ships from all homeports can, and have, been deployed to the Middle East.



Homeport	Flight I	Flight II	Flight IIA	Total
Pearl Harbor, HI	3	1	3	7
Everett, WA			2	2
San Diego, CA	3	2	13	18
Norfolk, VA	9	4	11	24
Mayport, FL	2		2	4
Yokosuka, Japan	4		3	7
Rota, Spain	2*	2*		4*

*Ships will be transferred from east coast ports to Rota, Spain beginning in 2014

Figure 4: Map of DDG Homeports and Number of Ships Assigned ("The US Navy Fact File: Destroyers" 2013; McMichael 2012; "Free Editable Worldmap" 2013)

The DDG 51 has proven to be an effective combatant as proven by the fact the Navy continues to buy them. Production of the Flight IIA DDGs was supposed to be completed with the contract for the USS Michael Murphy (DDG 112). With the cancellation of the CG(X) program, the Navy was left with a need for small combatant warships and no new program to fill that need. At the same time the DDG 51 shipbuilding program was coming to an end as the last ships were making their way through the production lines. In order to take advantage of the stable and mature infrastructure the Navy restarted the line by issuing a contract for four more DDG 51s in September 2011 ("DDG 51 Class Ship Construction Contract Awards Announced" 2013). The next step for the DDG 51 program is the Flight III. Work is under way for the design, which is expected to include an enhanced Air and Missile Defense Radar. Procurement of the Flight III is expected to begin in 2016 (Lundquist 2012).

In addition to the work in new ship construction, the first DDG 51s are now entering a period where they will receive major upgrades and modernizations. The first ship to complete this modernization was the USS John Paul Jones (DDG 53) in 2010 ("Sea 21 Combatant Modernization Program" 2013). This is a two-phase upgrade with the first phase focusing on the hull, mechanical, and electrical components and the second phase focusing on weapons systems and sensor upgrades.

3.2 Ship Characteristics and Engineering Plant

Table 1 provides an overview of the general characteristics of an Arleigh Burke class destroyer. The ships are designed to deploy independently or as members of

Carrier Strike Groups (CSG), Expeditionary Strike Groups (ESG), or Missile Defense Action Groups ("PEO Ships DDG 51" 2013). Additionally, sensors and weapons are carried to enable such mission areas as Air Warfare (AW), Ballistic Missile Defense (BMD), Undersea Warfare (USW), Surface Warfare (SUW), Naval Surface Fire Support (NSFS) for forces ashore, and Strike Warfare (SW) ("Sea 21 Combatant Modernization Program" 2013).

Table 1: Arleigh Burke Class General Characteristics ("Arleigh Burke-class Destroyer" 2013)

Displacement:	Fully loaded:
	Flight I: 8,315 t (8,184 long tons; 9,166 short tons)
	Flight II: 8,400 t (8,300 long tons; 9,300 short tons)
	Flight IIA: 9,200 t (9,100 long tons; 10,100 short tons)
Length:	505 ft (154 m) (Flights I and II)
	509 ft (155 m) (Flight IIA)
Beam:	66 ft (20 m)
Draft:	30.5 ft (9.3 m)
Installed power:	3x Allison Generators (2500kW each, 440V) (DDG 51-88)
	3x Allison Generators (3000kW each, 440V) (DDG 89-112)
Propulsion:	4 General Electric LM2500-30 gas turbines each generating 27,000 shp (20,000 kW);coupled to two shafts, each driving a five-bladed reversible controllable pitch propeller; Total output: 108,000 shp (81,000 kW)
Speed:	In excess of 30 kn (56 km/h; 35 mph)
Range:	4,400 nmi (8,100 km) at 20 kn (37 km/h; 23 mph)
Boats & landing craft carried	2 Rigid hull inflatable boats
Complement:	Flight I: 303 total
	Flight IIA: 23 officers, 300 enlisted
Aircraft carried:	Flights I and II: None
	Flight IIA onwards: up to two MH-60R Seahawk LAMPS III helicopters
Aviation facilities:	Flights I and II: Flight deck only, but LAMPS III electronics installed on landing deck for coordinated DDG-51/helo ASW operations
	Flight IIA onwards: Flight deck and enclosed hangars for two MH-60R LAMPS III helicopters

At the most basic level, the DDG 51 engineering plant consists of four GE LM2500 gas turbine main engines, connected two to a shaft, propelling the ship with controllable pitch propellers. Electrical power is provided by three Allison 501-K34 gas turbine generator sets. A simplified version of the propulsion system arrangement is shown in Figure 5.

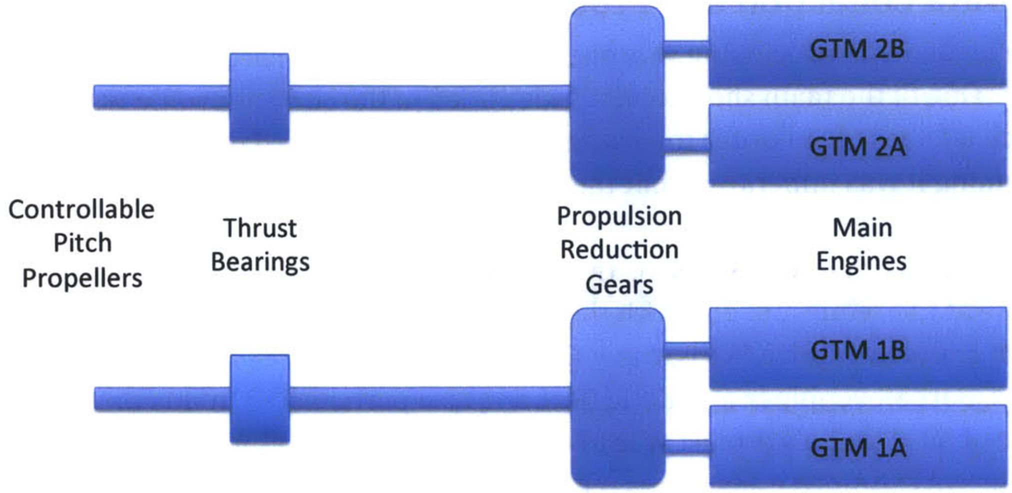


Figure 5: Simplified Propulsion System Arrangement Diagram

This arrangement enables the engineering plant to be operated in three primary modes: trail shaft, split plant, and full power. Trail shaft mode is when one main engine is online and the other shaft is left to spin free. Split plant mode is one main engine online per shaft. Full power is all main engines online. As the number of main engines online is increased, the power available increases and thus higher speeds can be achieved. Split plant and full power modes also add extra redundancy as both shafts and additional main engines are available for power. With the extra power available also comes increased fuel consumption. Thus, the main driver for engineering plant mode selection is to have as few main engines online as is allowed by the tactical environment.

4 Data Collection and Processing

Data collection and processing was one of the most difficult parts of creating the profiles. One of the main shortcomings identified in the current profile was the data on which it is based. In order to ensure the profiles developed overcame this shortcoming it was imperative that the proper data was collected and analyzed.

The work in this chapter, as well as the profile development and validation chapters, was done at the request of and with the support of Mr. Stephen Markle from Program Executive Office Ships/Navy Electric Ship Office (PMS320). Two other students, Bart Sievenpiper and Katie Gerhard, also participated in this project. The purpose of Mr. Markle's project was to create an updated DDG 51 speed-time profile for use by NAVSEA program offices with DDG 51 relayed projects. An unpublished technical report was provided to PMS320 documenting the work completed (Anderson, Gerhard, and Sievenpiper 2012). Additionally, the work was presented at the 2013 ASNE Day Symposia and published to the proceedings (Anderson, Gerhard, and Sievenpiper 2013).

4.1 The Collection Process

Before the collection process could begin decisions had to be made about what data should be collected. These decisions included identifying what data to collect, which ship types to collect from, where the operations occurred, during what timeframe the operations occurred, how many months of data to collect, and if we should target specific types of operations from the ships.

Attempts were made to collect and analyze digital data from shipboard logging systems, but insufficient data was available in the archive to achieve the desired sample size. This left the deck and engineering logs as the sole source of data. Deck and engineering logs are (usually) handwritten documents that act as the legal record of the ship's happenings. Both sets of logs are recorded as events occur in as small as one minute intervals. Deck logs contain such information as course and ordered speed changes, set and drift, small boat and helicopter operations, operational area assigned or port location, general description of the mission, and notes on any significant events. Engineering logs contain such things as GTM and GTG starts and stops, maintenance performed, electric plant shifts, and casualty reports. The deck and engineering logs were found to include all of the data needed to create the desired profiles. Specifically, time of event, fleet assigned to, general indication of mission, ordered speed, flight quarters, and when GTMs and GTGs are placed online or taken offline.

Once it was known what data was needed and the source documents for the data were identified, deciding which ships to include was next. To ensure the profiles represented the most recent data only the most recent logs were included. Logs are retained onboard for at least one year before being sent to archive. Therefore, in order to get the most recent logs, they had to be obtained from visits to the ships. In order to eliminate any differences based on homeport, ships from Norfolk, VA, San Diego, CA, and Pearl Harbor, HI, were included. While it would have been ideal to include data from ships homeported in Yokosuka, Japan, time and budget constraints did not support.

The goal at each homeport was to visit as many ships as possible and collect logs. This was completely driven by the ship's schedules as to which ships were in-port, and of those in-port that could support visitors. In order to ensure a broad sample that was indicative of the entire class, ships from all Flights were included.

An important aspect of the data collection process was how much data should be collected from each of the ships. Two options were identified: the first was to collect a year of data from a few ships and the second was to collect a few months of data from many ships. By collecting a full year of data it is possible to get a broader view of how a ship operates over the deployment cycle. The drawback is that since there are fewer ships in the profile, if one of the ships surveyed operates in a manner wildly inconsistent with the rest of the fleet it can have an undue influence on the profiles. The full year method was used by Rodeghiero et al. at the Center for Naval Analysis. The second method, which was ultimately used, overcomes the drawback of undue influence by including many ships in the profile. However, a drawback is now added that a few months, which was nominally chosen to be three, does not encompass the full range of operations undertaken during the deployment cycle. The mitigation method for this drawback was to choose specific time periods from the ships visited to ensure data was collected from all portions of the deployment cycle.

Once at the ships, the logs were collected for later processing. A portable scanner was used to make electronic copies of all of the logs. This method minimized the impact on the crew as we were self-sufficient and did not require a copy machine or other resources. In all, 28,214 hours of data were collected from 16 different ships. The data is summarized in Table 2. Although ship names are included in this table, from this point forward the ships are referred to by randomly assigned numbers. This is done in an abundance of caution to prevent singling out certain ships and more importantly, because ship names are not significant to the results.

Table 2: Summary of Ship Data Collected

Hull	Name	Flight	Homeport	Fleet	Months Used In Profile	Hours Of Data
52	USS Barry	I	Norfolk, VA	2	JUN12, JUL12, AUG12	2184
53	USS John Paul Jones	I	San Diego, CA	5	MAR12, APR12, MAY12	2208
59	USS Russell	I	Pearl Harbor, HI	5	JAN12, FEB12, MAR12	2177
61	USS Ramage	I	Norfolk, VA	6	OCT11, NOV11, DEC11	2206
70	USS Hopper	I	Pearl Harbor, HI	3	APR12, MAY12	783
84	USS Bulkeley	IIA	Norfolk, VA	2	JUN12, JUL12, AUG12	1968
87	USS Mason	IIA	Norfolk, VA	2	AUG11, OCT11	1488
88	USS Preble	IIA	San Diego, CA	3	APR12, MAY12, JUN12	2185
90	USS Chafee	IIA	Pearl Harbor, HI	7	JUN12	192
91	USS Pinckney	IIA	San Diego, CA	5,7,3	JAN12, FEB12, MAR12	2193
95	USS James E. Williams	IIA	Norfolk, VA	2	AUG11, SEP11	1438
97	USS Halsey	IIA	San Diego, CA	5,7	FEB12, MAR12, APR12	2159
100	USS Kidd	IIA	San Diego, CA	5,3	DEC11, JAN12, MAR12, APR12, MAY12	3418
102	USS Sampson	IIA	San Diego, CA	3	MAY12	744
103	USS Truxtun	IIA	Norfolk, VA	5	SEP11, OCT11	1407
104	USS Sterett	IIA	San Diego, CA	5	APR12, MAY12	1464

4.2 Data Processing

Once the data was collected it had to be compiled from the handwritten logs to an electronic database. This involved the tedious process of reading through all of the log entries and extracting the relevant information to a spreadsheet. These spreadsheets enabled the data to be easily analyzed to create the desired profiles.

For the creation of the profiles the data had to be sorted by engineering plant configuration, mission type, and speed. This was accomplished through a MATLAB script that sorted the data to a three-dimensional matrix. A depiction of the matrix is shown in Figure 6. Sorting the data in this manner enabled the desired profiles to be obtained by simply collapsing the matrix on any given axis to remove the undesired variable.

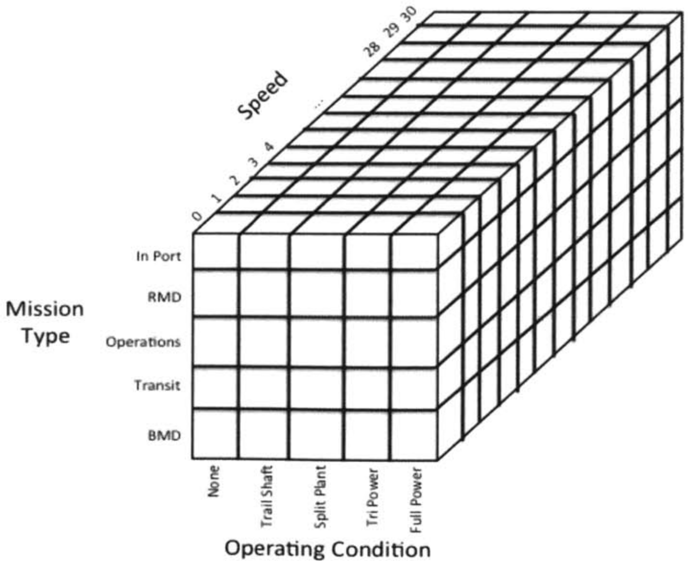


Figure 6: The Data Storage Matrix

5 The Operational Profiles

The results of the data collection and processing are most easily interpreted in the form of operating profiles. These profiles reflect some aspect of how the ship is operated and display that aspect as a percent of time. Three profile types were used to describe DDG 51 operations. The first was the speed-time profile. The other two are the engineering plant mode-time profile and the mission-time profile.

5.1 The Speed-Time Profile

One of the main goals of the research was to update the speed-time profile. By implementing the data collection plan discussed in the previous section most of the shortcomings of the previous speed-time profile were overcome. The composite profile, which includes data from all of the ships combined, is shown in Figure 7.

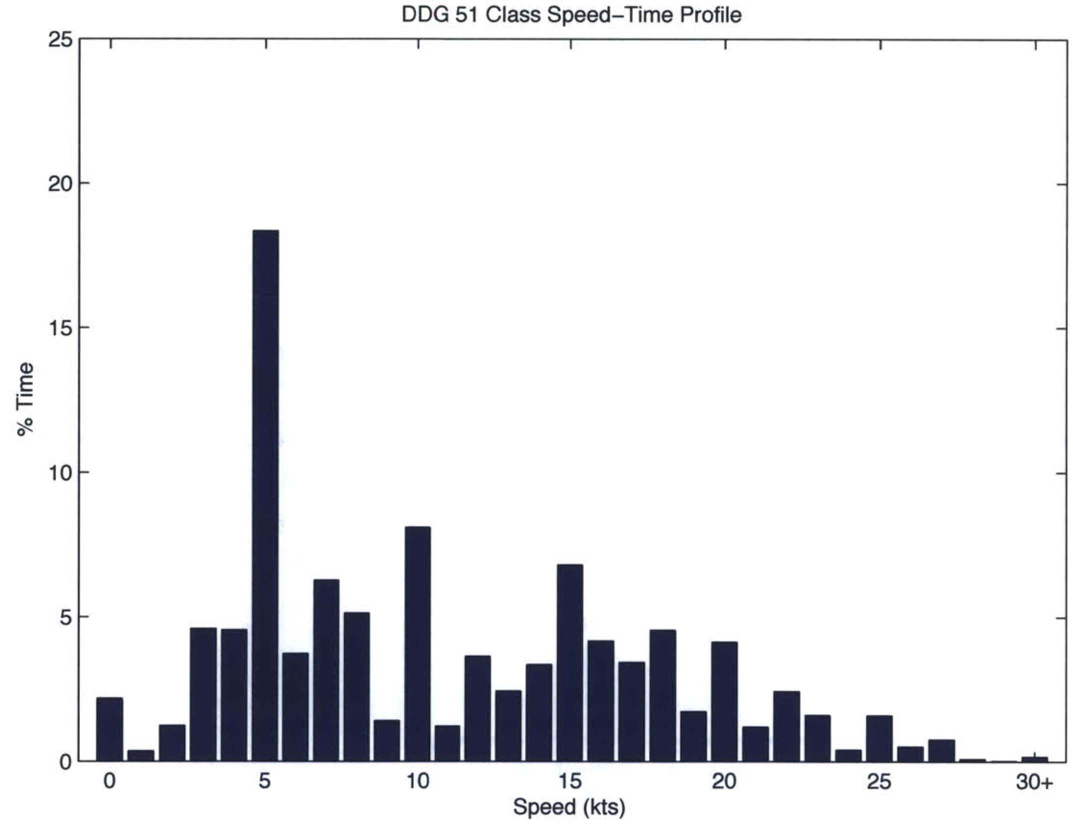


Figure 7: Composite DDG 51-Class Speed-Time Profile

This profile is a significant improvement over the previous profile. One of the most obvious improvements is the profile is now depicted in one-knot increments. This increased fidelity of the profile enables designers to better understand how the ships are operated and to quickly identify the speeds that are important.

There are many features that can be identified from this profile. The peaks at 5 knot increments are one of the most predominant features. These speeds (0, 5, 10...) correspond to the standard bell orders (1/3, 2/3, Full...). In total, over 40% of the time is spent operating at a standard bell order speed. The next feature is the bi-modal appearance of the plot with groupings in the 3-8 knot range and in the 15-20 knot range. These ranges correspond to speeds spent conducting operations and transiting, as will be shown later in the chapter. One final feature worth mentioning is that very little time is spent at high speeds, with 27 knots and above accounting for only 1% of the time.

5.2 The Engineering Plant Mode-Time Profile

As was discussed earlier, the engineering plant can be operated in three different line-ups, or modes. It is vital to know how much time is spent in each mode in order to conduct the profile validation. Fuel usage changes based on the number of engines online and thus the engine operating mode-time profile must be known to conduct a validation using the amount of fuel burned. The previous NAVSEA profile used an assumption of 20% trail shaft, 60% split plant, and 20% full power (NAVSEA Code 05Z1 2003). This was found using an iterative approach of adjusting the engineering plant mode-time profile until the estimated fuel usage was within 5% of the NEURS five-year average reported usage. No source of data or justification of the 20-60-20 breakdown is provided and thus needs to be studied.

As part of the data processing, time in each engine operating mode was tracked for all of the ships in the profile as well as the associated speeds. This enabled a more accurate determination of how much time is spent in each mode. From the profile shown in Figure 8 it can be seen the results are quite different. A much more accurate assumption of engineering plant operations is 69% trail shaft, 24% split plant, and 7% full power.

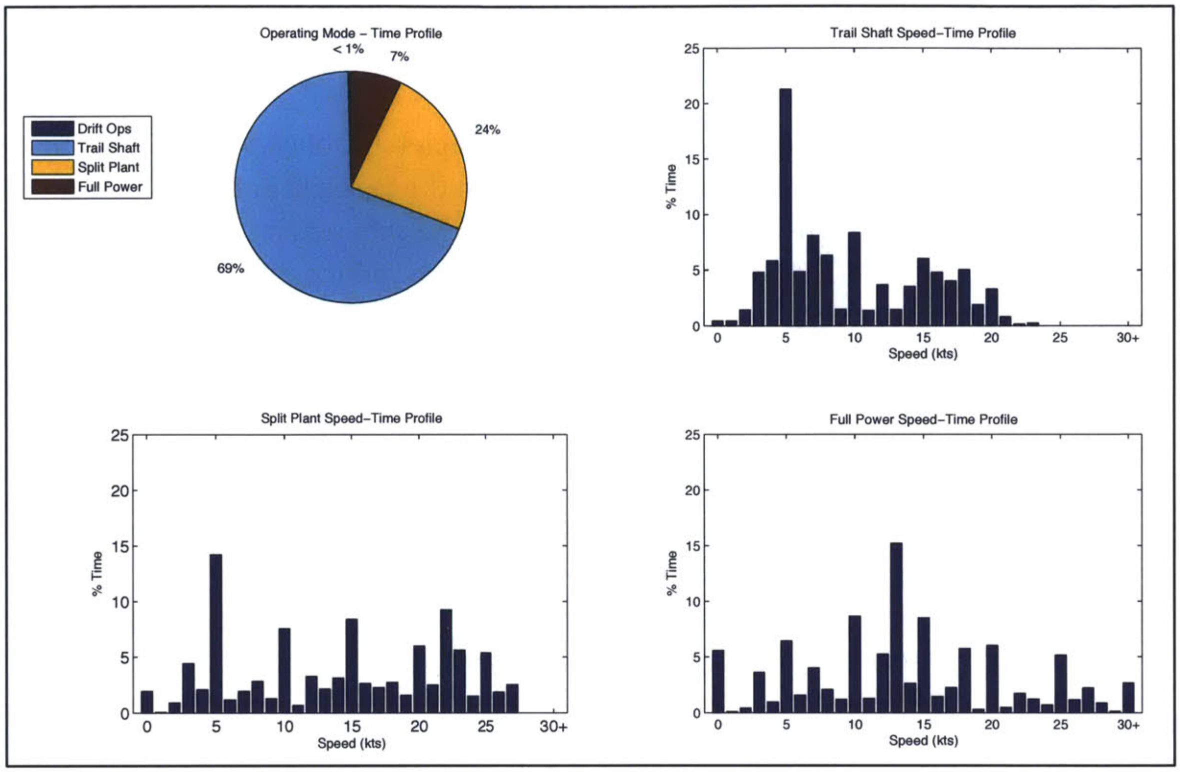


Figure 8: Engineering Plant Mode-Time Operating Profile

Individual speed-time profiles were also developed for each of the engine operating modes. Many of the features in the individual profiles are similar to those in the composite speed-time profile. However, now we have a little more information about each of those features. One of the most significant is the bi-modal distribution in the trail shaft profile. This mode has a major effect on the composite profile as nearly 70% of a ship's time is spent in trail shaft. Both the split plant and full power profiles exhibit the peaks at the standard operating bells. The split plant profile has a slight increase at the higher speeds (20-23 knots), which are often used as an efficient higher-end transit speed. The final feature is the peak at 13 knots in the full power profile. This speed corresponds to the underway replenishment and refueling speed. Although prominent in the full power profile it is unnoticeable in the composite profile due to the relatively small contribution of 7%.

5.3 The Mission-Time Profile

The final profile to discuss is the mission-time profile. While the speed-time profiles and engine operating mode-time profiles are completely objective and based on hard data, the mission-time profile has a subjective element to it. Logs are not normally specifically taken annotating the mission a ship is performing. Furthermore, it is very possible that ships could be performing multiple missions simultaneously. In order to ensure the mission groupings were as objective as possible four broad mission types were used; in-port, restricted maneuvering doctrine (RMD), operations, and transit.

The in-port and RMD mission types fall into the completely objective portion of the profile. Both mission types are easily identifiable in the logs and are consistently utilized across the fleet. In-port was used any time the ship was made up to a pier or when at anchor. RMD, which puts the ship in it most redundant, reliable, and ready configuration, is normally used for entering/exiting port and when operating near another ship for replenishment or refueling. Both of these entries normally occur in the deck and engineering logs.

The officer of the deck makes an entry on the top of each page in the deck logs to indicate the ship is either operating at a specified area or conducing passage from one area to another. This entry was used to determine if the ship was transiting or conducting operations. Passage from one area to another was classified as the transit mission type and operating at a specified area was the operations mission type.

The transit and operations mission types form the subjective portion of the profile. There were times when the transition between transit and operations was very obvious, and other times it was not. Another factor is that one page of deck logs can cover a time span anywhere between 1-2 minutes to an entire day depending on what the ship is doing. Therefore, on a page that covers many hours, it can be very difficult to determine when the transition was made. As all of the researchers have experience as ship drivers, our best judgment was used in making those determinations.

The results of the mission-time profile analysis are shown in Figure 9. The general take-away from this profile is that about two-thirds of the time is spent performing operations of some sort and one-third of the time is spent getting there.

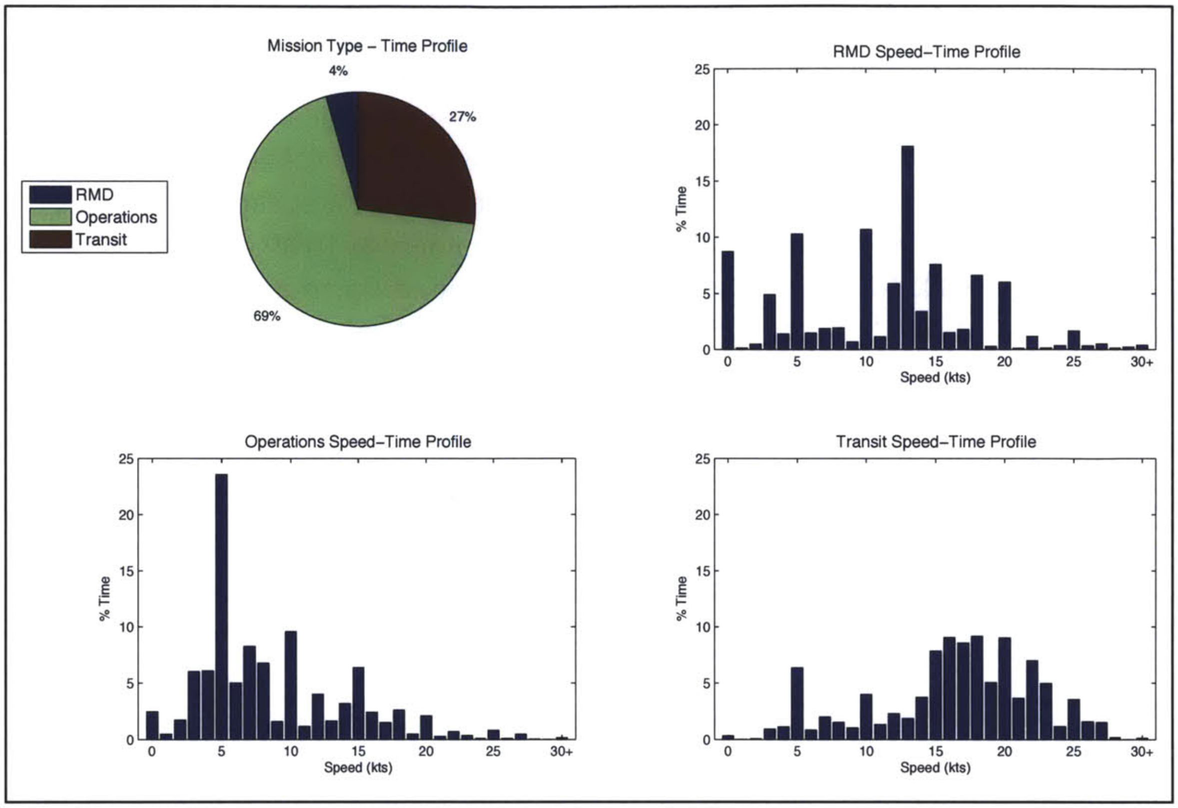


Figure 9: Mission Type-Time Operating Profile

With this final piece of the puzzle we are able to really gain an understanding of how the DDG 51 operates. In both the composite and trail-shaft speed-time profiles a bi-modal distribution was noted. With the knowledge gained from the mission-time profile we can identify the lower speed mode correlates to the operations mission type while the higher speed mode correlates to the transit mission type. The RMD speed-time profile very closely matches the full power speed-time profile indicating that full power is rarely utilized outside of RMD. Any differences between RMD and full power can be accounted for in the transit speed-time profile.

6 Profile Validation Through Fuel Use Modeling

The final step in the operational profile development was to validate the profiles using a known metric. Previous speed-time profiles were validated using data from the Navy Energy Use Reporting System (NEURS). NEURS is a collection of monthly self-reported data from US Navy ships documenting the amount and types of fuel received and used as well as the number of hours underway (UW) and not underway (NUW). NEURS data was also used to validate the profiles developed in this work as it provides a completely objective source of data separate from that used in profile development.

In order to perform a perfect validation a few key pieces of information are needed. The first is to have full knowledge of when the fuel consumers are consuming. For the DDG 51 the fuel consumers are the GTMs and GTGs. The data collection process used recorded all GTM and GTG starts and stops (excluding water washes) and therefore the data needed is available.

The next piece of information needed is the rate at which the consumers are consuming. For the GTMs this data is contained within the speed-time profile. Fuel consumption rates based on ships speed have been developed by NAVSEA through a series of ship trials (Hill and Barros 2001). This data, however, is incomplete and provides only extrapolated fuel rates for 10 knots and below. As this is the region where the ship spends a majority of its time, knowing the rates was vital to the validation. Additional fuel rate data for the low speeds was received from a subject mater expert at the Navy Ship Systems Engineering Station (NAVSSES) in Philadelphia, PA (Halpin 2012).

From our data it is not possible to estimate GTG fuel consumption rates of the ships. The GTG fuel rates are determined by the amount of load on each generator. Loading data is only logged electronically and therefore was not part of the data collection process. The best substitute in this case was found to be the 24-hour average electrical loading. After searching several sources it was clear that there is not a definitive 24-hour electrical load for the DDG 51 class, with results ranging from 1,900 kW to 3,000 kW. Based on the NAVSSES recommendation the loading used in the validation was 3,000 kW (Halpin 2012).

An additional difficulty with GTG fuel rates was encountered due to many conflicting sources that provided fuel rates. This was in part due to the fact that there are two different ratings of GTGs installed on the DDG 51 class. During the production of the Flight II ships larger GTGs were installed and the rating was increased from 2,500 kW to 3,000 kW per machine. As a result, all of the fuel rate sources were analyzed and the a rate of 400 gallons per hour (gph) was utilized ("Model Specification 922A: Model 501-K34" 1987). The GTG fuel rate was then added to GTM fuel rates to produce a table of total ship fuel consumption.

The final piece of data needed was the NEURS reported hours UW and fuel burned UW. In FY12 a total of 179,828 hours were spent UW with 4,373,174 barrels of fuel consumed ("Navy Energy Use Reporting System Annual Reports" FY2012). The results from the engine operating mode-time profile analysis were then used to determine the amount of time spent at each speed in each engine operating mode. Each time was then multiplied by the associated fuel rate to estimate the fuel consumed. An example of the time breakdown for FY12 is shown in Table 3. The total fuel consumed was summed and compared to the NEURS reported fuel burned UW. The estimated fuel burned was 4,301,943 barrels, which is 1.6% less than the NEURS reported value. This is well within the goal of validation to within 3% of a known metric.

Table 3: Hours Breakdown Used in Profile Validation

Speed	Drift Fraction	Hours	Trail Fraction	Hours	Split Fraction	Hours	Full Fraction	Hours
0	1	679	0.0148	1830	0.0264	1128	0.1307	1667
1	0	0	0.0046	569	0.0009	38	0.0012	15
2	0	0	0.0143	1768	0.0091	389	0.0039	50
3	0	0	0.0476	5886	0.044	1881	0.0392	500
4	0	0	0.058	7172	0.0207	885	0.0094	120
5	0	0	0.2107	26054	0.1412	6035	0.0602	768
6	0	0	0.0483	5972	0.0118	504	0.0137	175
7	0	0	0.0805	9954	0.0193	825	0.0351	448
8	0	0	0.0628	7765	0.0282	1205	0.0179	228
9	0	0	0.0147	1818	0.0129	551	0.0102	130
10	0	0	0.083	10263	0.0748	3197	0.0797	1016
11	0	0	0.0138	1706	0.0068	291	0.0119	152
12	0	0	0.0363	4489	0.0327	1398	0.0477	608
13	0	0	0.0145	1793	0.0214	915	0.1288	1643
14	0	0	0.0351	4340	0.0312	1334	0.0264	337
15	0	0	0.0599	7407	0.0831	3552	0.0775	988
16	0	0	0.0475	5873	0.0262	1120	0.0173	221
17	0	0	0.0398	4921	0.0226	966	0.02	255
18	0	0	0.0497	6146	0.0272	1163	0.0545	695
19	0	0	0.0188	2325	0.0156	667	0.0063	80
20	0	0	0.0327	4043	0.0595	2543	0.0571	728
21	0	0	0.0082	1014	0.0248	1060	0.004	51
22	0	0	0.0017	210	0.0916	3915	0.0178	227
23	0	0	0.0026	321	0.0558	2385	0.0103	131
24	0	0	0	0	0.0149	637	0.0062	79
25	0	0	0	0	0.0534	2282	0.0448	571
26	0	0	0	0	0.0186	795	0.0097	124
27	0	0	0	0	0.0253	1081	0.0212	270
28	0	0	0	0	0	0	0.0116	148
29	0	0	0	0	0	0	0.0025	32
30	0	0	0	0	0	0	0.0231	295
Sums		679		123640		42743		12752

Although the validation was deemed successful and accepted by the NAVSEA technical warrant holder, some question could remain regarding the GTG fuel rates. In an effort to understand the effect of the GTGs and the 24-hour average loading a quick sensitivity analysis was conducted. The analysis, shown in Table 4, was conducted over the possible range of average electrical loadings and shows the overall effect on the estimated fuel burned compared to actual fuel burned.

Table 4: Sensitivity Analysis of Validation to Average 24-Hour Electrical Loading

Generator Loading (kW)	Fuel Rate (GPH)	Difference in Consumption (Barrels)	% Difference (Est/NEURS)
1900	332	-292435	-8.3%
2000	337	-269742	-7.8%
2100	344	-238486	-7.1%
2200	351	-211512	-6.5%
2300	357	-184538	-5.8%
2400	363	-157564	-5.2%
2500	372	-119885	-4.4%
2600	376	-103615	-4.0%
2700	382	-76641	-3.4%
2800	388	-49667	-2.8%
2900	395	-22693	-2.1%
3000	400	0	-1.6%

While this analysis provides some indication of the effect of generator loading it is much more difficult to analyze for sensitivity to the GTM fuel rates. This is due to the large number of assumptions used in their determination. These assumptions include displacement, hull fouling, instrument error, and age deterioration factors that were not analyzed for or adjusted. Further research into the GTM fuel rates may be warranted.

7 A Statistical Description of the Data

7.1 The Analyses

The operational information presented thus far has provided a description of how a nominal DDG 51 is operated. This description was developed through reviewing 41 months of data from 16 different ships between August of 2011 and August of 2012. This chapter describes how the nominal ship relates to actual ship operations using a variety of statistical methods. It also describes how each of the ships surveyed compare to the nominal speed-time profile.

The first group of analyses looks at the variance of the data used for the composite speed-time profile. With these analyses, a range of probable speed-time profiles can be developed to describe the ship operations. The second group of analyses looks at how the individual ship profiles compare to the composite profile. This information helps us to better understand the data that is the basis for the composite profile and aids in the identification of outliers.

7.2 A Region of Likely Composite Speed-Time Profiles

The composite speed-time profile was created by analyzing the amount of time spent at a given speed for all of the ships combined. The composite profile does not contain information about which ship the data came from and no other relations can be made. Thus, it only provides the nominal amount of time all of the ships spent at a particular speed. One would not expect a ship operating in the fleet to have the same exact profile as the nominal ship and herein lies the challenge - How might a ship operating in the fleet differ from the nominal ship? The goal of this section is to provide a speed-time profile not as a point representation of a nominal ship, but as a region where likely speed-time profiles may reside.

This concept builds on the earlier quote from Surko and Osborne that shipboard machinery studies must be based on modal data because mean data may or may not accurately reflect ship operations. The information gained from this section specifically addresses this concern. An analysis of the variance is performed to create the most likely region for the profile to reside in. Then principal component analysis is performed to inform the choices of profiles from within that region. The combination of these two analyses ensures that a range of profiles can be selected that represents actual operating conditions rather than just merely the mean.

Additionally, the data can be used to determine the likelihood of off-design conditions. Studies, such as a shipboard machinery study, must not only consider how the ship is expected to operate, but what the effect will be if the ship operates in a significantly different manner. The information gained from these two analyses enables a determination of how likely a profile is to occur in actual fleet operations.

7.2.1 Composite Profile with One Standard Deviation Bands

The first analysis performed was a simple test to find the weighted variance of the data and place error bars on the composite profile showing the first standard deviation. The result is shown in Figure 10.

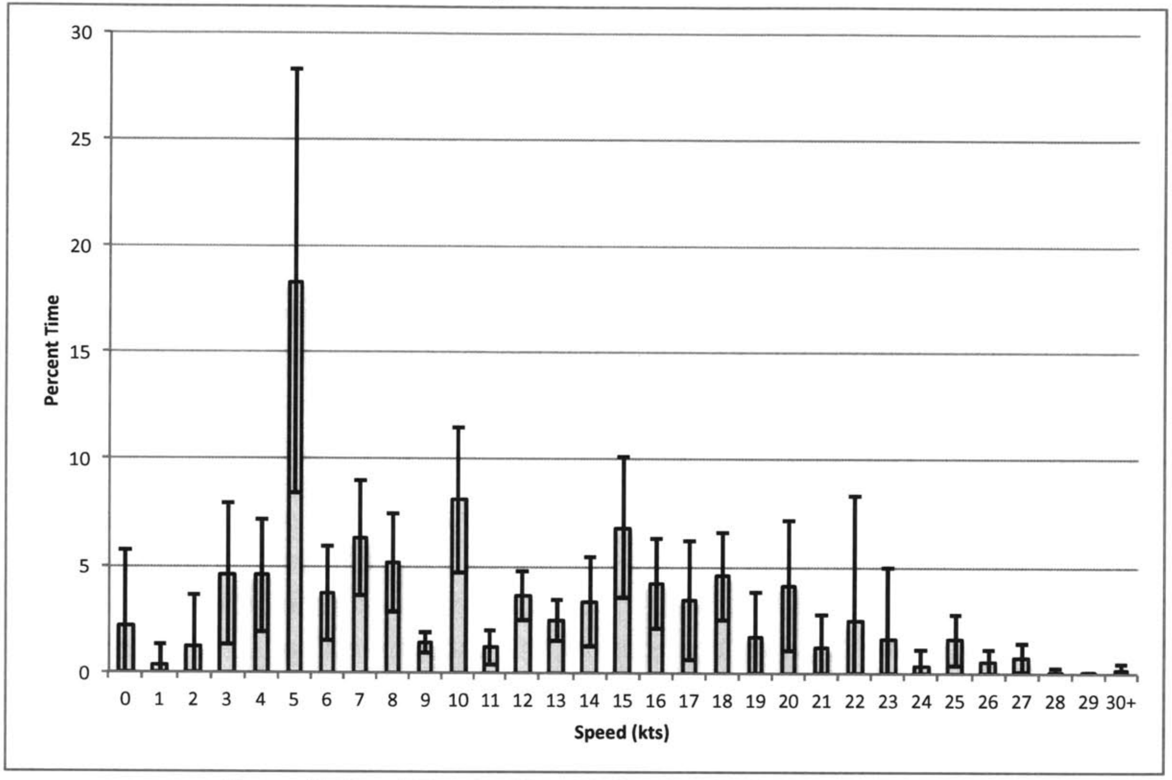


Figure 10: Speed-Time Profile with One Standard Deviation Bands

Each of the bands is a function of the variation from the composite profile each ship displayed at that given speed. Since the amount of data collected from each ship was different, the variance was found using weights based on the number of hours of logs that were analyzed per ship. The weighted means, which are the values from the composite profile, are also found using hours of logs as the weights. The sample variances for each speed were found using (Webster 1998):

$$s_s^2 = \frac{\mathbf{1}}{\sum_{i=1}^{N} \boldsymbol{h_i}} \sum_{i=1}^{N} \boldsymbol{h_i}(\boldsymbol{x_{i,s}} - \mu_s^*)^2$$

where: $s_s^2 = sample\ variance\ at\ speed\ s$
$h_i = hours\ sampled\ for\ each\ i^{th}\ ship$
$x_{i,s} = percent\ of\ time\ ship\ spent\ at\ a\ speed$
$\mu_s^* = percent\ of\ time\ from\ composite\ profile\ at\ a\ speed$
$N = number\ of\ ships\ included\ in\ profile$

The sample standard deviation is then just the square root of the sample variance. One standard deviation bands represent a region where it is expected that 68% of the values will fall given they are normally distributed. For this analysis, the values that are assumed to be normally distributed are the percent of time the ships spent at a given speed. The Lilliefors Test was used as a test for normality to ensure that this was a good assumption.

Lilliefors test is a two-sided goodness-of-fit test that compares the sample data to a normal distribution with the same mean and variance as the sample data ("Lilliefors Test - MATLAB Lillietest" 2013). Lilliefors test is a special application of the Kolmogorov-Smirnov (KS) test that makes use of a table developed to account for the case where the sampled data is used as an estimator for properties of the distribution (Lilliefors 1967). The table was tested through the use of a Monte Carlo simulation and Lilliefors found the standard KS table to be overly conservative. Lilliefors' results were also compared to the chi-squared test. For small sample sizes the Lilliefors test was found to be more accurate than the chi-square test (Lilliefors 1967).

For the results of this test, 14 of the 31 speeds did not display normal behavior at the 5% significance level. However, the speeds that did display normal behavior accounted for 84% of the total time. Therefore, the results and one standard deviation error bands are still significant and provide a good indication of the region in which real ship operations are likely to occur.

7.2.2 Principal Component Analysis

Principal component analysis (PCA) is a non-parametric method used to reduce a complex data set to a lower dimension (Shlens 2009). This in turn may enable one to identify the sometimes hidden, simpler structures that underlie the data. In this case, it was used as a method to further define the variation in ship profiles to better understand the composite profile.

The PCA analysis was conducted using MATLAB (R2012B) software from The MathWorks, Inc. Input data was arranged such that each ship's speed-time profile was represented as a row in a matrix. The final matrix was of size 16x31 for the 16 ships and the 31 possible speeds. A weighting was also applied to each of the rows based on the percentage of each ship's contribution to the overall profile in hours. This is the same weighting used in generating the composite profile and one standard deviation bands and prevents outliers from unduly influencing the results. The PCA script then uses the singular value decomposition method to find the principal components ("MATLAB PCA" 2013).

PCA works by transforming the data to a new set of variables, the principal components, which are uncorrelated and ordered such that the first few principal components contain most of the variation present in all of the original variables (Jolliffe 2002). During the process of the PCA script the data is centered on the mean for each given column (speed). With the associated weights applied, this mean is equivalent to the value in the composite speed-time profile. Therefore, each of the principal components is representative of the variation in the ship profiles from the composite profile.

Once the data is mean centered the mathematical heavy lifting takes place. The singular value decomposition (SVD) of a $m \times n$ matrix A is represented by a factorization of the form (Strang 2007):

$$A = U \Sigma V^T$$

where: $U = m \times m$ unitary matrix
$\Sigma = m \times n$ rectangular diagonal matrix of non-negative real numbers
$V^T = n \times n$ unitary matrix

The diagonal of matrix Σ contains the singular values of A. The columns of U and V are, respectively, the left-and right-singular vectors for the corresponding singular values. It is these columns that form the orthonormal bases. Some important properties of singular value decomposition, which is similar to eigendecomposition, are (Strang 2007):

- The left-singular values of A are eigenvectors of AA^T
- The right-singular values of A are eigenvectors of A^TA
- The non-zero singular values of A (the diagonal values of Σ) are the square roots of the non-zero eigenvalues of AA^T and A^TA

In the PCA analysis, the principal components are the eigenvectors. Each principal component is a vector comprised of the coefficients for each variable. The amount of variation explained by each principal component is contained in the singular values, which are on the diagonal of Σ. Using SVD for PCA analysis is relatively straightforward when A is a square matrix, but quickly becomes much more rigorous for non-square matrices. The PCA script uses many properties of linear algebra to determine the full set of eigenvectors and eigenvalues.

From the results, the two items of the most interest were the coefficients matrix and the vector describing how much of the total variation is explained in each principal component. The first six principal components, along with the amount of variation explained, are shown in Table 5. These first six principal components account for over 90% of the variation.

Table 5: First Six Principal Components and Percent Variation Explained

Speed (kts)	PC1	PC2	PC3	PC4	PC5	PC6
0	-0.03425	-0.14552	0.05202	0.52338	0.53822	-0.22187
1	-0.02041	-0.06093	0.00422	-0.14525	0.10495	0.04163
2	-0.06956	-0.18071	-0.00082	-0.34497	0.19095	0.02966
3	-0.09152	-0.31580	0.15096	0.03248	-0.46439	-0.28247
4	-0.01608	-0.26709	0.11492	-0.30823	0.02709	-0.00652
5	0.89204	0.27316	-0.00298	-0.02271	-0.07263	-0.03404
6	0.12076	-0.13705	0.10426	-0.05426	-0.08781	0.02890
7	0.09211	-0.17359	0.21292	0.05928	0.08675	-0.16288
8	-0.00713	-0.21490	0.11807	-0.28327	0.19646	0.16310
9	0.01953	-0.01905	0.01761	0.04741	-0.01374	-0.01188
10	0.15204	-0.23065	0.29482	0.27741	0.06936	0.05947
11	0.03265	0.03052	-0.03249	0.03877	0.04282	0.01537
12	-0.02374	-0.04380	-0.01518	0.02560	-0.19218	0.04628
13	-0.03232	-0.00269	-0.00485	0.01725	-0.11849	0.17513
14	-0.00447	-0.02537	-0.10134	-0.34952	0.04699	0.15896
15	-0.11834	-0.05975	-0.00097	0.38650	-0.31984	0.58389
16	-0.03167	0.05934	-0.22245	-0.14691	0.02007	-0.02369
17	-0.10810	0.17733	-0.35252	0.06242	-0.04454	0.03475
18	-0.05510	-0.01363	-0.22149	0.04218	0.30351	0.01297
19	-0.04384	0.18312	-0.22798	0.01536	0.06976	0.11043
20	-0.12323	0.03345	-0.29820	0.03609	-0.24539	-0.57071
21	-0.02513	0.14488	-0.15082	0.04501	0.05499	-0.06384
22	-0.25212	0.57739	0.63072	-0.10729	-0.02148	-0.13715
23	-0.16476	0.33508	0.04599	0.02982	0.13281	0.11214
24	-0.02533	0.05692	-0.04729	0.00934	0.00429	0.08291
25	-0.02317	0.00097	0.00761	0.07005	-0.19727	0.05152
26	-0.01201	0.03347	-0.04492	-0.01083	-0.05286	-0.05815
27	-0.01918	-0.01061	-0.03953	0.01722	-0.05014	-0.14778
28	-0.00328	0.00619	0.00297	0.00515	-0.00240	0.00343
29	-0.00104	-0.00184	-0.00071	0.00392	0.00280	-0.00409
30+	-0.00335	-0.00883	0.00744	0.02862	-0.00866	0.01453
% Explained	45.13	16.36	11.27	7.94	5.70	4.02

A Pareto plot of the percent explained variation was used to help show which principal components are most important. The plot is shown in Figure 11. There is a very clear break between PC1 and PC2 indicating that PC1 is significant. PC6 was chosen as the cutoff as there is very little change between PC6 and PC7 and through PC6 over 90% of the variation is accounted for.

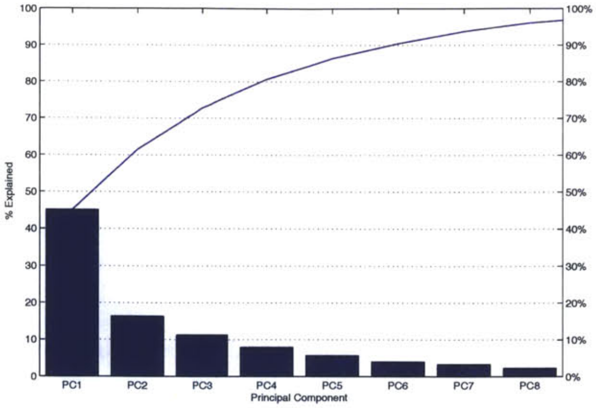


Figure 11: Pareto Plot of the Percent Explained Variation

One of the main benefits of the coefficients is to help visualize the sources of the variation in the data. This was achieved by plotting the coefficients in several different manners to visualize the effects and is shown in Figure 12.

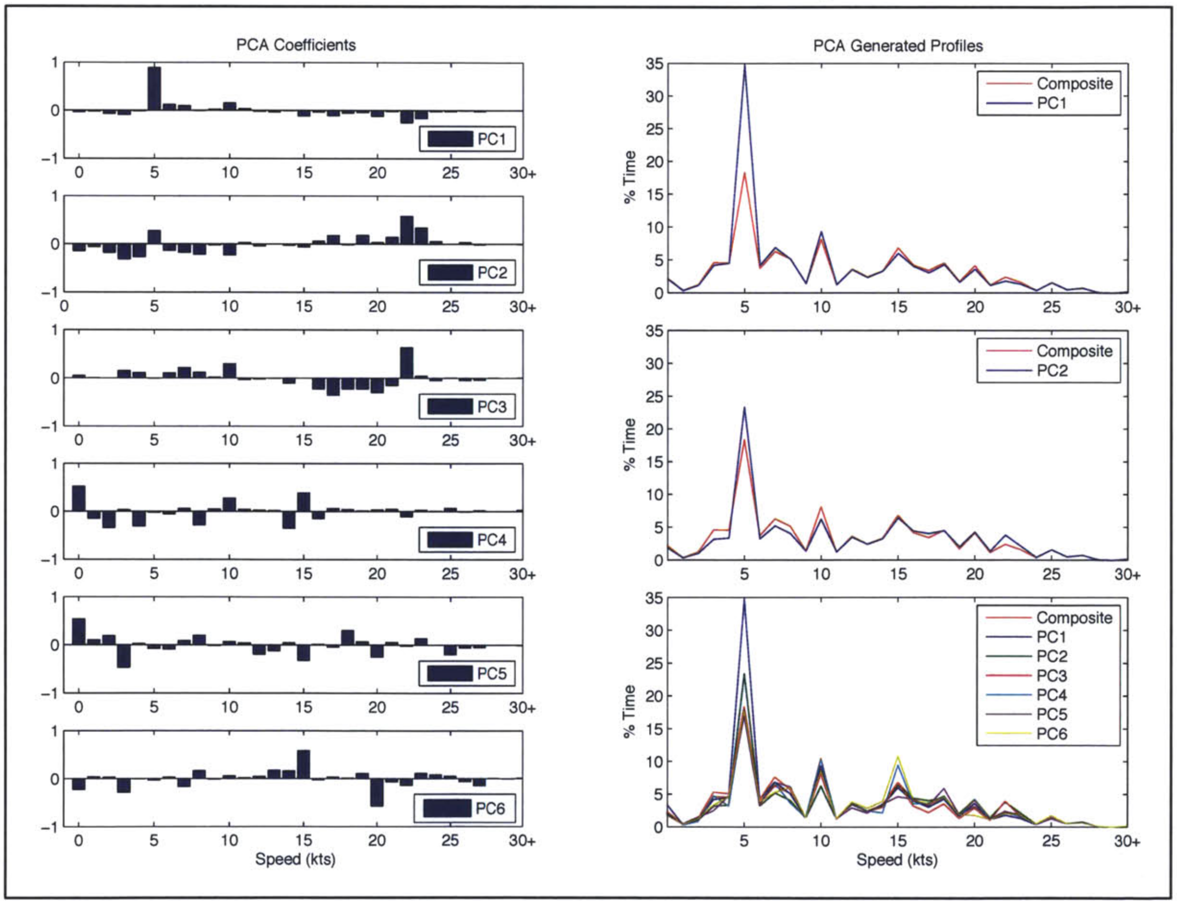


Figure 12: Bar Chart of First Six Principal Components and Principal Component Profiles Compared to the Composite Speed-Time Profile

One property of the principal components is that they are orthonormal and therefore completely independent of each other. Each of the bar charts helps to identify where in the profiles the variation exists. In PC1, which accounts for 45% of all the variation, the most predominant source is at 5 kts. This is in keeping with the results shown in Figure 10 in the previous section, as the largest amount of variation occurs at 5 kts.

It is also helps to visualize the effect shown in PC2 where there is a slight negative variation at low speeds and a slight positive variation at higher speeds. An interesting aspect of PC2 is that 5 kts still shows positive variation while all the rest of the speeds below 10 kts show negative variation. This is important when optimizing around a certain speed because although many of the lower speeds show negative variation, the largest source of positive variation is located in the same region. One could not therefore optimize for the largest source of variation, 5 kts, without optimizing for the adjacent regions of negative variation. The positive and negative variations are directly related to increasing or decreasing the percentage of time the ship will spend at a given speed.

The plots on the right side of Figure 12 provide another means to quickly interpret the principal components. Although speed-time profiles are not continuous, these plots provide a quick method to identify the differences and gain a sense of the magnitude of the variation. These profiles are created by multiplying the composite profile values by the associated coefficients from each principal component. Because the coefficients can have both positive and negative values the principal component profiles will either increase or decrease from the composite profile. The top two profiles on the right show PC1 and PC2 plotted with the composite profile. It is easy to see the large magnitude of the variation in PC1 at 5 knots and the slight decrease across the rest of the profile. For PC2, one can quickly identify that there is a slight decrease at lower speeds and a slight increase at higher speeds. The plot in the lower right shows all of the principal components on one plot. The speeds where the lines separate indicate the areas with high variations.

Although having a rigorous mathematical method that produces results to a large number of decimal points may make one feel that they have very precise information, it may not be the best way to glean the desired knowledge from a principal component analysis. What may be of more interest is the general pattern of the coefficients, which can be obtained through a simplified table of coefficients as shown in Table 6 (Jolliffe 2002). To create the table, the coefficients in each principal component are first normalized so that the maximum value is ±1. The symbols + and – are used to represent coefficients whose absolute value is greater than half of the maximum coefficient, with the appropriate symbol representing the sign of the coefficient. Similarly, (+) and (-) are used to represent coefficients whose absolute value is between a quarter and a half of the maximum coefficient. This method allows one to quickly identify the sources of variation in each principal component.

Table 6: Simplified Table of PCA Coefficients

Speed	PC1	PC2	PC3	PC4	PC5	PC6
0		(-)		+	+	(-)
1				(-)		
2		(-)		-	(+)	
3		-			-	(-)
4		(-)		-		
5	+	(+)				
6						
7		(-)	(+)			(-)
8		(-)		-	(+)	(+)
9						
10		(-)	(+)	+		
11						
12					(-)	
13						(+)
14				-		(+)
15				+	-	+
16			(-)	(-)		
17		(+)	-			
18			(-)		+	
19		(+)	(-)			
20			(-)		(-)	-
21		(+)				
22	(-)	+	+			
23		+				
24						
25					(-)	
26						
27						(-)
28						
29						
30						
Explained	45.13	16.36	11.27	7.94	5.70	4.02

In this form one can quickly identify that the 5 kt speed is the dominant source of variation. The next significant source of variation, which is predominant in PC1, PC2, and PC3, is the 22 kt speed. The variation at 22 kts is most likely due to one ship, which may be an extreme outlier. Further analysis to identify potential outliers will be conducted in the next section.

7.2.3 The Composite Profile Range

The results from the one standard deviation analysis and the principal component analysis can be used to identify, or help guide, the selection of likely speed-time profiles. Figure 13 shows the region bounded by the one standard deviation bands in green. A speed-time profile could be created from this region by selecting values from within the green range that sum to 100%. Any possible combination would be considered likely. The results from the PCA can help make those selections by guiding the decisions in areas of high variability. An example of this could be to pick a percent time for 5 kts at 22% vice 9% since the first two principal components indicate that there is a lot of positive variation. This region would be very useful in an optimization problem and could be applies as a constraint, with the results of the PCA enabling one to assign weights to the sample profiles.

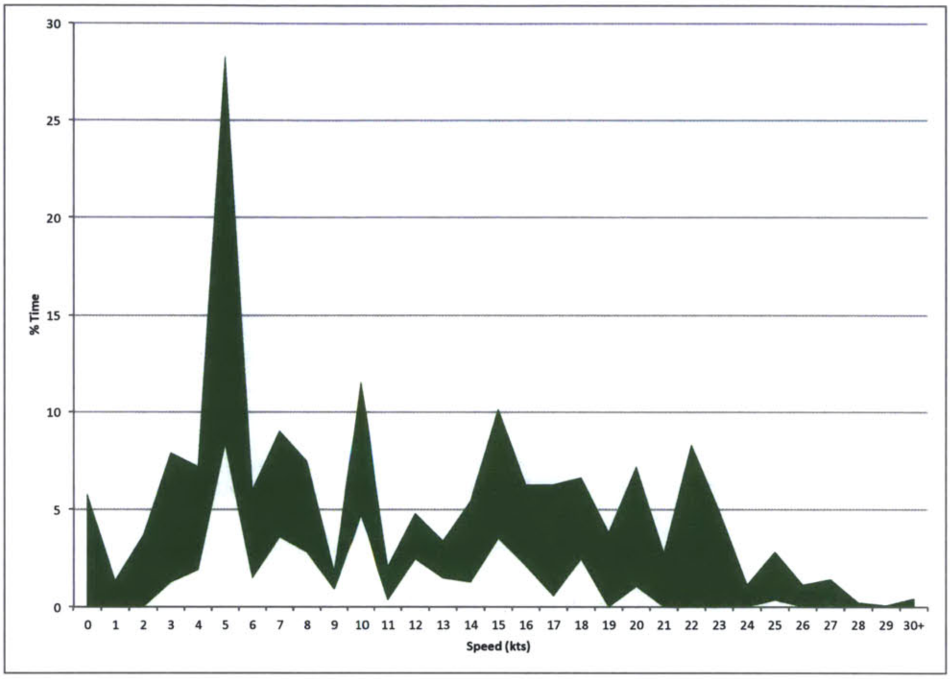


Figure 13: Region of Likely Speed-Time Profiles

7.3 The Individual Profiles

The next set of analyses focused on the individual ship profiles. The profiles were analyzed to determine if they could have come from the same distribution and if they did not, how much different are they. Several statistical tests were used along with different methods of visualizing the data. The first visual method is the next logical step from the previous section – does the range of likely profiles capture the individual ship profiles? The results are shown in Figure 14. Individual ship profiles in this figure are not weighted.

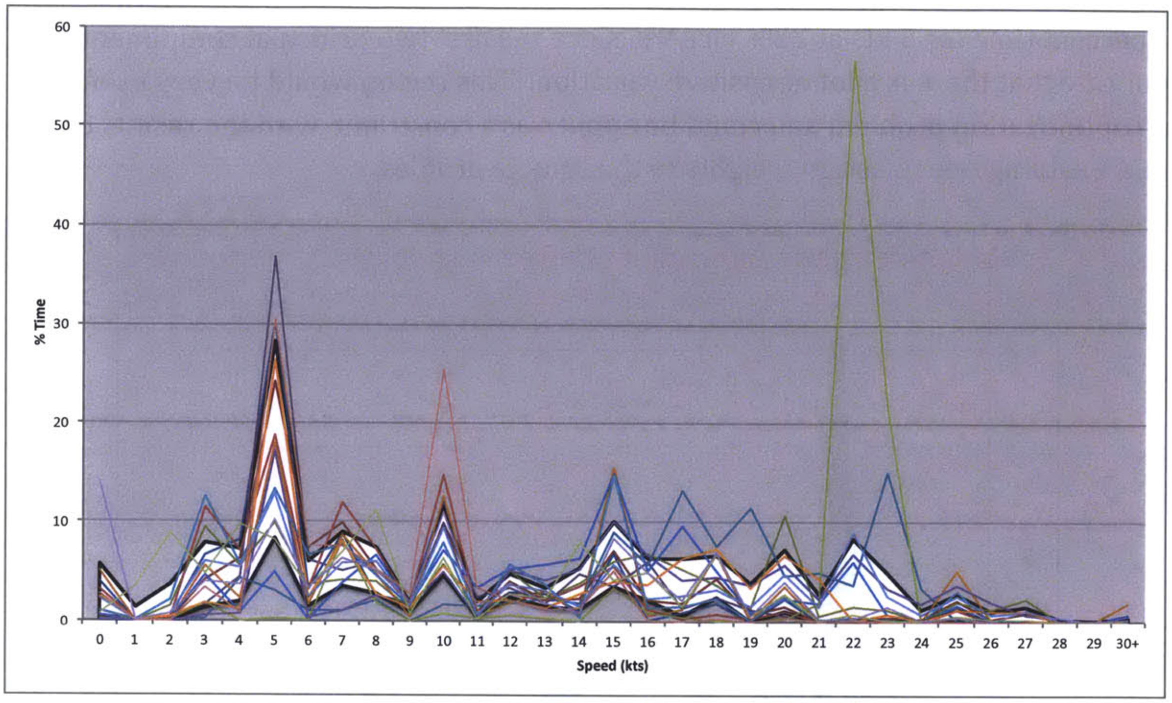


Figure 14: One Standard Deviation Region Overlaid with Individual Ship Profiles

Most of the ship profiles in Figure 14 appear to fall within the one standard deviation band. However, upon further analysis, none of the profiles fall completely within the band and a few are significantly out of the band. The full results of this assessment are included in Appendix A.

Each of the ship profiles and the composite speed-time profile were plotted as cumulative distribution functions (CDF) and are shown in Figure 15. The CDF plot provides an alternative method to visualize the data. The distributions are also important in that they are the basis for comparison in all of the following statistical tests. Each of the tests is used to identify either if the individual ship distributions could have been come from the same distribution or if the individual ship distributions could have come from the same distribution as the composite speed-time profile distribution.

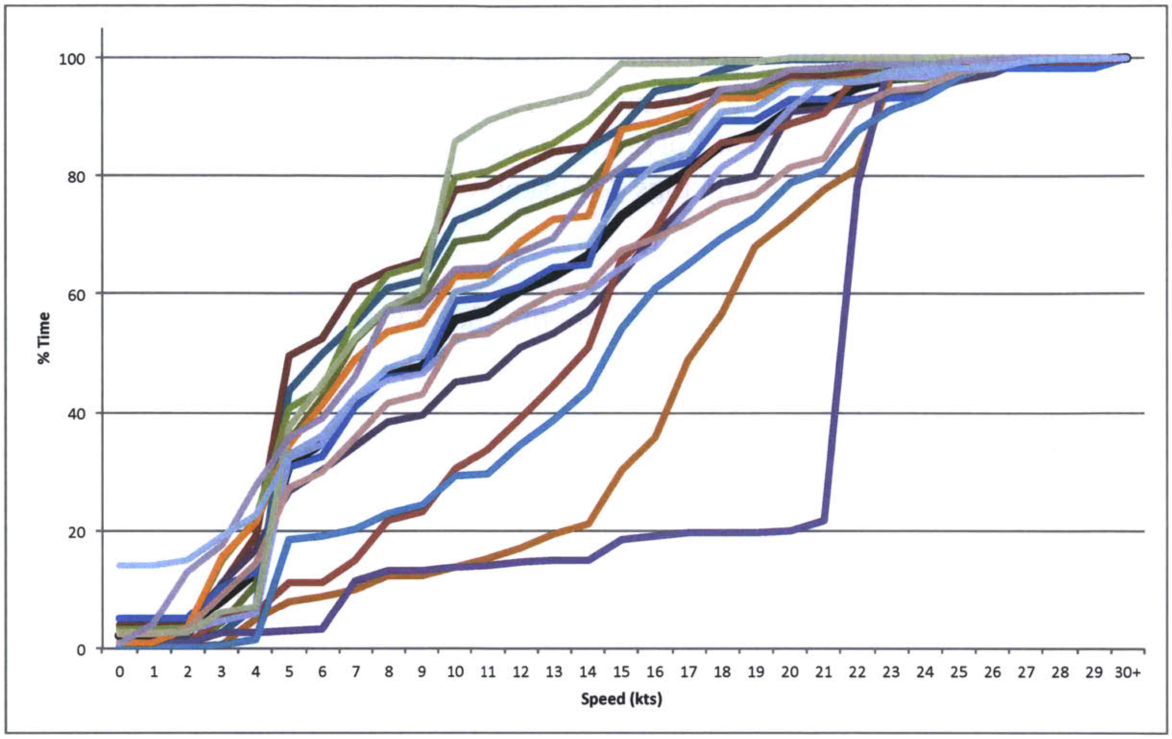


Figure 15: All Ship Profiles as Cumulative Distribution Functions

7.3.1 Kruskal-Wallis and Multiple Comparison Tests

The Kruskal-Wallis (KW) test is a nonparametric version of the classical one-way analysis of variance (ANOVA), and an extension of the Wilcoxon rank sum test to more than two groups (Webster 1998). The results of this test either indicate the sample data originated from the same distribution or that at least one sample median is significantly different from the others.

The first step in the KW test is to rank each data point against all of the other data points from all of the groups. The data groups (each ship) are maintained, but the data is ranked against all other ships (Webster 1998). For this test, since each ship has 31 data points and there are 16 ships the rankings would be from 1 to 496. The KW test statistic is then (Webster 1998):

$$K = \frac{12}{n(n+1)}\left[\sum \frac{R_i^2}{n_i}\right] - 3(n+1)$$

where: n_i = number of observations in i^{th} sample

n = total number of observations in all samples

R_i = sum of the ranks in i^{th} sample

The test statistic, *K*, is then compared to a critical value. The distribution of *K* is approximated by a chi-square distribution with *k*-1 degrees of freedom, where *k* is the number of samples. The critical value for 15 degrees of freedom and an α-value of 5% is 24.996 (Webster 1998). Correction factors are used to adjust the K value in the event there are ties in the rankings ("Kruskal–Wallis One-way Analysis of Variance" 2013).

Based on the knowledge we have of the data thus far, it would be expected that the test would reject the null hypothesis – indicating that at least one sample mean is significantly different than the others – and it does. However, beneficial data is gained through a boxplot of the data, produced by the MATLAB test script, and is shown in Figure 16.

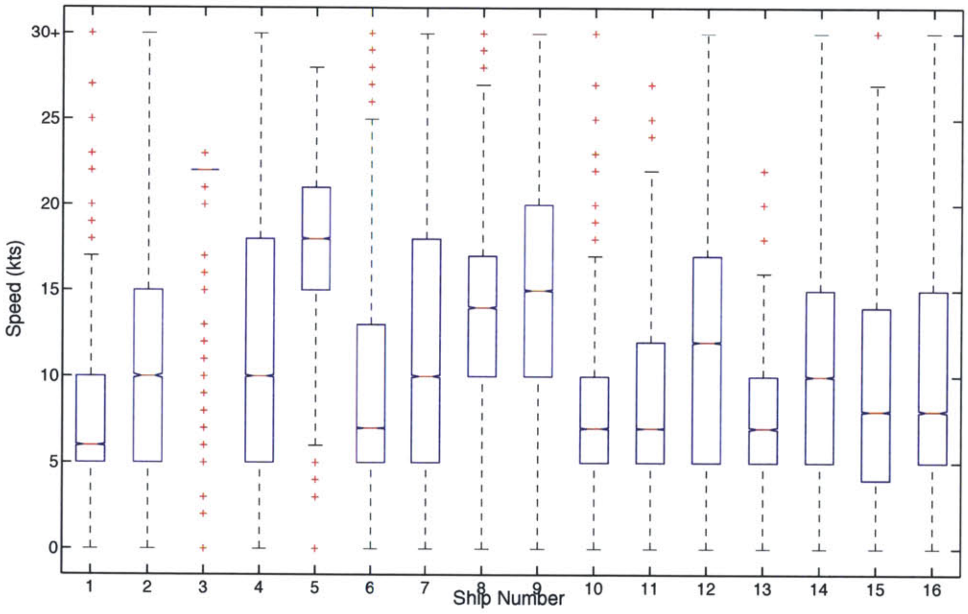


Figure 16: Boxplot of Ship Profile Data

From Figure 16 it is clear that ship numbers 3 and 5 display properties that are considerably different from the other ships. Ships 3 and 5 have the highest means and are also the only ships with outliers at low speeds. Ships 8 and 9 also are immediately noticeable with their lower quartile at 10 kts instead of 5 kts like nearly all the other ships. This provides the first indication of which ships may be outliers.

A very closely related test to the KW test is the MATLAB Multiple Comparison test. This function uses the output from the KW test to perform pairwise comparisons between each of the samples. A 95% confidence interval is applied to the mean rank of each group. The results are easily interpreted and analyzed using an interactive MATLAB figure, an example of which is shown in Figure 17.

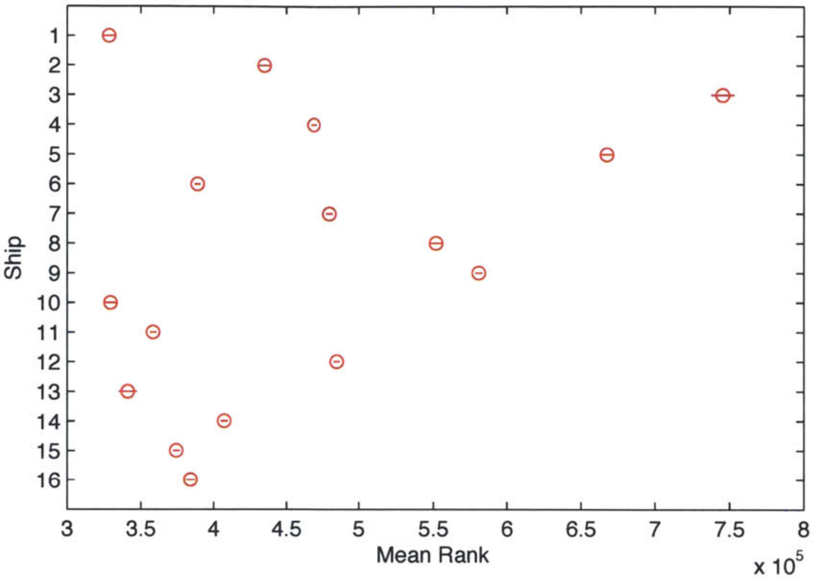


Figure 17: Comparison of Mean Ranks from Kruskal-Wallis Test Using the Multiple Comparison Test

The results of the KW test only provided the information that one of the samples was different than the rest. With the Multiple Compare test a method is provided to analyze the samples individually to determine which have significantly different mean ranks and which have similar ranks. Having mean ranks of similar value is an indication that the two samples are from the same distribution.

From an analysis of Figure 17, only ships 1 and 10 and 6 and 16 were found to have mean ranks that overlap within the confidence intervals. There are some other interesting features of this plot that are worth noting. The KW test uses ranks instead of the actual sample values. The sample values (speeds) are ranked against all samples from slowest to fastest. Therefore, ships with a lower mean rank have slower overall profiles and ships with a high mean rank have faster overall profiles. Although quite large, there is a grouping of ships in the 300,000 to 500,000 range. Again, the same ships that stood out in the boxplot stand out again (Ships 3, 5, 8, and 9).

7.3.2 Chi-Square Test

The χ^2 test is used as a goodness-of-fit test to determine if the individual ship profiles "fit" our expectation. In this case our expectation is the composite speed-time profile. The test uses the form (Holman 2001):

$$\chi^2 = \sum_{i=1}^{K} \frac{(O_i - E_i)^2}{E_i}$$

where O_i = observed value
E_i = expected value
K = number of observations

The test was performed with the ship profile data as the observed values and the composite speed-time profile values as the expected values over the entire range of speeds, *K*. For this test there are *K-1=30* degrees of freedom. From a table of the chi-square distribution we find $\chi^2_{0.05,30} = 43.773$ (Webster 1998). The results from each profile are then compared to this critical value. If the profile has a $\chi^2 \leq 43.773$, the null hypothesis is not rejected. In this case, the null hypothesis is that the ship profile being tested came from the same distribution as the composite speed-time profile. Chi-square test values greater than the critical value are rejected. The results are summarized in Table 7.

Table 7: Results of Chi-Square Test for Goodness-of-Fit

Ship	χ^2	*p*	Reject?	Weight
1	37.597	0.160		2.18%
2	62.968	0.000	Reject	2.24%
3	1540.3711	0.000	Reject	0.89%
4	33.4777	0.302		12.20%
5	273.8133	0.000	Reject	3.33%
6	21.0354	0.887		12.11%
7	26.8252	0.632		8.10%
8	63.2626	0.000	Reject	3.03%
9	53.5853	0.005	Reject	7.94%
10	43.5831	0.052		2.93%
11	43.3908	0.054		11.78%
12	32.0184	0.367		11.48%
13	87.3316	0.000	Reject	1.29%
14	81.5334	0.000	Reject	7.46%
15	110.8691	0.000	Reject	8.85%
16	46.3603	0.029	Reject	4.19%

These results indicate that a majority of the ship profiles are significantly different than the composite profile. If the *p*-value were to be relaxed to the 0.5% level, the new critical value is $\chi^2_{0.005,30} = 53.672$. At this level ships 9 and 16 would be accepted.

The weight column was added to show that although the ships each contribute differently to the composite profile it is not their contribution that drives the result of this test. Some ships that contributed greatly to the composite profile are rejected and some ships that contributed very little are accepted. Ship 3 and 5 continue to exhibit characteristics that they are outliers.

7.3.3 The Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov (KS) test is another non-parametric goodness-of-fit test. One of the main differences between the KS test and the chi-square test is the KS test is a "distance test" (Romeu 2003). The KS test has one-sample and two-sample versions. In the one-sample version, the test sample empirical cumulative distribution function (ECDF) is compared to a reference cumulative distribution function (CDF). In the two-sample version, which is the test that was used, the ECDFs from the two samples are compared. The test statistic, D, is then the largest difference (distance) between the two functions at any given point. An example is shown in Figure 18, where the black vertical line represents D.

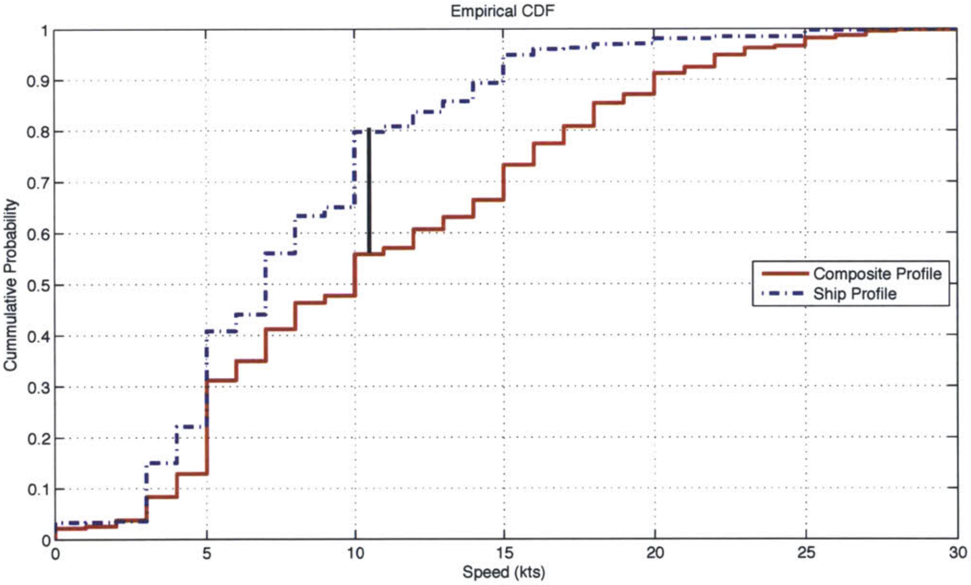


Figure 18: Example of Two-Sample KS Test

The test statistic was found for each profile by comparing an ECDF created from all of the ship data combined to each ship's ECDF. The maximum distance between the two curves was found and that distance is D. Each value of D must then be compared to a critical value to determine whether or not to reject the null hypothesis. The null hypothesis in this case is again that the two samples are from the same distribution.

The critical value is found by:

$$D_\alpha = c(\alpha)\sqrt{\frac{n_1 + n_2}{n_1 n_2}}$$

Where $c(\alpha = 0.05) = 1.36$, and $n_1 = n_2 = 31$, which is the sample size for both samples (Wessel 2013). The resulting critical value is 0.3454.

Table 8: Kolmogorov-Smirnov Goodness of Fit Test Results

Ship	D	Reject?
1	0.2199	
2	0.0747	
3	0.7140	Reject
4	0.0933	
5	0.4523	Reject
6	0.1319	
7	0.1039	
8	0.2619	
9	0.2737	
10	0.2385	
11	0.1828	
12	0.1092	
13	0.3231	
14	0.1167	
15	0.1464	
16	0.1465	
Critical D: 0.345, α=0.05		

Again, the results are consistent with the previous analyses. Ships 3 and 5 both exhibit characteristics that they are from a different distribution than the composite profile. Other ships that are near the critical value, ships 8, 9, and 13, were rejected in previous tests.

7.3.4 Summary of Individual Profile Tests

Four tests were used to analyze the individual profiles. The first two, the Kruskal-Wallis and Multiple Comparison tests, used a rankings approach to compare the profiles as a group and then in a pair-wise manner. The next two, the Chi-square and Kolmogorov-Smirnov tests, compared the ship cumulative distribution functions to the composite speed-time profile cumulative distribution function. A summary of the Chi-square and KS results is shown in Table 9.

Table 9: Summary of Chi-square and Kolmogorov Test Results

	Chi-Square Test			KS Test		
Ship	**$\chi 2$**	**p**	**Reject?**	**D**	**Reject?**	**Weight**
1	37.5972	0.160		0.2199		2.18%
2	62.968	0.000	Reject	0.0747		2.24%
3	1540.3711	0.000	Reject	0.7140	Reject	0.89%
4	33.4777	0.302		0.0933		12.20%
5	273.8133	0.000	Reject	0.4523	Reject	3.33%
6	21.0354	0.887		0.1319		12.11%
7	26.8252	0.632		0.1039		8.10%
8	63.2626	0.000	Reject	0.2619		3.03%
9	53.5853	0.005	Reject	0.2737		7.94%
10	43.5831	0.052		0.2385		2.93%
11	43.3908	0.054		0.1828		11.78%
12	32.0184	0.367		0.1092		11.48%
13	87.3316	0.000	Reject	0.3231		1.29%
14	81.5334	0.000	Reject	0.1167		7.46%
15	110.8691	0.000	Reject	0.1464		8.85%
16	46.3603	0.029	Reject	0.1465		4.19%
	$\chi^2_{0.05,30}=43.773$, $\alpha=0.05$			Critical D: 0.345, $\alpha=0.05$		
H_0: The ship CDF and composite profile CDF are from the same distribution.						
H_1: The ship profiles are from different distributions.						

The results of all of the tests provided information on whether the ship profiles differed from other ship profiles and if the ship profiles differed from the composite speed-time profile. This information can be used in a few ways. The first is to understand the data that underlies the composite profile. We now have statistical data as to how the ship profiles relate to each other and the composite profile. Another aspect is we have an indication of which profiles are outliers – ships that operate significantly different from other ships and the composite profile. Outliers are not necessarily bad and are expected. Where it could be a concern is for ships like Ship 3, where the 22 kt value is over nine standard deviations different. This could provide an indication that the original data is suspect and warrant further review. In this case, Ship 3 came from operations over a short time that encompassed a high-speed transit. The most prudent response would be to either remove the data from the composite profile or to gather more data for the data set to meet the collection requirements described earlier.

Another, somewhat more subtle, conclusion can be drawn from the ships that are identified as outliers. Only ships that operated with faster speed-time profiles were found to be outliers – there are no slow speed outliers. Although seemingly obvious and a very simple conclusion, it is not normal for ships to spend a lot of time at high speeds. This point is slightly different from that made from looking at only the composite profile. The composite profile tends to indicate a more even distribution of the speeds among all ships. However, by analyzing Figure 16 and Figure 17, one can see that most ships operate at relatively lower speeds while just a few operate at high speeds a majority of the time. This is an important fact when performing an optimization based on the speed-time profile because it indicates that one should most likely optimize at the lower speeds rather than the higher speeds. This shift towards lower speeds is most likely the result of fuel-savings efforts implemented by the Navy in order to reduce operating costs.

8 Applications and Effects of the New Speed-Time Profile

As was mentioned earlier, one of the main applications of the profile data is in estimating fuel use. Fuel use estimating is important because of the large quantities of fuel used by the Navy and the expense associated with it. Much focus has been placed on methods to reduce fuel consumption. Evaluations of many of those methods rely heavily on assumptions about how the ships are operated, such as the operational profile that was developed and analyzed in this thesis.

An example of how the speed-time profile can affect the results of such a study will be shown here. This example will use the results of a study on stern-end bulbs (SEB) conducted by Naval Surface Warfare Center Carderock Division (NSWCCD). The first step will be to show how fuel use estimates for the SEB differ when using the 2003 speed-time profile and the newly developed composite profile. These results will also be compared to a ship with just a stern flap, and one with an unmodified transom.

The second step will then be to evaluate the SEB with several 'test' speed-time profiles. The profiles will be developed such that they are within the one standard deviation region. By analyzing several likely speed-time profiles one can gain a sense of just how much of an effect changes to the profile can have.

8.1 Stern End Bulbs and Stern Flaps

Stern end bulbs and stern flaps help to reduce separation and therefore reduce the overall resistance of the ship. This enables the ship to use less power to achieve the same speed. As the power the gas turbines produce is directly related to the rate at which fuel is consumed, a lower power at the same speed equates to fuel savings. Examples of a SEB and stern flap are shown in Figure 19 and Figure 20.

Figure 19: Example of a Stern End Bulb (Cusanelli and Karafiath 2012)

Figure 20: Example of a DDG 51 Stern Flap (Cusanelli and Karafiath 2012)

These two components were analyzed at NSWCCD through tow-tank model testing as well as computational methods. Results of these studies were published showing the effect of the devices compared to a baseline, which is a DDG 51 Flight IIA with a stern flap installed. All ships in the class were either built with a stern flap or have had one retrofitted. The results for the SEB are shown in Figure 21. Stern Bulb H was utilized by Karafiath in his paper as the best overall and will also be used for this example. Also, this analysis was conducted using ship wave inviscid flow theory (SWIFT) rather than model tests.

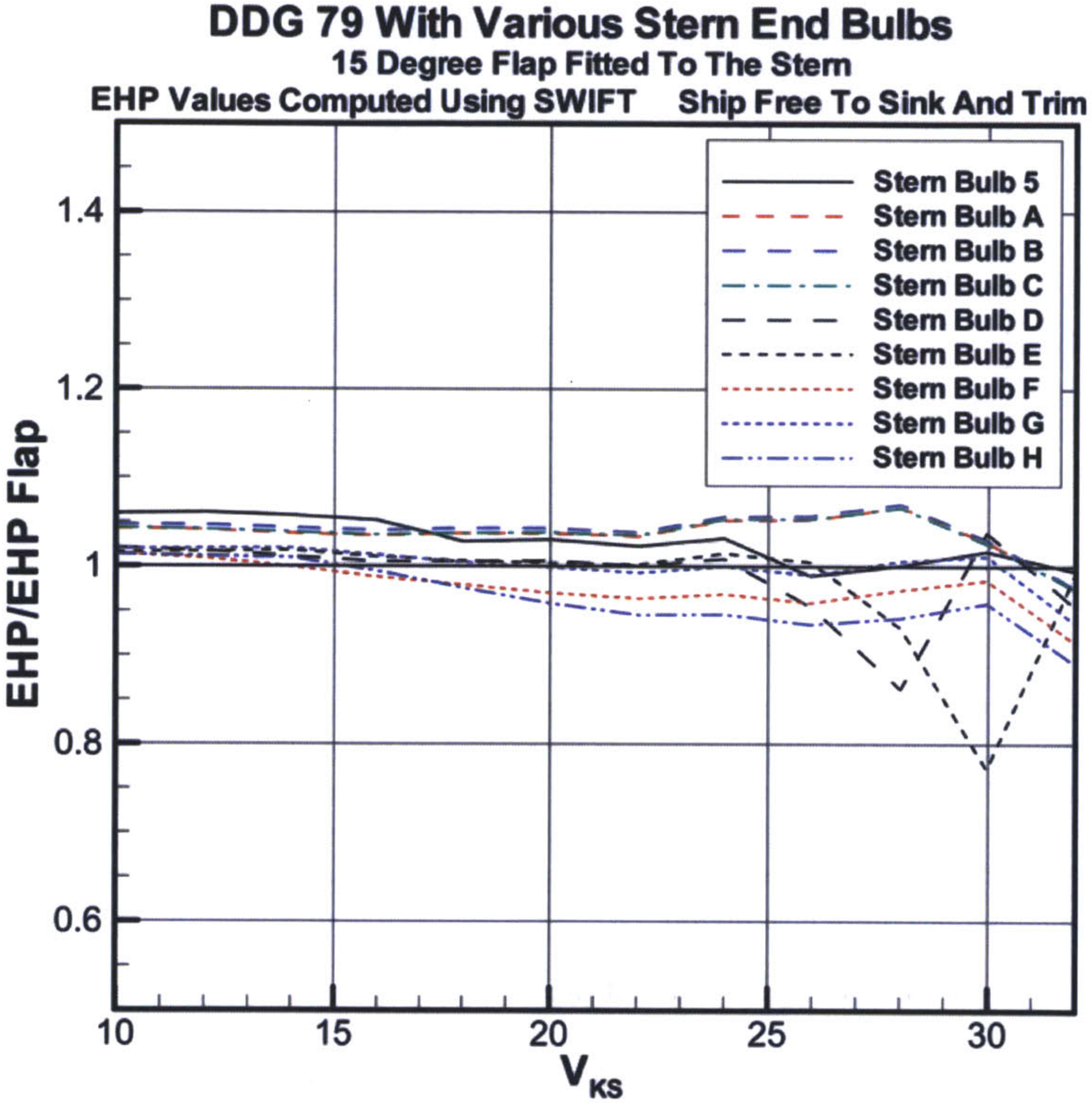


Figure 21: Effective Power Ratios for Stern Bulb Variants (Karafiath 2012)

Additionally, Karafiath made several comparisons between bare hulls, hulls with stern flaps, and hulls with stern flaps and a SEB. This data was used to determine the effectiveness of the stern flap and stern flap and bulb combination. Separating the components enables the effects of each to be analyzed as well as identify what happens when the components are combined. Figure 22 shows how hulls with and without stern flaps compare. In this chart the line marked 'B' indicates the bare hull and the line marked 'J' represents the reference hulls with a Flight IIA stern flap installed.

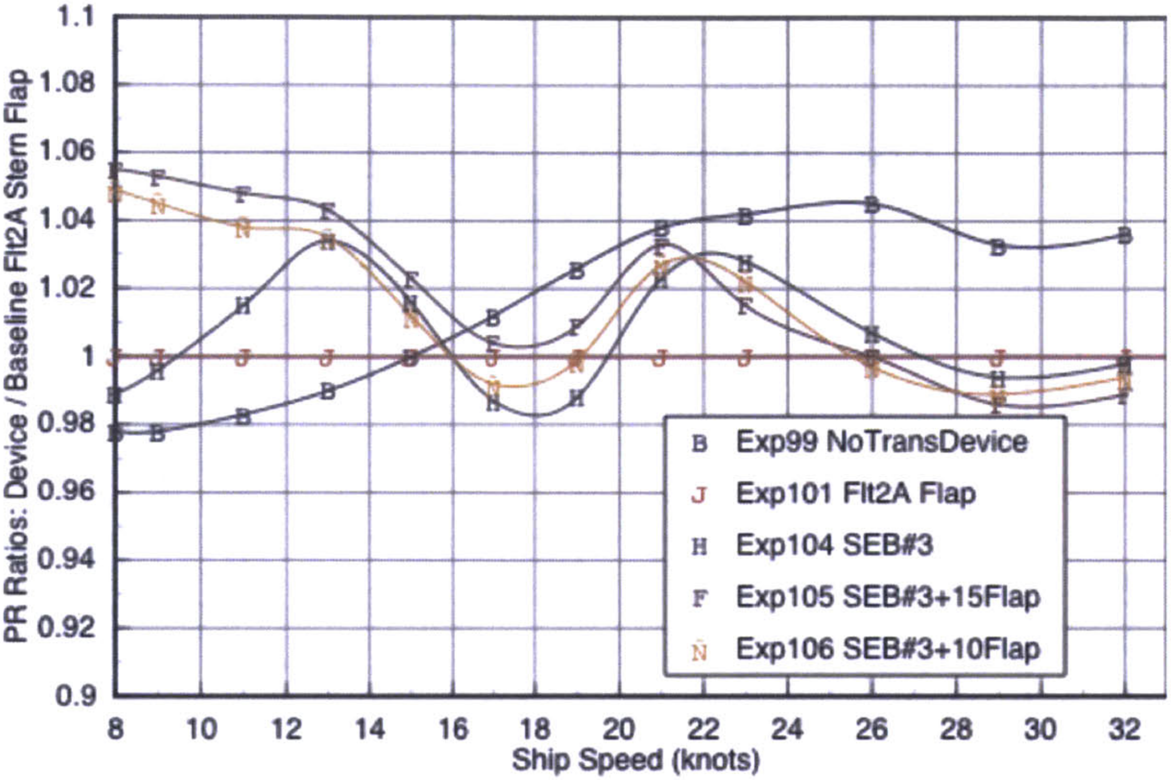


Figure 22: Power Ratios of Flight IIA Stern Flap Compared to No Transom Device (Karafiath 2012)

The results depicted in the previous two figures were used to estimate the change in power required at the different speeds for each component. The data used is not exact and is not meant to represent actual test results or actual fuel use estimates for the components. Rather, this provides a real world example and illustrates how the speed-time profile can have a large impact when evaluating technologies that claim to reduce fuel consumption.

8.2 Method of Calculating Fuel Usage

Analysis of the SEB and stern flap was conducted in a manner very similar to that of the composite profile validation in Chapter 6. This is also similar to the method used by Karafiath and Cusanelli in their evaluations of hydrodynamic energy saving enhancements for the DDG 51 (Cusanelli and Karafiath 2012). The speed-time profiles were used to find the amount of time spent at each speed for each of the engineering plant operating modes.

The fuel rate data used for the profile validation provided the rate in gallons per hour for a given speed and engineering plant operating mode. The shaft horsepower (SHP) for each speed and mode for a baseline DDG 51 was also provided. Using the data from Figure 21, the SHP required for each speed was increased or decreased by the amount shown for the line representing 'Stern Bulb H'. These changes were relatively minor with a 1.2% increase in the beginning and ending with a 6% decrease. This produced a new table of required SHP needed to achieve the same speed.

Since fuel rate must be adjusted to change the power output of the gas turbines the new fuel rates for each speed must be found. A linear interpolation was used to find the fuel rates using the baseline DDG 51 data as the reference. Because the data available in the chart does not include speeds less than 10 kts it was assumed that the change in power was inconsequential and therefore zero. This appears to be a conservative assumption that slightly favors the SEB based on the trend from the data that is available. Another justification to this assumption is that speed is controlled through pitch control at speeds of 8 kts and below while engine power remains roughly constant. The same method was used to determine the change in fuel rate for a hull without a stern flap installed using Figure 22 to find the changes in power.

The final step in determining the total fuel used was then to simply multiple the time spent at each speed by the associated fuel rate. In trying to provide a similar analysis to that by Karafiath, an average annual underway hours of 3,134 was used (Cusanelli and Karafiath 2012). This process produced estimated total annual fuel consumption for a DDG 51 with a bare transom, one with a stern flap installed, and one with a stern flap and stern end bulb.

8.3 Fuel Estimation Results

The results of the fuel estimation analysis for the three different configurations using both the 2003 speed-time profile and the new composite speed-time profile indicate that the older profile underestimates the savings that could be achieved. A summary of the results is contained in Table 10. Due to the sensitive nature of some of the details of the calculations, such as SHP and fuel rates, only summary data can be provided.

Table 10: Summary of SEB and Stern Flap Fuel Estimations Comparing 2003 and Composite Speed-Time Profiles (BBLs/year)

Configuration	2003 Profile	Composite Profile	Difference
Bare Transom	92509	74255	
Stern Flap	92127	73848	
Savings	382	407	-6.54%
Stern Flap	92127	73848	
SEB	91583	73256	
Savings	544	592	-8.82%

One of the most striking differences between the two profiles is the large difference in estimated annual fuel consumption no matter what the configuration. The reference data that was used by Karafiath and Cusanelli was 3,134 hours and 76,269 barrels consumed annually. The table entry for stern flap and composite profile, 73,848 barrels, most closely represents the fleet today and this reference point. This indicates that the profile and fuel rate data utilized are estimating consumption about 3.2% below the reference. This is just beyond the 3% goal set for the thesis, but still much better than the 20.8% error in the 2003 profile.

The estimated savings for the stern flap and SEB for both profiles can be looked at in three different ways: (1) the magnitude of change based on the profile, (2) the percent by which the 2003 profile underestimates the savings, and (3) the percent savings when compared to annual fuel consumption. The magnitude of change clearly indicates that by using the updated composite speed-time profile the estimated savings will increase. This effect is most likely due to the increased fidelity of the composite profile gained by providing the data in one-knot increments. For the 2003 profile much of the time is grouped and therefore attributed a higher fuel rate than it should have which negates some of the savings.

In order to quantify the effect of using the new profile the percent change in savings between the two profiles was used. For the stern flap, which is present on all ships, the 2003 profile would have underestimated the savings by 6.5%. For the SEB, which is still being researched, the older profile underestimates the savings by 8.8%.

Overall, the fractional savings when compared to the annual fuel consumption are small. The SEB savings using the 2003 profile represent about a 0.6% savings, while the composite profile savings are 0.8%. Although small, the savings provided by the SEB for both profiles are similar to or greater than the savings estimated for the stern flap addition. This provides some indication that if the savings for the stern flap were great enough to install them on all ships of the class it may also be the same for the SEB, dependent on the cost of the modification.

In summary, when using the 2003 and composite speed-time profiles to evaluate fuel saving technologies, the 2003 profile tends to underestimate the savings. The same fuel rates were used for all of the analysis in order to isolate any changes in consumption to the changes in the profile alone. As with earlier analyses, the composite profile much more closely reflects the current fleet with estimates within 3.2% of the baseline. This is in stark contrast to the 2003 profile that was over 20% greater for the same reference data. From this it can be concluded that the composite profile should be used for evaluating new hydrodynamic fuel saving technologies.

8.4 Effects of the Speed-Time Profile Range on Results

Now that it has been shown the composite speed-time profile performs better for analyzing the SEB and stern flap, the composite speed-time profile range developed in Chapter 7 will be evaluated. The range was developed by placing one standard deviation error bands on the composite speed-time profile. Likely speed-time profiles can then be created as long as they fall within the band. PCA was used to further understand the structure of the data to inform the choices when developing likely profiles.

To test the range of speed-time profiles the same SEB analysis that was performed in the previous section will be redone with three new test profiles. These profiles will represent an overall faster profile, an overall slower profile, and a profile considered more likely that was guided by the PCA results. The profiles are shown in Figure 23 with the one standard deviation band and in Figure 24 as CDFs.

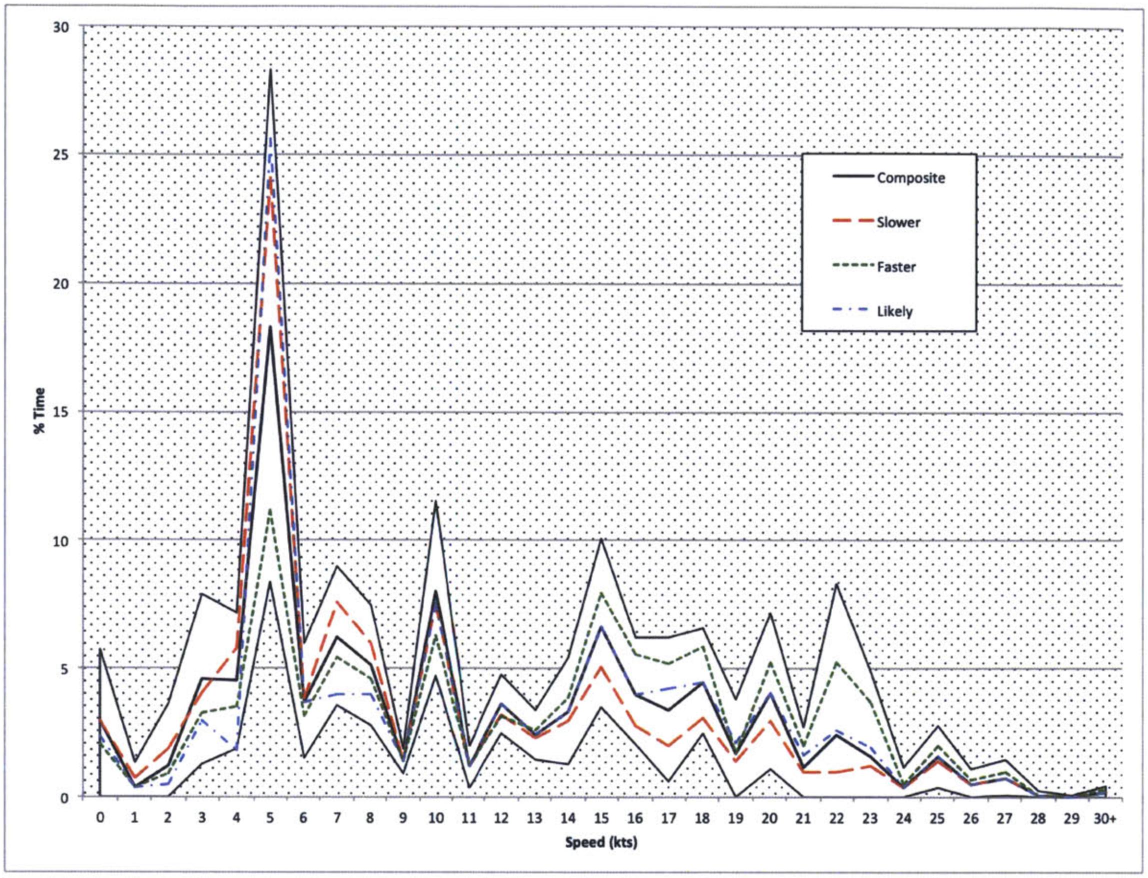


Figure 23: Test Profiles Developed from the One Standard Deviation Region

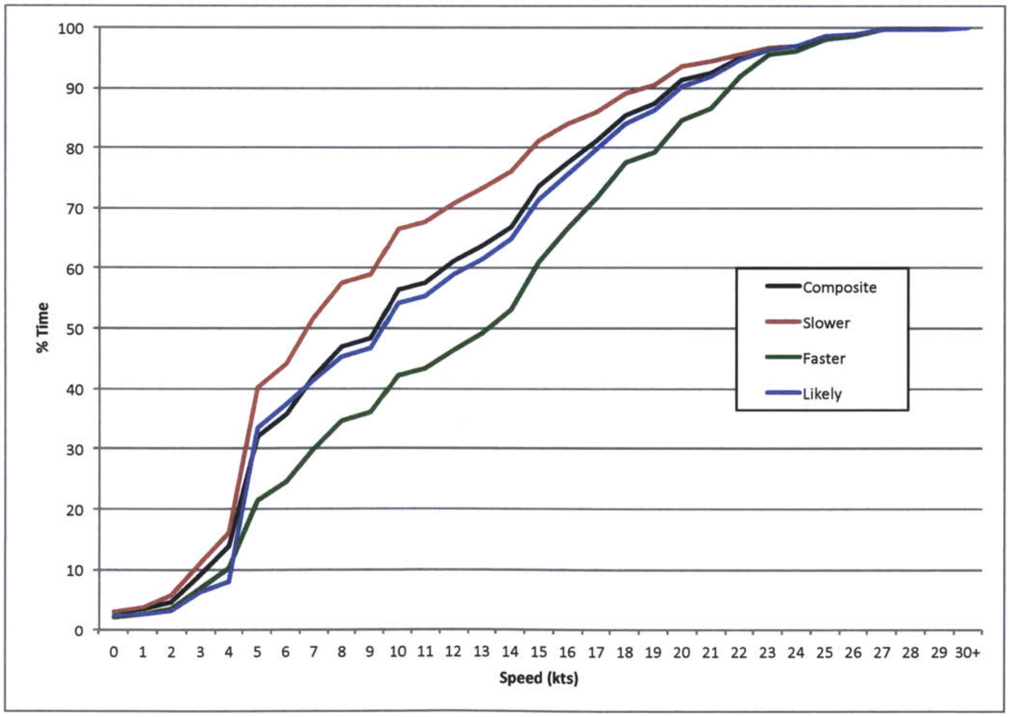


Figure 24: Test Profiles as Cumulative Distribution Functions

The slower and faster profiles were designed so that they would start to push the one standard deviation boundaries of the range. These two profiles will help to quantify the deviations from the composite profile that can be clearly seen in the CDFs in terms of fuel consumption. The profile labeled likely was developed using the simplified table of PCA coefficients that was shown in Table 6. Adjustments were made to the composite profile in order of the principal components and with a magnitude in line with the explained variation. Therefore, PC1 had a very large increase for 5 kts (from 18% to 23%) and a small decrease for 22 kts (2.4% to 1.8%). Similar adjustments were made for PC2 and PC3 while ensuring the total time summed to 100%.

Potential fuel savings, per ship per year, were calculated from the estimated annual fuel consumption for a ship with a stern flap only and one with a SEB with each of the profiles as an input. The results are shown in Table 11.

Table 11: Analysis of Per Ship Annual Fuel Consumption Estimates for SEB with Test Profiles

Profile	With SEB (BBLs)	Stern Flap Only (BBLs)	Fuel Savings (BBLs)
Slower	68,381	68,829	448
Composite	73,256	73,848	592
Likely	74,364	75,002	638
Faster	81,579	82,502	923

The results of this analysis begin to address the concerns of Surko and Osborne. The composite profile, which represents the mean data, provided the potential savings for a nominal DDG 51. The likely profile starts to work towards data that better represents ship operations because its development was guided by the results of the PCA. The slower and faster profiles also fall within the region where 68% of all ship profiles can be expected. Although the slower and faster profiles do not define the extreme bounds of the range of likely profiles, they do begin to bracket in the scope of possible savings.

9 Conclusions and Future work

The process described and utilized for ship operational profile development proved to be a viable and repeatable means to collect, analyze, and present data on DDG 51 class operations. Operations were defined in terms of a composite speed-time profile as well as engineering plant mode profiles and mission type profiles. Shortcomings that had been identified in earlier developed speed-time profiles were overcome and the benefits of these improvements were shown through examples of the profiles use. Profile validation was conducted as a means to test that the profile reflected current fleet operations, passing the test with only a 1.6% error.

Statistical analyses were performed to quantify, explain, and understand the variation in the underlying ship data. The results of these analyses were critical to understanding how actual ship operations may differ from the nominal composite speed-time profile that was developed. From this, a range of likely speed-time profiles was created along with some guidance for choosing likely profiles. Individual ship profiles were analyzed to help further understand how ships vary from the composite profile as well as to identify which profiles may be considered extreme. A range of speed-time profiles were used in the example to show how fuel savings for the SEB can vary widely even within the set of likely profiles.

The results of the operational profile development provided new insight into how the class operates. One of the most important pieces of information gained is that the ships tend to spend more time at lower speeds than previous profiles predicted. The new profile along with the first real engineering plant mode-time profile will prove vital to improving the accuracy of fuel use predictions.

There are also a few key conclusions that can be drawn from taking a holistic look at the process and results. The first is that whatever the design, component, or technology being evaluated, it needs to be able to improve performance over a range of speeds or conditions. Just as the speed-time profile was expanded from a point solution to a range of solutions, analysis should be expanded to account for that range.

The second is that it is important to recognize that sometimes even the newest and best available operational profile data may not best suit all applications. Profiles are created using data collected from past operations influenced by the world events, tactics, and equipment status of the time. Changes to these profile influences can cause dramatic shifts and render the past data obsolete. One example in which this could be a factor is the analysis of hybrid electric drive (HED) systems for the

DDG 51. Installation of such a system will cause a fundamental change to the way the ships are operated. Just as the current profiles are dominated by standard bell orders, adding a component such as HED will shift the profile towards its new, more efficient, operating points. The detailed analysis of the ship operations and how the current engineering plant is operated can help guide development of new profiles in the event of such engineering changes.

One area ripe for future work is to develop a method to collect, retain, and analyze the electronic log data from the ships to provide more rapid and frequent updates to the operational profiles. While the mission data requires user input and is not electronically logged at this point, all other data needed for profile development is captured electronically at this time. However, at this time the data is not retained and is used mostly for forensic analysis in the event of a machinery casualty.

Fuel use estimates require two main inputs - the amount of time spent at a given speed, and the fuel rate associated with that speed. This thesis described in detail how to determine the amount of time spent at a speed. However, fuel rate data was very limited and originated from a ship trial conducted in 2001. I feel there could be a great benefit to further investigating propulsion fuel rates. Similarly, electrical loading and the associated fuel requirements are not well defined and warrant further study.

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Appendix A: Analysis of Ship Profiles and the One Standard Deviation Band

The table below shows which data points for the individual ship profiles fall outside of the one standard deviation bands. Every ship is outside of the bands for at least one speed and every speed has at least one ship outside of the bands. The values on the periphery of the table indicate how many data points are outside of the bands for that particular row or column. Similarly, the percent within value shows the percent of data points within the bands. For one standard deviation 68% of the values should fall within the bands. Four ships clearly fall outside of this range, and three ships are at the limit.

Table A-1: Analysis of Individual Ship Profiles within the One Standard Deviation Bands

Speed	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	# Outside	% Within
0	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	1	0.94
1	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	1	0.94
2	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	1	0.94
3	YES	YES	YES	YES	NO	YES	YES	YES	NO	NO	YES	NO	YES	YES	YES	NO	5	0.69
4	NO	YES	NO	NO	YES	YES	YES	NO	NO	YES	YES	YES	NO	YES	NO	YES	7	0.56
5	NO	YES	NO	YES	NO	YES	YES	NO	YES	YES	NO	YES	NO	YES	NO	YES	7	0.56
6	YES	YES	NO	YES	NO	NO	YES	NO	NO	YES	NO	YES	NO	YES	YES	NO	8	0.50
7	YES	YES	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES	YES	YES	YES	YES	4	0.75
8	NO	YES	NO	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	NO	YES	5	0.69
9	YES	NO	NO	YES	NO	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO	YES	6	0.63
10	NO	NO	NO	YES	NO	YES	YES	YES	YES	NO	YES	YES	NO	YES	YES	YES	6	0.63
11	YES	YES	NO	YES	YES	YES	YES	NO	YES	YES	NO	YES	NO	YES	NO	NO	6	0.63
12	YES	NO	NO	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES	NO	9	0.44
13	YES	YES	NO	NO	YES	YES	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	6	0.63
14	NO	NO	NO	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	NO	NO	NO	7	0.56
15	YES	NO	NO	YES	YES	YES	YES	NO	NO	YES	NO	YES	YES	YES	YES	NO	6	0.63
16	NO	NO	NO	YES	YES	YES	YES	YES	NO	NO	YES	NO	NO	YES	YES	NO	8	0.50
17	YES	YES	NO	NO	NO	YES	YES	NO	YES	NO	YES	YES	NO	YES	YES	YES	6	0.63
18	NO	NO	NO	NO	NO	YES	YES	YES	YES	NO	NO	YES	NO	NO	NO	NO	11	0.31
19	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	1	0.94
20	YES	YES	NO	YES	YES	YES	YES	YES	YES	NO	NO	NO	NO	YES	YES	YES	5	0.69
21	YES	YES	YES	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	2	0.88
22	YES	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	2	0.88
23	YES	YES	NO	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	2	0.88
24	YES	YES	YES	YES	NO	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	2	0.88
25	YES	NO	NO	YES	NO	YES	YES	YES	NO	YES	NO	YES	NO	YES	YES	NO	7	0.56
26	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	YES	NO	YES	YES	YES	YES	2	0.88
27	NO	NO	NO	YES	NO	YES	YES	YES	YES	YES	NO	NO	NO	YES	YES	YES	7	0.56
28	YES	YES	YES	YES	YES	YES	NO	YES	NO	YES	YES	YES	YES	YES	YES	YES	2	0.88
29	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES	NO	YES	YES	2	0.88
30+	NO	NO	YES	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	3	0.81
# Outside	9	10	19	6	16	2	2	10	13	7	8	7	14	5	9	10		
% Within	0.71	0.68	0.39	0.81	0.48	0.94	0.94	0.68	0.58	0.77	0.74	0.77	0.55	0.84	0.71	0.68		