Trends in Operational Fuel Use

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Trends in Operational Fuel Use

CNA-initiated study

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In this CNA-initiated study, we examined fuel-use data over the past 25 years to determine whether there are indications of increasing efficiency since the Navy began its high-level focus on energy.

Summary of key findings

- We analyzed DDG-51 class fuel use data to determine whether at-sea fuel efficiency improved after 2008, when the Navy increased its focus on energy.
- Using NEURS fuel use data we found:
  - Fuel efficiency did indeed improve post-2008, compared to the 1991-2008 period.
  - Stern flaps on the DDGs are saving about 4,000 barrels (bbl) of fuel per ship per year – almost exactly what NAVSEA pre-installation engineering estimates predicted.
  - Multiple regression models using WedSked ship activity data provide a way to "correct" fuel usage at sea for the types of activity ships engage in, to better allow assessment of trends and comparisons across ships.

Here are our key findings.

Background and study questions

- Events of 2008
  - Spike in oil prices ($140/bbl); CNO concern about steaming days and flying hours
    - CNO afloat goal of 15% by 2020
    - Navy creates TFE, NECO
    - Secretary Mabus and his energy priorities
- Fundamental question posed to CNA by N45:
  - Is there any indication all our energy investments and initiatives are increasing operational energy efficiency?
    - And how can we even measure that?
- This study focused on DDG-51 class, underway only, diesel (does not include JP)

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A confluence of events caused the Navy to get very serious about energy efficiency starting around 2008. In 2008 we saw the huge spike in oil prices, to around $140 per bbl, that had the Chief of Naval Operations worried about whether the Navy could afford sufficient steaming days and flying hours to maintain readiness [1]. The influential Defense Science Board report, "More Fuel – Less Fight" [2], was published that year, and the newly arriving Secretary of the Navy, Ray Mabus, made energy efficiency one of his top priorities—a focus he maintained throughout his eight-year tenure.

As a result, the Secretary of the Navy created a Deputy Assistant Secretary for Energy, the CNO set the goal to reduce the Navy afloat fossil-fuel consumption by FY 2020 to 85 percent of that used in FY 2008 [1, 3], and the Navy created its Navy Energy Coordination Office within OPNAV and its Task Force Energy—programs that persist to this day.

The Director of the Energy and Environmental Readiness Division (N45) within OPNAV recently noted to CNA that, although everyone thinks the Navy is getting more efficient in terms of operations energy use, data-based evidence has not been developed, and he posed to us the questions noted on this slide. In this CNA-initiated effort, we addressed these questions. To keep this study to a manageable scope, we restricted our study to DDG-51 class underway fuel use only (we did not consider in-port steaming), and we did not consider aviation fuel use.

Data source: NEURS

- Navy Energy Useage Reporting System (NEURS)
  - 1984-2015
- DDG-51: Jun-1991 – Dec-2015
  - Fuel use, steaming hours by ship by month
    - Data entry = monthly for each ship
- Data checks to remove erroneous entries (~6%)
  - Total hours per month do not add up
  - Steaming but no fuel use; fuel use but no steaming
  - UW burn rate > 100 bbl/hour
 - UW burn rate < 7 bbl/hour

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For data on Navy fuel use, we used the Navy Energy Usage Reporting System (NEURS) database [4], which goes back to 1984. We extracted data for all the DDG-51s, which gave us a 25-year dataset from 1991 through 2015. NEURS provided monthly values for underway fuel use and hours steaming underway for all DDGs. Appendix-1 shows the size of our DDG dataset over this time period.

As a first step, we performed some basic error-checks on the NEURS data. We deleted entries for which the total of ship hours per month (sum of in-port hours and underway hours) did not add up to the number of hours in that month. For burn rate checks, we deleted entries with total monthly underway burn rates >100 bbl/hour (which would exceed the 30-kt full power rate), and with rates less than 7 bbl/hour (7 is the burn rate of the Allison501-K34 generator at 2000 kw – a basic hotel load) [5]. These data checks resulted in the exclusion of about 6 percent of the monthly entries and left a data set of 8,519 values.

Section 1: Trends in fuel use:

Is efficiency increasing?

First we looked for overall trends in fuel efficiency to address the question of whether the DDGs seem to be more fuel efficient post-2008.

Fuel use vs. days underway
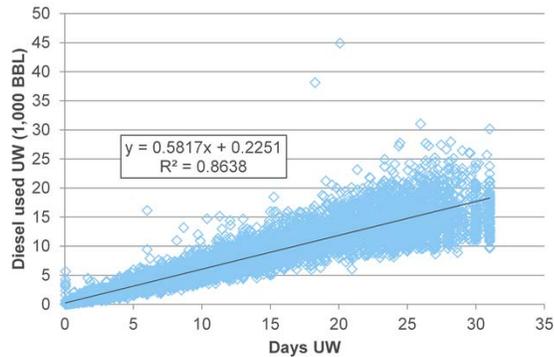
To look at fuel use, the obvious first question was: how much of the variability in fuel use is simply due to underway (UW) time?

Each point on the plot shown above is a single DDG for a single month. We computed the regression line using Excel. More than 86 percent of the variability in monthly fuel use is explained by the amount of time underway. The slope of the regression line suggests an underway fuel use of about 581 bbl per day on average, which is very consistent with DDG burn rate curves [6] (this equates to the burn rate for a DDG in split plant at about 14 kt).

Because fuel use is so highly correlated with UW time, any search for efficiency trends has to look at fuel use per day UW.

Is afloat efficiency increasing (underway burn rate)?

$y = -3.3594x + 7342.4$
$R^2 = 0.5059$
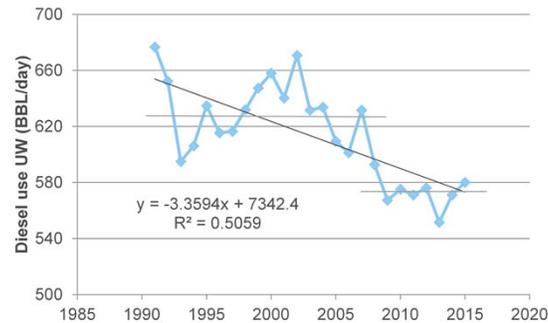
Pre- vs. Post NECO

	BBL/day
1991-08	626
2009-15	570

Across DDG Variant

|	BBL/day
FLT I	616
FLT II	590
FLT IIA	587

To look for time trends in efficiency, we started with the simplest view – bbl of diesel burned per day underway, on a yearly basis.

As the above graph shows, there is a downward trend in burn rate (a least-squares trend line for this entire data series shows a downward slope of greater than 3 bbl/day UW per year), and the period 2009-2015 is at a much lower level than the period pre-2009. The fuel burned per ship-day underway for the period 1991-2008 is 626 bbl, and for the period 2009-2015 it is 570bbl.

Pre vs. Post - 2008
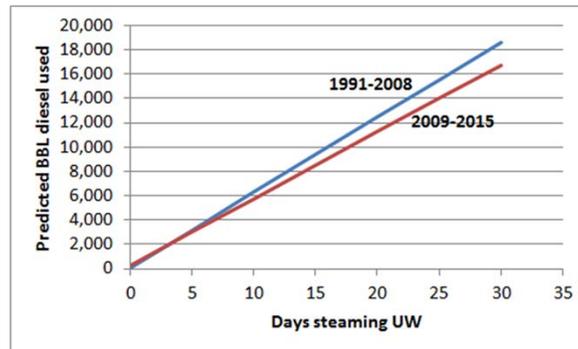
Chow Test: Significant structural break at 2008

To look further at this question (did efficiency really start improving after 2008?) we used a statistical method called a Chow Test [7]. The Chow Test is used to examine whether there is a change in the relationship between two variables over the course of a time series—where, in this case, we looked for a change in the slope of the line relating fuel use to days underway. Our model was a simple two-parameter model of the form: fuel use = A * days UW + C.

We performed the test to compare FY91-FY08 with FY09-FY15, and the test did indeed show a statistically significant decrease in bbl per day underway. By "statistically significant" we mean one can reject the null hypothesis that the slope of the line relating fuel use to days UW has not changed. Or, in more simple terms, we see a change in the overall fuel use per day UW when comparing pre- and post-2008, and that change is big enough that it is unlikely to be due to random variability (i.e., it is unlikely the pre- and post-2008 samples are random draws from the same population).

Potential volume of fuel saved
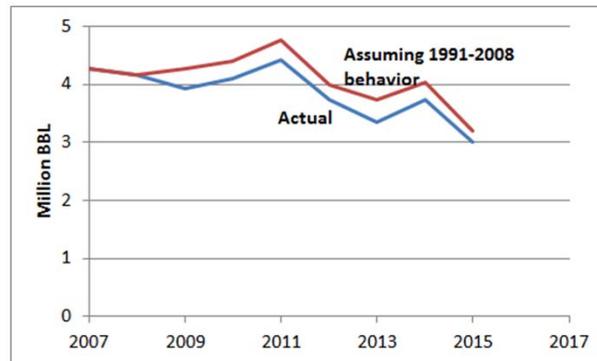
Total savings = 2.17 million BBL

How much fuel might this post-2008 efficiency improvement have saved?

We show the actual fuel used along with the amount that would have been used post-2008 if we continued to burn at the rate defined by the regression relationship from 1991-2008. Overall, we estimate a saving of about 2.17 million bbl over the period Jan 2009-Sept 2015.

So, it looks like fuel use per day underway did indeed decrease post 2008. The question now is: Are ships really getting more fuel efficient or are they doing different things at sea that are less fuel intensive? One would expect that fuel use depends on what a ship is doing, so if we want to know if DDGs are really more efficient post-2008 we have to correct for changes in their types of activities.

Multiple regression of fuel use on at-sea activity

	Coefficients	Lower 95%	Upper 95%
Intercept	397	294	500
OPS_Operations	490	483	497
OPS_Enroute and transit	653	642	664
TRAIN_Training	468	453	482
EXER_Major exercise	582	560	604
TRAIN_Training and inspections	410	377	443
TRAIN_Training exercises	573	538	607
TRAIN_Training support services	448	404	492
TRAIN_Marine training	456	405	506
INSP_Inspections	316	193	440
OPS_Barrier patrol/surv./blockade/SAR	513	465	561
All other	470	455	486

8519 observations; R=.88; All coefficients significant (P<<.05)

Multiple regression model:

Monthly bbls of fuel used = 397 + 490*(# days of "OPS") + 653*(#days of "Enroute/transit") + ...

....+...513*(#days of "Barrier") + 470*(# days doing anything else)

Interpretation: On average, one more day of transit results in 653 more bbl used per month, all else equal

The Navy's WebSked database provides a way to look at the effect of ship activity type on fuel use [8, 9]. WebSked gives, for all Navy ships, the type of activity the ship was engaged in at all times. A major activity and a secondary activity are given for each day.

Here we show the results of a multiple regression of bbl of fuel used UW per month, on the number of days that month for which the major activity was each of the 10 items listed on the slide. We used the top 10 major activity types, in terms of total number of DDG-days from 1991-2015. These 10 account for more than 97 percent of total DDG-days. We show the regression coefficient relating bbl used per month to the number of days in that month the major activity was as shown. We also give the upper and lower 95-percent confidence bounds on the regression coefficient[1].

Due primarily to the large number of observations, all coefficients are highly significant (non-zero). Three activity types stand out in terms of fuel use. Transiting ("Enroute and Transit") is by far the most fuel-intensive of the activity types followed by the two types of at-sea exercises (major exercises and training exercises).

The results on this slide show that fuel use does indeed depend on ship activity type, that some activities are much more fuel-intensive than others, and that multiple regression allows us to account for activity type in examining fuel use. The question now is: Are DDGs really more efficient post-2008 when we account for ship activity type?

1. The non-zero intercept likely represents fuel consumed during days on which the ship did not spend a sufficient amount of time at sea to be counted as a day underway in WebSked. More fundamentally however, the y-intercept is somewhat meaningless because the independent variables in our data are not all equal to zero for any observation, and they can't be because we are not looking at ships in port.
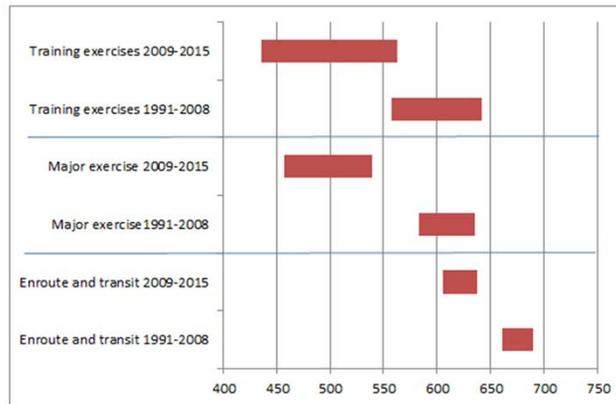
Here we look to see whether the burn rate during the three high-burn-rate activity types changed after 2008. We show the coefficients relating fuel used per month to number of days per month a DDG is doing each of these activities (we show the 95-percent confidence range for each coefficient).

In all three cases, the burn rate decreased, significantly.

Appendix-2 shows the 1991-2008 and 2009-2015 regression coefficients for the remaining activity types. In almost all cases, the coefficients were lower for 2009-2015 than for 1991-2008, indicating that fuel use per day underway shows a decrease even when correcting for ship activity type.

Section 2: Technology driver:
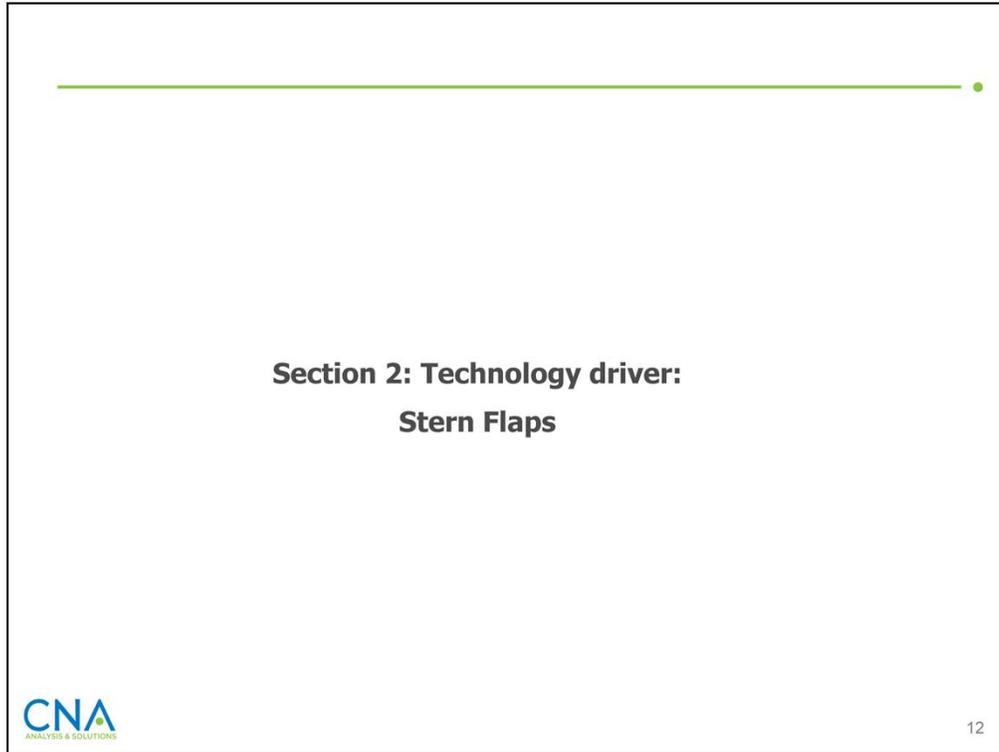
Stern Flaps

Stern flaps are one of the Navy's main fuel-savings initiatives for the DDGs. The pre-installation engineering studies estimated they would save about 4,000 bbl per ship per month [11]. We looked at whether a "stern flap signal" can be seen in our DDG fuel-use data.

Technology driver: Stern Flaps
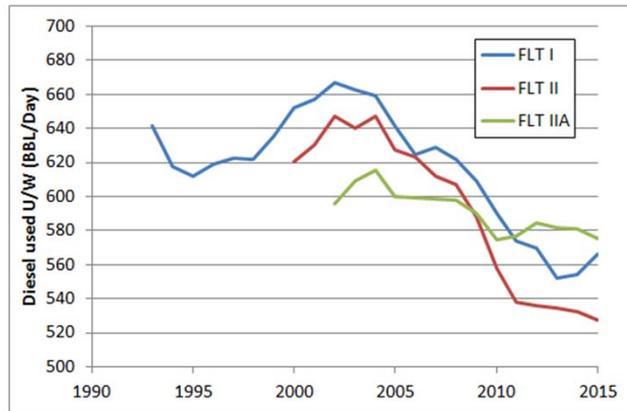
Note: FLT I/II: stern flap installation began in FY00; FLT IIA have stern flaps built in

All DDG FLT IIA ships were built with stern flaps included. For the FLT I and II ships, backfitting began in 2000 (installation dates are given in Appendix-3).

Here we show total class-wide fuel use per day underway broken out by DDG variant. The FLT IIA burn rates are lower in the early years of the IIA program, but, as more and more FLT I and II ships got stern flaps, the overall burn rates for these two DDG-variants came down significantly—starting a bit after 2000. This graphic is consistent with a significant effect from the flaps.

As we showed previously, fuel use is strongly dependent on the type of activities in which ships are engaged. Therefore, to examine the fuel savings from stern flaps, we need to correct for type of activity.

Effect of stern flaps: regression results

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	840.51	96.74	8.69	5.09E-18	650.85	1,030.17
Stern Flap	**-342.27**	90.75	-3.77	1.64E-04	-520.17	-164.36
Operations	480.12	5.17	92.89	0.00E+00	469.98	490.25
Enroute and transit	674.87	8.56	78.80	0.00E+00	658.08	691.66
Training	450.29	10.68	42.15	0.00E+00	429.35	471.24
Major exercise	553.19	15.31	36.14	4.25E-251	523.18	583.20
MISC_Other descriptions	465.46	10.28	45.29	0.00E+00	445.32	485.61
Training and inspections	394.16	27.34	14.42	4.32E-46	340.56	447.76
Training exercises	564.37	25.00	22.58	5.97E-107	515.36	613.38
Training support services	424.39	33.81	12.55	1.53E-35	358.11	490.68
Other items	236.56	43.23	5.47	4.70E-08	151.80	321.32
Marine training	440.00	31.76	13.85	9.17E-43	377.74	502.27
sum of all others	482.79	20.20	23.90	6.75E-119	443.19	522.39

Regression Statistics	
Multiple R	0.870731
R Square	0.758173
Adjusted R Square	0.757523
Standard Error	2678.443
Observations	4478

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We performed a multiple regression of monthly underway fuel use vs. number of days engaged in the various activities—now including an indicator variable for whether the ship had stern flaps. We included only those ships shown on slide Appendix-3 to prevent any possible confounding effects from inclusion of FLT IIA ships, which differ slightly from Flights I and II.

Note the regression coefficient for stern flaps shown on this slide: -342, indicating stern flaps save ships 342 bbl of fuel per month. This is very consistent with pre-installation engineering estimates of expected fuel savings from stern flaps [11]—but it is a much more robust estimate, being based on 16 ships over multiple years and, most importantly, accounting for variation in ship's activities.

Section 3: Measuring efficiency

We look now at how to measure efficiency across ships.

Regression-based benchmark

Intercept	765.293
FLT IIA (yes/no)	-185.335
Stern Flap (yes/no)	-352.267*
OPS_Operations	492.828
OPS_Enroute and transit	659.856
TRAIN_Training	467.614
EXER_Major exercise	576.549
MISC_Other descriptions	482.957
TRAIN_Training and inspections	405.282
TRAIN_Training exercises	564.885
TRAIN_Training support services	451.634
MISC_Other items	288.218
TRAIN_Marine training	457.616
Sum of all other categories of operation	463.27

* Regression now includes DDG FLT IIA

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To examine differences in efficiency across ships, we modeled monthly fuel use as before, now including a variable for whether it was a FLT I/II, or a FTL IIA.

We show our regression results on this slide. The regression coefficients have changed slightly from those shown previously because we now include FLT-IIA ships along with a FLT IIA indicator variable.

Benchmarking ship fuel use performance
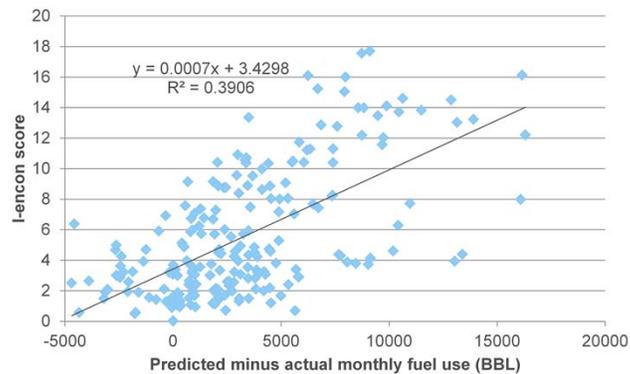
i-ENCON score has correct behavior with respect to observed fuel efficiency
- But misses many over-achievers

We used our regression equation shown on the previous slide to calculate the predicted minus observed quarterly fuel use for each DDG, where a positive value indicates a ship is using less than would be expected from the regression equation. We compared this measure of fuel savings performance with the i-ENCON (Incentivized Energy Conservation – a SecNav awards program to encourage ship energy awareness) score published on the Navy's i-ENCON website and used to determine the quarterly SecNav energy award-winning ships [12].

Linear correlation between these two parameters is apparent; a t-test indicates that the correlation shown is highly significant (at the .001 level) [13]. Other measures suggest the correlation is even greater. The Pearson correlation coefficient and the Spearman-ρ statistic are large, roughly 0.6, and statistically significant. (Spearman's-ρ is the correlation coefficient of the ranks of the two variables. Because the i-ENCON score may be an ordinal measure but not a cardinal measure, Spearman's-ρ may be more appropriate than the correlation coefficient.)

This result indicates a benchmark, like the one we developed here, that accounts for the types of activities the ships are engaged in, provides an objective measure of fuel savings performance, and is worth considering as a factor in energy awards and energy program management.

Section 4: Summary & Conclusions

We now summarize

Summary of findings

- Variability in afloat fuel use is largely explained by number of steaming days
  - Efficiency must be based on fuel use per day UW
- To assess trends in fuel efficiency, or to compare across ships, the type of ship activity must be accounted for
  - WebSked provides a tool to do this
  - A multiple-regression-based approach seems most appropriate
    - Consistent with i-ENCON scores
    - Provides quantitative bases for cross-ship comparison / SecNav awards
- DDG afloat float fuel efficiency is increasing post-2008
  - Possible overall class-wide savings of >2 million BBL
- Stern flaps are indeed providing promised savings

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Because underway fuel use is strongly dependent upon the number of underway steaming days, any examination of efficiencies must be based on fuel use per day underway.

To assess changes in fuel efficiency or compare across ships, the types of vessel activities must be accounted for because some ship activities are much more fuel intensive than are others. The Navy's WebSked database provides ship activity data that allows this type of analysis, and a multiple regression approach is a good way to model fuel use and "correct for" the type of activity the ships engage in. Taking this approach, we developed models of fuel use that are qualitatively consistent with the i-Encon scores used in determining SecNav award winners, but are much more data-driven and analytically based.

Fuel use data for the DDG class indicates that ships are more energy efficient post-2008, which is roughly the year the Navy began many of its operational energy programs. The Navy's primary energy-saving initiative for the DDGs, installation of stern flaps, looks to be saving fuel exactly as predicted by pre-installation engineering estimates—reducing DDG fuel use by about 5 percent.

Way ahead

- Scoping study yielded very interesting findings
- Stern flaps analysis is a successful proof-of-concept
  - Our estimate is highly significant and practically meaningful: 4,000 bbl per ship per year
    - Validates the estimate the Navy used prior to retrofitting
      - And is a much more robust estimate: 16 years of data and accounts for variation in ship activities
  - Examine other ship energy-improving initiatives or retro-fits; refurbished LM-2500s?
- Way ahead could include:
  - Search for other efficiency breakpoints and corresponding ship Mods
  - Additional ship classes
    - Efficiency trends; results of efficiency initiatives; quantitative basis for SecNav awards
  - Aviation

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This small, scoping-level study yielded encouraging findings regarding trends in operational fuel efficiency, as well as in data availability and mathematical methods to assess efficiencies across time and across ships.

Our stern flap analysis was a successful proof-of-concept for evaluating the performance of specific energy-savings initiatives, and showed that stern flaps are delivering just as promised in terms of fuel savings—roughly 4,000 bbl per year per ship. This finding is based on 16 years of data across multiple ships. We think it would be interesting to apply regression-based methods like this to other energy initiatives, including refurbishment of DDG's LM-2500 engines.

Further study could search for other efficiency breakpoints (we considered 2008) to determine whether they correspond to major programs or ship mods. Additional ship classes should be examined for efficiency trends and results of specific fuel-savings initiatives, and formulation of regression-based models like the one developed here for comparisons across ships as a quantitative metric for SecNav energy awards.

An additional study could look similarly at Naval aviation.

Appendix Slides

Appendix-1: DDG data-set by year
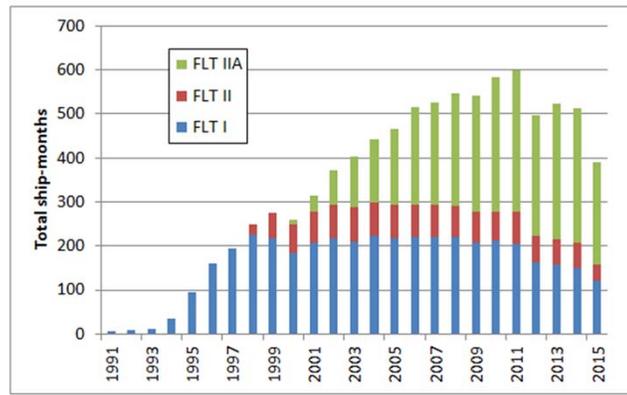
This slide summarizes the size of our data set. It gives the total ship-months of data per year, broken out by DDG Flight. Hulls 51-71 are FLT-I; hulls 72-78 are FLT II; hulls 79 and higher are FLT IIA.

Appendix 2: Change in fuel use, by ship activity type

	1991-2008			2009-2015		
	coefficient	Lower 95%	Upper 95%	coefficient	Lower 95%	Upper 95%
Intercept	369	232	505	409	250	568
OPS_Operations	506	495	517	482	473	491
OPS_Enroute and transit	675	661	689	621	605	637
TRAIN_Training	470	450	489	468	447	490
EXER_Major exercise	609	583	635	499	458	540
TRAIN_Training and inspections	413	375	452	398	335	461
TRAIN_Training exercises	600	558	641	499	436	563
TRAIN_Training support services	462	390	534	442	387	497
TRAIN_Marine training	444	389	498	527	401	652
INSP_Inspections	171	-27	368	411	254	568
OPS_Barrier patrol sureveillance blockade and SAR	528	476	580	409	288	529
All other	471	455	488	448	389	508

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This table is an annex to slide 11, showing pre- vs. post-2008 regression coefficients for all activity types (slide 11 showed only the leading three). Coefficients are lower post-2008 for nine of the eleven activity categories shown.

Appendix 3: Stern flap backfit on FLTs I and II

Ship	Date of installation
DDG 51	10/3/2000
DDG 52	9/21/2001
DDG 54	12/2/1999
DDG 56	7/8/2000
DDG 57	4/15/2003
DDG 58	5/6/2002
DDG 59	1/5/2000
DDG 60	4/21/2000
DDG 61	6/5/2000
DDG 63	5/3/2001
DDG 64	11/16/2000
DDG 65	7/13/2001
DDG 66	12/5/2003
DDG 67	12/4/2000
DDG 68	11/16/2000
DDG 69	9/27/2001
DDG 70	3/4/2002
DDG 71	7/9/2001
DDG 72	9/21/2001
DDG 73	11/6/2001
DDG 74	10/22/2001
DDG 75	9/16/2002
DDG 77	7/23/2001
DDG 78	12/19/2001

We obtained stern flap installation dates for the FLT 1 and II ships from the Navy's 3M (OARS) database. Installation dates are shown on this slide.

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