EEDI Absurdities

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Abstract

This paper, based on work by Krüger, shows that, for tankers, bulk carriers, and LNG carriers, EEDI leads to the absurd result that the design speed of a large ship should be less than the design speed of a smaller ship of the same type. For example, for tankers the design speed of a 300,000 dwt VLCC should be about 1.5 knots lower than the design speed of a 100,000 ton Aframax. Based on work by Psaraftis, the paper shows that the "fix" to EEDI, suggested by Greece, leads to even more absurd results.

These absurdities highlight the fact that there has been no real analysis of the implications of EEDI. In direct contravention of IMO rules, the MEPC is about to enact draconian regulation with no study of what EEDI means for cost, safety, reliability, maneuverability, and heavy weather performance. All we know about EEDI is that it violates one of the most basics principles of naval architecture.

1 Froude Number

One of the most basic principles of ship design is the concept that a longer ship will create less wave-making resistance than a shorter ship at the same speed. This concept was first quantified by William Froude in the 1860's. Froude showed that wave-making resistance goes as $V/\sqrt{L}$ where V is speed and L is the ship's length. This ratio became known as the Froude Number.[1] Froude number says, if we double the ship's length, we can increase the speed by about 40% and still have the same wave-making situation. It is also true that resistance goes as wetted surface, and everything else being equal, doubling the carrying capacity of the ship increases wetted surface only about 60%. For both these reasons, ***the economic speed of a large ship is higher than that for a small ship of the same type.*** Archimedes' principle aside, this is perhaps the most fundamental tenet of naval architecture.

2 Enter EEDI

IMO is very close to imposing something called Energy Efficiency Design Index (EEDI) on ship designers. To simplify considerably, EEDI is the ratio of the ship's CO2 emissions divided by the product of the ship's deadweight and speed as measured in trial conditions at 75% of installed power.

$$EEDI = \frac{P \cdot sfc \cdot C_f}{dwt \cdot v} \tag{1}$$

where P is installed power measured at 75% the engine's Maximum Continuous Rating (MCR), sfc is the engine specific fuel consumption at this power in grams per kilowatt-hour, C_f is the grams of CO2 emitted per gram of fuel consumed, about 3.1 for most marine fuels. dwt is the ship's deadweight, and v is the ship's calm water speed at power P.

The regulation will require that a ship's EEDI be a certain percentage below a baseline value, which percentage will increase over time. The baseline value is determine by a power law regression of the EEDI's of the fleet of existing ships of each ship type in which the regressed variable is dwt. Such a regression takes the form of $a \cdot dwt^{-b}$.

So for each ship type the rule will be of the form

$$\frac{P \cdot sfc \cdot C_f}{dwt \cdot v} \leq a \cdot dwt^{-b} \tag{2}$$

[1] The modern form is $V/\sqrt{g \cdot L}$ where g is the acceleration due to gravity. For our purposes, we can use the old form.

Professor Stefan Krüger of the Technische Universität Hamburg-Harburg has produced the following argument.[2] Power and speed are related. For a given ship type, this relationship can be roughly approximated by

$$P = c_p \cdot dwt^{2/3} v^{3+k} \tag{3}$$

where c_p and k are ship-type dependent.[3] k is usually between 0 and 1.

If following Professor Krüger, we substitute this relationship into (2) and solve for v, we end up with

$$v^{2+k} = \frac{a \cdot dwt^{1-b-2/3}}{sfc \cdot C_f \cdot c_p} \tag{4}$$

The interesting term is $dwt^{1-b-2/3}$. Everything else is roughly constant for a given ship type. What Equation 4 says is, if the b resulting from the baseline regression is less than 1/3, then the allowable speed under EEDI increases with increasing ship size. ***But if b is greater than one-third, then the allowable speed decreases with increasing ship size.***

Table 1 shows the results of a number of baseline regressions taken from the literature.

SHIP TYPE	b	Source
Ro-RO	0.714	Deltamarin/EMSA
Car Carriers	0.588	EE-WG 1/2/4
Tankers	0.534	Deltamarin/EMSA
Tankers	0.534	GHG WG 2/2/7
Bulk Carrier	0.512	Deltamarin/EMSA
Bulk Carrier	0.489	EE-WG 1/2/
Tankers	0.487	EE-WG 1/2/
Tankers	0.468	MEPC 60/4/15
Bulk Carrier	0.462	MEPC 60/4/15
LNG	0.460	GHG WG 2/2/7
General Cargo	0.330	Deltamarin/EMSA
Container	0.217	MEPC 60/4/14
Container	0.151	MEPC 60/4/15

Table 1: Sample of baseline regression b's

There is some scatter; but all ship types other than general cargo and containerships have b's well above 0.333. Only containerships have a b well below 0.333.[4]

For the great bulk of the fleet afloat, EEDI will impose a lower speed on larger ships, violating one of the most fundamental principles of ship design. William Froude must be spinning in his grave.

3 EEDI Tanker Speeds

Table 2 shows what happens when you apply Equation 4 to tankers over the range 100,000 dwt tons to 300,000 dwt tons. Over this range, the assumption that displacement is linear in deadweight is quite close. A 102,000 ton Aframax tanker will have a lightweight of about 15,100 tons (displacement/dwt = 1.148). A 305,000 dwt VLCC will have a lightweight of about 43,000 tons (displacement/dwt = 1.141). For tankers the current baseline a is 1950.7 and b is 0.5337. The table shows the resulting allowable speed and power. The power shown is calm water at design (not full load) draft.[5]

According to EEDI, a 100,000 ton Aframax tanker should have a design speed about 1.5 knots higher than a 300,000 ton VLCC. This is absurd.[6]

[2] Krüger, S., Mathematical Evaluation of the Applicability of the EEDI Concept for RoRo Vessel, Hamburg Harburg Institute of Ship Design and Ship safety, March, 2011.

[3] Equation 3 is a modified form of the Admiralty Equation in which displacement is assumed to be linear in deadweight, which is approximately true for most ship types as long as you don't go too small.

[4] The actual value of the b's has no physical meaning. Very small ships have much larger EEDI's than very large ships which force high b on the arbitrarily chosen regression form. It just so happens there are few small containerships.

[5] Appendix A shows the Perl script which was used to create this Table 2. The key input numbers are shown at the top of the script.

[6] An Aframax will have a waterline length of about 230 m; a VLCC about 320 m. Based on Froude number alone, the VLCC should be 19% faster. But for big tankers much of the resistance is frictional. In actual practice, a standard VLCC has a design calm water speed of about 16 knots; a standard Aframax about 14.5 knots.

Dead-weight	Baseline		Phase 1 EEDI down 10%		Phase 2 EEDI down 25%		Phase 3 EEDI down 35%	
	kts	kW	kts	kW	kts	kW	kts	kW
100000	16.73	12444	15.87	10624	14.49	8082	13.49	6521
150000	16.07	14432	15.24	12322	13.91	9374	12.95	7563
200000	15.61	16033	14.81	13689	13.52	10414	12.58	8402
250000	15.26	17396	14.48	14853	13.22	11299	12.31	9116
300000	14.99	18595	14.22	15876	12.98	12078	12.08	9744

Table 2: Tanker allowable speed and power as a function of deadweight

4 The Greek Fix

In an attempt to remedy this absurdity, Greece has suggested a modified baseline regression.[7] Instead of regressing against deadweight, regress against dwt adjusted by v^{2+k} where k is ship type dependent. If you apply the Section 2 reasoning to this form, Psaraftis has shown that Equation 4 becomes[8]

$$a \cdot dwt^{1/3-b} = sfc \cdot C_f \cdot c_p \tag{5}$$

Ship speed has disappeared from the EEDI constraint. Thus, the designer cannot manipulate speed to meet his EEDI.[9]

When this form of regression is used, b comes out well above one-third, at least for all the ship types that have been tested so far. This means that Equation 5 is strongly biased against big ships. In fact, if the ship is small enough, Equation 5 doesn't care how much CO2 the ship emits. And for any given ship type and technology, Equation 5 imposes a totally artificial upper bound on deadweight. ***Equation 5 will impose no limit on smaller ships and prevent owners from building really big ships.***

Yet increasing ship size is one of the best things a designer can do for CO2 emissions. If he can replace two ships with a single ship with twice the capacity, he obtains

1. A lower Froude number and less wave-making resistance.
2. A 40% saving in wetted surface and frictional resistance
3. A bigger, slower turning engine with a better SFC and a more efficient propeller.
4. A single larger engine room to which he can economically apply more energy saving devices.

Table 3 shows what happens when you apply Equation 5 to tankers using the latest regression results ($a = 19.164$, $b = 0.599$), and assume no improvement in technology.

	Maximum deadweight
Baseline, no reduction in EEDI	733,877
Phase 1, 10% reduction in EEDI	527,505
Phase 2, 25% reduction in EEDI	265,700
Phase 3, 35% reduction in EEDI	155,208

Table 3: Maximum tanker deadweight, Greek fix, no improvement in technology

Under these assumptions, the Greek fix would outlaw VLCC's while at the same time requiring no improvement at all for tankers under 150,000 tons, regardless of what technology is available. The only impact of the Greek fix will be to get rid of all tankers above about 150,000 tons, which are precisely the ships that transport oil most efficiently in terms of both dollars and CO2.

All the Greek fix does is trade one absurdity for another.

5 EEDI is unsafe, ineffective and wasteful

In the past, CTX and others have argued that:

EEDI is unsafe EEDI will result in a drastic reduction in installed power. CTX estimates that Phase 3 EEDI will require VLCC's with half the installed power of current ships.[10] This will result in badly

[7] IMO document EE-WG 1/2/7.

[8] Psaraftis, H., A Fix for the EEDI Formulation, NTUA LMT Memo, March, 2011.

[9] This is not necessarily a good thing. Efficient regulation, such as a CO2 tax, recognizes that higher speeds means more CO2, and promotes lower speeds.

[10] The Impact of EEDI on VLCC Design and CO2 Emission Also see Table 1.

degraded maneuverability and heavy weather performance. It will mean 30% more ships on the water. It implies these smaller engines will be pushed much harder. ***Yet despite this there has been no study of the implications of this dramatic reduction in installed power for reliability and safety.*** This directly contravenes IMO's own rules which require a Formal Safety Assessment of any regulation which could affect safety or pollution.

EEDI is ineffective At least in the sectors where slow-steaming is practiced, EEDI will result in little or no reduction in CO2 emissions over no regulation at all.

1. EEDI effectively limits installed power. But at current and expected BFO prices, a ship owner in these sectors uses all his installed power only in a full boom. So for the great bulk of her life, a non-EEDI ship uses little or no more power than an EEDI-compliant ship.
2. In limiting installed power, EEDI induces owners to use smaller bore, higher RPM engines. These engines have higher Specific Fuel Consumption and more importantly require a smaller, less efficient propeller. This means the EEDI-compliant VLCC consumes more fuel when the market is not in boom, which is 90% of the time.[11]

Unlike a tax, EEDI does not encourage slow-steaming. EEDI only puts a limit on how fast the ships can go in a boom, which is precisely the time we want them to go fast if we are to avoid wastefully building ships just to handle a boom.

EEDI is inefficient EEDI has all kinds of strange quirks and biases including

1. A geared bulk carrier has a higher EEDI than an ungeared ship despite the fact that the geared system may produced less CO2 overall.
2. A fragile, low lightweight ship has a lower EEDI despite the fact that a robust, longer lived ship will produce less CO2 overall.[12]
3. A post-panamax container ship has a higher EEDI than a panamax containership even though the bigger ship produces less CO2 per TEU delivered.[13]
4. A 15 knot large tanker has to reduce power by half. A 26 knot containership hardly at all.[14] The idea behind the baseline concept is: reward the big polluters.

But on top of this we now have the mother of all inefficiencies. Professor Krüger's argument shows that EEDI is nonsensical.[15] Any regulation that imposes a lower speed on a larger ship than a smaller ship of the same type has totally lost touch with reality. The Greek fix is even worse.

6 We must have an EEDI Formal Safety Assessment

These crippling problems are all reflections of the fact that there is no theoretical basis for EEDI. EEDI is just a bunch of formulas hurriedly thrown together in an attempt to look green. In the process, cost, safety, reliability, maneuverability, heavy weather performance, and the basic principles of ship design have been ignored. ***If the proponents of EEDI dispute this, then it is incumbent on them to do a full, objective cost/benefit study of this draconian piece of regulation.*** This study must analyze all aspects of EEDI including

Economics How much will it cost? Or to put it more precisely, how much of the world's scarce resources will be required to implement this regulation? We are talking about fleets which will need to be at least one-third larger than the current fleet. To do this analysis, the study must design ships meeting the requirement for each major sector and ship size, and then compare the cost of the resulting fleet with that of the fleet which would exist without the regulation. The economic analysis must incorporate inventory carrying costs.

Seakeeping, maneuverability The drastic reduction in installed power will be accompanied by an increase in RPM and a decrease in propeller size. The EEDI-compliant designs must be put through a complete seakeeping and maneuverability analysis both to confirm that they can maintain course in heavy weather and more importantly to determine the speed made good as a function of weather. We must have

[11] ibid

[12] Gratsos et al, Life Cycle CO2 Emissions of Bulk Carriers, Int. Journal of Maritime Engineering, Vol 152, July-Sep, 2010.

[13] IMarEST, Influence of Design Parameters on EEDI for Tankers, Containerships, and LNG Carriers, MEPC 60/4/34, 2010-01-15.

[14] Akiyama and Taggi, Evaluation of EEDI Index, Tripartite Workshop on GHG Emissions, Beijing, 2010-06-03

[15] ***Professor Krüger points out that for RORO ships not only allowable speed but allowable power decreases with size.*** A 5000 ton RORO vessel is allowed 17,000kW. A 25,000 ton RORO vessel is allowed 6000 kW. At this point we are deep in Wonderland and the Queen of Hearts is in charge.

complete polar diagrams for these vessels. The speed/fuel curves both for economics and emissions analysis must be based on realistic weather conditions by trade, and not on calm water. We cannot just throw in a standard sea margin.

Structural Analysis The seakeeping results need to be fed into a structural analysis. Some loads, such as slamming, will get better, but the yards will automatically reduce steel accordingly. Fatigue could go either way. But we must know.

Safety A complete safety analysis of the EEDI compliant vessels must be undertaken. This analysis must recognize not only that we will have more exposure and higher vessel density; but also that, if a ship does get into a tight spot, such as a lee shore in heavy weather, it will have less capability of recovering.

The safety analysis must also recognize that the engines will be pushed very hard, — there will be be much less slow-steaming in the sense that the engines will be at part-load — and attempt to determine the impact of this on mean time between machinery failures.

Emissions Currently, the market badly under-prices emissions. In fact, it prices air pollution at zero because the atmosphere cannot be privatized. All we need to do to correct this is a carbon/SO2/NOx tax set at our best guess at the societal cost of these emissions. But if we fail to do this, we must compare the emissions of the EEDI compliant fleet with that of a fleet without this regulation. ***But this comparison must be comprehensive***

It must include not just CO2, but SO2, NOx, hydrocarbon vapors, and oil spillage. We must not look at each form of pollution separately in typical IMO style. All sorts of interactions exist. For obvious example, fitting scrubbers will become less economic as power goes down and number of ships increase.

The at-sea CO2 (and other) emissions must be based on realistic weather by trade. We must also incorporate the additional build/repair/scrap emissions, going deeper than Gratsos et al. We must also estimate the additional cargo loss emissions from tankers. We must also estimate the additional support emissions such as flying 30% more crews around, 30% more storing trips, etc, etc.

And most importantly, the study must recognize that a fully powered fleet will be at MCR only when the market is in boom in all the competitive sectors such as tankers, bulk carriers, and at least big containerships. For each sector, the study must be done over a complete market cycle.

Unless a comprehensive Formal Safety and Cost-Benefit analysis of EEDI is done, IMO will be in direct contravention of its own rules. Much more importantly, the members of the MEPC will be in grievous dereliction of their responsibility to the citizens of this planet.

Appendix A: Perl Script for producing Table 2

```
#!/usr/bin/perl -w
$c_f = 3.1144;     # grams CO2/gram fuel
$sfc = 180.0;      # 165 x 1.07 = 176
$k = 0;            # assume power is  cubic
$a = 1950.7;       # deltamarine baseline
$b = 0.5337;

$label{1.00} ="baseline, no reduction in EEDI";
$label{0.90} ="Phase 1, 10% reduction in EEDI";
$label{0.75} ="Phase 2, 25% reduction in EEDI";
$label{0.65} ="Phase 3, 35% reduction in EEDI";

$disp = 322168.0;  # MIn VLCC on design draft
$dwt  = 280000.0;  #Min, Choi, Study of the CFD Applciation for VLCC Hull-Form design
                   #24th Symposium on Naval Hydrodynamics, 2003
                   # http://www.nap.edu/catalog.php@record_id=10834#toc
$ehp = 13000;      # 15 kts, design draft, bare hull
$pe  = 0.73;       # propulsive efficiency

$disp_factor = ($dwt / $disp)**(2/3);

print "a=$a b=$b\n";
print "power is calm water at design draft, no sea margin\n";

$c_p = ($ehp / $pe) / ($disp ** (2/3) * 15**3);

print "c_p= $c_p\n";

for $phase (1.0, 0.90, 0.75, 0.65) {
    print "$label{$phase}\n";

    for $dwt (100.0e3, 150.0e3, 200.0e3, 250.0e3, 300.0e3) {
        $v_sq = $phase * $a * $dwt**(1 - $b - 0.667) * $disp_factor / ($sfc * $c_f * $c_p);
        $v{$phase}{$dwt} = $v_sq**0.5;
        $power{$phase}{$dwt} = $c_p * $dwt**(2/3) * $v{$phase}{$dwt}**3 / $disp_factor;
        printf("dwt=%6.0f v=%6.2f power=%6.0f\n", $dwt, $v{$phase}{$dwt}, $power{$phase}{$dwt});
    }
}
open(TEX, ">kruger.tex");
printf(TEX "\\begin{tabular}{l|rr|rr|rr|rr|}\n");

printf(TEX "Dead-&\\multicolumn{2}{|c|}{Baseline}&\\multicolumn{2}{|c|}{Phase 1}&");
printf(TEX "\\multicolumn{2}{|c|}{Phase 2}&\\multicolumn{2}{|c|}{Phase 3}\\\\\n");
printf(TEX "weight&\\multicolumn{2}{|c|}{}&\\multicolumn{2}{|c|}{EEDI down 10\\%}&");
printf(TEX "\\multicolumn{2}{|c|}{EEDI down 25\\%}&\\multicolumn{2}{|c|}{EEDI down 35\\%}\\\\\n");
printf(TEX "&kts&kW&kts&kW&kts&kW &kts&kW\\\\\n");
for $dwt (100.0e3, 150.0e3, 200.0e3, 250.0e3, 300.0e3) {
    printf(TEX  "%8.0f", $dwt);
    for $phase (1.0, 0.90, 0.75, 0.65) {
        printf(TEX  "&%6.2f&%6.0f", $v{$phase}{$dwt}, $power{$phase}{$dwt});
    }
    printf(TEX  "\\\\\n");
}
printf(TEX "\\end{tabular}\n");
```