Michelle Harris

From: djw1@c4tx.org
Sent: Tuesday, March 01, 2011 10:23 AM
To: Austin Schmitt; Secretary
Subject: FMC Slow Steaming --- Response to NOI
Attachments: paper.pdf; paper.pdf; paper pdf

Dear FMC,

The Center for Tankship Excellence has posted a number of papers/notes on slow-steaming at the CTX web-site http://www.c4tx.org/ctx/pub/

I have attached several that may be of most interest to this NOI.

KTF

Jack Devanney

The impact of EEDI on VLCC design and CO2 emissions

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This paper studies the impact of EEDI on VLCC CO2 emissions. In competitive sectors such as the VLCC market, this analysis must be performed over a market cycle adjusting a ship's steaming speed to the market rate and bunker cost. Our numbers indicated that, over a market cycle, imposition of EEDI will result in a slight ***increase*** in VLCC CO2 emissions, relative to no regulation at all. The problem is two-fold:

1. For VLCC's, EEDI effectively limits installed power. But at current and expected BFO prices, a non-EEDI VLCC owner uses all his installed power only in a full boom. For the great bulk of her life, a non-EEDI VLCC 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 a 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.

In contrast, we find that a $50 per ton CO2 bunkers tax will reduce VLCC CO2 emissions by more than 6% over a market cycle. And it will do so without forcing the world to devote 30% more resources to a greatly expanded, under-powered, over-driven VLCC fleet.

Keywords: EEDI; VLCC; CO2 Emissions; Slow steaming

Introduction

The International Maritime Organization (IMO) may be on the verge of enacting an amendment to MARPOL which would require all new large ships to meet an Energy Efficiency Design Index (EEDI). This is an attempt to reduce CO2 emissions from ocean transportation. This paper considers the impact of this legislation on one ocean transportation sector, Very Large Crude Carriers (VLCC's), and estimates the resulting reduction in CO2 emissions from these ships. These estimates are compared with those generated by a policy of imposing a fuel carbon tax (or an equivalent cap-and-trade permit price) on these ships.

EEDI is defined by MEPC 1, Circ.681 (MEPC, 2009). While the formula is complex, for VLCC's it basically boils down to the ratio of fuel consumed at 75% installed power to speed at that power.

IMO has yet to finalize the mandated decrease in EEDI; but the discussion has focused on the following reduction schedule

Phase 1	Phase 2	Phase 3
2013	2018	2023
10%	25%	35%

These reductions will be from a *baseline* that is determined by fitting a power law regression to the existing fleet. Due to biases in this ad hoc procedure, the EEDI of a current standard VLCC is about 9% above this baseline.(Ozaki et al., 2010)[1] In other words, newbuilding VLCC's will be required to have an EEDI which is 19% below current designs in 2013, 36% below current in 2018, and 47% below current in 2023.

There are essentially only two ways a VLCC designer can meet these EEDI requirements:

1. Reduce the fuel required at 75% installed power by employing fuel saving technology not already in use.
2. Reduce installed power. Unlike most mandated vehicle efficiency requirements such as CAFE, speed is not fixed. An automobile maker cannot meet his CAFE by testing his car at 10 mph rather than 55. But EEDI allows and encourages this. CAFE stands for Corporate Average Fuel Economy. Another difference between CAFE and EEDI is that EEDI is imposed on each individual ship, not on the builder's overall production. Very roughly, VLCC speed goes as the one-third power of installed power. So the expectation is that a 30% reduction in installed power will results in approximately a 10% reduction in speed at that power, and a 20% reduction in the EEDI ratio. We shall see that it is not quite that simple.

"True" Efficiency Improvements

The CTX has conducted a survey of what might be called the "true" efficiency improvements because they attempt to reduce fuel consumption without reducing speed (Devanney, 2010b).

We rejected several possibly economic measures as imprudent, including:

Contra-rotating propellers Contra-rotating props require complex epicyclic gearing and bearings. They are inherently far less reliable than a standard VLCC shaft and propeller, and would be a maintenance nightmare. No prudent owner could spec contra-rotating props on a single screw tanker.

[1] Like most things EEDI, these numbers are rubbery and constantly changing. There are proposals to correct this bias.

Reducing lightweight The EEDI formula includes a cargo capacity term. For VLCC's, it is deadweight. By reducing lightweight the designer can increase deadweight on the same displacement and reduce his EEDI. Unfortunately, VLCC hull structures are already over optimized, resulting in frequent fatigue cracking and short lived vessels. Nonetheless, EEDI will put additional pressure on VLCC designers to take chances in this area.

We rejected a number of ideas that have been around for decades, on the grounds that they have never been able to demonstrate a significant reduction in fuel consumption.

We rejected a number of possible fuel savings measures on some combination of economics, feasibility, or low availability. This category includes solar, kites, and other wind energy devices. Even if a VLCC owner invests in such measures, he cannot reduce his conventional installed power since energy from these sources is not always available.

We rejected a couple of promising measures as unproven including hull cavity.

We realized that our designer will have to cope with the Tier II NOX requirements which will cost him 2 to 3 g/kWh or about 1%

On the other hand, it is true that the massive, post-2005 increase in bunker prices has resulted in a number of measures which were not economic at $200 per ton Bunker Fuel Oil (BFO) now being economic at $450 per ton BFO. But when we added them up, rejecting those we regarded as imprudent or unproven, we were hard pressed to produce more than a 9% saving in EEDI.

About half of this savings was due to Waste Heat Recovery (WHR). With an investment of about 1.3 million dollars, it is possible to extract enough energy from a VLCC's cooling water and main engine exhaust to drive a 1000 kW generator, and meet a VLCC's normal at sea electric power requirements. The overall fuel savings is of the order of 4%. At current BFO prices, these WHR systems have a pay-back period of less than 2 years for a VLCC, and owners are flocking to install advanced WHR. In August, 2010, Wartsila counted 81 big ships including 33 VLCC's that have ordered Wartsila's version of WHR.(Antonopoulos, 2010)

A number of these now economic measures (for example, electronically controlled engines, variable pitch turbo-chargers, and multi-speed pumps) result in a substantial improvement in VLCC fuel efficiency at low loads, but have little or no impact on the ship's EEDI which is based on 75% MCR. Perhaps the single most important recent technological development is the ability of VLCC main engines to operate well below 50% load continuously and do it quite efficiently. This major change is ignored by EEDI.

A common feature of just about all the measures that make sense is that they will be implemented without any regulation.[2] In the jargon, they have *negative abatement cost*, meaning that the owner's bottom line will be improved by investing in them in his newbuildings. Most of them are already being implemented.

The problem for our VLCC designer is that, if you add up all the prudent, proven measures you are talking at most a 9% improvement in fuel consumption at 75% installed power, the EEDI design point.[3] This just gets him down to the Baseline. For the great bulk of his reduction in EEDI, he will have to reduce installed power.

Slow-steaming

Before we can estimate the impact of mandating a reduction in installed power, we must understand *slow-steaming*. The relationship between EEDI and tanker CO2 emissions is an indirect one. The amount of CO2 emitted by a VLCC (or any ship) depends ***not*** on the fuel consumption at installed power (or 75% of installed power), but on the power that the owner/term charterer actually uses and the fuel consumption at that power. The power that a VLCC owner/term charterer will actually use depends on three things:

1. the current VLCC spot rate
2. the owner's, term charterer's current fuel cost,
3. the ship's speed/consumption curve.

In any market situation (spot rate and bunker cost), the owner/term charterer will adjust the ship's steaming speed to maximize his daily net earnings or equivalently for the term charterer, minimize his unit cost of transportation.[1]

As Figure 1 shows, the VLCC market, an example of nearly textbook competition, is extremely volatile. The spot rate can vary by a factor of ten in a matter of months. At the bottom of the market, the owner will barely be paying his fuel bill. In a full scale boom, the entire $100,000,000 ship can be paid off in a dozen voyages.

[2] As will be new, still unproven technologies that turn out to be truly effective. Perhaps the number 1 candidate in this category is air cavity.

[3] greenship.org, a group that generally takes an optimistic view of the potential for vessel emissions reductions, studied a 35,000 ton bulk carrier to which they fitted just about every device applicable, and ended up with a 7% decrease in CO2 emissions.(Schack, 2010)

[1] It is well known that both the real owner in the spot market and a term charterer face essentially the same speed optimization problem. See for example Devanney (2009, Apprendix B) for a proof. Henceforth, I will shorten the klunky "owner/term charterer" to "owner" with the understanding that, for a term chartered tanker, the term charterer is the effective owner.

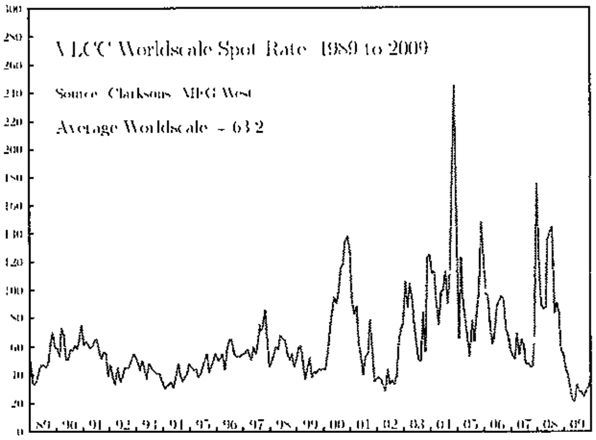

Figure 1. VLCC Spot Rates, 1989-2009

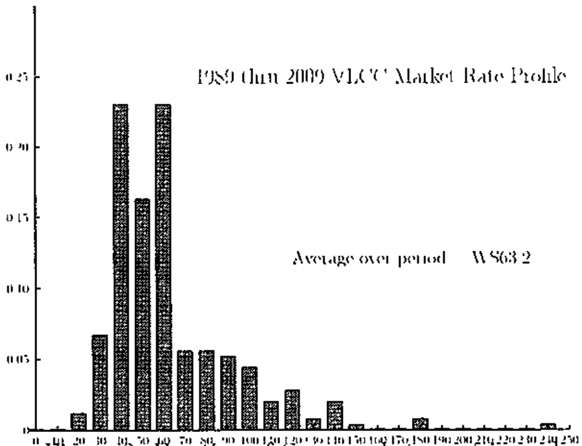

Figure 2. Fraction of time market spent in each Worlscale interval

The spot market cannot go below the owner's *Layup Rate* for any length of time. The Layup rate is the rate below which the owner is better off laying up his VLCC, rather than continuing to trade. In Worldscale terms, the VLCC lay-up rate is usually in the very high 20's

In the very long run, the spot rate must average the *Required Freight Rate (RFR)*. The RFR is the spot rate the owner would have to average over the ship's life in order to just break even on his investment, including his opportunity cost of capital. If over the very long run, the market averaged a spot rate higher than RFR this would attract more investment in VLCC's and depress the rate. If over the very long run, the market averaged a spot rate less than RFR, then capital would move out of the VLCC market raising the rate.

The VLCC Required Freight Rate over the last two decades is a bit of a moving target for several reasons, but mainly because the newbuilding price of a VLCC is constantly changing. When the shipbuilding market is very strong, the price of a VLCC can be double that when the yards are desperate for business But once again, over the long-run, the average newbuilding price has to be somewhere near the yards' present valued cost of building the ship, or we'd have capital continually flowing into or out of shipbuilding. A reasonable estimate of the average VLCC RFR over this period is WS62 +/- 5 Worldscale points. See Appendix A. The average spot rate over the period was WS63.2 In short, the actual average spot rate is about where we would expect it to be.

Figure 2 is a histogram showing the fraction of the time the market spent at each spot rate, between 1989 and 2009 inclusive.

For the purposes of this diagram, we broke the rates down into 10 Worldscale point intervals. As Figure 2 shows, the market spends most of its time between the Layup Rate (usually in the high twenties) and RFR (usually in the low sixties) with occasional spikes much higher in booms. For this 21 year period, the market was above WS 100 about 9% of the time and at or below the RFR about 70% of the time, a highly skewed distribution During a boom, rates can easily be 3 or 4 times the RFR, which means the market must spend a lot of time below RFR to compensate.

Table 1 shows the actual numbers. The column labeled "Standard" is the *market rate profile* which we used in averaging CO_2 emissions over a market cycle. In this profile, all rates above WS100 are considered to be full boom, and mapped to WS200. Our Standard rate profile is a reasonable approximation to the observed rates below WS100, but is intentionally biased upward, that is, in favor of the lower powered, EEDI compliant ship above WS100. The Standard profile has an average Worldscale of 70.9, comfortably above a newbuilding RFR, even for $620 bunkers. More importantly, in any market above WS100, it artificially speeds up the non-EEDI BASE ship more than the EEDI compliant ship which is often already at or near max speed at WS110 improving the lowered powered ships' advantage in emissions at the high end of the market.

Table 1 Actual and Standard Rate Profiles

World scale	Observed fraction	Standard fraction
20	0.012	0.00
30	0.067	0.08
40	0.230	0.20
50	0.163	0.20
60	0.230	0.20
70	0.056	0.06
80	0.056	0.06
90	0.052	0.05
100	0.044	0.05
110	0.020	
120	0.028	
130	0.008	
140	0.020	
150	0.004	
180	0.008	
200	0.000	0.10
210	0.004	

The BASE Route and Ship

Standard Route

In order to estimate VLCC CO2 emissions over a market cycle,

1. we must first figure out what the owners will do as a function of the spot rate.
2. then, using our market rate profile, combine these numbers to obtain his average CO2 emissions over a market cycle.

We will perform these calculations for a standard (no EEDI) VLCC and a standard route. We will them study various EEDI compliant variations of the standard ship on the same route.

The particulars of the route we used for all our calculations are shown in Table 2. The route is Fujairah to Ras Tanura to Yokohama to Fujairah via Malacca both ways. The ship was bunkered for the round trip at Fujairah. For these parameters none of the loadlines nor the Malacca draft requirement is limiting. The cargo limiting restriction is arrival draft at Yokohama. This route is reasonably representative of most VLCC voyages. The SFC adjustment corrects for overly optimistic book (manufacturer) SFC figures mainly due to an unrealistically high fuel Net Calorific Value (NCV).

Summer Dwt	308,000	SDWT draft	22.600
Tons per m	16,980	Tons/m2	61.0
Cargo Cubic	350,000	Loss%	2.00
Cargo density	0.85	Cargo value$/t	600.00
Demurrage($/day)	25,000	Cargo interest	5.0
Laytime(hrs)	72	Hrs to owner	48
Cylinder LO g/kWh	1.2	Cylinder LO $/t	1800
Brokers Commis %	1.25	Hotel TPD	10
Consumables(tons)	500	BFO Capacity tons	9,741
SFC Adjustment%	7.1	Speed adjustment	0.0
FUJA port charges	0	FUJA port hours	0
FUJA draft limit	99.9	FUJA port fuel(t)	0
FUJA/RAST miles	506	Sea Margin	15.0
RAST port charges	27,000	RAST port hours	48
RAST draft limit	32.0	RAST port fuel (t)	50
RAST/YOKO miles	6593	RAST/YOKO WS Rat	18.11
YOKO port charges	130,000	YOKO draft limit	20.9
YOKO port fuel (t)	250	YOKO/FUJA miles	6220

Table 2. Route used in VLCC Emissions Calculations

The cargo value (about $80 per barrel) and interest rate (5%) are used to compute the in-transit inventory carrying cost. Currently, oil companies tend to be rather cavalier about inventory carrying cost, for the most part ignoring them. This might be semi-forgivable when one is dealing with a difference of a day or two in loaded leg time. But since we will be dealing with a very wide range of vessel speeds, we really don't have this luxury. Therefore, our VLCC steaming speeds will be set to minimize the charterer's total cost of transporting a ton of oil including his inventory carrying costs.

We also made some test runs in which we set inventory carrying cost to zero. The ***relative*** differences between the non-EEDI and EEDI ships were almost unchanged. The main effect of including inventory carrying costs is to speed both ships up on the loaded leg at the bottom of the market. Within reason, whatever you assume about inventory carrying costs will not change our bottom line conclusions about the effectiveness of EEDI for VLCC's

Standard Ship

Fortunately, for our purposes, almost all VLCC's are very similar. The single most important characteristic of a VLCC from a CO2 point of view is the loaded and ballast speed/fuel consumption curves. The speed/fuel curves in turn are based on three curves:

1. The hull resistance curve, which determines the amount of power the hull requires as a function of speed.
2. Propulsive efficiency curve which determines the fraction of the main engine power that is converted to thrust to drive the hull.
3. The engine Specific Fuel Consumption (SFC) curve which determines the amount of fuel the engine needs to produce a given amount of power.

Hull form

In all our calculations, we kept the hull form constant. The hull we used is that studied by Min and Choi (2003). In the Min paper, our hull form is labeled Extreme V. It is clearly, the best of the three studied. The design draft (20.95 m) resistance curve of this hull is shown in Figure 3. It is close to cubic up to Froude number of 0.11 (15 knots) above which it turns upward a bit faster than cubic. To convert this design draft curve (wetted surface = 27,271 m2) to loaded and ballast curves, we assumed resistance was proportional to wetted surface and a loaded/ballast wetted surface of 28,500/21,000 m2.

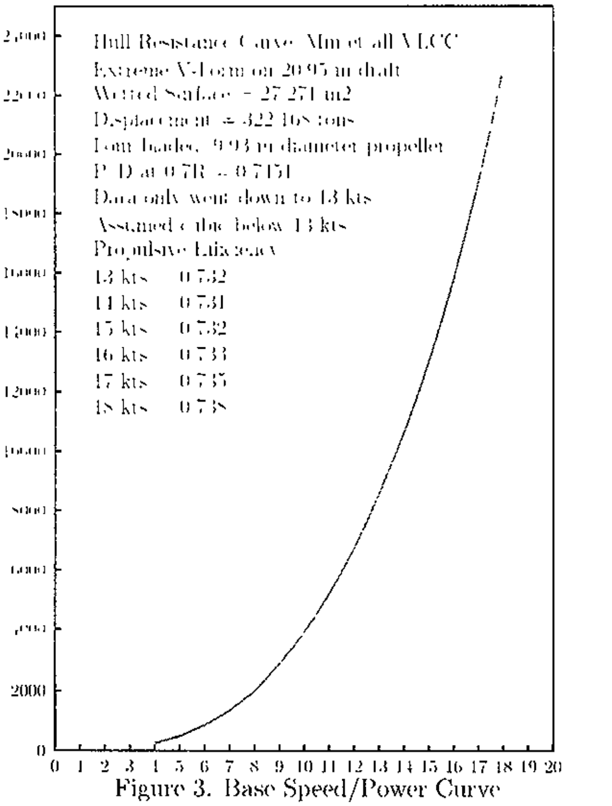

Figure 3. Base Speed/Power Curve

Propulsive efficiency curve

Our base ship uses a four bladed, 9.93 m propeller, with a constant propulsive efficiency (PE) of 0.73. In reality, PE will vary with speed, but, as Figure 3 shows, for this hull form and propeller, the variation was less than 1% over a range from 40% full power to 100% full power. This propeller is designed to accept about 27,000 kW at 76 RPM.

As we shall see, EEDI will produce drastic changes in VLCC powering. Phase 3 will require a halving of installed power inducing owners to use smaller bore, higher RPM engines. This in turn will generate drastic changes in propeller design. To attempt to predict what these propellers will look like and their performance, CTX used MIT's OpenProp program.(Epps et al., 2009) OpenProp is a modern lifting line program capable of creating wake adapted propellers. Open Prop takes as input a ship speed, a required thrust at that speed, an RPM, a diameter, a description of the wake, and returns the propeller that generates this thrust at minimum torque while meeting all the other constraints.

In our propeller analyses we held the hull constant. For each of Phase 1, 2 and 3, we held the engine constant. Using OpenProp we then searched over diameter, looking for the propeller that gave the vessel the maximum speed without exceeding the engine's torque, power capability. Finally, we checked that combination for EEDI compliance and, if necessary, derated the engine as required to meet the mandated EEDI.[5] In conducting this search we required that the blade loading on the propeller be no higher that that for the standard no-EEDI ship. See Devanney (2010c) for the details of these propeller studies.

For our axial wake profile, we used that measured for Samsung hull 1321, a VLCC which has almost exactly the same hull resistance (towing) curve as the Mm. Choi hull and nearly the same thrust deduction and wake fraction.(SSMB, 2000) Table 3 shows the SHI 1321 wake profile.

Table 3 Circumferential Mean Axial Wake Profile SHI 1321

Radius m	Wake Fraction
1.94	0.509
2.91	0.469
3.88	0.485
4.85	0.504
5.82	0.527
6.79	0.540
7.76	0.640
8.73	0.760
9.22	0.790
9.70	0.820

The important feature of this profile is that the high wake region extends out to about 5 m from the shaft centerline. This means that smaller diameter propellers must operate at an average wake fraction that is considerably higher than that for the standard 9.9 m prop. We shall see that the improvement in hull efficiency is more than compensated for by reduction in open water efficiency associated with the lower advance ratio.

Specific Fuel Consumption Curve

The base Specific Fuel Consumption Curve we will use is that for the Wartsila 7RTA84T engine. This is a standard seven cylinder engine used by many VLCC owners. It has an MCR (Maximum Continuous Rating) power of 27,516 kW at 76 RPM, at which point it has a book SFC of 168.0 g/kWh. The competitive engines have very similar characteristics. For reasons which will become clear we also studied 6, 5, and 4 cylinder engines with the same bore and stoke. These are essentially the same engine with less cylinders. The 5 and 4 cylinder variants don't actually exist because they would have extremely poor vibration characteristics, but for now we ignore that.

VLCC Speed/Fuel Curves

Speed/Fuel Curves for Existing VLCC's

Putting all our assumptions together, we arrive at the speed/fuel curves shown in Table 4 for existing VLCC's. The ship labeled 7RTA84T is a standard 7 cylinder, camshaft controlled VLCC. Most VLCC's currently trading will look pretty much like this ship. The ship labeled 6RTA84T is the same ship but fitted with a six cylinder engine of the same make and model. The third and fourth ships are imaginary; they are infeasible due to vibration problems. They were produced by simply removing additional cylinders from the same engine. All four designs use the same diameter propeller. In all four cases, the ***book*** SFC at MCR is 168.0 g/kWh.[6]

According to Table 4, the 7 cylinder ship has a poorer fuel consumption below about 14 knots loaded than the lowered powered ships as the SFC starts to climb with lower load. The 7 cylinder ship is also very limited as to how slow it can go. This is misleading. For a modest investment, the owner of the 7 cylinder ship can do everything the lower powered ships can do, including the vibrationally challenged 5 and 4 cylinder ships. To do this he must invest in a cylinder cut out system (less than $30,000) and variable pitch or multiple turbocharger fans (about $150,000). He can pay for this with a savings of 400 tons of fuel. At that point, he will be able to have the best of all worlds picking out the best SFC for each power in Table 4. And unlike the four and five cylinder engines, he will not have a vibration problem. The momentarily unused cylinders are in effect balancers. The resulting ship is shown in the rightmost

[5] In doing so we held RPM constant, moving vertically downward in the layout diagram. It is possible that by reducing RPM and going to a little higher pitch, we could come up with a very slightly better fuel consumption for this power and speed. But any such improvement would be insignificant for present purposes

[6] This is a manufacturer figure based on a fuel NCV that doesn't exist, optimistic ambient and NOX conditions. We will correct for this in the actual voyage calculations.

column. This ship is also a decent approximation for an electronically controlled VLCC fitted with a complete set of slow-steaming mods.

Loaded EEDI		7rta84t 2.54		6rta84t 2.30		Fake 5 cyl 2.01		Fake 4 cyl 1.77		7rta84t w. mods	
Kts	kW	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd
10.5	7507							165.7	29.8	165.7	29.8
11.0	8632							164.0	31.0	164.0	31.0
11.5	9863					165.0	39.0	162.9	38.6	162.9	38.6
12.0	11207			165.7	44.6	163.6	44.0	162.6	43.7	162.6	43.7
12.5	12667	166.2	50.5	164.3	49.9	162.8	49.5	163.4	49.7	162.8	49.5
13.0	14303	164.6	56.5	163.0	55.9	162.7	55.8	165.1	56.7	162.7	55.8
13.5	15946	163.4	62.5	162.6	62.2	163.5	62.6			162.6	62.2
14.0	17706	162.8	69.2	162.8	69.2	165.0	70.1			162.8	69.2
14.5	19626	162.6	76.6	163.9	77.2	168.0	79.1			162.6	76.6
15.0	21683	163.2	84.9	165.3	86.0					163.2	84.9
15.5	23928	164.6	94.5							164.6	94.5
16.0	26326	166.8	105.4							166.8	105.4
mcr s/t		16.2	110.9	15.4	95.1	14.5	79.2	13.4	63.1	16.2	110.9

Ballast		7rta84t		6rta84t		Fake 5 cyl		Fake 4 cyl		7rta84t	
Kts	kW	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd
11.5	7268							166.1	29.0	166.1	29.0
12.0	8258							164.5	32.6	164.5	32.6
12.5	9333					165.8	37.1	163.1	36.5	163.1	36.5
13.0	10539					164.3	41.6	162.6	41.1	162.6	41.1
13.5	11750			165.1	46.5	163.0	46.0	162.8	45.9	162.8	45.9
14.0	13016	165.8	51.9	163.9	51.3	162.7	50.9	163.8	51.3	162.7	50.9
14.5	14462	164.5	57.1	162.9	56.6	162.7	56.5	165.3	57.4	162.7	56.5
15.0	15977	163.4	62.7	162.6	62.4	163.5	62.7			162.6	62.4
15.5	17631	162.8	68.9	162.8	68.9	164.9	69.8			162.8	68.9
16.0	19398	162.5	75.7	163.7	76.2	167.6	78.0			162.5	75.7
16.5	21334	163.1	83.5	165.0	84.5					163.1	83.5
17.0	23402	164.2	92.2	167.8	94.2					164.2	92.2
17.5	25667	165.8	102.1							165.8	102.1
mcr s/t		17.8	110.9	17.0	95.1	16.0	79.2	14.9	63.1	17.8	110.9

Table 4. Speed-Fuel Curves for Existing Ships

Despite the big improvement over the unmodified leftmost ship at low load, our BASE VLCC has the same EEDI, 2.54. Akiyama and Tagg came up with an EEDI of 2.53 for their standard VLCC which is a slightly smaller ship.Ozaki et al. (2010). So this appears to be a reasonable number for existing VLCC's.

The Base Speed Fuel Curves for Newbulding VLCC's

Loaded EEDI		7rta84t 2.31		6rta84t 2.09		Fake 5 cyl 1.85		Fake 4 cyl 1.60		7rta84t w. mods	
Kts	kW	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd
10.5	7507							165.7	27.2	165.7	27.2
11.0	8632							164.0	31.0	164.0	31.0
11.5	9863					165.0	35.6	162.9	35.2	162.9	35.2
12.0	11207			165.7	40.7	163.6	40.1	162.6	39.9	162.6	39.9
12.5	12667	166.2	46.1	164.3	45.5	162.8	45.1	163.4	45.3	162.8	45.1
13.0	14303	164.6	51.5	163.0	51.0	162.7	50.9	165.1	51.7	162.7	50.9
13.5	15946	163.4	57.0	162.6	56.8	163.5	57.1			162.6	56.8
14.0	17706	162.8	63.1	162.8	63.1	165.0	63.9			162.8	63.1
14.5	19626	162.6	69.8	163.9	70.4	168.0	72.2			162.6	69.8
15.0	21683	163.2	77.4	165.3	78.1					163.2	77.4
15.5	23928	164.6	86.2							164.6	86.2
16.0	26326	166.8	96.1							166.8	96.1
mcr s/t		16.2	101.2	15.4	86.7	14.5	72.3	13.4	57.8	16.2	101.2

Ballast		7rta84t		6rta84t		Fake 5 cyl		Fake 4 cyl		7rta84t	
Kts	kW	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd
11.5	7268							166.1	26.4	166.1	26.4
12.0	8258							164.5	29.7	164.5	29.7
12.5	9333					165.8	33.9	163.1	33.3	163.1	33.3
13.0	10539					164.3	37.9	162.6	37.5	162.6	37.5
13.5	11750			165.1	42.4	163.0	41.9	162.8	41.9	162.8	41.9
14.0	13046	165.8	47.3	163.9	46.8	162.7	46.5	163.8	46.8	162.7	46.5
14.5	14462	164.5	52.1	162.9	51.6	162.7	51.5	165.3	52.3	162.7	51.5
15.0	15977	163.4	57.1	162.6	56.9	163.5	57.2			162.6	56.9
15.5	17631	162.8	62.8	162.8	62.8	164.9	63.6			162.8	62.8
16.0	19398	162.5	69.0	163.7	69.5	167.6	71.2			162.5	69.0
16.5	21334	163.1	76.1	165.0	77.1					163.1	76.1
17.0	23402	164.2	84.1	167.8	85.9					164.2	84.1
17.5	25667	165.8	93.2							165.8	93.2
mcr s/t		17.8	101.2	17.0	86.7	16.0	72.3	14.9	57.8	17.8	101.2

Table 5. Speed-Fuel Curves for Newbuilding VLCC's

When we take advantage of additional Waste Heat Recovery (about 4% reduction) and assume other true improvements in efficiency amounting to 5% in total, we obtain the Table 5, newbuilding counterparts to the ships in Table 4. The ship on the right will be our BASE newbuilding VLCC, the ship that would be built with no new regulation. This ship has an EEDI of 2.31, well above the Phase 1 requirement of 2.09.

Phase 1 EEDI

Slow-steaming curves for $465 BFO cost

The proposed VLCC baseline EEDI is 2.32, and the proposed Phase 1 reduction is 10% resulting in a required EEDI of 2.09. A glance at Table 5 reveals that our BASE 7 cylinder ship is illegal, but the six cylinder ship just meets the proposed Phase 1 requirement.

The MCR RPM is unchanged at 76. OpenProp indicates that the optimal diameter remains 9.93 m, but by adjusting pitch distribution and blade area was able to increase the propulsive efficiency to 0.731. The downside was that OpenProp ended up with an Expanded Area Ratio of 0.112, an unheard of number for a VLCC propeller. This propeller should be carefully checked for cavitation, strength and heavy weather performance. For present purposes we accepted the calm water OpenProp results.

Tables 6 and 7 show the slow-steaming tables for the 7 cylinder (no-EEDI) and the 6 cylinder (Phase 1) ships on our standard Ras Tanura-Yokohama route for an assumed bunker cost of $465 per ton, about the current market price.

Table 6

Slow-steaming Curve for no-EEDI VLCC, $465 BFO

WS	AVE SPD	BFO RT	Days /RT	Cargo tons	BPD	CO2/ TPD
30	10.00	1540	59.50	276980	33506	1.0593
40	10.47	1670	57.00	276980	34974	1.1002
50	10.90	1820	54.92	276980	36299	1.1551
60	12.21	2113	49.33	276786	40381	1.2056
70	13.18	2500	45.18	276672	44073	1.3071
80	14.21	2724	42.96	276550	46327	1.3551
90	15.00	2969	41.00	276119	48525	1.4099
100	15.49	3126	39.83	276274	49922	1.4427
110	15.99	3335	38.71	276190	51353	1.4963
120	16.25	3466	38.15	276190	52098	1.5331
130	16.49	3567	37.65	276097	52771	1.5576
140	16.84	3752	36.95	275990	53756	1.6083
150	16.84	3752	36.95	275990	53756	1.6083
160	17.02	3851	36.61	275898	54237	1.6361
.				. .	.....	. .
300	17.02	3851	36.61	275898	54237	1.6361

These tables display the owner's optimal average (loaded ballast) steaming speed as a function of spot rate, the resulting round trip fuel consumed, round trip voyage time, cargo per trip, and the barrels per day delivered. These numbers were computed using the MFIX package which was the standard voyage analysis software used by Hellespont Shipping between 1995 and 2002 in operating their fleet of VLCC's and ULCC's. This program optimizes loaded and ballast speed in half-knot increments, so the speed-up can be a little jumpy.

Table 7

Slow-steaming Curve for Phase 1 VLCC, $465 BFO

WS	AVE SPD	BFO /RT	Days /RT	Cargo tons	BPD	CO2/ TPD
30	10.00	1531	59.50	276983	33506	1.0531
40	10.47	1661	57.00	276983	34974	1.0946
50	10.90	1812	54.92	276983	36299	1.1500
60	12.24	2106	49.33	276789	40382	1.2015
70	13.48	2489	45.18	276676	44074	1.3013
80	14.00	2619	43.64	276556	45609	1.3231
90	14.75	2863	41.63	276421	47790	1.3803
100	15.25	3057	40.39	276352	49237	1.4306
110	15.72	3258	39.31	276272	50584	1.4843
120	15.96	3360	38.78	276178	51259	1.5102
130	15.96	3360	38.78	276178	51259	1.5102
140	16.19	3471	38.28	276076	51909	1.5407
150	16.19	3471	38.28	276076	51909	1.5407
160	16.19	3471	38.28	276076	51909	1.5407
170	16.21	3486	38.23	276062	51972	1.5455
...	.....	.	. .	.	. ..	.
300	16.21	3486	38.23	276062	51972	1.5455

The column on the right shows the tons CO2 emitted per ton per day cargo delivered. This column adjusts the fleet size to achieve the same tons per day delivered, but does ***not*** adjust CO2 emissions for the additional Build/Repair/Scrap emissions, nor the CO2 produced by flying more crews around, extra cargo evaporation, etc. associated with slower speed and a bigger fleet.

Comparing Tables 6 and 7 below WS80, both ships are going the same speed, so there is no difference. This is where the market spends most of its time. Between WS90 and WS140, the more fuel efficient (at these speeds) 7 cylinder ship speeds up a bit faster, and the 6 cylinder ship produces 1 to 3% less CO2 per ton delivered per period. Between WS140 and 190 the lowered powered ship is going just about as fast it can, and the difference is about 4%. The higher powered ship still has one gear left, which it uses at WS200. At WS200 and above, the difference is about 6%.

Table 8. Phase 1 Percent Reduction in CO2

BASE vs 6 cylinder ship BFO=$465

WS	Avespd BASE	Avespd 6CYL	Ratio CO2	% Diff
30	10.25	10.25	1.0000	-0.0
40	10.74	10.74	1.0000	-0.0
50	11.19	11.19	1.0000	-0.0
60	11.97	11.97	1.0000	-0.0
70	13.20	13.20	1.0000	-0.0
80	14.21	14.00	0.9820	-1.8
90	15.00	14.75	0.9846	-1.5
100	15.49	15.25	0.9948	-0.5
110	15.99	15.49	0.9732	-2.7
120	16.25	15.91	0.9903	-1.0
130	16.49	15.91	0.9747	-2.5
140	16.72	16.17	0.9762	-2.4
150	16.83	16.17	0.9632	-3.7
160	16.83	16.17	0.9632	-3.7
170	16.83	16.17	0.9632	-3.7
180	16.83	16.17	0.9632	-3.7
190	16.83	16.17	0.9632	-3.7
200	16.97	16.17	0.9427	-5.7
Average	1.238	1.226		-1.0

Table 8 summarizes this comparison. The fourth column in Table 8 is just the ratio of the rightmost columns in Tables 6 and 7. The last column is this ratio converted to a percent. The bottom line shows the CO2/TPD delivered for each of the two ships averaged over the market cycle, and the resulting average percentage reduction associated with the ship on the right.

Under our Standard spot rate profile, over a market cycle a fleet of the BASE ships would average 1.238 tons of CO2 per ton per day delivered; a fleet of the 6 cylinder ships would average 1.226 tons of CO2/TPD. Despite our rate profile being intentionally biased toward the lowered powered ship, we end up with a 1% reduction in VLCC CO2 emissions due to Phase 1 EEDI. Due to the tenuous connection between installed power and power actually used, a 10% reduction in EEDI results in very little reduction in operational CO2 emissions over a market cycle.

When we throw in the seven cylinder ship's superior heavy weather performance, and the fact that in a boom we would need 4.4% more six cylinder ships to move the same amount of oil and thus 4.4% more B/R/S emissions, the difference in CO2 emissions is in the noise. It is also obvious from these tables, that, over a market cycle, the seven cylinder engine is on average operating at a considerably lower percent of MCR which means a substantial decrease in main engine failures.

Slow-steaming curves for $620 BFO cost

If you repeat these analyses for a BFO cost of $620 per ton, you will find that the difference in CO2 emissions from the two ships over a market cycle is even smaller than for $465 BFO cost. See Devanney (2010b) for the details. As rates improve, both ships speed up more slowly. The lowered powered ship does not reach its speed constraint until WS220. Below WS150, there is nil difference in speed or CO2 emissions; between WS150 and WS250 the difference is about 3%, and it is not until you get to WS270, that we see the both-ships-at-full-speed 5.5% difference. Using our Standard spot rate profile, the BASE ship averages 1.167 tons of CO2/TPD, the EEDI compliant ship 1.162, a difference of 0.5%.[7]

The Impact of a $50 per ton CO2 Carbon Tax

A far more interesting comparison is to match the slow steaming curve for the BASE ship at $465 bunkers, with the slow steaming curve for the same ship at $620 bunkers, as Table 9 does. If the $150 difference in owner's fuel cost is caused by a $50 per ton carbon tax (or equivalent cap-and-trade permit price), we are looking at how a VLCC owner would react to a $50 per ton CO2 carbon emissions price, assuming no EEDI.

[7] The RFR and the long run average of the spot rates will be about 5 Worldscale points higher (assuming the same flat rate as we have) for $620 bunker cost than for $465 bunker cost. This is one of the reasons we biased our Standard profile toward the high end.

Table 9. Percent Reduction CO2, $50/ton CO2 tax
BASE ship at $465 versus $620 BFO cost

WS	Avespd 465	Avespd 620	Ratio CO2	% Diff.
30	10.00	9.48	0.9656	-3.4
40	10.47	9.75	0.9462	-5.4
50	10.90	10.24	0.9331	-6.7
60	12.24	10.69	0.9336	-6.6
70	13.48	11.47	0.8902	-11.0
80	14.24	12.21	0.8897	-11.0
90	15.00	13.24	0.9091	-9.1
100	15.49	14.00	0.9216	-7.8
110	15.99	14.50	0.9141	-8.6
120	16.25	15.25	0.9296	-7.0
130	16.49	15.49	0.9262	-7.4
140	16.84	15.75	0.9173	-8.3
150	16.84	15.99	0.9301	-7.0
160	17.02	16.49	0.9520	-4.8
170	17.02	16.49	0.9520	-4.8
180	17.02	16.72	0.9710	-2.9
190	17.02	16.84	0.9830	-1.7
200	17.02	16.84	0.9830	-1.7
210	17.02	17.02	1.0000	-0.0
..	..		. . .	
300	17.02	17.02	1.0000	-0.0
Average	1.243	1.167		-6.1

At WS30, an owner facing the $620 BFO cost will steam about 0.5 knot slower than he would at $465 bunkers, resulting in a 3% reduction in CO2 per TPD delivered. As rates improve, an owner facing the higher BFO cost will speed up more slowly and at WS70 to WS80 the speed difference is about 2 knots and the reduction in CO2/TPD 11%.[8] As rates further improve the speed difference begins to drop until at WS210, our owner will steam as fast as he can even at $620 BFO and there is no difference in CO2/TPD. Over the market cycle, the higher fuel cost will produce 6.1% less CO2 per TPD delivered.

It is extremely important to focus on how the bunkers tax achieves this reduction. Below about WS150 — in other words almost all the time — the non-EEDI compliant ship with the tax (Table 9, column 3) is steaming ***more slowly*** than the Phase I EEDI compliant ship without the tax (Table 8, column 3). ***It is only in an all-out full boom that the non-EEDI ship with tax steams faster than the Phase I EEDI compliant ship without the tax.*** But this is exactly what we want for it avoids wastefully expending resources on additional ships, just to handle a boom.[9]

Phase 1 Summary

Speed reduction is not a **measure** as most vessel CO2 emissions studies would have us believe. ***It is a*** **reaction.** It is the owner/term charterer's reaction to the current spot rate, his bunker cost, and his speed-fuel curve. At current and likely bunker prices, a well-designed VLCC will be operating at maximum speed only in a full scale boom, less than 10% of the ship's life. Most of the time, the ship will be operating at a percentage of full power, often much less than full power.

EEDI affects this reaction indirectly by reducing the owner's max speed. The net effect over a market cycle is that the Phase 1 EEDI requirement will reduce VLCC operational CO2 emissions by 1% or less for the ships that are actually affected by this regulation while at the same time increasing the amount of resources society must devote to the VLCC sector, and reducing safety.

An increase in bunker cost affects the owner's reaction directly. This could be accomplished most simply and most efficiently by a carbon based bunkers tax. Over a market cycle, a $50 per ton CO2 BFO tax would reduce VLCC CO2 emissions by more than 6% and it would apply to the entire fleet, and it would do so without EEDI's expensive and pernicious side-effects.

So far we have been acting as if society's goal were to minimize CO2 emissions. In fact, the goal is (or at least should be) minimizing the sum of the societal cost of CO2 plus all the other costs associated with moving the oil. The six cylinder ship will have a market cost which is about 1.2 million dollars less than the 7 cylinder, a savings of about 1.3% in initial cost. But as we have seen we will need about 1% more of them, so the 7 cylinder ship has a clear superiority here. This of course is why almost all existing VLCC's have the power they do. By forcing owners to buy less power than they would have, we are forcing the world to devote more scarce resources to building VLCC's. Any intelligent regulatory policy would take this into account.

Phase 2 EEDI

Slow-steaming curves for $465 BFO cost

The proposed VLCC baseline EEDI is 2.32, and the proposed Phase 2 reduction is 25% resulting in a required EEDI of 1.74. A glance at Table 5 reveals that our imaginary 5 cylinder ship is illegal, but the 4 cylinder would easily meet the EEDI requirement. Unfortunately, neither of these engines have acceptable vibration characteristics. To meet the EEDI requirement with a 6 cylinder engine, the owner will have to go down to a 650 mm bore cylinder. The engine we will use for Phase 2 is a MAN 6S65ME with an MCR of 17,220 KW at 95 RPM. The best propeller OpenProp could come up with for this engine has a diameter of 8.5 m resulting in a propulsive efficiency of 0.647, about a 7% loss in propulsive efficiency relative to the no-EEDI ship. On top of this, the smaller bore engine has a 3 g/KW-hr (2%) disadvantage in SFC.

Table 10 shows the fuel consumption curves for this engine for 6 through 3 cylinders. As usual we examine vibrationally infeasible engines to study the impact of cylinder cutout. This engine still does not quite meet the Phase 2 EEDI requirement. Therefore the owner will

[8] The long-run average Worldscale rate will be about 5 WS points higher in a $620 BFO cost world than a $465 BFO cost world. To be totally correct, we should compare, say, WS50 and $465 BFO with WS55 and $620 BFO; but, as Table 9 shows, it wouldn't make that much difference.

[9] In economic jargon, the marginal societal value of VLCC capacity is at least 10 times higher in a boom than a slump. A tax adjusts efficiently to this changing valuation. EEDI does not. For a more complete discussion of this issue, see Devanney (2010a).

have to derate the engine slightly to an MCR of 16,800, resulting in the fuel consumption curve at the far right. This ship will have a loaded, trial speed of about 13.6 knots.

Loaded EEDI		6s65me 1.78		5 cyl 1.57		4 cyl 1.36		3 cyl 1.12		6s65me w. mods	
Kts	kW	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd
8.5	4330							167.9	15.9	167.9	15.9
9.0	5140							166.1	18.7	166.1	18.7
9.5	6046					167.5	22.2	165.5	21.9	165.5	21.9
10.0	7052			168.3	26.0	165.9	25.6	166.6	25.7	165.9	25.6
10.5	8162	168.8	30.2	166.6	29.8	165.6	29.6	169.5	30.3	165.6	29.6
11.0	9386	167.1	34.3	165.7	34.0	166.6	34.2			165.7	34.0
11.5	10724	165.9	38.9	165.8	38.9	169.2	39.7			165.8	38.9
12.0	12185	165.5	44.2	167.2	44.6					165.5	44.2
12.5	13772	166.3	50.1	169.9	51.2					166.3	50.1
13.0	15552	168.1	57.3							168.4	57.3
Ballast		6s65me		5 cyl		4 cyl		3 cyl		6s65me	
Kts	kW	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd	Sfc	Tpd
9.5	4455							167.7	16.3	167.7	16.3
10.0	5196					169.1	19.3	166.0	18.9	166.0	18.9
10.5	6014					167.5	22.1	165.5	21.8	165.5	21.8
11.0	6916			168.5	25.5	166.0	25.1	166.1	25.2	166.0	25.1
11.5	7902	169.2	29.3	167.0	28.9	165.6	28.6	168.8	29.2	165.6	28.6
12.0	8978	167.6	32.9	165.9	32.6	166.1	32.6			165.9	32.6
12.5	10148	166.2	36.9	165.5	36.8	167.9	37.3			165.5	36.8
13.0	11459	165.7	41.6	166.3	41.7	170.9	42.9			165.7	41.6
13.5	12775	165.8	46.3	168.1	47.0					165.8	46.3
14.0	14185	166.7	51.8	170.7	53.0					166.7	51.8
14.5	15724	168.6	58.0							168.6	58.0

Table 10. Speed-Fuel Curves for 650mm Bore Ships

Table 11 shows the slow-steaming table for this ship for a bunker cost of $465 per ton. At WS110 and this bunker cost, the Phase 2 VLCC is going as fast it can.

Table 11

Slow-steaming Curve for Phase 2 Compliant VLCC

WS	AVE SPD	BFO RT	Days RT	Cargo tons	BPD	C02 TPD
30	9.50	1483	62.12	277004	31940	1.0700
40	9.97	1630	59.66	277004	33415	1.1242
50	10.39	1795	57.39	277004	34739	1.1910
60	11.47	2049	52.37	276850	38047	1.2407
70	12.24	2270	49.33	276733	40373	1.2955
80	13.25	2599	45.89	276535	43369	1.3807
90	13.71	2775	44.19	276463	44725	1.4298
100	13.94	2864	43.80	276380	45416	1.4532
110	14.13	2946	43.28	276305	45948	1.4773
		...	.	.	.	.
300	14.13	2946	43.28	276305	45948	1.4773

If we compare this ship with the non-EEDI BASE ship from Table 6, we obtain Table 12.

These numbers are biased in favor of the lower powered ship. They are calm water numbers plus a 15% sea margin for both ships. In reality, in heavy weather the low powered ship's performance will deteriorate more rapidly than the higher powered ship's. The low powered ship will suffer a larger speed reduction due to prop cavitation and limited torque; but also that larger reduction will be from a smaller base. A 2 knot reduction from 13 knots will increase voyage time by 18%. A 2 knot reduction from 15 knots will increase voyage time by 15%.

But assuming calm water, below WS100, the BASE ship puts out less CO2 thanks to its more efficient propeller and engine. At WS110 and above the BASE ship is steaming faster than the Phase 2 ship, and the CO2 balance shifts in favor of the speed limited, lower powered ship. At WS200, an all-out boom, a fleet of Phase 2 EEDI-compliant VLCC's produces 10% less operational CO2 than a fleet of BASE ships. In this situation, we need about 18% more EEDI-compliant ships to move the same amount of oil.

Table 12. Phase 2 Percent CO2 Reduction BASE ship vs 6S65ME at $465 BFO cost

WS	Avespd	Avespd	Ratio CO2	% Diff.
30	10.00	9.50	1.0101	+1.0
40	10.47	9.97	1.0218	+2.2
50	10.90	10.39	1.0311	+3.1
60	12.24	11.47	1.0291	+2.9
70	13.48	12.24	0.9911	-0.9
80	14.24	13.25	1.0189	+1.9
90	15.00	13.71	1.0141	+1.4
100	15.49	13.94	1.0073	+0.7
110	15.99	14.13	0.9873	-1.3
120	16.25	14.13	0.9636	-3.6
130	16.49	14.13	0.9484	-5.2
140	16.84	14.13	0.9185	-8.1
150	16.84	14.13	0.9185	-8.1
160	17.02	14.13	0.9029	-9.7
...	.	.	...	...
300	17.02	14.13	0.9029	-9.7
Average	1.243	1.249		+0.5

If we apply our Standard spot rate profile to this comparison, we find that a fleet of the non-EEDI ships averages 1.243 tons CO2/per ton per day delivered; the EEDI compliant ships average 1.249. The overall effect of EEDI Phase 2 at this bunker price is to ***increase*** VLCC CO2 emissions by about 0.5%.

Gratsos et al (2010) argue that at least 2.15 tons of CO2 are produced per ton of ship steel in the building and scrapping process. If we assume a VLCC lightweight of 43,000 tons and a 25 year ship life, then building/scrapping emissions are about 3.1% of operational emissions. With these numbers, an 18% larger fleet is equivalent to a 0.6% increase in operational emissions.

Slow-steaming curves for $620 BFO cost

We repeated these analyses for $620 bunkers.(Devanney, 2010b) Once again the higher bunker price shifted the numbers in favor of the BASE ship. Both ships speed up more slowly at higher BFO cost, extending the Worldscale range over which the more fuel efficient, higher powered ship produces less CO2. In any market except an all-out boom, the non-EEDI fleet emits less CO2 than the Phase 2 fleet. Assuming the Standard spot rate profile, the non-EEDI BASE fleet averages 1.167 tons CO2/TPD, the EEDI compliant fleet 1.161, a virtual tie.

Phase 2 Summary

- The Phase 2 EEDI regulations will not result in any noticeable decrease in operational VLCC CO2 emissions over a market cycle. The fuel savings due to forcing the owner to go slower in booms are balanced by the inefficiencies associated with a much smaller than optimal power plant for this sized ship. These are calm water numbers. In heavy weather, the balance shifts further in favor of the non-EEDI ship.

- The Phase 2 regulations will eventually result in a 18% larger fleet. The resulting increase in building/scrapping emissions will be equivalent to about another 0.6% increase in operational emissions.
- The Phase 2 regulations will require that just about 18% more of the world's resources be devoted to VLCC transportation, great news if you are a shipyard.
- The Phase 2 regulations will increase our exposure to VLCC casualties by 18% even before we account for the fact that the EEDI compliant ship will be less maneuverable, less able to get out of trouble than the non-EEDI ship.

Phase 3 EEDI

Slow-steaming curves for $465 BFO cost

The proposed VLCC baseline EEDI is 2.32, and the proposed Phase 3 reduction is 35% resulting in a required EEDI of 1.51. To meet the EEDI requirement with a 6 cylinder engine without throwing away a lot of power, the owner will have to go down to a 600 mm bore cylinder. The engine we used for Phase 3 is a MAN 6S60ME with an MCR of 14,280 KW at 105 RPM. According to MAN, this engine has the same SFC curve as the 650 mm bore engine, but the increase in RPM reduces the optimal propeller diameter to about 8.0 m and consequently smaller propeller will result in a 5% loss in propulsive efficiency relative to the 650 mm bore machine.

Even with the reduction in bore, this engine normally rated does not meet the required EEDI of 1.51. The owner will have to derate the engine to an MCR of about 13,240 kW. ***Phase 3 will require VLCC owners to cut installed power in half.*** This ship will have a loaded calm water, trial speed of about 12.1 knots.

Table 13. Percent CO2 Reduction.
BASE ship vs 6S60ME at $465 BFO cost

WS	Avespd	Avespd	Ratio CO2	% Diff
30	10.00	9.21	1.0427	+4.3
40	10.47	9.68	1.0604	+6.0
50	10.90	9.89	1.0111	+1.1
60	12.24	10.97	1.0118	+1.2
70	13.48	11.71	1.0091	+0.9
80	14.24	12.34	1.0084	+0.8
90	15.00	12.58	0.9860	-1.4
100	15.49	12.81	0.9819	-1.8
110	15.99	12.81	0.9467	-5.3
120	16.25	12.81	0.9240	-7.6
130	16.49	12.81	0.9095	-9.1
140	16.84	12.81	0.8808	-11.9
150	16.84	12.81	0.8808	-11.9
160	17.02	12.81	0.8658	-13.4
..	.....	..	.	.
300	17.02	12.81	0.8658	-13.4
Average	1.243	1.257		+1.1

The details of these Phase 3 calculations can be found in the CTX report.(Devanney, 2010b). Table 13 summarizes the $465 BFO results. This ship is so under-powered that at WS100, she is already going as fast as she can. This ship's engine will be pushed hard. The Phase 3 VLCC fleet will need to be 33% larger than the BASE fleet to move the same amount of oil in a boom. And that's in calm water. This ship will have lousy heavy weather performance. If we apply our Standard spot rate profile to these numbers, the non-EEDI BASE fleet averages 1.243 tons of CO2 per ton per day delivered; the EEDI-compliant fleet averages 1.257.

Slow-steaming curves for $620 BFO cost

We repeated the Phase 3 analyses for $620 BFO.(Devanney, 2010b). When you apply our Standard spot rate profile to the resulting numbers, the non-EEDI BASE ship averages 1.167 tons of CO2 per ton per day delivered; the EEDI-compliant vessel averages 1.183, for an average increase of 1.4%.

Phase 3 Summary

The Phase 3 results followed a now familiar pattern.

- Even assuming calm water, a Phase 3 EEDI compliant VLCC fleet will not produce less CO2 emissions than an non-EEDI fleet, despite the drastic reduction in installed power. In fact, the numbers indicate that, over a market cycle, the net effect of Phase 3 EEDI will be to increase calm water VLCC CO2 emissions by a little more than 1%, even before we adjust for the differences in heavy weather performance.
- The Phase 3 regulations will eventually result in a 33% larger fleet. Using the Gratsos numbers, the resulting increase in building/scrapping emissions is equivalent to about another 1.1% increase in operational emissions.
- The Phase 3 regulations will require that about 33% more of the world's resources be devoted to VLCC transportation.
- The Phase 3 regulations will increase our exposure to VLCC casualties by 33% even before we account for the fact that the dangerously under-powered EEDI compliant VLCC will be less reliable and less maneuverable than the non-EEDI ship.
- Finally, over the market cycle, the engines of the EEDI-compliant ships will be pushed much harder than those of the no-EEDI ships which will generate a big jump in machinery failure rates.

Conclusion

Table 14 summarizes our results.

Table 14. Overall Summary of Results
Pct reduction in CO2 Emissions averaged over market cycle
Negative implies EEDI compliant fleet better

BFO COST	Phase 1	Phase 2	Phase 3
$465	-1.0%	-0.5%	+1.1%
$620	-0.5%	-0.2%	+1.4%

The Phase 2 and Phase 3 EEDI fleet produce ***more*** CO2 than the non-regulated fleet. How can this be? The answer is two fold:

1. EEDI effectively limits installed power. But at current and expected BFO prices, a non-EEDI VLCC owner 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. Table 15 summarizes CTX's estimate of how VLCC owners will respond to EEDI. 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.

Table 15. Main Propulsion Parameters of EEDI Compliant VLCC's

	No EEDI	Phase 1	Phase 2	Phase 3
EEDI	2.54	2.09	1.71	1.51
MCR(kW)	27,500	23,600	16,800*	13,200**
Cylinders	7	6	6	6
BORE(mm)	840	840	650	600
RPM(MCR)	76	76	95	105
MCR SFC(book)	168	168	171	171
Prop Diam(m)	9.9	9.9	8.5	8.0
Propulsive Eff.	0.730	0.731	0.682	0.647
Exp. Area Ratio	0.487	0.412	0.447	0.431
Loaded Trial Spd	16.5	15.5	13.6	12.1

- *De-rated from 17,200 kW. **De-rated from 14,400 kW.
- Dis-allowed less than 6 cylinders on vibration grounds. Reduction gear not considered
- Lower powered ships spend much more of the market cycle at or close to MCR
and above the min SFC point
- Heavy weather, maneuvering characteristics of ships on right need to be carefully studied
- Strength, cavitation, heavy weather performance of unprecedentedly narrow VLCC propeller blades needs careful study.

And this is only at-sea emissions. Table 16 shows the VLCC fleet size requirements of EEDI.

Table 16. Increase in Fleet Size for same transport capacity

	Phase 1	Phase 2	Phase 3
Fleet Size	+4%	+18%	+33%
B/R/S CO2	+0.1%	0.6%	+1.1%

The increase in Build/Repair Scrap emissions is based on Gratsos et al. (2010) converted to equivalent at-sea emissions. These authors considered only emissions at building, repair and breaking yards. Mining, flying crews around, additional cargo loss due to tank breathing, etc were not included.

Finally, these are all calm water numbers. The low-powered EEDI compliant ship will have considerably poorer performance in heavy weather than the non-EEDI ship. As Table 15 shows, in order to meet Phase 3 EEDI, VLCC's will have to go down to about 13,000 KW MCR. ***This is less than half present practice.*** This ship will not only have great difficulty maintaining any speed in bad weather, but also her engine will be pushed much harder over the market cycle than the non-EEDI ship's. And that means a big jump in machinery failures.

As far as I know, similar studies have not been done for smaller tankers, bulkers, or big containerships; but there is every reason to believe that such studies would generate very similar results.

EEDI is a loser. So what should we do? The answer will be obvious to any first year economics student: charge the polluter for his pollution. Table 9 shows that a $50 per ton CO2 dumping fee would generate a 6.1% reduction in CO2, far more than any level of EEDI. And it will do it without wasting resources on unnecessary ships. And it will do it without forcing owners to build dangerously under-powered ships.

A carbon dumping fee is effective, efficient, and safe. EEDI is none of the above.

A VLCC Required Freight Rate

The right way to compute Required Freight Rate is to combine the investment parameters with a market rate profile, allowing the ship to use the optimal speed for whatever market it is currently in. Then adjust the profile so the investment just breaks even, and find the average of that break even profile. The standard and incorrect way to compute RFR is to assume a constant market rate throughout the ship's life, and find that rate for which the investment just breaks-even. We will use this second incorrect approach both because it is the standard definition of RFR and it is close enough for present purposes.

MFIX has the capability of computing standard RFR's, so we can use the same route, etc that we used in the slow-steaming calculations. The ship we used was our non-EEDI BASE VLCC.[10] For representative financial parameters, we fixed the following.

Yard Terms	10/10/10/0/70
Loan Terms	60 million at 7.7%, 7 years, level
OPEX	$9000 per day
Drydocking	Every 4 years, 15 days, $3,000,000
Inflation	3% per year
Scrap value	$400 per lt-ton, 43,000 ton ltwt

We varied ship price (80, 100, 120) million dollars, ship life (20, 25) years, discount rate (10%, 15%), and fuel price ($465, $620) per ton. Table 17 summarizes the results. Obviously, you can move these numbers around by varying the parameters, but a reasonable ball park figure for $465/t is high 50's, low 60's.

Since Worldscale is tied to bunker prices with a lag, the $620/t BFO numbers are not really applicable. If BFO cost did move to $620 for a year or so, then the Worldscale flat rate would be adjusted upward, pushing the RFR numbers back down to those we see for current bunker cost.

[10] The EEDI compliant ships will have a higher RFR representing the long-run market cost to society of the regulation.

Table 17. Representative RFR's

20 year ship life				
	$465/t BFO			$620/t
Price	80mm$	100mm$	120mm$	100mm$
10%	WS54.7	WS59.6	WS64.5	WS67.5
15%	WS60.5	WS67.4	WS71.3	WS75.3
25 year ship life				
	$465/t BFO			$620/t
Price	80mm$	100mm$	120mm$	100mm$
10%	WS53.5	WS57.9	WS62.4	WS65.5
15%	WS59.7	WS66.2	WS72.8	WS74.1

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