Comparison of Three Marine Black Carbon Measurement Methods

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BACKGROUND & MOTIVATION

- Ship transportation plays a major role in the global economy and international trade by contributing to 80% of global trade by volume and over 70% of global trade by value.

- **Marine Black Carbon**
- Black carbon (BC) emissions from ocean going vessels (OGVs) have been a concern in terms of global warming and human health, especially in the Arctic area where BC is associated with the ice melting problems due to the light absorbing ability of BC deposits on ice. BC is the most strongly light-absorbing component of particulate matter (PM) and second to carbon dioxide as the largest contributor to human induced climate warming.

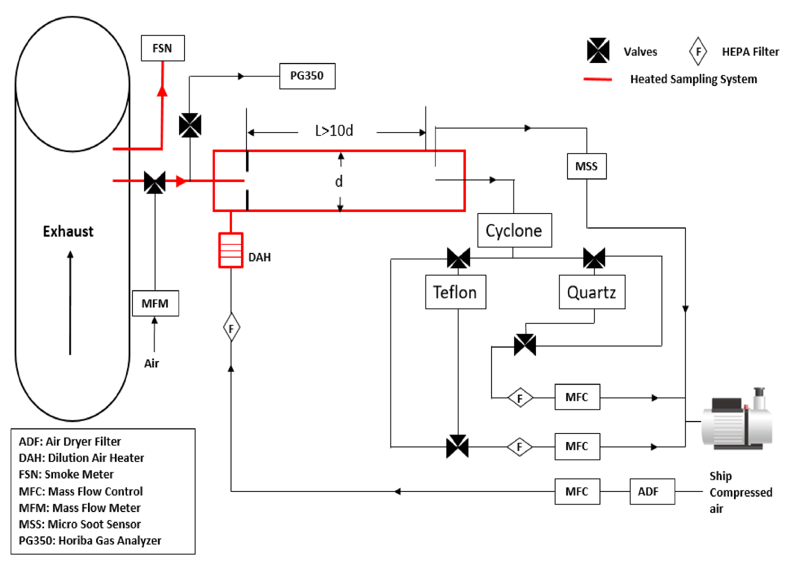
- Currently, ship-related BC emission factors range from 0.1 to 1 g/kg fuel. Further complicating the uncertainty in the reported BC emission factors is the use of a multitude of analytical instruments in measuring BC. Even though each instrument is properly set up and calibrated, since the scientific principle used for the measurement differs between. It is necessary to quantify and standard a way to measure BC emissions on OGVs.

- **Marine NOx emissions**
- NOx emissions from OGVs have been a concern of human health due to atmospheric reactions for O_3 formation. It is more of a concern since the NOx emissions has been reduced significantly by the application of SCR systems for on-road heavy duty diesel trucks and large off-road equipment.

- To address the IMO low sulfur regulation and the upcoming NOx technical code, as well as to improve the fuel economy of the marine shipping, advanced engine technologies (electronic controlled fuel and lube oil injection, EGR, turbocharger cutoff operation) and advance aftertreatment technologies (scrubber, SCR, DPF) are beginning to be commercialized. Few studies have been done in this area to understand the NOx performance of these advanced engine and aftertreatment technologies.

EXPERIMENTAL METHODS

Ship Sampling System



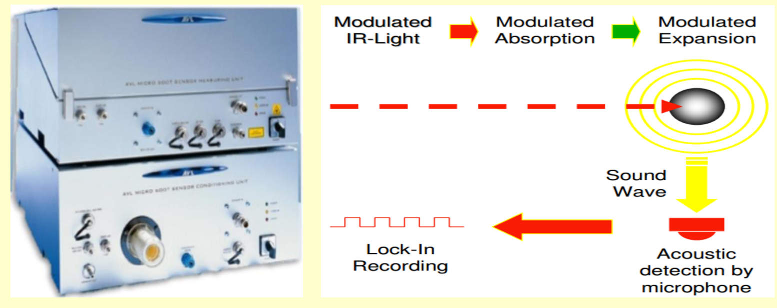
Instrumentation

- **Sampling System** (control of dilution ratio and filter sampling temperature)
- Horiba PG350 multi-gas analyzer (NOx, CO, CO_2, SO_2, O_2).
- **PM Mass**: 47mm Teflon filter
- **Black Carbon**
  - light absorption photoacoustic: AVL MSS 483
  - Paper based light absorption method: AVL FSN 415SE
  - NIOSH thermal optical method: Quartz ECOC Filter

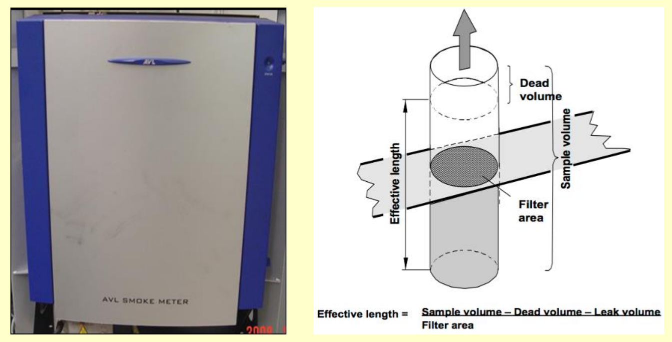
Test Protocol

- ISO E2 test cycle for the main engine (ME) uses a weighting value of 0.2, 0.5, 0.15, and 0.15 for the 100%, 75%, 50%, 25% load points.
- Marine engines were operated and stabilized at least 30 minutes before testing.

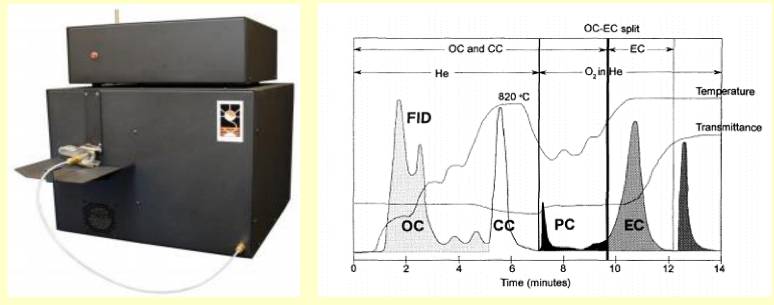
AVL Microsoot Sensor (MSS)

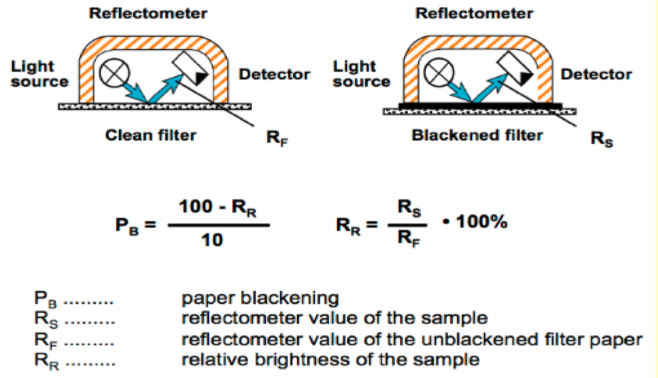


AVL Smoke Meter



Sunset Laboratory ECOC



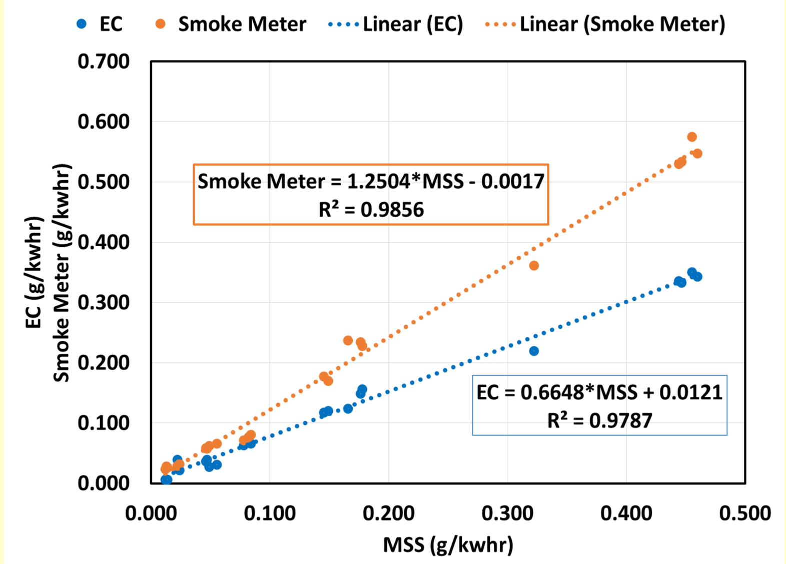


Marine Black Carbon Measurement

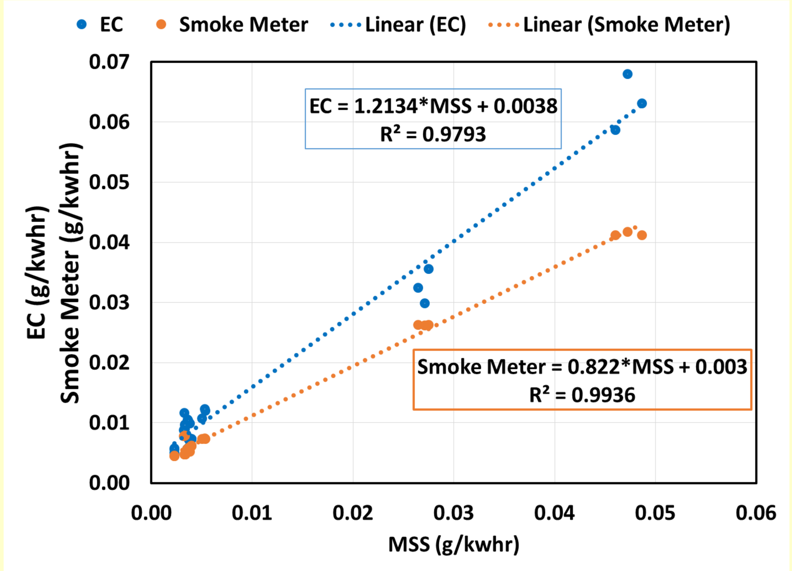
Test Vessels, Engines, and Fuels

	Engine Test	Vessel 1	Vessel 2	Vessel 3
Year Build	1976	1987	2012	2015
Vessel Type	AE Engine	Container	Container	Ro-Ro
IMO Category	Tier 0	Tier 0	Tier 2	Tier 2
ME Engine	Detroit Diesel	Mitsui Man B&W	Mitsui Man B&W	Hyundai Man B&W
Year Build	1976	1986	2011	2014
Model	6-71N	7L70	12K98ME6.14	8S60ME-C8.2
Power Capacity (MW)	0.19	16.60	69.68	15.56
Test Fuel	MGO (<0.1% S), HFO (<0.1%), and HFO (3.2% S)	HFO (1.9% S)	MGO (<0.1% S)	HFO (2.5% S)

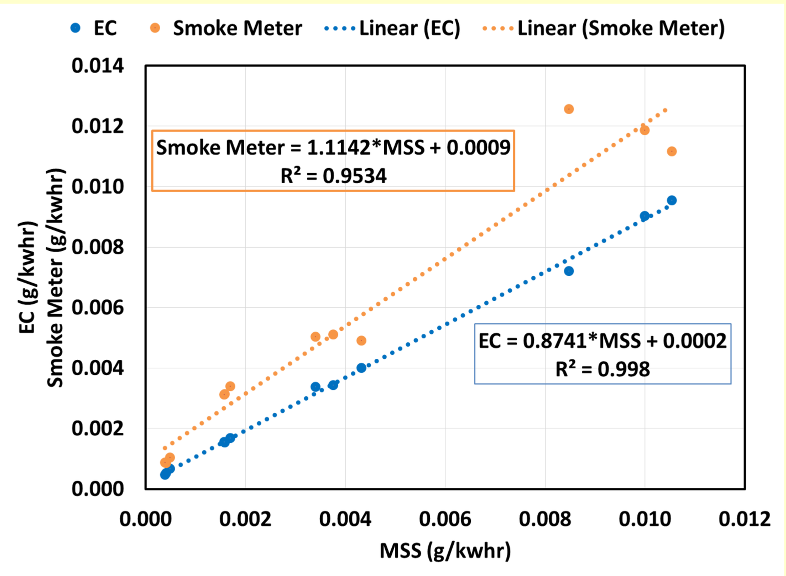
Previous Engine Dyno Testing



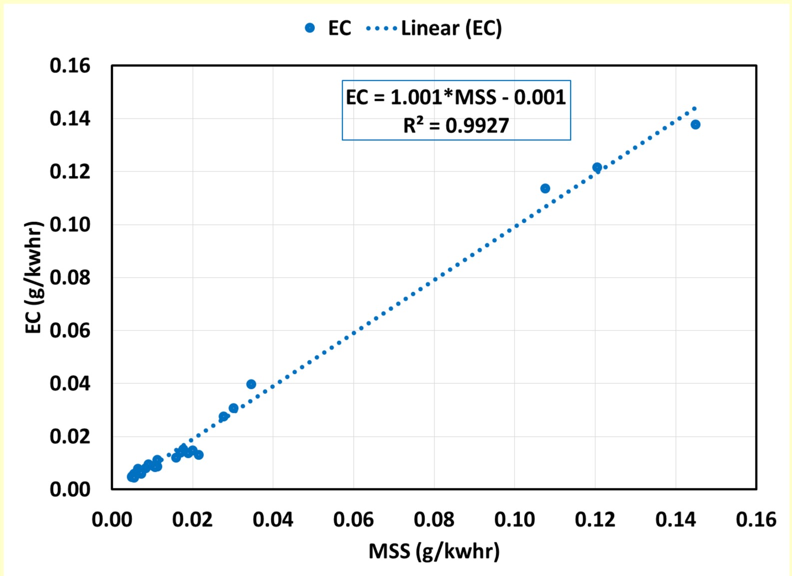
Vessel 1



Vessel 2



Vessel 3



- Comparing the data from the OGVs to our previous engine dyno study, there is an inconsistent trend observed from Smoke Meter and ECOC compared to MSS. The inconsistent trend indicates that the different BC measurement methods could be impacted under different conditions.
- The results from OGVs indicate that the sulfur content in the fuel seems to be the reason for the inconsistencies, although this trend was not observed in the engine dyno study.
- Looking into the filter PM composition, it appears that the filters from engine dyno study are mostly EC and OC. In contrast, PM composition from large 2-stroke marine engines with high sulfur fuel show sulfate ion to be the dominating species.
- The sulfate PM on the filters is known to exist in its hydrophilic compound form ($H_2SO4*6.65H_20$). It is not surprising the inclusion of water due to the hygroscopic property of the sulfuric acid.
- Sulfate PM on the filters is determined to impact the different BC measurement methods.

Compound (μg/filter)	Engine Test	Vessel 1	Vessel 2	Vessel 3
EC	4 - 476	2 - 82	2 - 44	8 - 147
OC	9 - 515	55 - 493	167 - 600	240 - 599
$SO4^-$	1 - 100	102 - 3380	-	122 - 1830

Smoke Meter (Paper Based Light Absorption)

- Smoke Meter uses reflectometer method with PM loaded filters.
- Once heavy amounts of sulfuric acid water hydrophilic compounds are loaded on the filters, the reflectometer value of the sample (Rs) will go up, as well as the relative brightness of the sample (R_R) value, which then leads to a lower paper blackening value (P_B).
- This could explain why the Smoke Meter has a lower value in high sulfur fuel.

ECOC (Thermal Optical)

- The high concentrations of sulfate PM on the filters could potentially uptake water from OC, along with forming sulfonated organics compounds, at low temperatures. The sulfonated organics are able to absorb red laser, which subsequently impacts the ECOC split point. This could lead to higher EC levels.

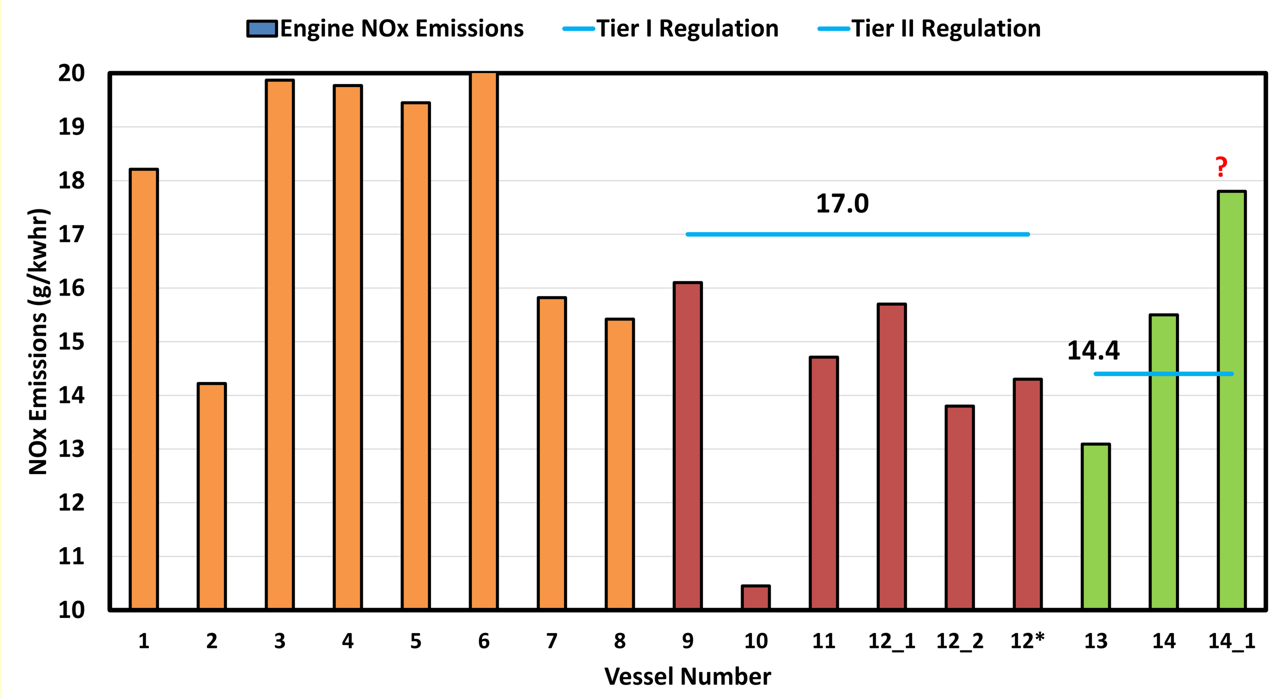
Marine NOx Emission Factor

Test Vessels, Engines, and Fuels

	Vessel Type	IMO Category	ME Engine	Year Build	Model	Power Capacity (MW)	Test Fuel	Special Technology on ME	NOx (g/kwhr)	Sources
1	Container	Tier 0	Man B&W	1995	11K90MC-C	5.03	HFO (2.05% S)	None	18.21	CECERT: Harshit_2008_AE
2	Container_RoRo	Tier 0	Kincaid B&W	1985	6L90 GBE	20.20	HFO (1.97% S)	None	14.22	Moldanova_2009_AE
3	Crude Oil Tanker	Tier 0	Sulzer	NA	6RTA72	15.75	HFO (2.85% S)	None	19.87	CECERT: Harshit_2008_EST
4	Container	Tier 0	Hitachi Man B&W	1998	12K90MC	5.48	HFO (3.01% S)	None	19.77	CECERT: Harshit_2010_JGR
5	container	Tier 0	Sulzer	1997	9RTA84C	36.74	HFO (2.15-3.14% S)	None	19.45	CECERT: Khan_2013_JAWMA
6	Container	Tier 0	Samsung Man B&W	2000	12K90MC	55.66	HFO (0.95% S) and MGO (0.3% S)	None	20.25	CECERT
7	Container	Tier 0	Mitsui B&W	1987	7L70	16.58	HFO (1.88% S)	Scubber	15.82	CECERT
8	Container	Tier 0	NA	1985	NA	17.50	HFO (2.4% S)	NA	15.42	Fridell_2008_AE
9	Container	Tier 1	Hyundai B&W	2009	11K98ME7	68.53	HFO (2.51% S) and MGO (0.17% S)	None	16.1	CECERT: Khan_2012_EST
10	Crude Oil Tanker	Tier 1	Man B&W	2006	6L48/60	6.30	LSHFO and MGO (<0.1% S)	Variable Injection Timing (VVT)	10.45	CECERT: Gysel_2017_EST
11	RoRo	Tier 1	NA	2004	NA	20.07	HFO (2.2% S)	None	14.71	Fridell_2008_AE
12	RoRo	Tier 1	Man B&W	2006	9L60MC-C	21.06	HFO (2.3% S)	Scrubber	15.7-13.8	Fridell_2014_JEME
12*	RoRo	Tier 1	Man B&W	2006	9L60MC-C	21.06	HFO (2.2% S)	Scrubber	14.3	Danish EPA_2012
13	RoRo	Tier 2	Hyundai B&W	2014	8S60ME-C8	15.56	HFO (2.5% S)	Electronic Controlled Fuel and Oil Injection; Scrubber	13.1	CECERT
14	Container	Tier 2	Man B&W	2011	12K98ME6.1	69.68	MGO <(0.1% S)	Electronic Controlled Fuel and Oil Injection; Turbocharger cut off fuel economy operation	15.5 or 17.8	CECERT

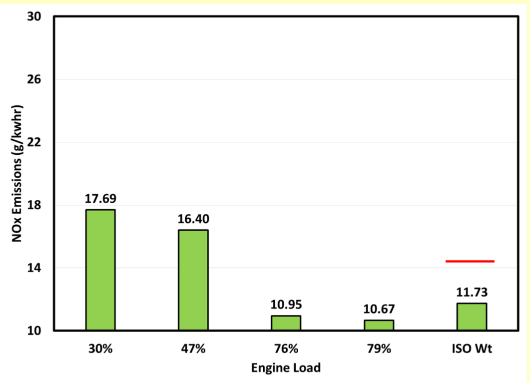
*Danish Ministry of Environment has repeated the test of this scrubber vessel.

Large Ocean Going Vessel (rpm<130) NOx Emission Factor

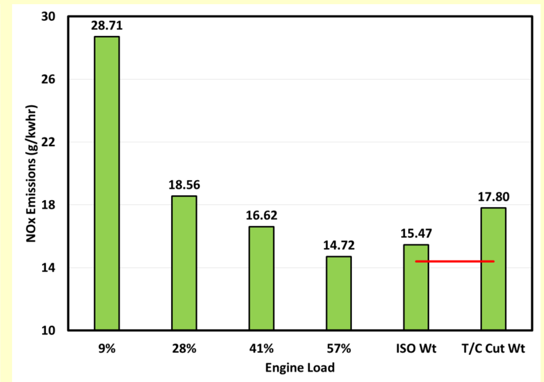


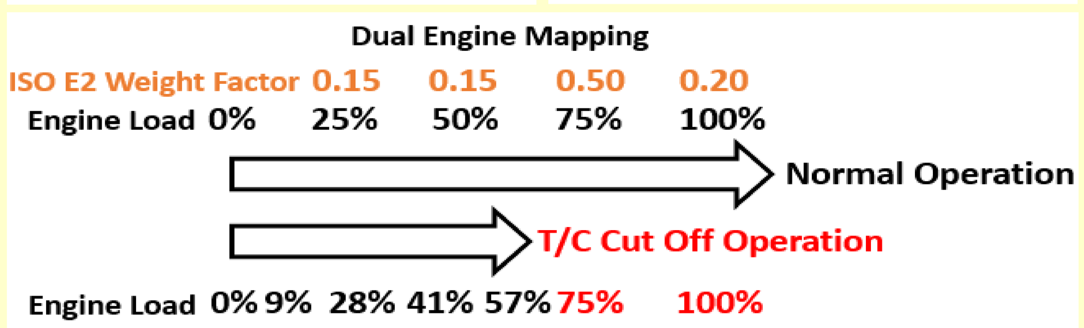
- **Scrubber:** Does not change the NOx emissions.
- **ECFOI and VVT:** Reduce the NOx emissions by controlling the peak combustion temperature.
- **T/C Cut for Slow Steaming Operation:** could potentially increase NOx emissions.

Tier II Normal Operation

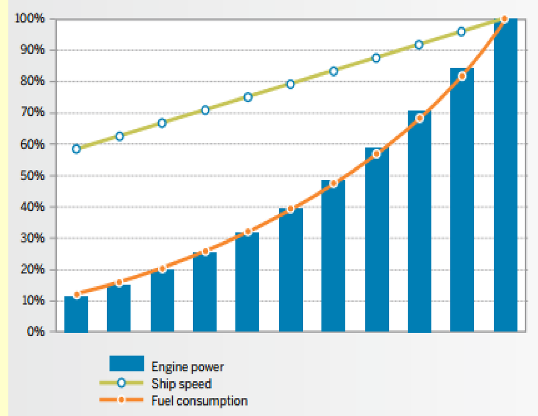


Tier II T/C Cut Off Operation

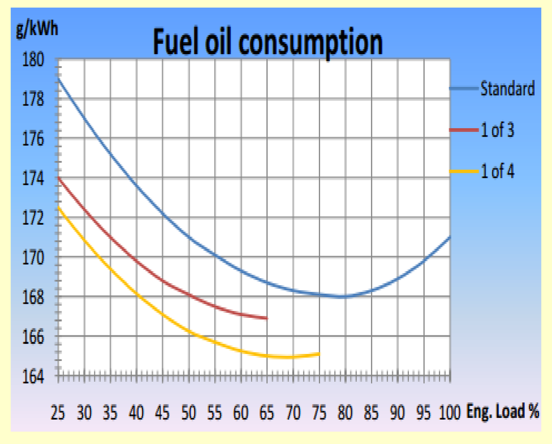




Why Slow Steaming?



Why T/C Cut Off?



- **Slow Steaming:** The easiest way to reduce this cost is to reduce the ship's speed.
- **Turbocharger (T/C) Cut Off Operation for Slow Steaming:** When the engine is operating at part load, one of the turbochargers is intentionally cut off to increase scavenging air pressure, compression air pressure, and maximum combustion pressure. This pressure increase boosts thermal efficiency.

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