Establishing the Baseline for Measurements and Technology Evaluation

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Why is a better baseline needed?

- Current data (published) is very sparse
  - e.g., Lloyd's measured 60 engines on 50 ships
  - study focused on older, oceangoing cargo ships
- Limited samples do not reflect diverse fleet
  - e.g., ferry vessels are currently being studied
  - e.g., even fewer inland river towboats tested
- Technology choices may differ across types
  - e.g., costs and feasibility may differ greatly

Take home message: Monitoring is a Technology Enabler

- Emerging consensus that more testing needed
- Industry looking for guidance on testing and on technology alternatives
  - motivated by port needs, state implementation plans, national and international policy action
- Technologies are available now, with advanced emissions control systems emerging
- Efforts need to be reported in a way that makes their insights comparable and robust
- Market-based efforts require low-cost monitoring that is both accurate (enough) and verifiable

Outline

- What is our current understanding? Gaps?
- Emissions measurement overview
  - – Current testing standards
  - – "Gold standard" emissions monitoring
  - – Industry-friendly options that meet policy goals
- Technology evaluation overview
  - – Getting beyond sticker shock
  - – Drawing insights out of the demonstrations
  - – Better performance through modernization
  - – Innovations in vessel, port, cargo interface

Current MTS Trends

- Overarching trend: globalization and integration of transportation systems
- Modernization and expansion
- Multiple constraints and policy issues
  - ship air pollution only newest issue for industry
- Industry and government (DOT, MARAD) increased partnering to promote U.S. fleet
  - U.S. opportunity to be proactive, not left behind
  - U.S. domestic waterborne freight offers capacity

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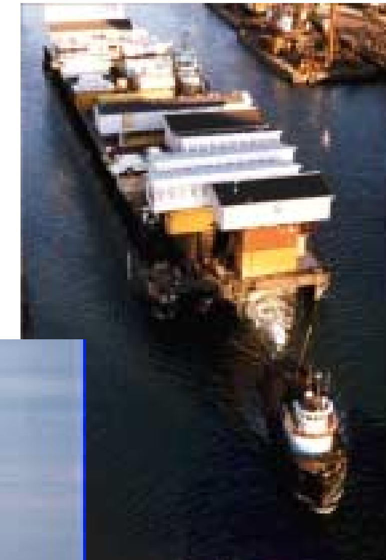
Complex System



- Tug and towboats
  - 1-30 barges: .5-4 MW
- High speed ferries
  - 150-350 passengers: 2-4 MW
- Roll-on\Roll-off
  - 200-600 vehicles: 15-25 MW
- Tankers
  - 250,000 tons of oil: 25-35 MW
- Container
  - 1750 TEU: 20-25 MW
  - 4300TEU: 35-45 MW
  - 6000 TEU: 55-65 MW

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Maritime Transportation Emissions: Evolving Consensus

Previous views about ship emissions:		Current understanding:
2% of CO_2 therefore not significant	→	14% of NOx, 5% of SOx, 2% of CO_2 from fossil fuel
Offshore, so no impact	→	Nearshore and long range impacts
Difficult to control	→	Feasible technologies at reasonable costs
		Policy needed

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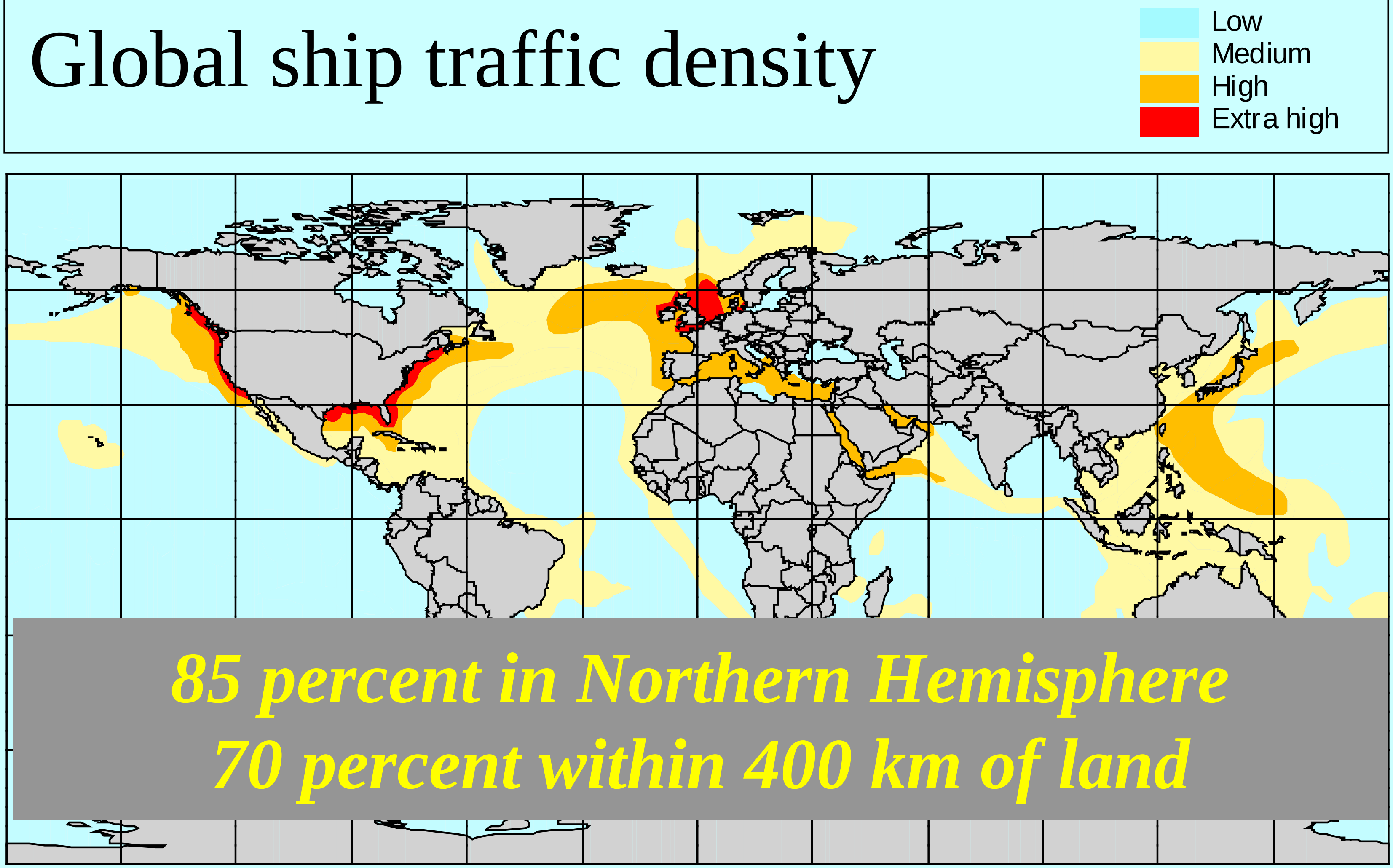
Ship Emissions Overview

- Cargo ships produce ~70% of ship emissions
- Ships are natural leaders in fuel economy, resulting in lower CO_2 per cargo-mile
- Last unregulated source for traditional air pollutants (SOx, PM, NOx)
  - Residual fuels result in higher emissions of particulate matter (PM) and sulfur oxides (SOx)
  - Marine diesel engines emit more NOx, contributing to regional air pollution

The goal is to achieve win-win reductions

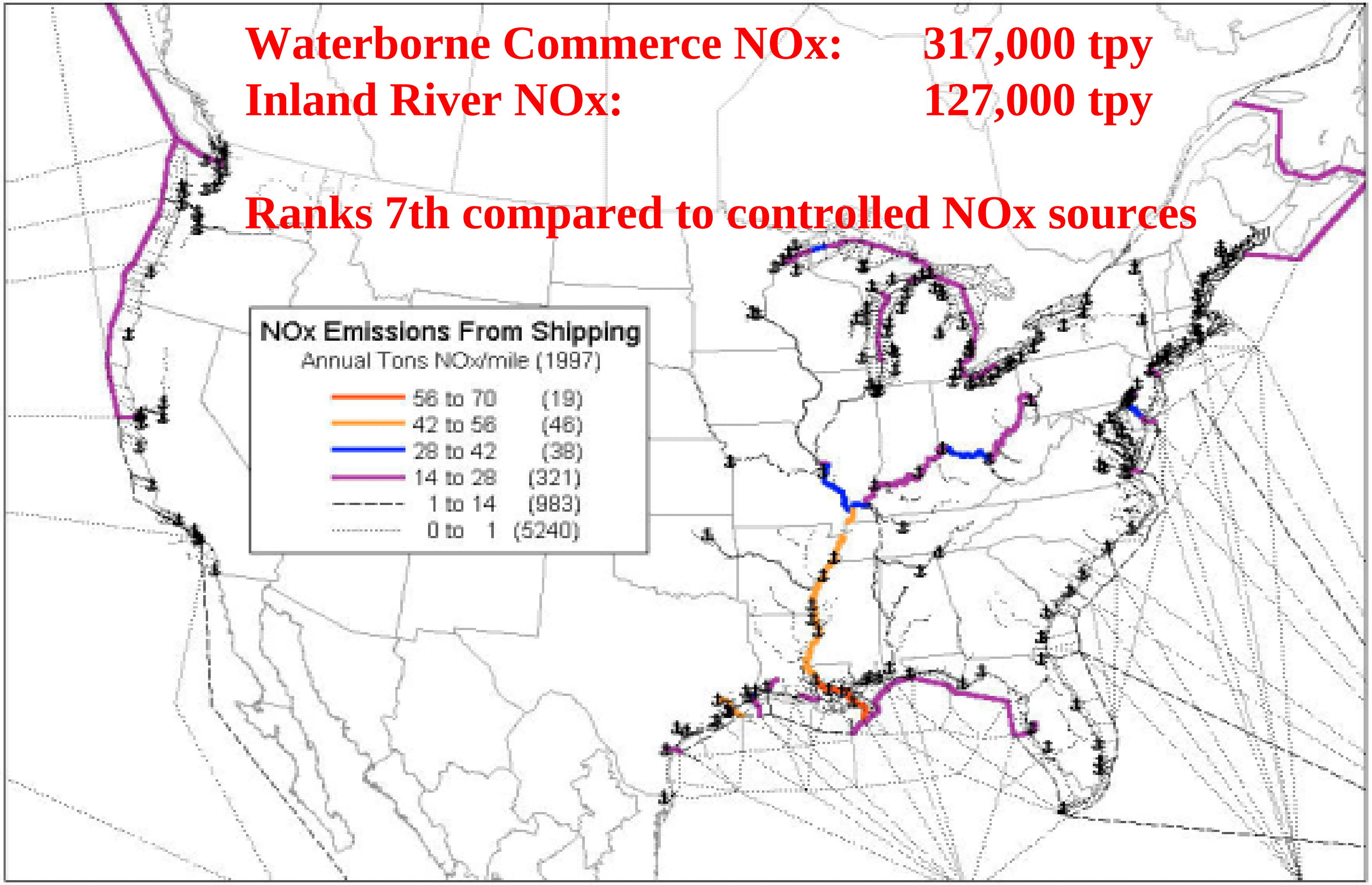
Global ship traffic density



85 percent in Northern Hemisphere
70 percent within 400 km of land

Source: IMO Study on Greenhouse Gas Emissions from Ships, MEPC 45(8), 2000.

NO_X Emissions From US Ships



Source: J. Corbett and P. Fischbeck, ES&T, 2000

Gaps in current understanding

- Challenges
  - geographic characterization
  - treatment of uncertainty
- Important modeling weaknesses
  - model assumptions may not be "real world"
    - in-service sampling is too limited to adequately inform models
  - calculations typically use large-scale averages
    - ignore regional variability in activity
    - in-plume chemistry may be very different than ambient average
  - inverse modeling of actual observations requires simultaneous monitoring and case-specific analysis

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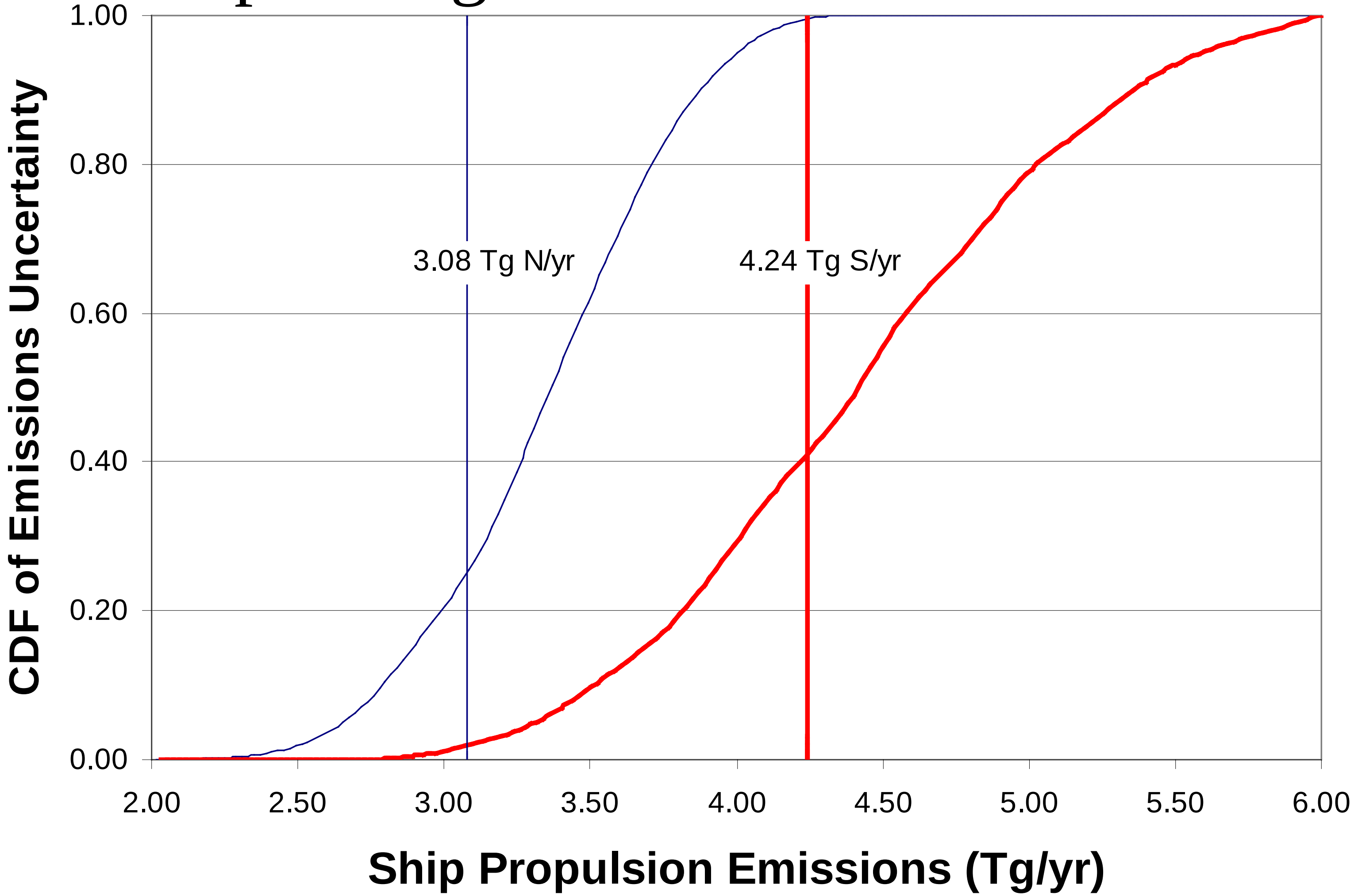
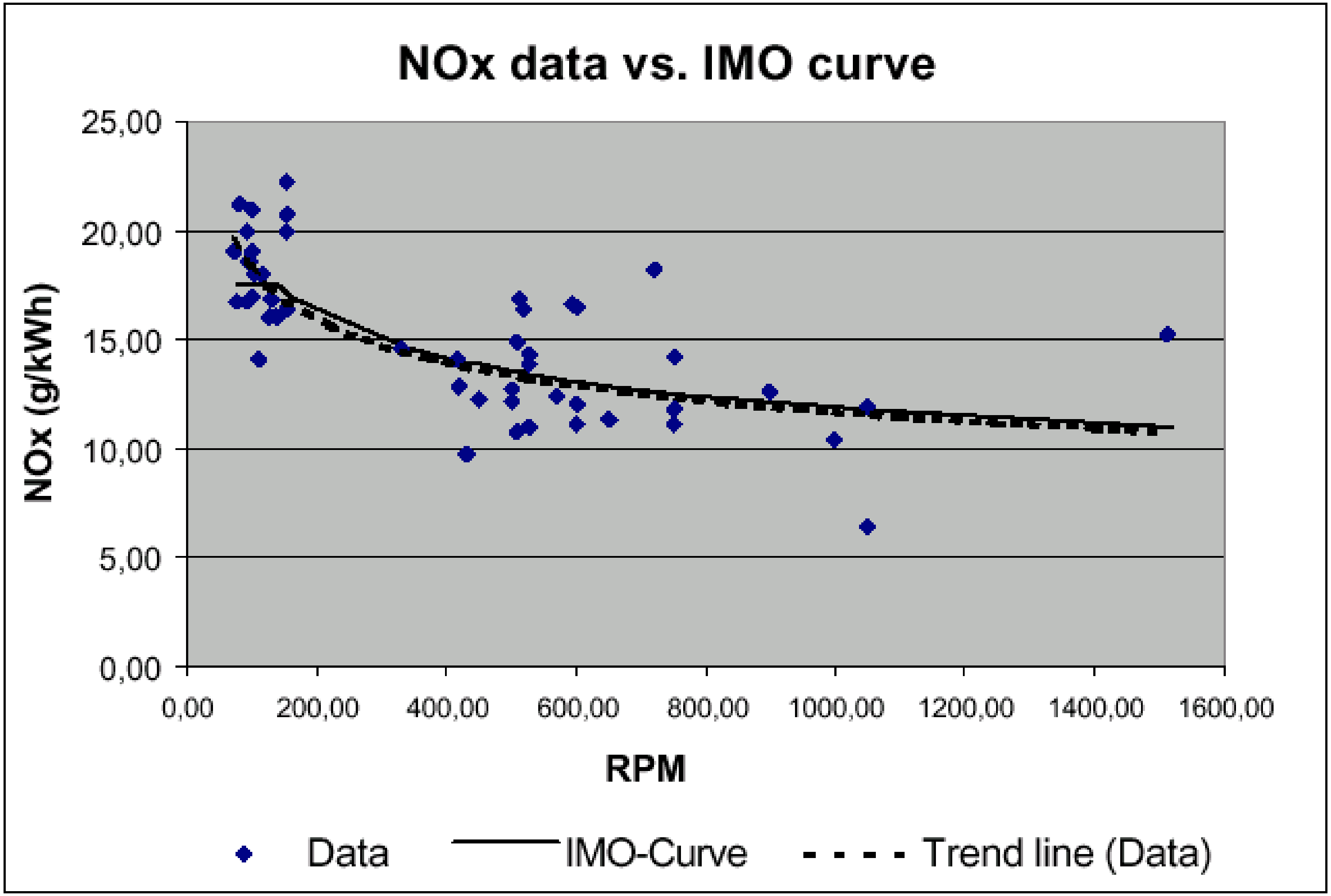
Uncertainty Analysis for International Ship Nitrogen and Sulfur Emissions



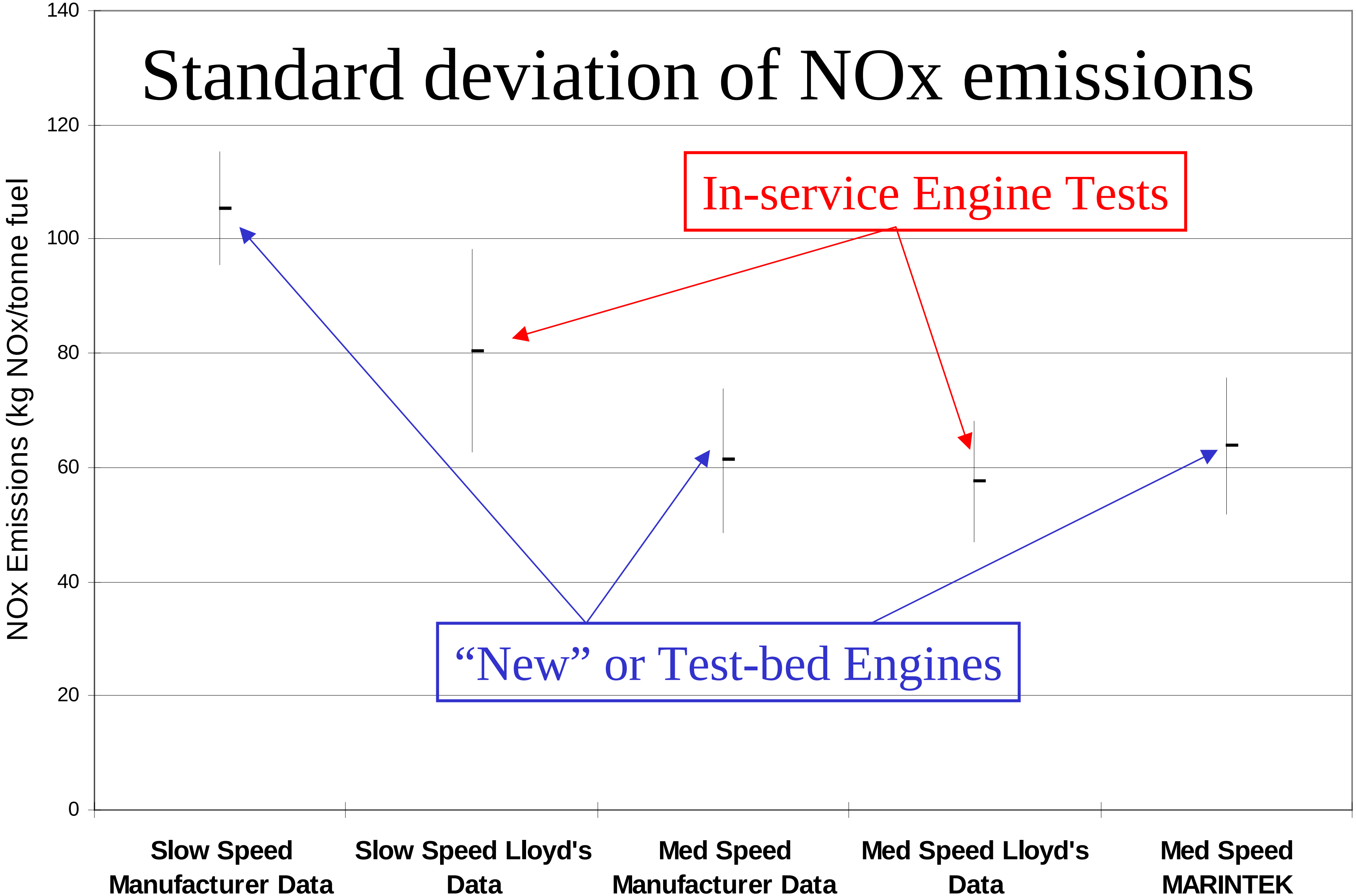
Engine Test Standards

- ISO 8137 (Parts 1-9) is the source
  - Only Parts 2 addresses in-service tests
  - Part 4 defines standard marine duty cycles
- IMO NOx Technical Code is similar
- Measured at steady-state load points
- Produces ***one*** average emissions factor
- EPA requires the ISO E3 duty cycle
- Only EPA regulations address transients

In general, the data reveals important insights: IMO standard describes the current trend



Source: IMO Study on Greenhouse Gas Emissions from Ships, MEPC 45(8), 2000.



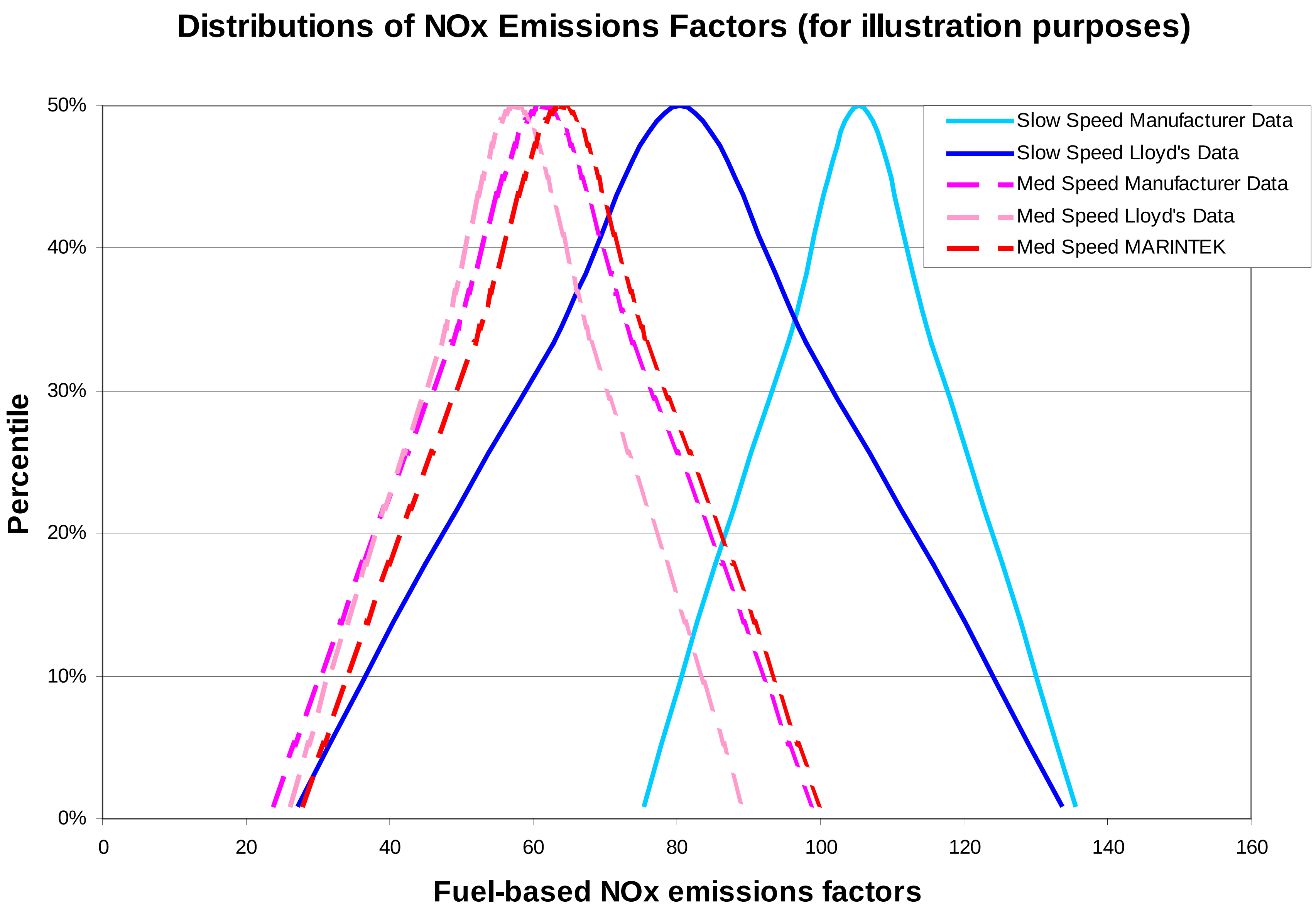
Source: IMO Study on Greenhouse Gas Emissions from Ships, MEPC 45(8), 2000.

Can we aggregate these data?

- Each of these summaries represent different numbers of engines, different techniques
- Aggregating is tough enough with good data, but what makes the data good?
  - Briefcase NOx (single-pollutant) monitor only?
  - Measure several combustion products?
  - Response time enables transient readings?
  - Engine load versus propeller load

Some Key Research Questions

- Is there a change in emissions with age?
- How large is the difference between engines types?
- Do these data apply to ferries, towboats, tugs?


Distributions of NOx Emissions Factors (for illustration purposes)
Percentile
50%
40%
30%
20%
10%
0%
0
20
40
60
80
100
120
140
160
Fuel-based NOx emissions factors
Slow Speed Manufacturer Data
Slow Speed Lloyd's Data
Med Speed Manufacturer Data
Med Speed Lloyd's Data
Med Speed MARINTEK

More measurement studies underway

TABLE 1. Comparison of Average NO_x Factor for Small Tow with Current In-Use Fleet Averages of Other Diesel-Based Transportation Modes

diesel-powered vehicle type	NO_x EF (kg NO_x /t fuel)	NO_x EF (g/kWh)
Small Tow (this work)[a]	70	15.3
medium-speed marine engine[b]	57	12
slow-speed marine engine[b]	87	17
truck diesel engine[c]	33	7
locomotive engine[c]	81	18
non-road vehicle engine[c]	50	11
EPA Tier 2 standard for new CI marine engines[d]	33	7.2

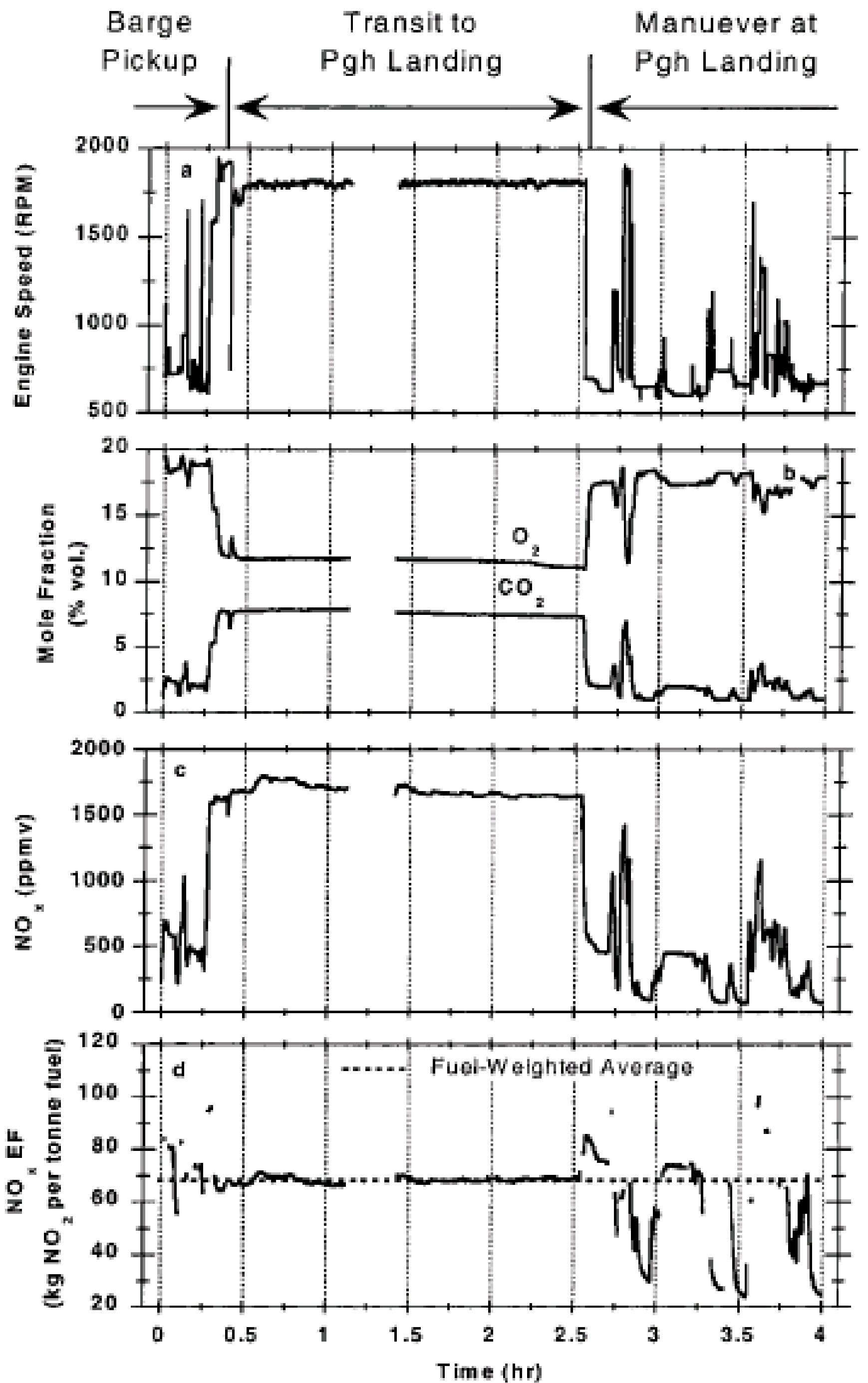
[a] Fuel-flow-weighted average. Conversion to g/kWh for Small Tow assumes an engine efficiency of 0.45. [b] Lloyd's Marine Exhaust Emissions Program (*7*). [c] AP-42: Compilation of Air Pollutant Emission Factors (*19*). [d] U.S. EPA (*5*).

Source: Corbett and Robinson, 2000.

Continuous Monitoring Captures Transients:

- Engine speed measured directly
- Combustion products provide fuel balance (oxygen or carbon based)
- Raw measurements of NOx (ppmv) identify pollutant
- Enables us to calculate engine fuel-based emissions factor

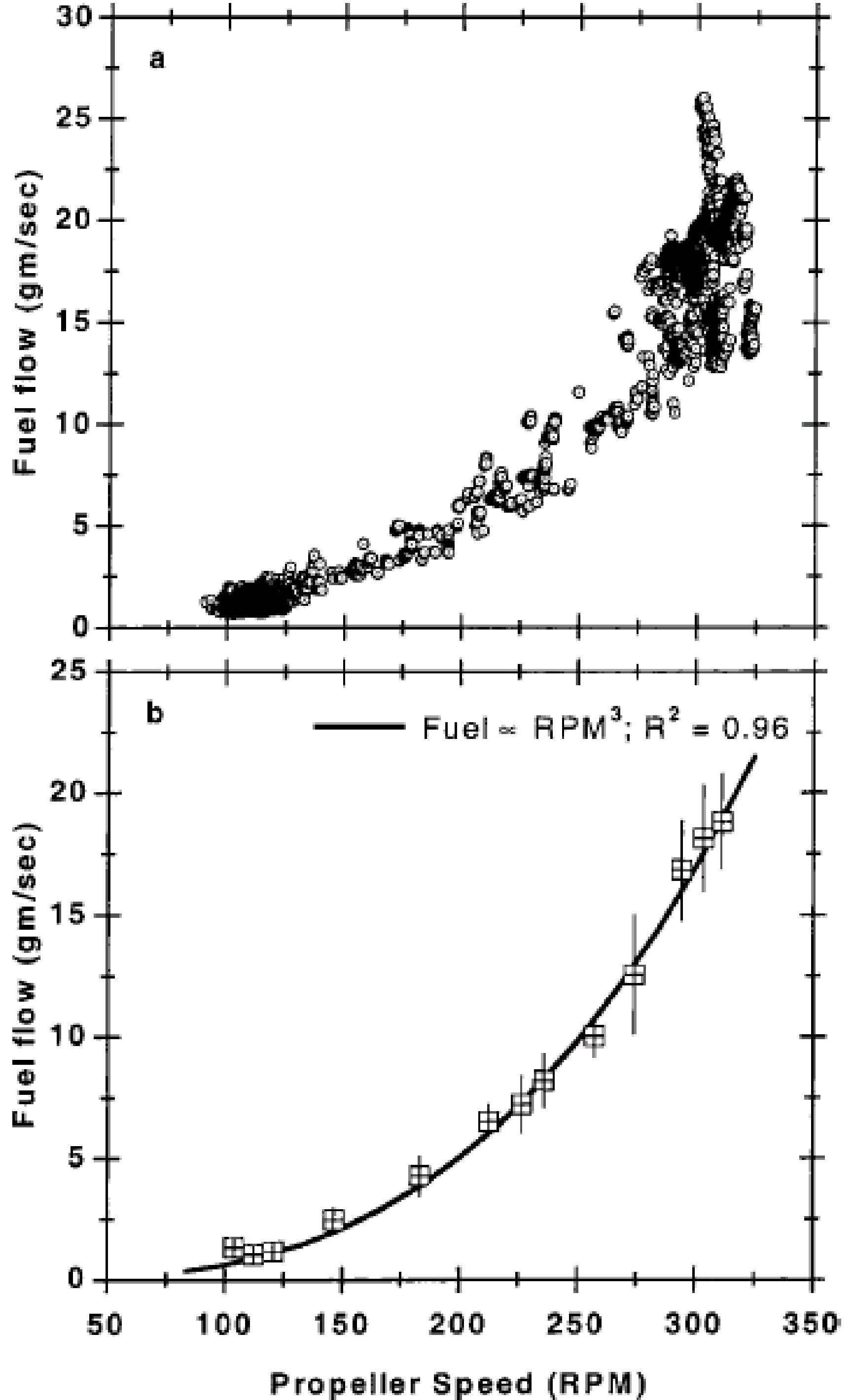
- Need shaft horsepower to get ship power-based emissions factor



Source: Corbett and Robinson, 2000.

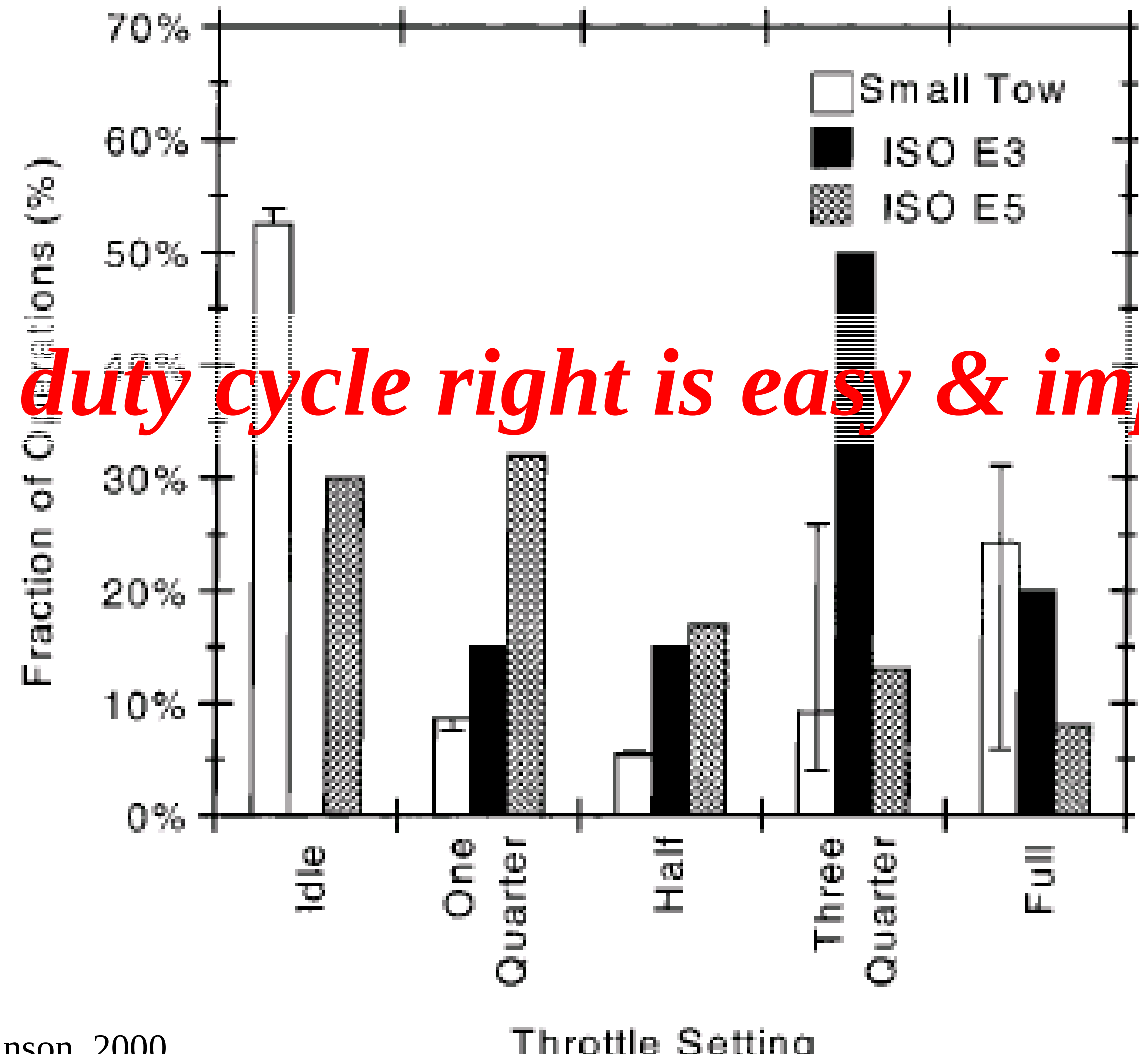
The challenge of moving from engine-fuel to shaft-power emissions:

- Propeller curve for a given vessel may vary with load, current, etc.
- However, the overall relationship is very strong
- How this may differ between hull designs can be generally inferred but has not been measured
  - Faster hull designs and advanced propulsion may require special tests



Source: Corbett and Robinson, 2000.

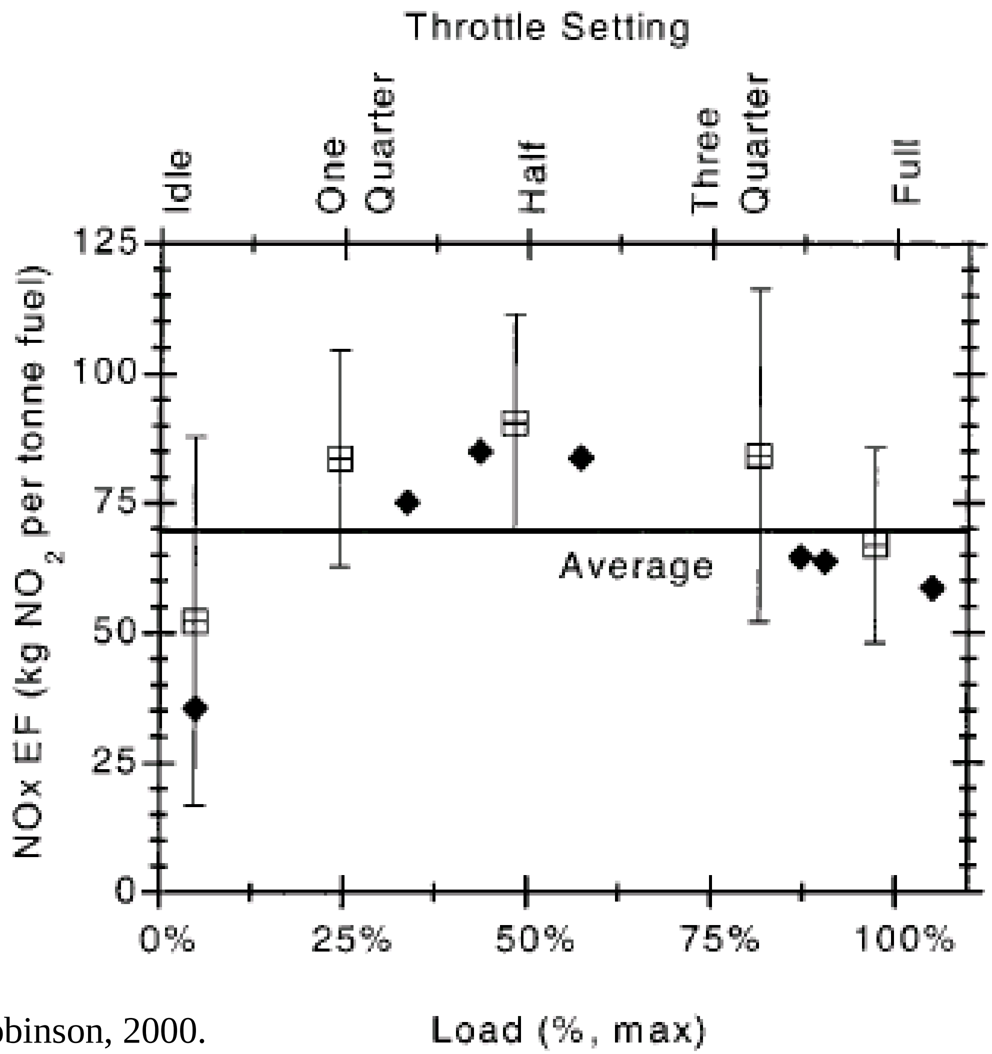
By ignoring idle, both ISO E3 and E5 overestimate average emissions factor for this vessel by ~14%



Getting duty cycle right is easy & important

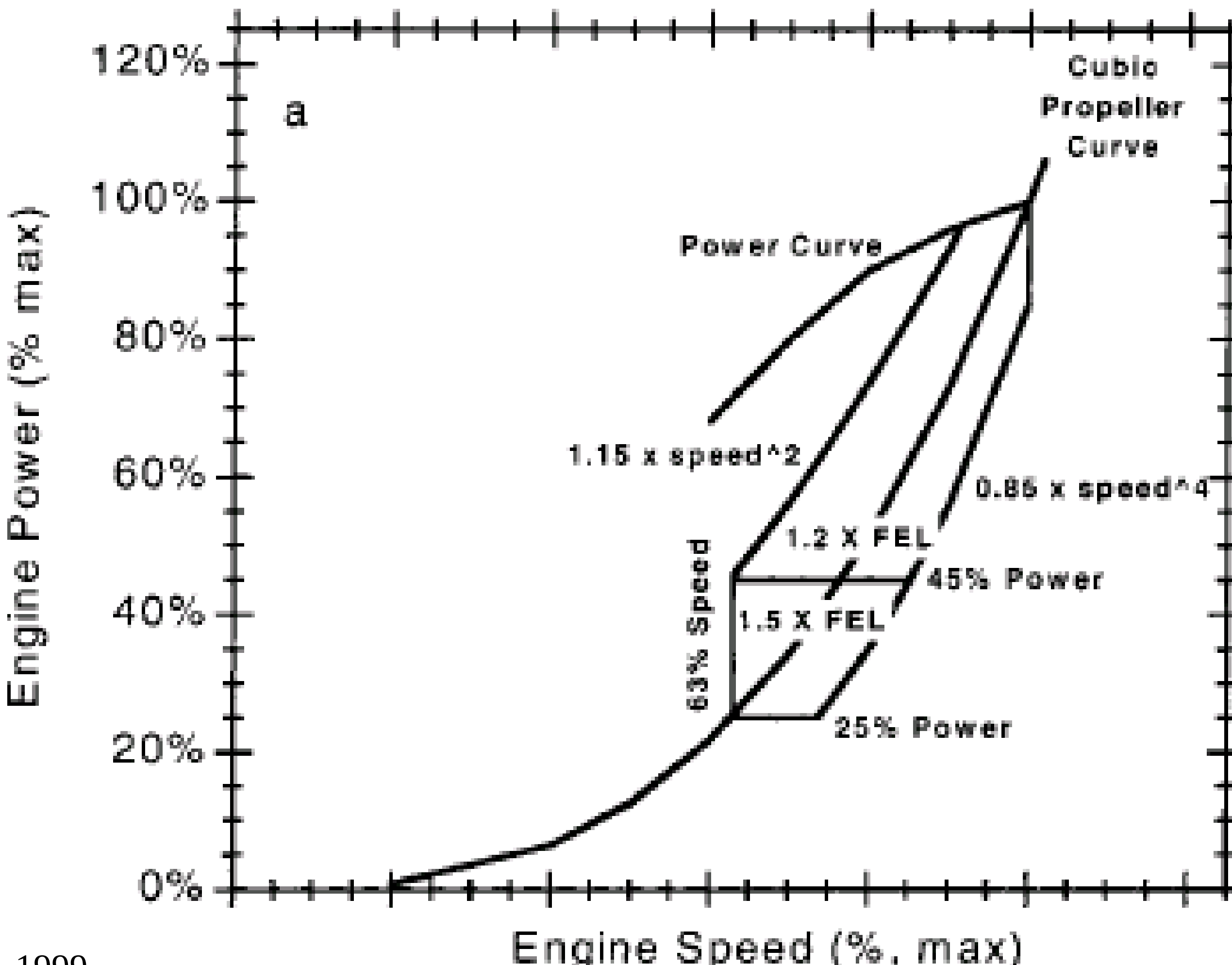
Source: Corbett and Robinson, 2000.

Measuring at steady-state versus averaging normal operations shows same trends, but different values



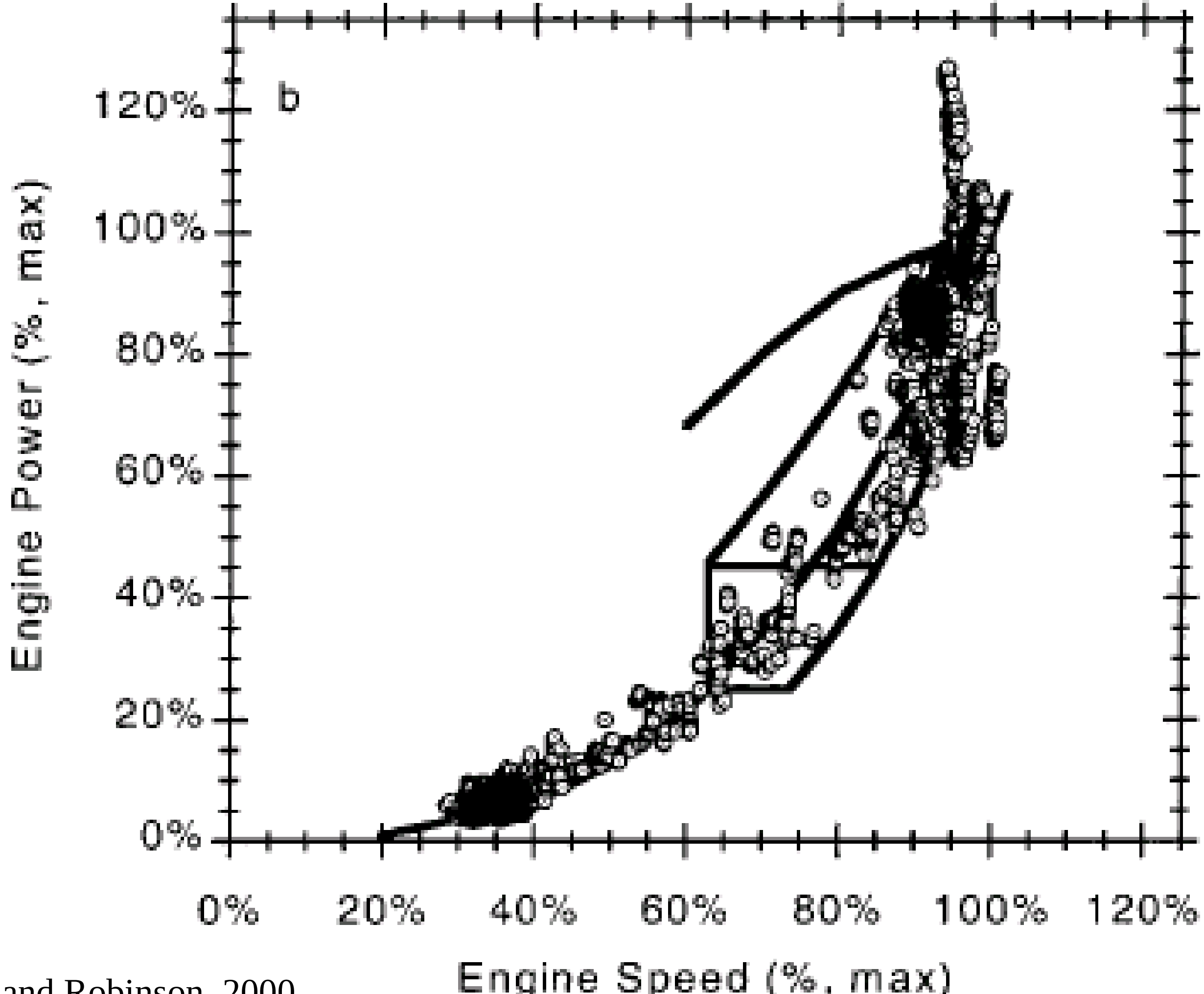
Source: Corbett and Robinson, 2000.

EPA limits on transients



Source: EPA 1999.

At least on one vessel, EPA standards for transients miss 61% of load profile



Source: Corbett and Robinson, 2000.

Technology Perspectives

- Demo projects produce learning-by-doing
- Evaluating technologies requires more than vendor estimates of capital costs
  - Needs to include life-cycle costs to ship, acknowledge that costs decline over time
  - May need to consider infrastructure and port costs/impacts
  - Should be extended to consider costs/impacts on other units
    - per ship, per voyage, per year
    - per TEU (ton cargo or per passenger), per ton-mile (or pass-mile)

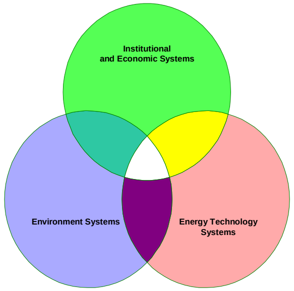
Technology costs will come down with market penetration, demo successes

Opportunities to Reduce Emissions

- Short-term: Operational measures, limited potential
    - IMO study showed potential for slower speeds to reduce emissions
    - Being tried in Southern California under voluntary plan
    - Other operational improvements possible, but difficult to enforce

- Near-term: After-treatment retrofits, cleaner diesels
    - This is being done in Europe! Demonstration projects in U.S.

- Long-term: Alternative fuels for diesels, advanced engine technologies, alternative propulsion
    - Need for demonstration projects, policy and business incentives



New design requirements in the MTS context?

- Global shipping may be "market-optimized" for low CO_2 emissions unless innovation occurs
- Not simply a NOx-reduction problem
- Pollution control may incur CO_2 penalties

Technologies for Existing Engines:

Performance Attributes Summary of NOx Control Technologies for Existing Engines

Control Technology	Nominal NOx Reduction (%)	Nominal Reduction in PM and Other Pollutants (%)[a]	Nominal Increased Fuel Use (%)	NPV Costs (15% interest annually over 23 years)	Global Cost Effectiveness ($/ton NOx)
Aftercooler upgrade	10	-1	2	$184,000	$620
Engine derating	14	-10	4	$386,000	$933
Fuel pressure increase	14	-21	2	$220,000	$523
Injector upgrade	16	-21	2	$192,000	$410
Injection Timing Retard	19	-11	4	$363,000	$618
Water in combustion air	28	1	3	$365,000	$468
Exhaust gas recirculation	34	-51	0	$16,900,000	$16,377
Water/fuel emulsion	42	15	2	$325,000	$284
Selective catalytic reduction	81	0	0	$475,000	$227

Source: J. Corbett and P. Fischbeck, MEETS 2001

Implications of Different Policy Frameworks: Variation in annual costs dominated by fuel penalties

NOx Control Technology (Percent Change in NOx)	Policy Scenario	NPV Costs (10 yrs at *i*=15%)	% of Annual Costs in NPV	Cost-effectiveness ($/ton NOx)
Aftercooler upgrade (-10%)	Port Control	**$21,000**	43%	$920
	Regional control	**$103,000**	89%	$640
	Global control	**$146,000**	92%	$620
Fuel system upgrade (-14%)	Port Control	$180,000	80%	$2,420
	Regional control	$180,000	80%	$770
	Global control	$180,000	80%	$520
Unit injection upgrade (-16%)	Port Control	$160,000	74%	$1,877
	Regional control	$160,000	74%	$600
	Global control	$160,000	74%	$410
Injection retard timing (-19%)	Port Control	**$19,000**	99%	$790
	Regional control	$194,000	100%	$620
	Global control	$285,000	100%	$620
Water in combustion air (-28%)	Port Control	**$146,000**	8%	$1,100
	Regional control	$257,000	48%	$560
	Global control	$315,000	58%	$470
Water/Fuel Emulsion (-42%)	Port Control	**$130,000**	8%	$670
	Regional control	$229,000	48%	$340
	Global control	$281,000	58%	**$280**
Selective Catalytic Reduction (-81%)	Port Control	$295,000	3%	$670
	Regional control	$386,000	26%	**$300**
	Global control	$434,000	34%	**$230**

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Source: J. Corbett and P. Fischbeck, MEETS 2001

Monitoring helps define way ahead

- Our approach is to begin with "research standard" and look for least-cost equivalent
  - How bad do the data get if we estimate this element less well?
  - Is Better the Enemy of Good Enough?

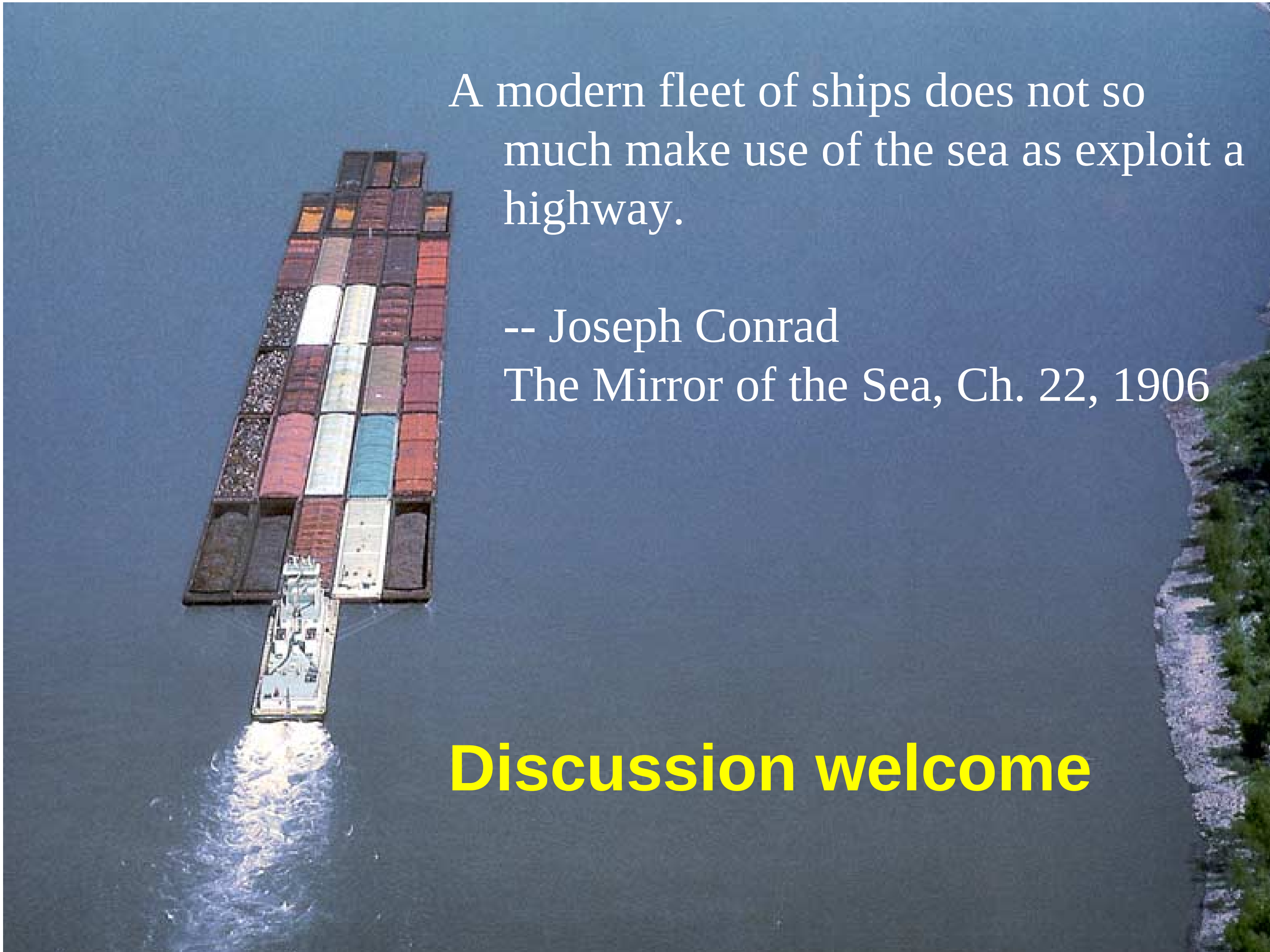
Is a Better Baseline the Enemy?

- Better is the enemy of Good Enough.
  - Motto that hung on the wall of Admiral Sergei Gorshkov, head of the Russian Navy, 1950's-1980's, to remind him of the relative quality of the U.S. and Soviet fleets.
- Today, we are no where near good enough
  - Monitoring provides inadequate detail, accuracy
  - Technology evaluations are not vessel-specific
  - Costs are very sensitive to assumptions, interest rates, and market penetration

Better Baseline is not the Enemy

We need to proceed with testing, but ensure that we can compare results

Monitoring for baseline will lead to monitoring for reductions


A modern fleet of ships does not so much make use of the sea as exploit a highway.
-- Joseph Conrad
The Mirror of the Sea, Ch. 22, 1906
Discussion welcome
http://www.riverbarges.com/riverfun/riverpics/picsintro.htm