Total Fuel Cycle Analysis for Marine Fuels: Sulfur and CO_2 Emissions Tradeoffs of California's Proposed Low-Sulfur Marine Fuel Rule

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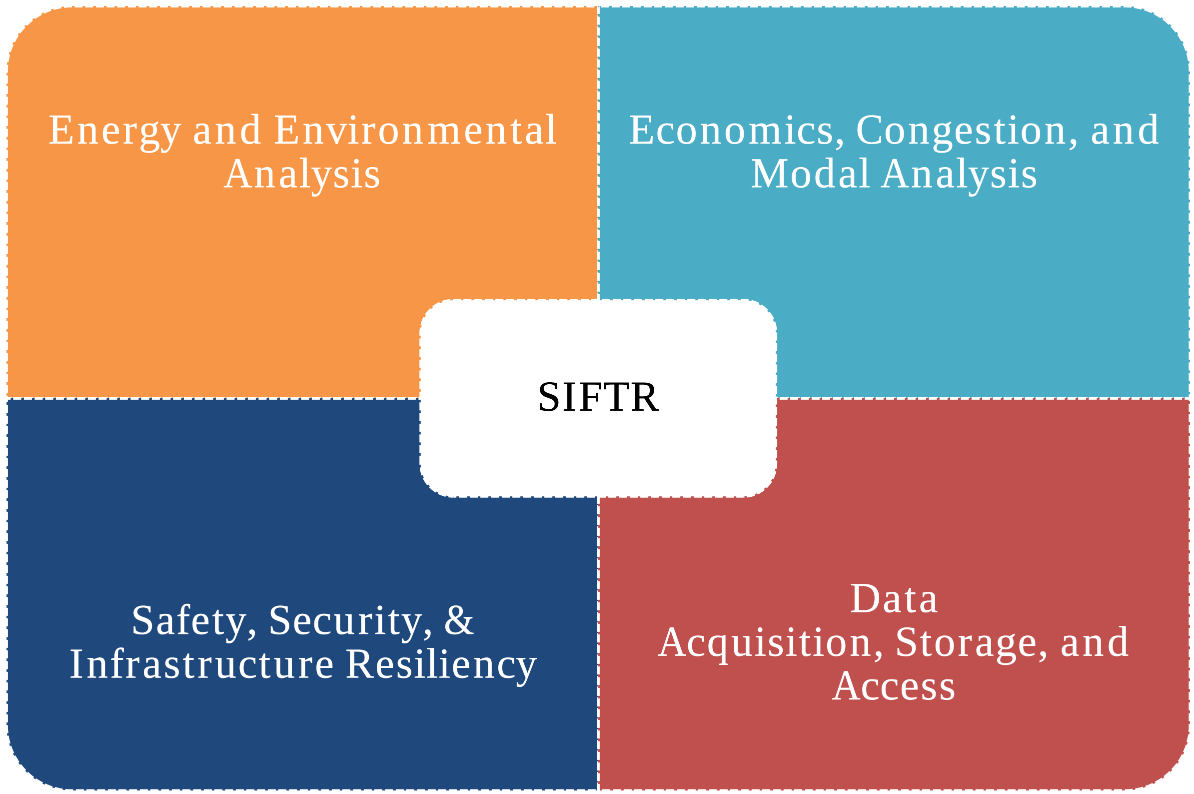
SIFTR: Four Key Research Areas

- Energy and Environmental Analysis.
- Economic, Congestion, a nd Modal Analysis.
- Safety, Security, and Infrastructure Resiliency .
- Data Acquisition, Storage, an d Access.

Our SIFTR Vision

Sustainable Intermodal Freight Transportation Research (SIFTR) *improves freight decisions through* collaborative, innovative, data-driven *transformative research to make the future of freight more sustainable*.

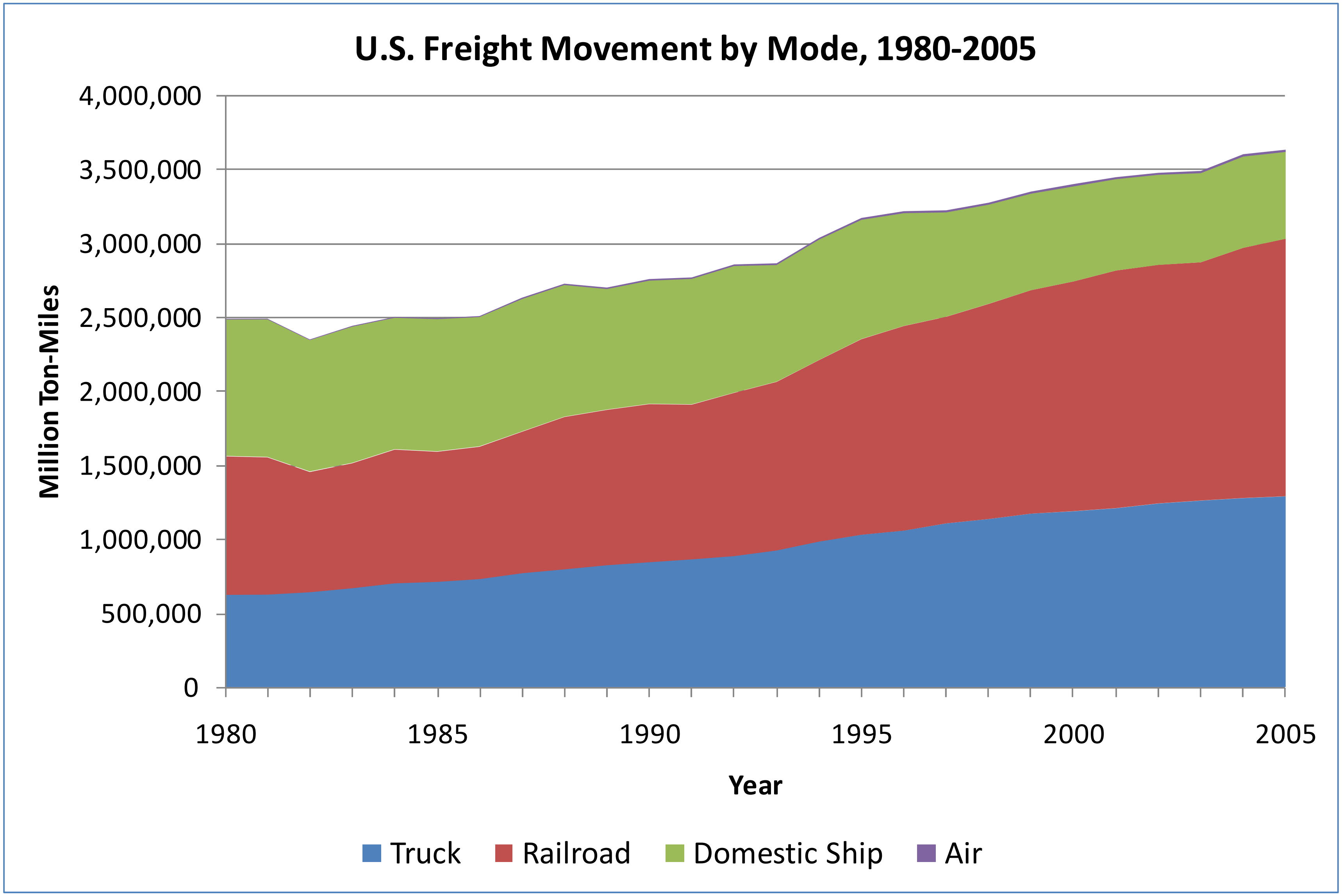


Overview of Presentation

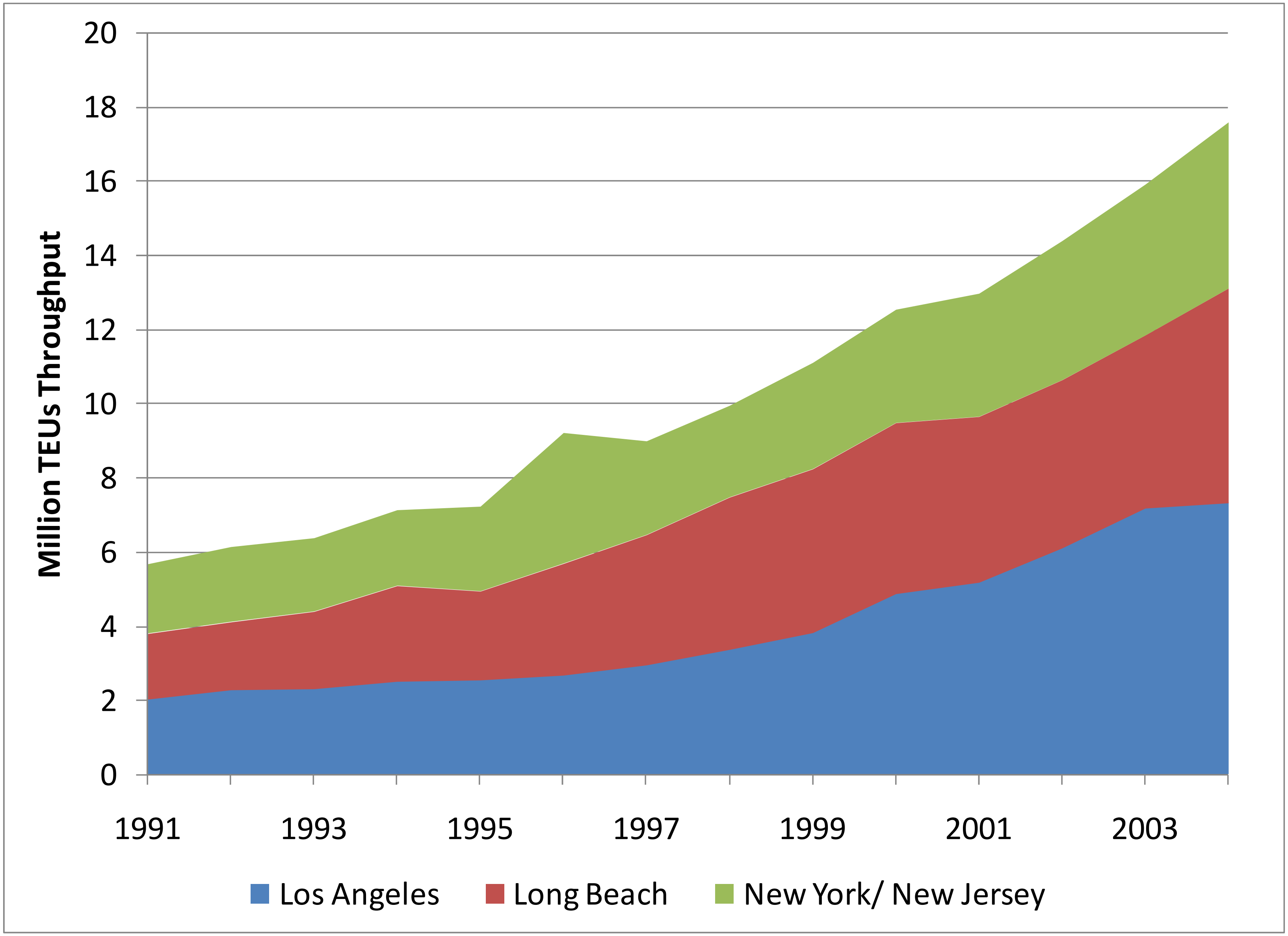
- Goods Movement, the Economy, and Emissions
- The Marine Sector and Associated Health Impacts
- Total Fuel Cycle Analysis and the TEAMS Model
- Results
- Questions and Discussion

GOODS MOVEMENT, THE ECONOMY, AND EMISSIONS

Domestic Trends by Mode

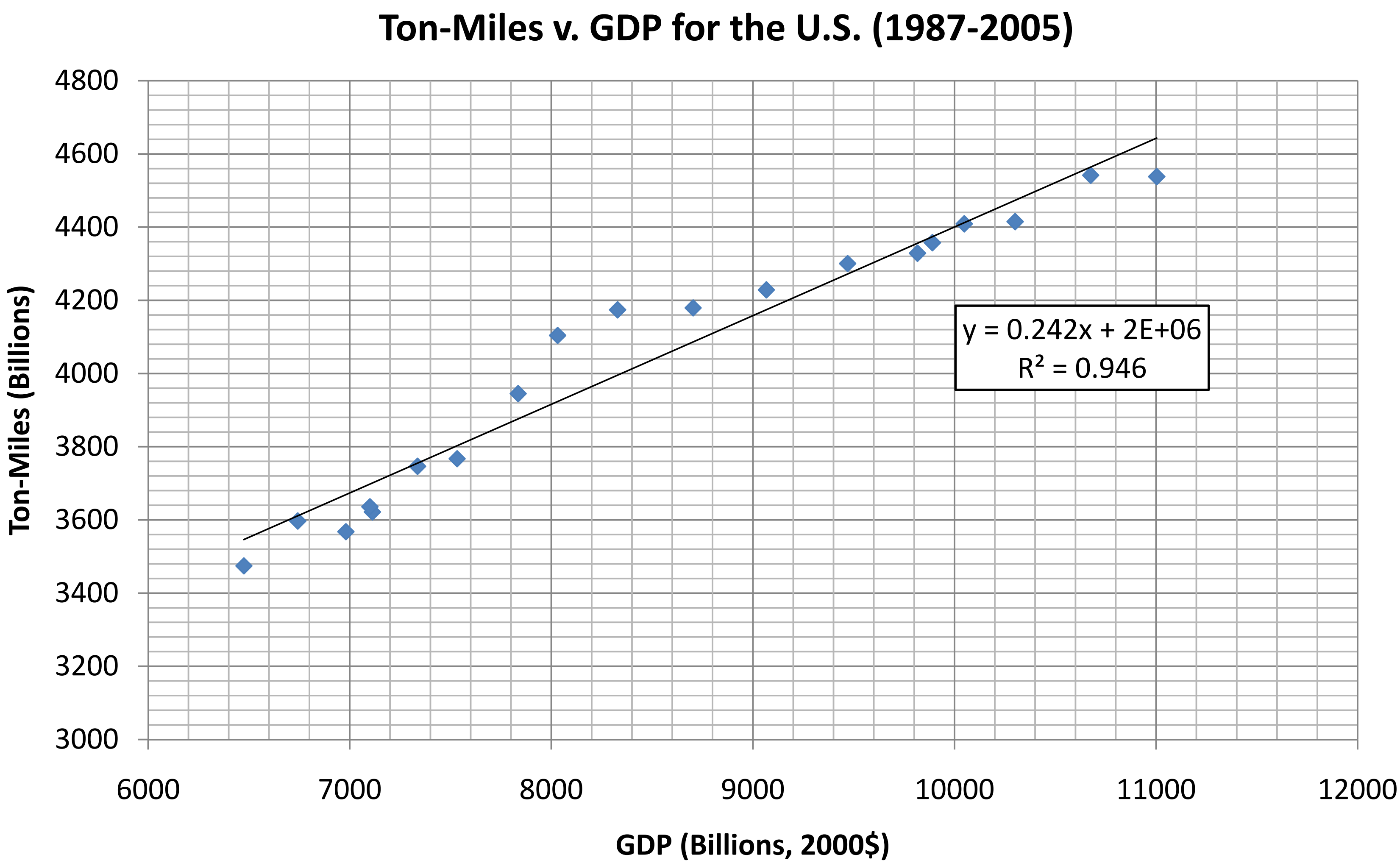


International Container Trends

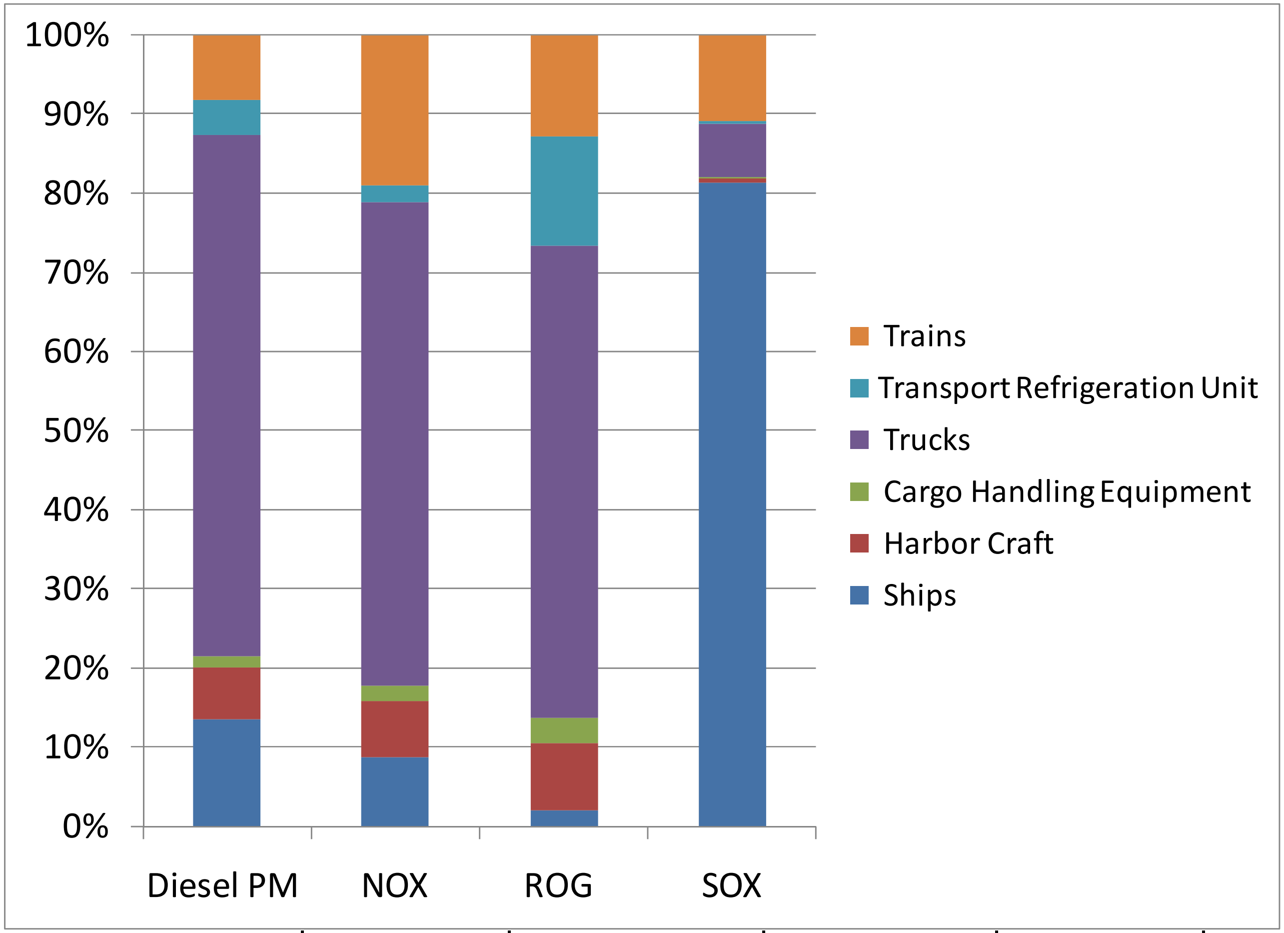


http://www.kmi.re.kr/english/statistics/world2004.asp

The Economic-Goods Movement Relationship

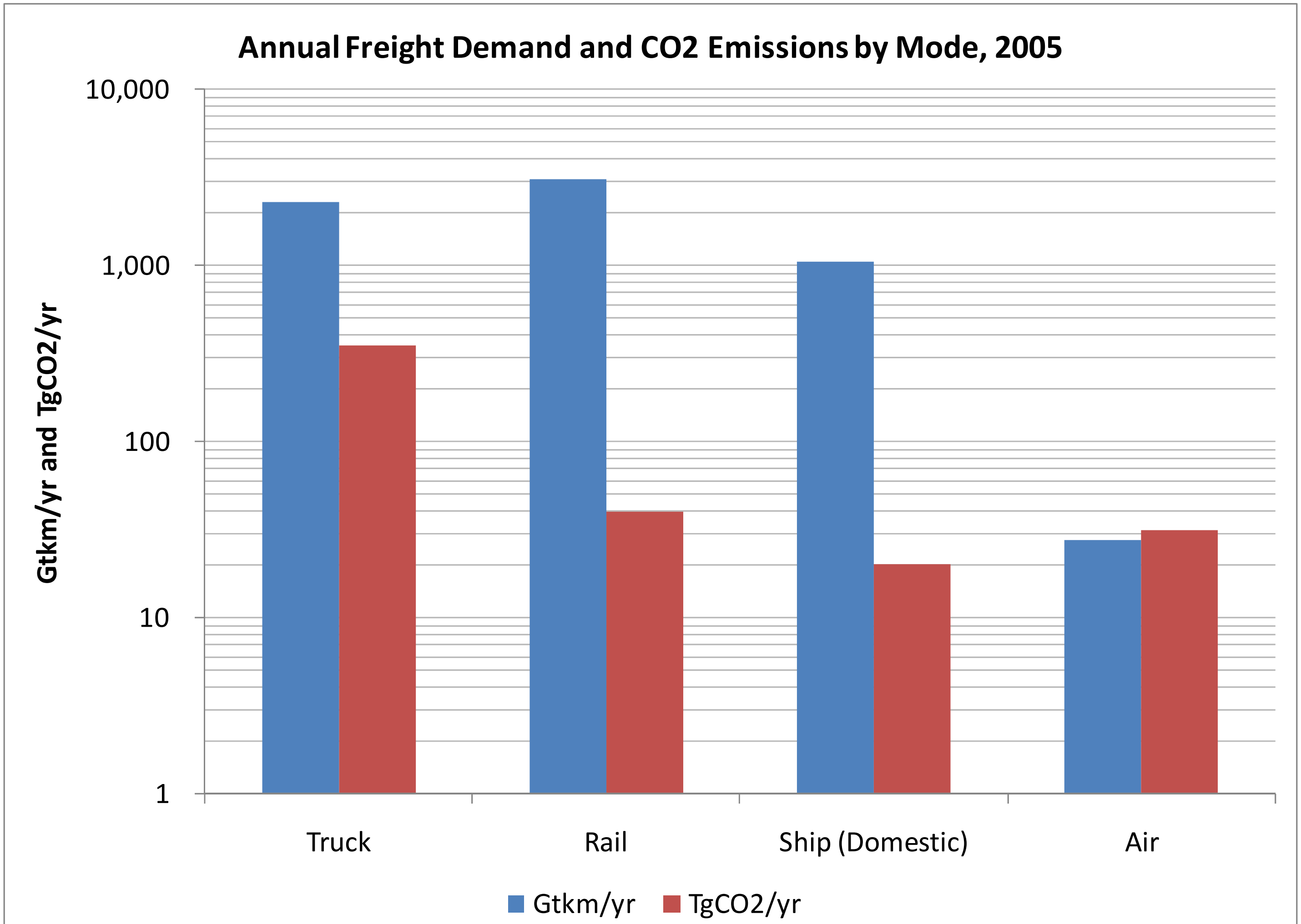


Goods Movement and Emissions in CA



Pollutant	Ships	Harbor Craft	Cargo Handling Equipment	Trucks	Transport Refrigeration Unit	Trains	Total
Diesel PM	2847	1387	292	13761	913	1716	20915
NOX	34675	27375	7665	239075	8030	74095	390550
ROG	730	2920	1095	20440	4745	4380	33945
SOX	21900	146	37	1825	73	2920	26645

Source: CARB, 2006.



	Gtkm/yr	$TgCO_2$/yr	Btu/tkm	gCO_2/tkm
Truck	2294.3	350.4	2080	153
Rail	3075.7	39.9	178	13
Ship (Domestic)	1048.9	20.1	243	19
Air	27.9	31.7	16013	1135

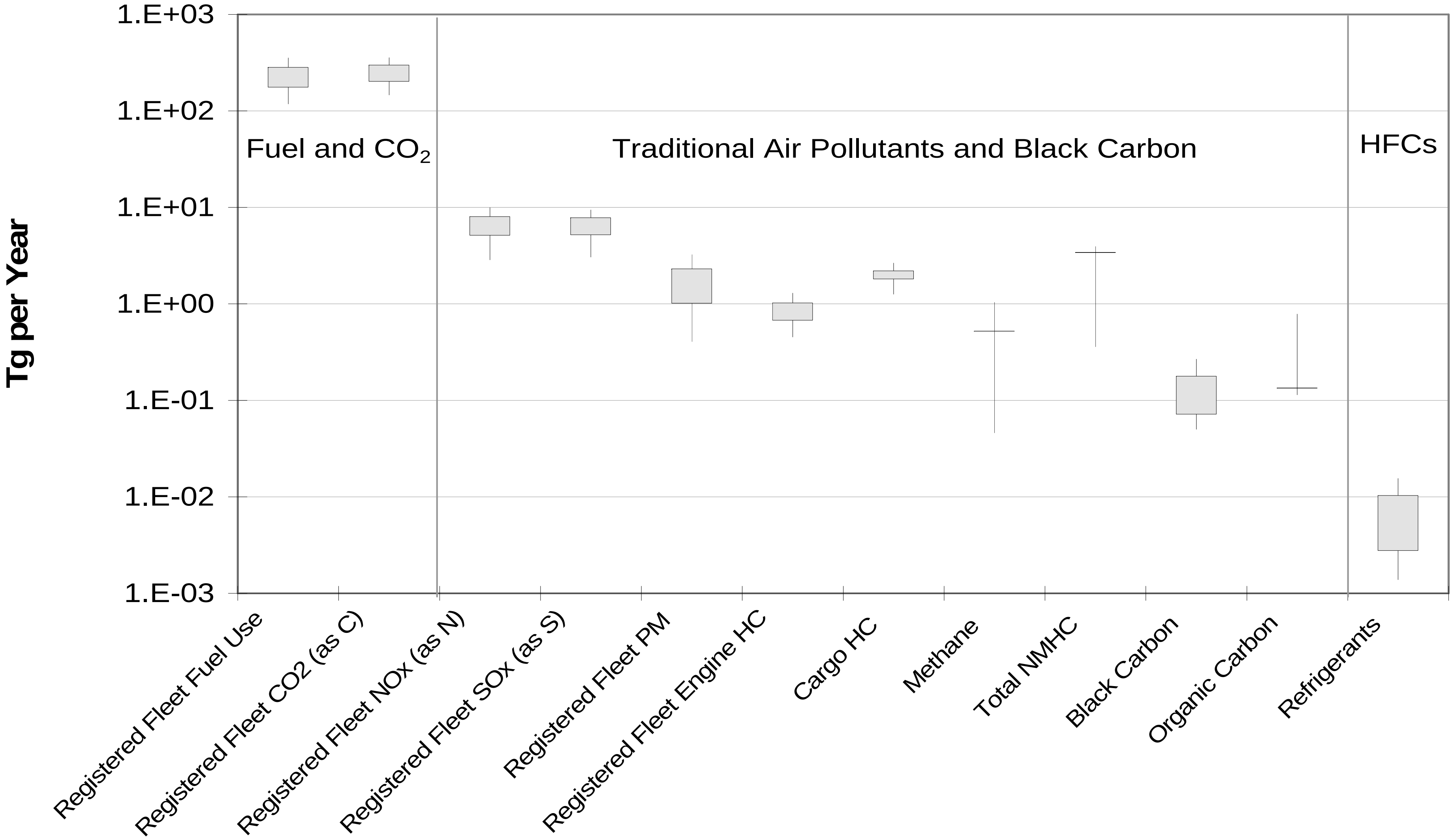
Data derived from BTS, Table 1-46b: http://www.bts.gov/publications/national_transportation_statistics/.

THE MARINE SECTOR

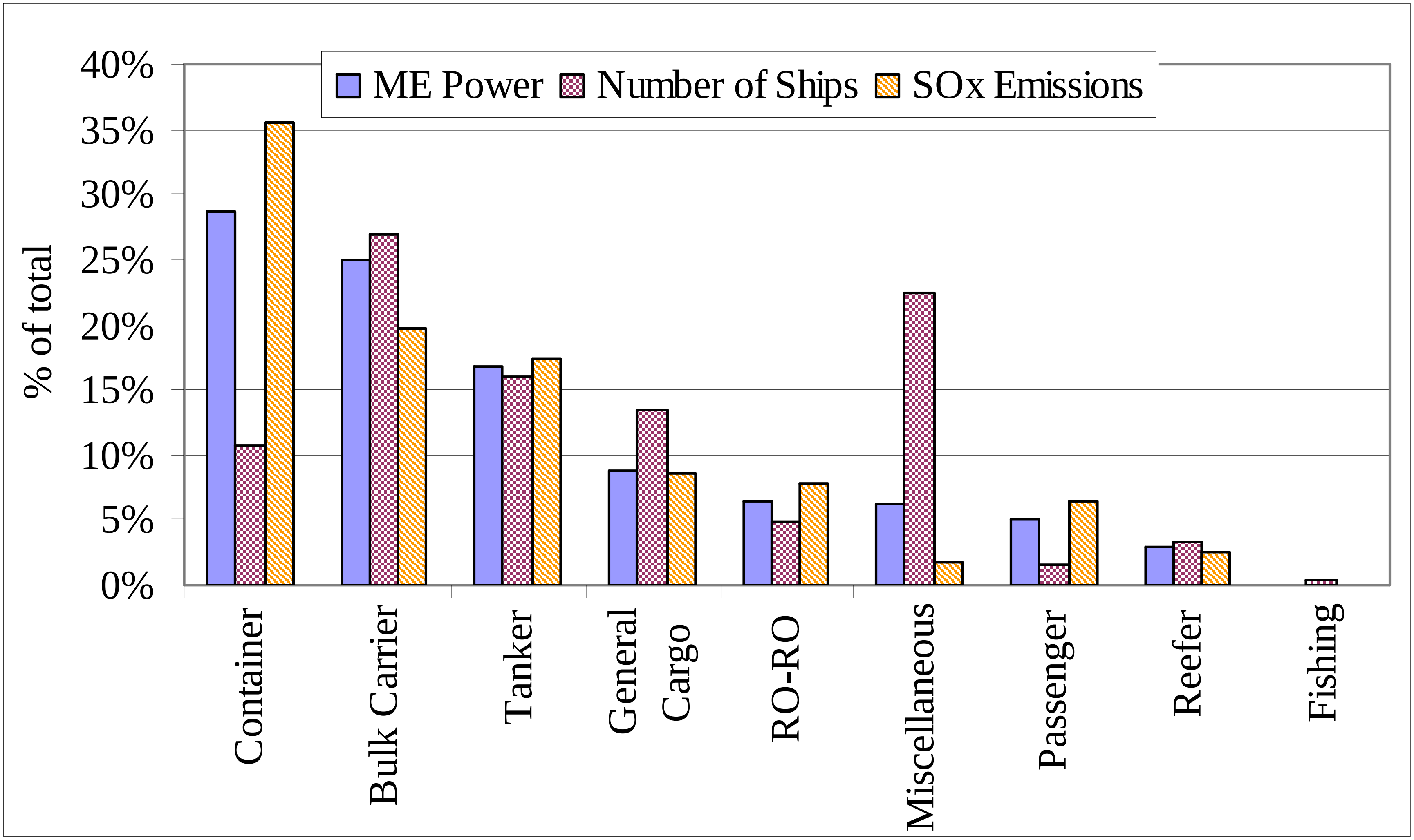
The World Fleet Profile

Ship type	Number of ships	Percent of world fleet	Number of main engines	Percent of main engines	Installed power (MW)	Percent of total power	Percent of energy demand[1]
Cargo Fleet	43,852						
Container vessels	2,662	2%	2755	2%	43,764	10%	13%
General cargo vessels	23,739	22%	31,331	21%	72,314	16%	22%
Tankers	9,098	8%	10,258	7%	48,386	11%	15%
Bulk/combined carriers	8,353	8%	8781	6%	51,251	11%	16%
Non-Cargo Fleet	44,808						
Passenger	8,370	8%	15,646	10%	19,523	4%	6%
Fishing vessels	23,371	22%	24,009	16%	18,474	4%	6%
Tugboats	9,348	9%	16,000	11%	16,116	4%	5%
Other (research, supply)	3,719	3%	7500	5%	10,265	2%	3%
Registered Fleet Total	88,660	82%	116,280	77%	280,093	62%	86%
Military Vessels[2]	19,646	18%	34,633	23%	172,478	38%	14%
World Fleet Total	108,306	100%	150,913	100%	452,571	100%	100%

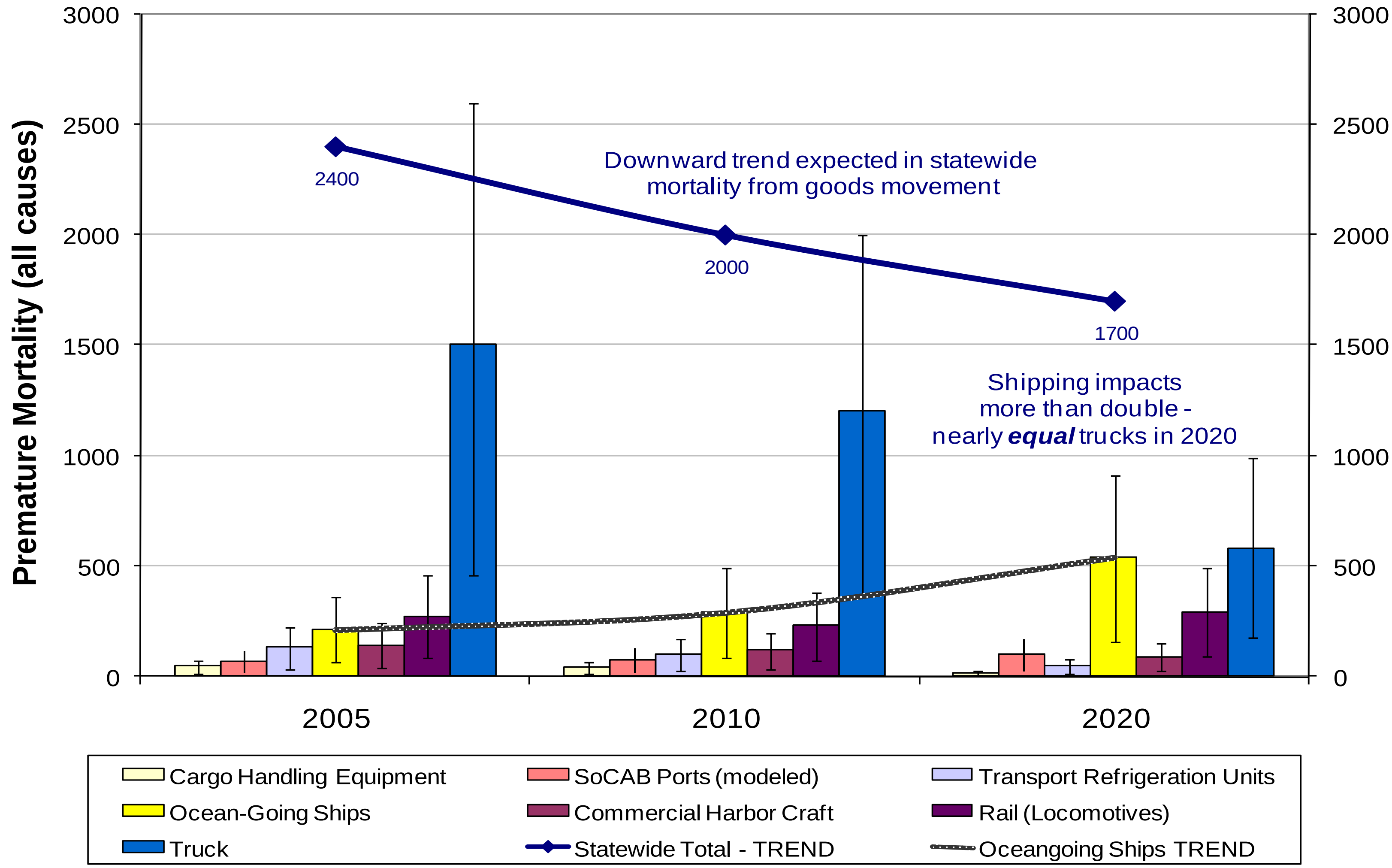
Global Emissions from Shipping



North American Vessel Profile and SOx Emissions



CA Goods Movement Health Impacts

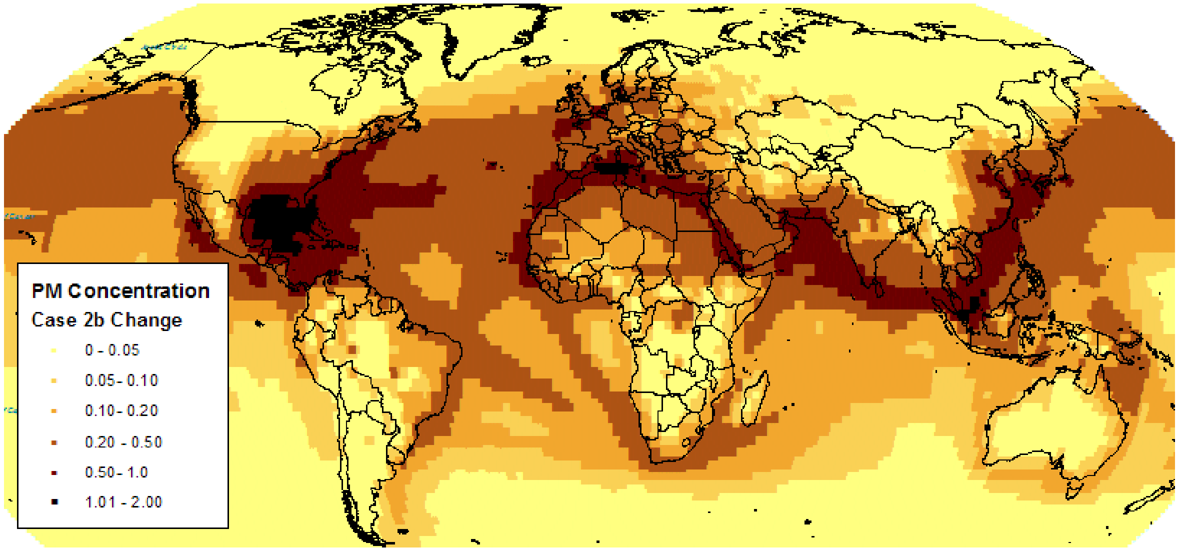


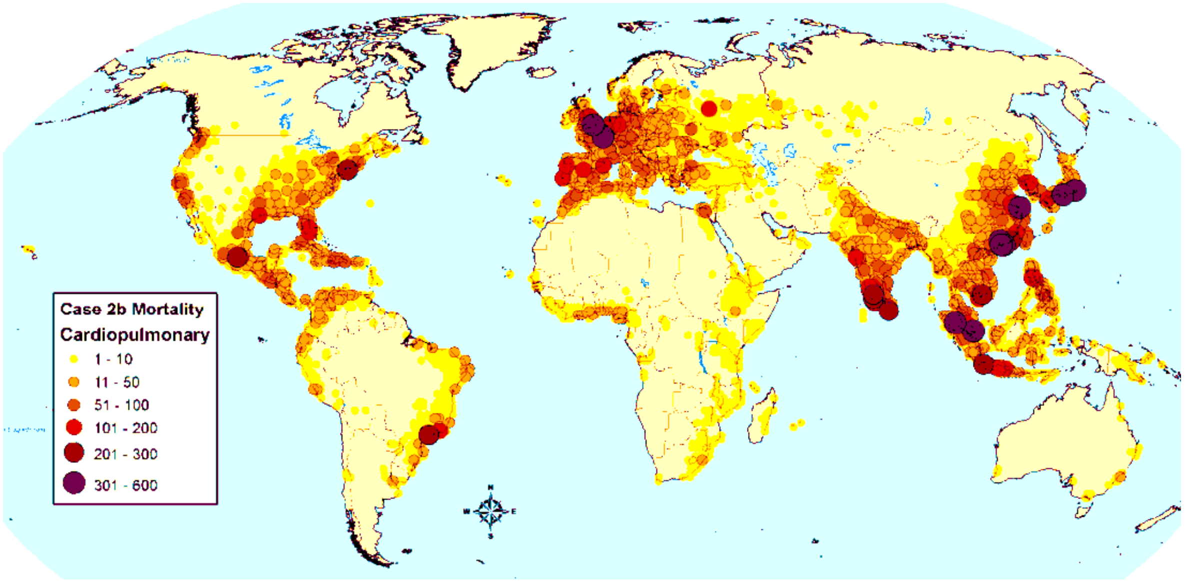
Source: CARB, 2006.

WHY TOTAL FUEL CYCLE ANALYSIS IS IMPORTANT FOR MARINE FUELS:

Health impacts are driving marine fuels to lower sulfur fuels.

Can low sulfur marine fuels cause increased GHG emissions on a total fuel cycle basis?



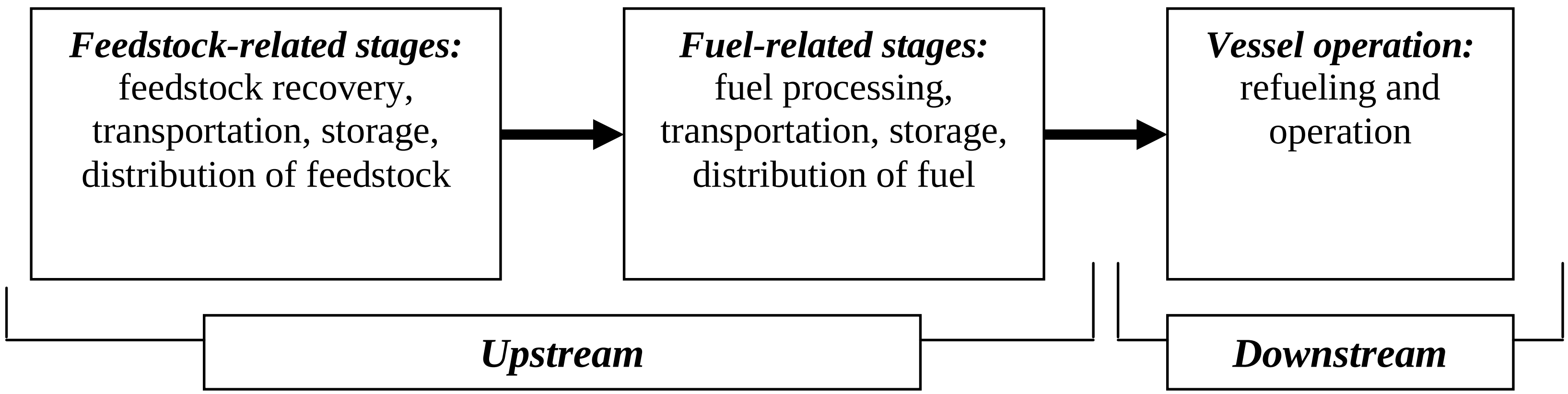


Source: Corbett, James J., James J. Winebrake, Erin H. Green, Prasad Kasibhatla, Veronika Eyring, Axel Lauer, "Mortality from Ship Emissions: A Global Assessment," *Environmental Science & Technology*, 41(24), December 15, 2007, pp. 8512-8518.

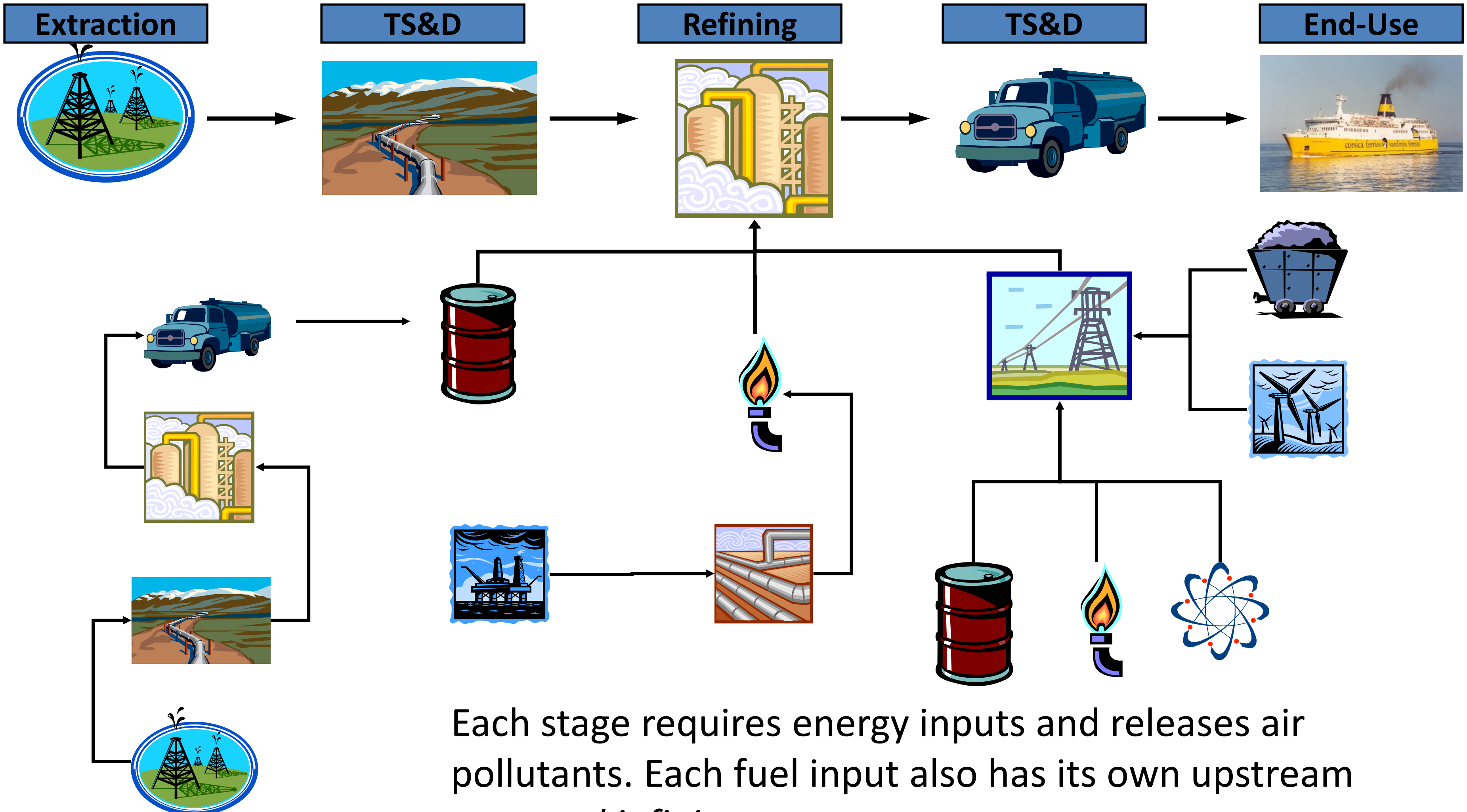
TOTAL FUEL CYCLE ANALYSIS AND THE TEAMS MODEL

Well-to-Hull Analysis (W2H)

W2H Analysis accounts for energy consumption and emissions along the entire fuel cycle of a given fuel.



An Example of Well-to-Hull for Petroleum



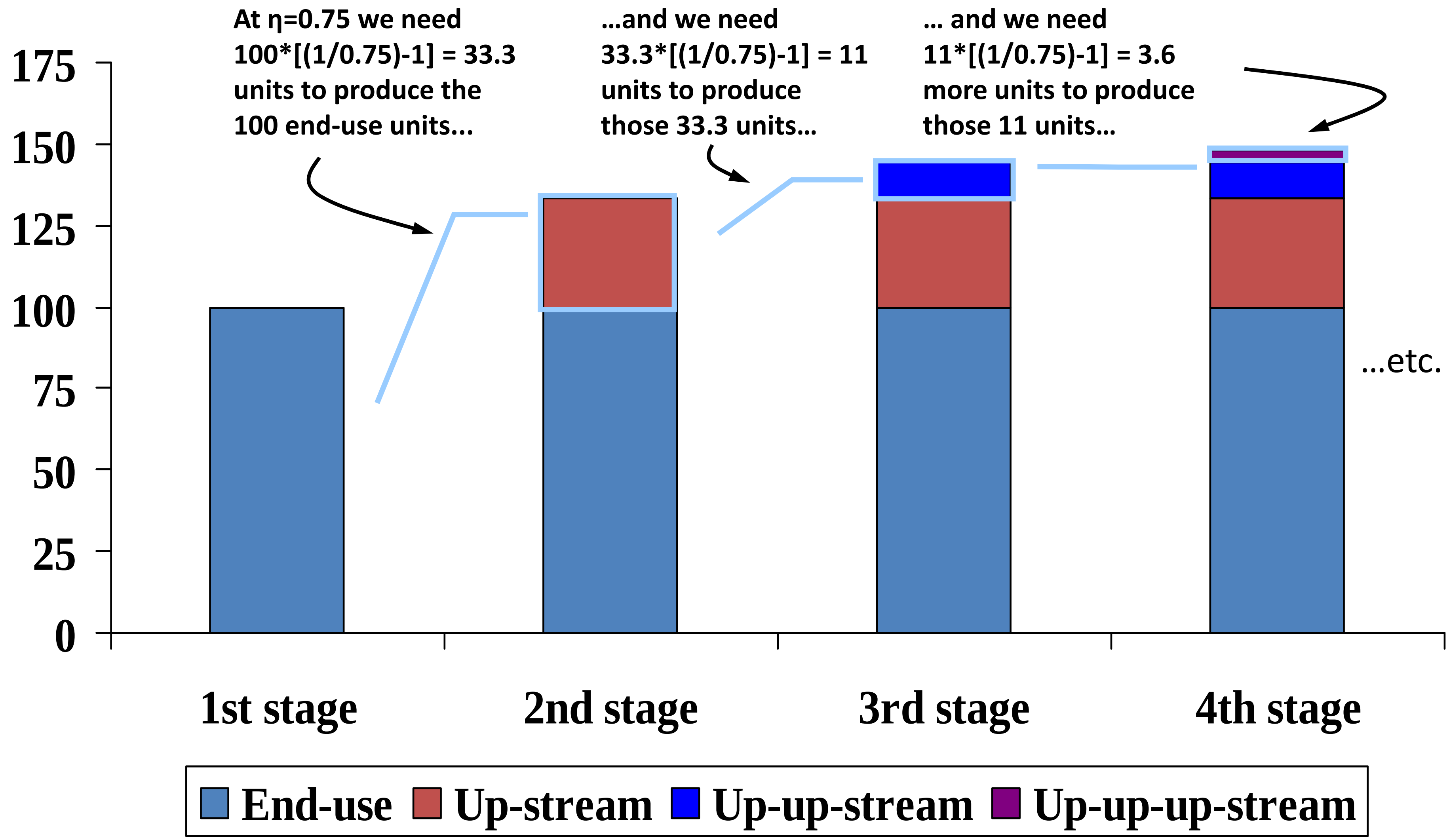
Each stage requires energy inputs and releases air pollutants. Each fuel input also has its own upstream stage, *ad infinitum*.

The TEAMS Model

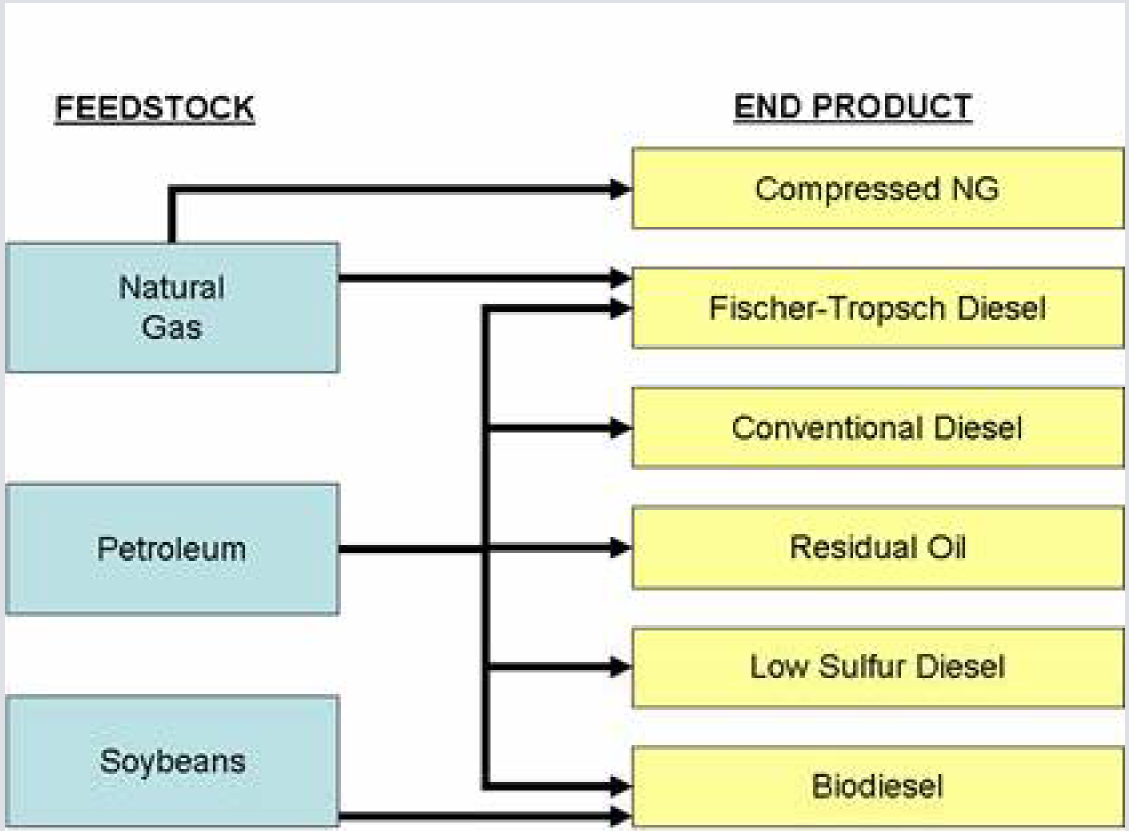
- *TEAMS*: Total Energy and Emissions Analysis for Marine Systems Model
- Applies the ANL GREET fuel-cycle algorithm, which has been peer-reviewed and widely accepted as the TFC "gold-standard"
- Calculates total fuel cycle energy use (Btu/trip) and emissions (grams/trip) for vessels; modified in this project to calculate energy use and emissions on a per BTU basis for different fuels.
- Considers combustion and non-combustion events in all upstream and downstream stages
- Published in Winebrake, Corbett, and Meyer (2007) and Corbett and Winebrake (2008).

Simple Example of Nth Order Effects

(assuming 75% efficiency from one stage to the next)



Original TEAMS Pathways & Emissions



- TEAMS can model three types of GHGs (CH_4, N_2O, and CO_2) and five criteria pollutants (CO, NOx, VOC, PM, SOx).
- TEAMS allows for a wide-range of inputs characterizing refineries, trips, and prime movers.
- TEAMS is a flexible model that we modified to include other types of marine fuels.

Fuels Analyzed in This Study

Fuel Type	Description
IFO 380	Intermediate fuel oil with a viscosity of 380 centistokes at 50^o C.
IFO 180	Intermediate fuel oil with a viscosity of 180 centistokes at 50^o C.
DMA (0.1% Sulfur)	Marine gas oil that is characteristic of all DMA sold globally that would also meet proposed ARB compliance standards for sulfur (0.1%).
DMA (Global)	Marine gas oil that is characteristic of all DMA sold globally.
DMB (0.1% Sulfur)	Marine diesel oil that is characteristic of all DMB sold globally that would also meet proposed ARB compliance standards for sulfur (0.1%).
DMB (Global)	Marine diesel oil that is characteristic of all DMB sold globally.

Fuel Quality Assumptions

Sulfur content by fuel used in the analysis.

Fuel	Sample Min (% S)	Sample Mean (% S)	Sample Max (% S)
IFO 380	0.50	2.600	4.00
IFO 180	0.50	2.400	4.00
DMA (0.1% Sulfur)	0.05	0.061	0.10
DMA (Global)	0.05	0.380	2.12
DMB (0.1% Sulfur)	0.05	0.061	0.10
DMB (Global)	0.05	0.350	3.15

Physical density by fuel used in the analysis.

Fuel	Sample Lower (g/gal)	Sample Mean (g/gal)	Sample Upper (g/gal)
IFO 380	3759	3805	3759
IFO 180	3739	3767	3739
DMA (0.1% Sulfur)	3184	3278	3416
DMA (Global)	3127	3300	3564
DMB (0.1% Sulfur)	3172	3295	3450
DMB (Global)	3125	3355	3629

Fuel Quality (cont'd)

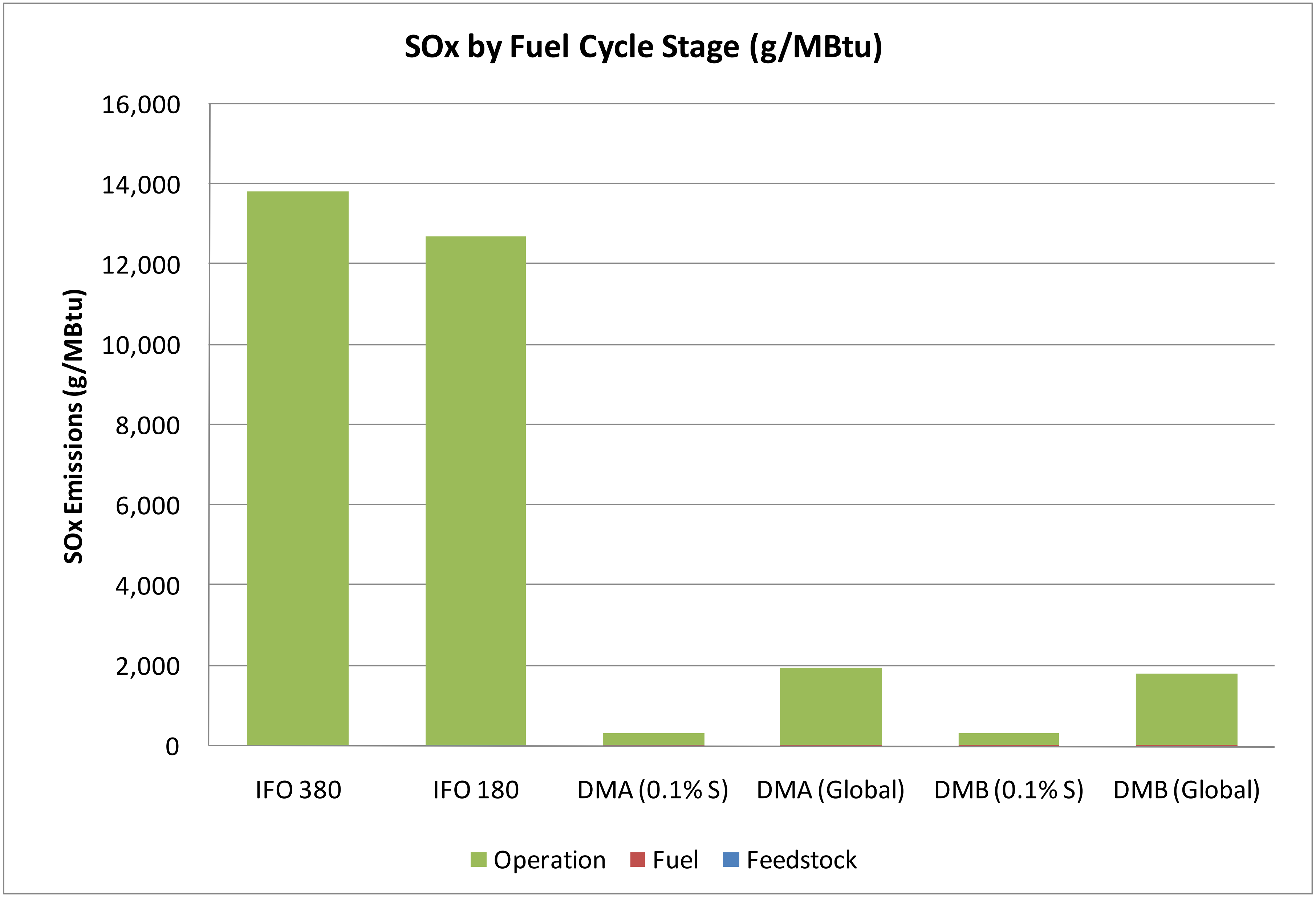
- We applied energy content formulas from *ISO 8217* relating *net specific energy* to physical density of the fuel and sulfur content; separate formulas were applied to the residual fuel and the distillates per ISO guidance.

- We ignore water content and ash content for this analysis, as these have a negligible effect on energy content for the fuels we evaluate.

Refining Efficiency Assumptions

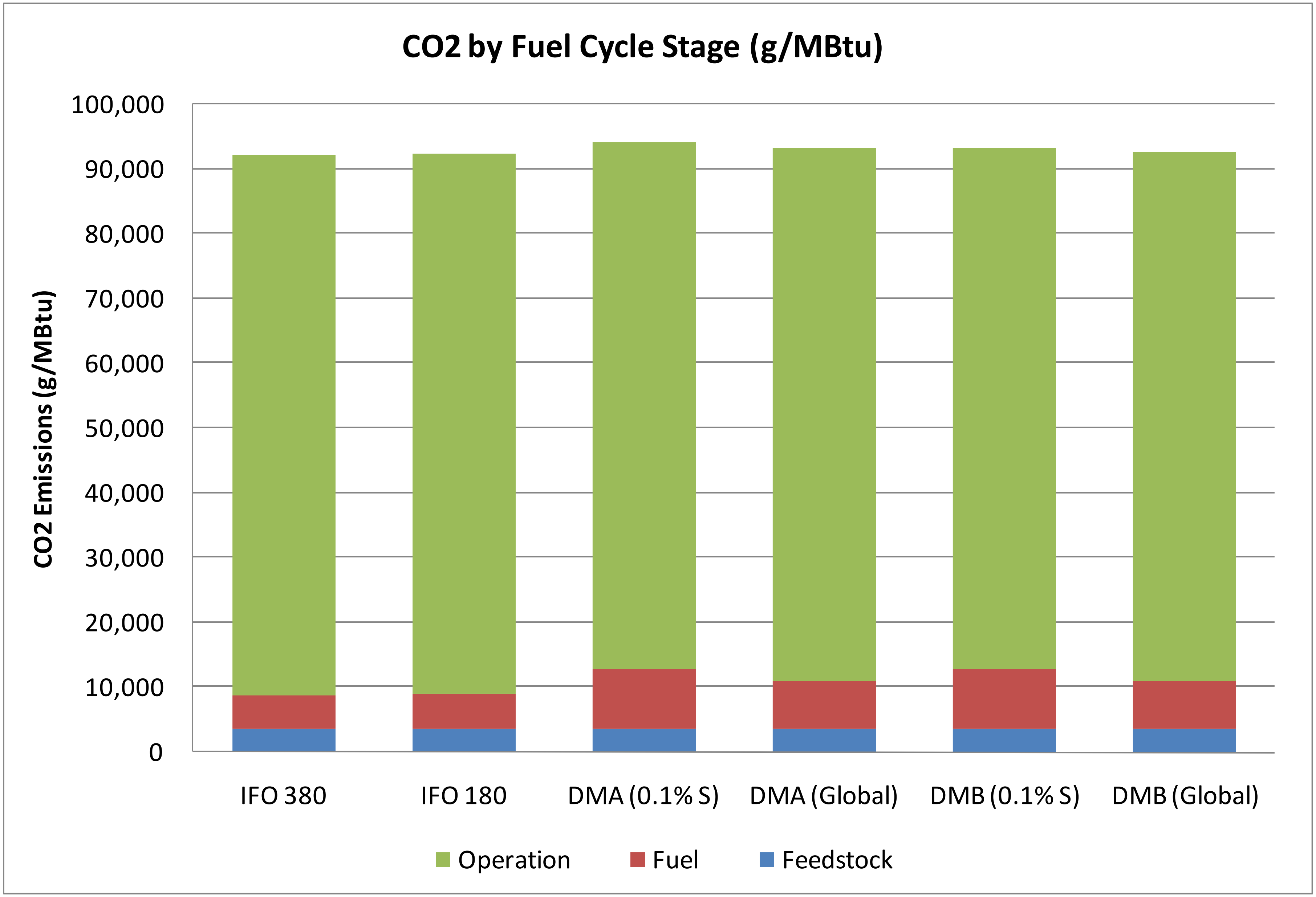
Fuel	Lower (%)	Average (%)	Upper (%)
IFO 380	93.2%	95.2%	95.7%
IFO 180	93.2%	95.1%	95.7%
DMA (0.1% Sulfur)	90.5%	90.8%	91.3%
DMA (Global)	90.5%	92.9%	94.9%
DMB (0.1% Sulfur)	90.5%	90.8%	91.3%
DMB (Global)	90.5%	92.8%	95.4%

RESULTS


SOx by Fuel Cycle Stage (g/MBtu)
SOx Emissions (g/MBtu)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
IFO 380
IFO 180
DMA (0.1% S)
DMA (Global)
DMB (0.1% S)
DMB (Global)
Operation
Fuel
Feedstock

SOx Emissions by Stage

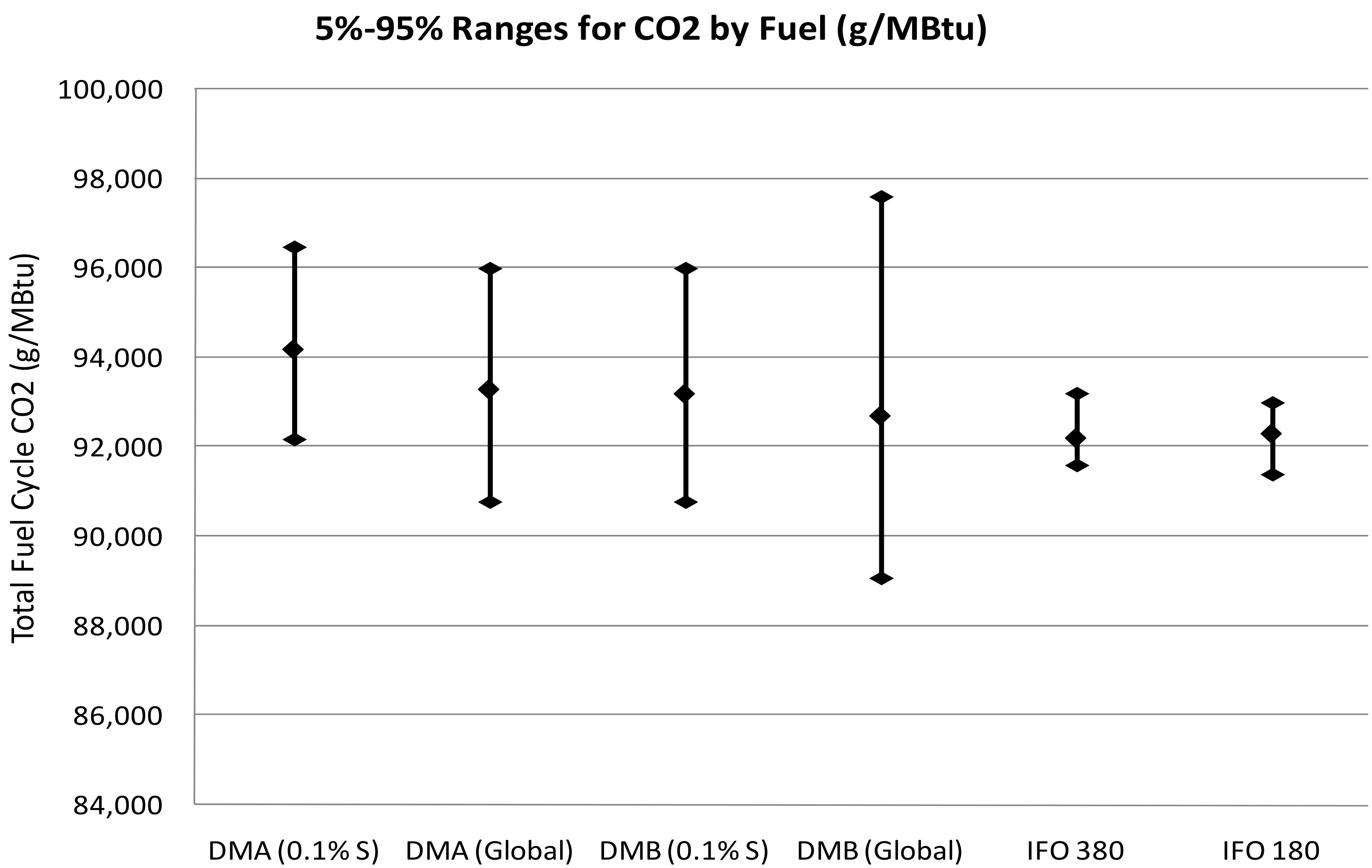
Fuel	Feedstock	%	Fuel Processing	%	Operation	%	Total	% Change from IFO 380
IFO 380	8	0.06%	11	0.08%	13,800	99.86%	13,820	--
IFO 180	8	0.06%	11	0.09%	12,690	99.85%	12,710	-8.05%
DMA (0.1% S)	8	2.40%	15	4.50%	310	93.09%	330	-97.59%
DMA (Global)	8	0.41%	13	0.67%	1,930	98.92%	1,950	-85.89%
DMB (0.1% S)	8	2.40%	15	4.49%	310	93.41%	330	-97.58%
DMB (Global)	8	0.44%	13	0.72%	1,780	98.89%	1,800	-86.96%


CO2 by Fuel Cycle Stage (g/MBtu)
CO2 Emissions (g/MBtu)
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
IFO 380
IFO 180
DMA (0.1% S)
DMA (Global)
DMB (0.1% S)
DMB (Global)
Operation
Fuel
Feedstock

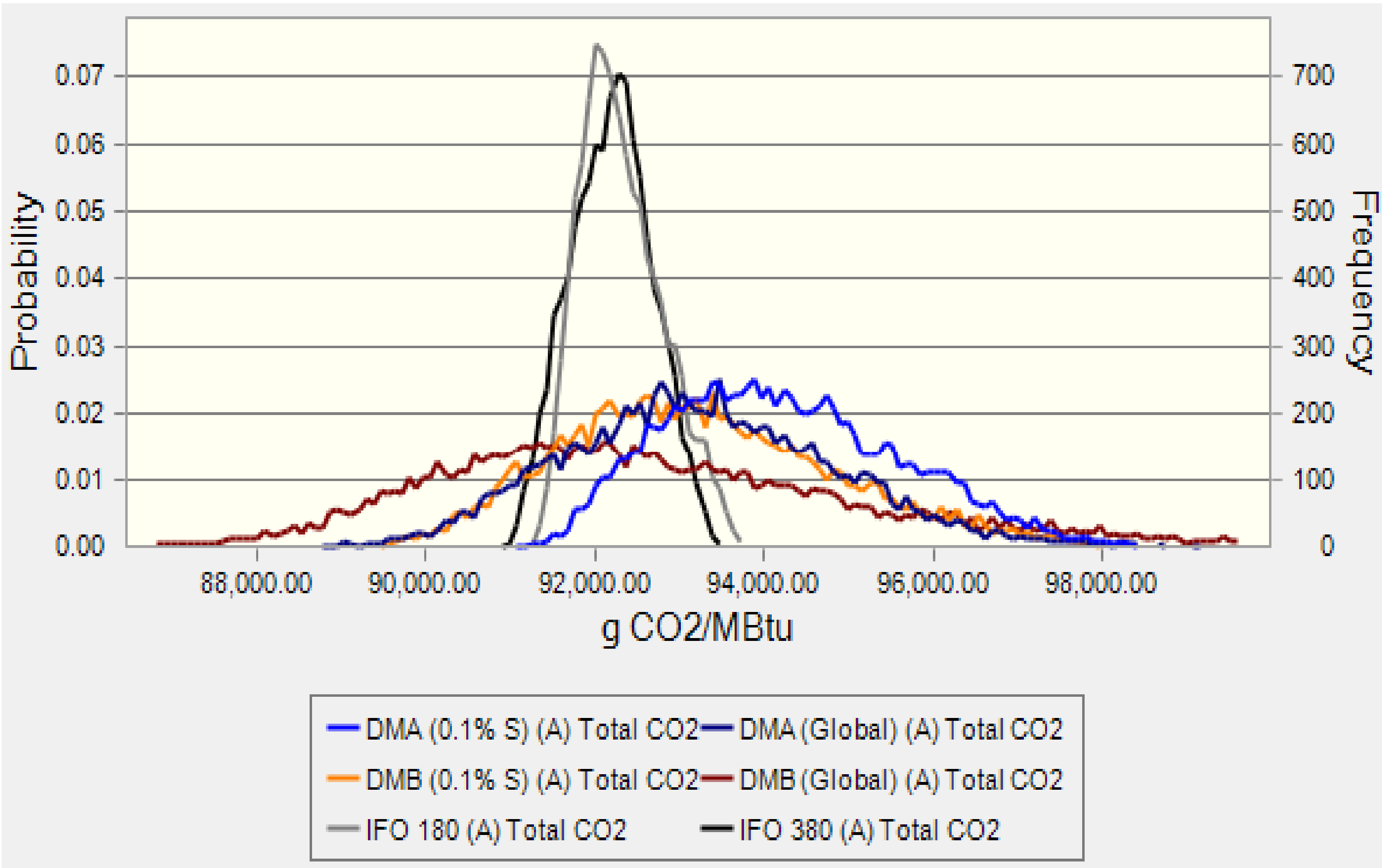
CO_2 Emissions by Stage

Fuel	Feedstock	%	Fuel Processing	%	Operation	%	Total	% Change from IFO 380
IFO 380	3,500	3.84%	5,200	5.68%	83,400	90.49%	92,200	--
IFO 180	3,600	3.85%	5,300	5.78%	83,400	90.37%	92,300	0.11%
DMA (0.1% S)	3,600	3.83%	9,200	9.81%	81,300	86.35%	94,200	2.17%
DMA (Global)	3,600	3.90%	7,300	7.90%	82,300	88.21%	93,300	1.19%
DMB (0.1% S)	3,600	3.83%	9,200	9.83%	80,500	86.32%	93,200	1.08%
DMB (Global)	3,600	3.91%	7,400	8.00%	81,700	88.08%	92,700	0.54%

TFCA CO_2/Mbtu for Different Fuels

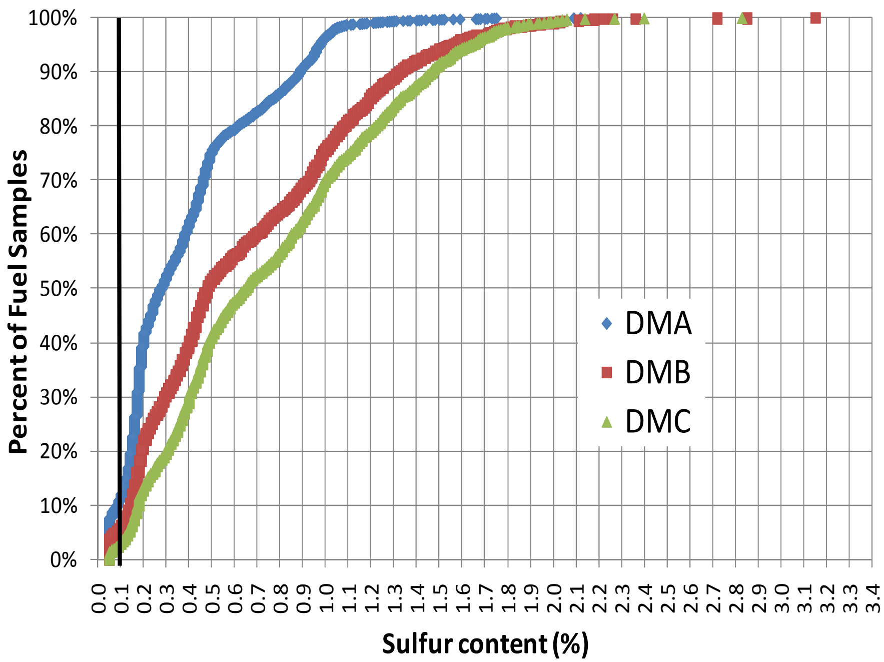


TFCA CO_2/Mbtu for Different Fuels

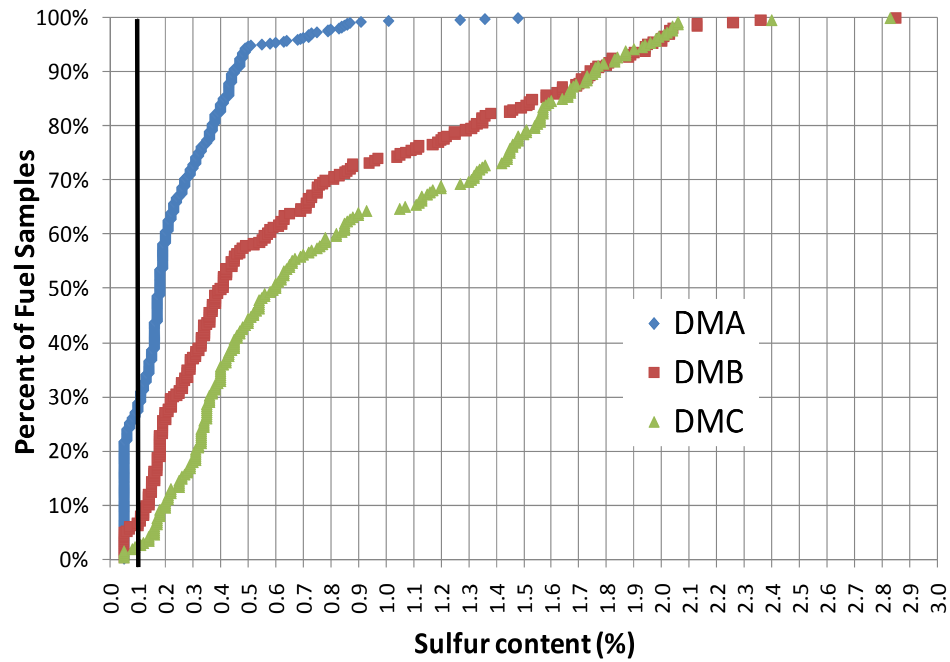


DISTILLATE SUPPLY ISSUES

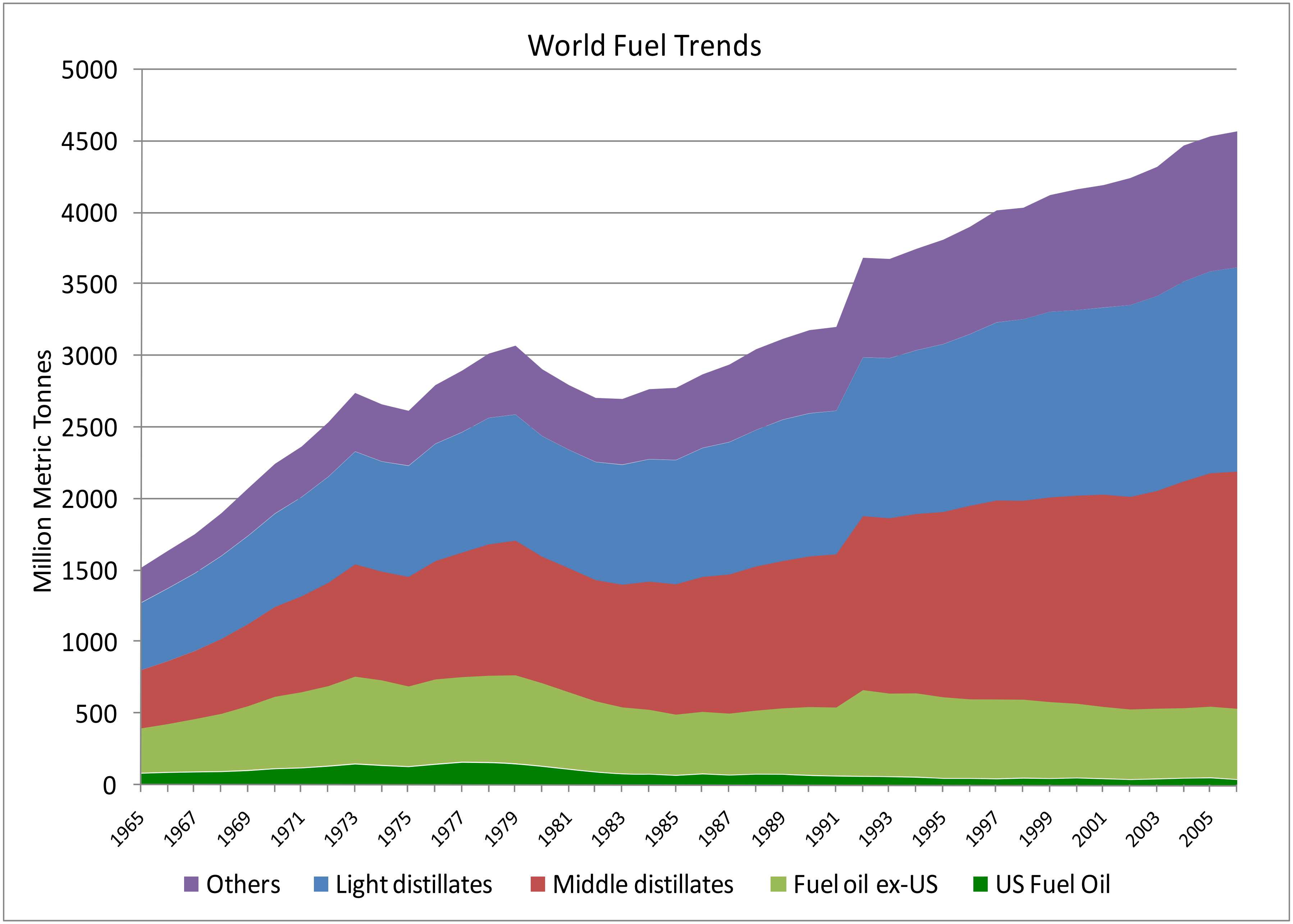
Fuel Use by Sulfur Content
(based on tests of fuel sampled at sale)

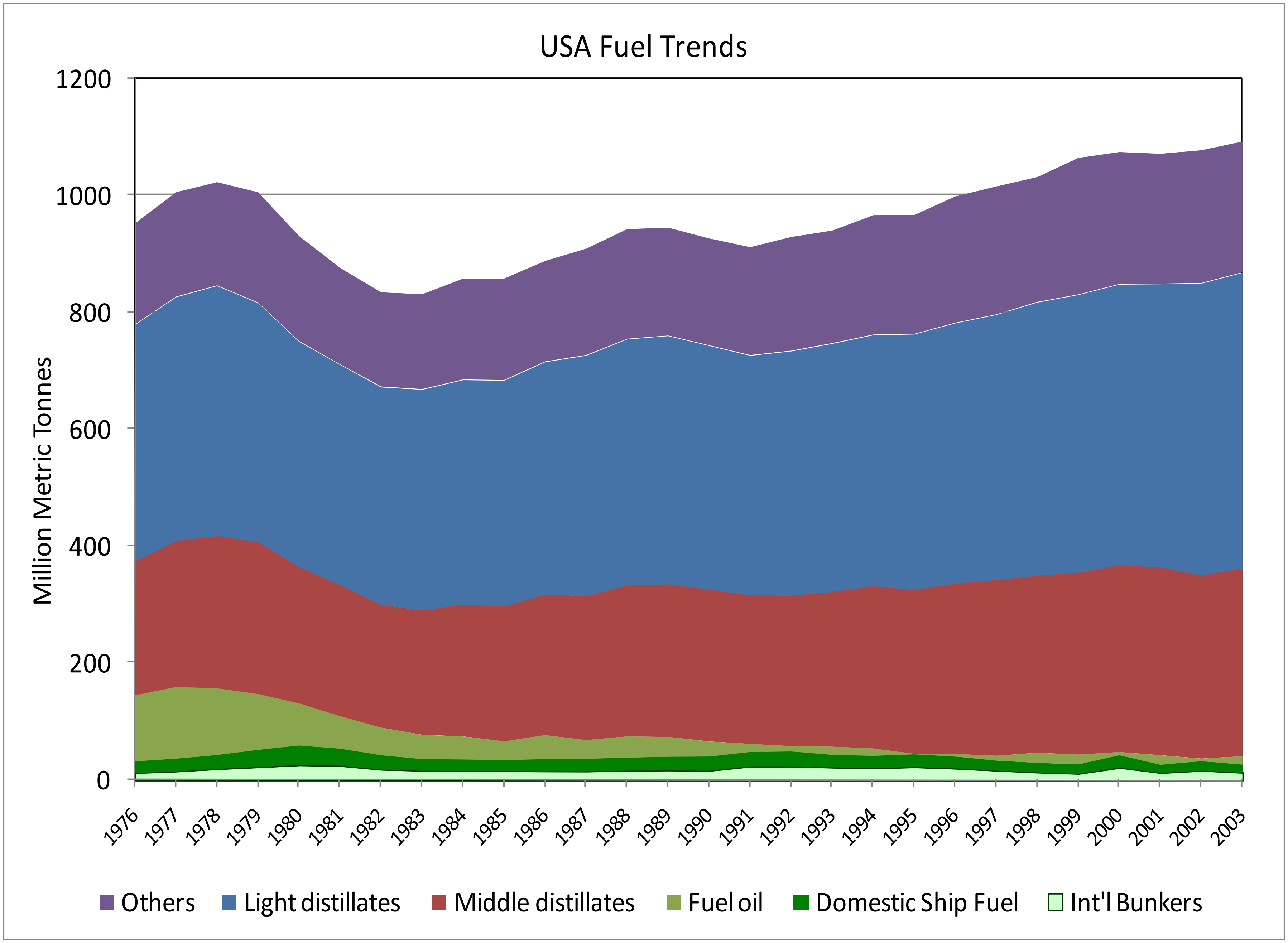


Global Samples
DMA: n > 4400
DMB: n > 2200
DMC: n > 1600



U.S. Samples
DMA: n > 570
DMB: n > 267
DMC: n > 262


World Fuel Trends
Million Metric Tonnes
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005
Others
Light distillates
Middle distillates
Fuel oil ex-US
US Fuel Oil



USA Fuel Trends
1200
1000
800
600
400
200
0
Million Metric Tonnes
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Others
Light distillates
Middle distillates
Fuel oil
Domestic Ship Fuel
Int'l Bunkers

QUESTIONS & DISCUSSION