Appendix H

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

Final Report

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FINAL REPORT

Prepared for the California Air Resources Board

by

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Executive Summary

Worldwide concerns about emissions of sulfur oxides (SO_x) from marine vessels have created an impetus to replace high-sulfur, marine residual oil with cleaner, lower-sulfur fuels. Two such fuels being discussed as substitutes for residual oil are marine gas oil (MGO) and marine diesel oil (MDO). Vessel operators could use these fuels directly or may blend these fuels with residual oil in order to achieve environmental and economic objectives. Although expected to be much cleaner in terms of SO_x, questions remain about carbon dioxide (CO_2) emissions associated with the production and use of these fuels [1, 2]. These concerns derive from the fact that MGO and MDO require additional energy in the "upstream" stages of the fuel cycle (i.e., fuel processing and refining).

This report examines emissions tradeoffs associated with proposed California Air Resources Board (ARB) regulations that would require oceangoing vessels to switch from residual oil to lower sulfur distillate fuels within 24 nautical miles (nm) of California's coastline [3]. In particular, we conduct a total fuel life cycle emissions analysis for two types of residual oil (IFO 380 and IFO 180) and two types of distillate fuel (marine gas oil [DMA] and marine diesel oil [DMB]). Our analysis estimates the total fuel cycle CO_2 and SO_x emissions associated with fuel extraction, fuel processing, fuel distribution, and fuel consumption of these fuels in grams per million BTU (g/MBtu). For our analysis, we employ a modified version of the Total Energy and Emissions Analysis for Marine Systems (TEAMS) model, updated to include MGO and MDO [4].

We find that requiring a switch from residual fuel to 0.1% sulfur distillate fuel will achieve ~97% reduction in sulfur emissions. These reductions would correspond to a net increase in CO_2 emissions of approximately 1% to 2% over the total fuel cycle. This net change in fuel-cycle CO_2 is a function of increased energy required at the refining stage to produce compliant distillate fuel and decreased energy during ship operation on distillate fuel compared to residual fuel. These results assume no effort by refineries to improve energy efficiency while maintaining, upgrading, or expanding their capacity to produce distillate fuels; therefore these total fuel cycle increases may be conservatively high.

Our evaluation of available fuel-test data assumes that fuel properties from test sample distributions are representative of fuel properties across all fuel sold. Given this, our analysis suggests that no more than ~1.6 million tons/year of distillate would be needed to satisfy ARB's proposed rule by 2020—an amount equivalent to less than 0.5% of the estimated ~375 million tons of US distillate supply in 2006. This new fuel demand represents about 15-18% of the 0.1% marine distillate supply available (estimated at ~6 million tons/year in 2006 and growing to about 10 million tons/year by 2020) assuming no change in the current mix of US distillate supply. Further analysis would be required to evaluate potential changes in sulfur contents of US distillates given future shifts in distillate supply and demand, both with and without proposed regulations at the state and federal levels.

This report is divided into four sections. Section 1 of the report provides background information and an overview of greenhouse gas (GHG) emissions and ships, with emphasis placed on CO_2 emissions. Sections 2 and 3 discuss our methodology and the results of our analysis. Section 4 of the report presents potential distillate supply issues that might be associated with the proposed ARB regulation.

1 GHG Emissions and Ships

1.1 Freight energy and emissions overview

The freight sector is a vital and growing enabler of the US economy. The US spends about 6-7% of its GDP on freight transport annually, and US reliance on the freight transportation system has been growing considerably for some time [5]. More generally, the role of exported and imported goods and services represented approximately 22% of US GDP in 2005, up from 12% in 1990 and 10% in 1970 as product manufacturing moved to globalized markets[6]. A modal comparison for US goods movement is shown in Figure 1. Over 6,400 billion tonne-kilometers (gigatonne-kilometers, or Gtkm) of freight moves domestically each year, with truck and rail modes dominant, moving about 36% and 48% of the total Gtkm in the US, respectively. Domestic marine shipping moves about 16% and air moves about 0.4% [7]

Freight growth is likely to continue in the coming decades due to increasing international and domestic trade. For instance, according to the US Department of Energy, the total vehicle miles traveled (VMT) for freight trucking in the US is expected to increase from 230 billion VMT to 400 billion VMT between 2005 and 2030, an annual increase of 2.3%. Likewise, US rail freight transport is expected to increase from about 2,800 Gtkm to 4,300 (1.7%/yr) over the same period, while domestic marine freight is expected to increase from 1,100 Gtkm to 1,400 Gtkm (1.0%/yr). Notably, air freight is expected to increase from about 40 Gtkm to almost 150 Gtkm (4.9%/yr) during this period [8].

The freight sector is also a major contributor to emissions inventories worldwide [9-11]. Energy use and emissions from freight transport are increasing faster than other types of transportation. In the US in 2005, domestic freight transport accounted for over 6,800 trillion Btu (TBtu) of energy consumption, representing approximately one-quarter of total non-military transportation energy use. This consumption is expected to increase at an average rate of 1.8% per annum (compared to 1.4% for the transportation sector as a whole and compared to 1.1% for the electric utility sector). As such, by 2030 energy consumption from freight transport is expected to grow by almost 60% to 10,500 TBtu, representing 28.6% of total transportation energy use [8]. Along with this increase in energy consumption are concomitant and problematic increases in petroleum consumption and emissions of GHGs and other pollutants.

Heavy duty truck, rail, and water transport together account for about 25% of US CO_2 emissions, about 50% of nitrogen oxides (NO_x) emissions, and nearly 40% of particulate matter (PM) emissions from all mobile sources [12-14]. Similarly scaled impacts are also seen in Europe where freight transportation is responsible for more than 30% of the transportation sector's CO_2 emissions [15]. Figure 1 illustrates statistics for US shipping demand (Gtkm), and CO_2 emissions (in teragrams of CO_2 per year, or $TgCO_2$/yr). (Note that one Tg is equivalent to one million metric tonne). The *emissions intensity* for each mode as measured in gCO_2/tkm of freight moved is shown in Table 1. This table demonstrates that rail and coastal shipping offer the lowest carbon intensity (measured as gCO_2/Gtkm), while aviation is highest.

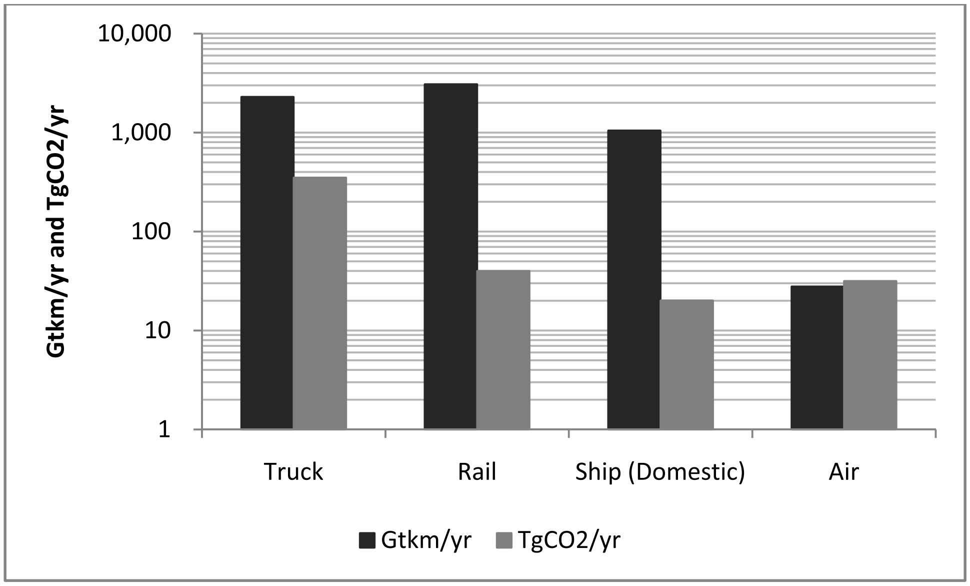


Figure 1. Comparison of freight mode shares (annual Gtkm and CO_2) for the US (2005) [7, 14]. Note units are on log scale.

Table 1.Average Energy and Carbon Intensity for US by Mode

Summary Table	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

Adapted from: [7, 14]

1.2 Oceangoing fleet profile and emissions estimates

1.2.1 Global Fleet profile

The global fleet of oceangoing vessels numbers over 108,000; of these, ~46,000 are used to move cargo (see Table 2). These ships are responsible for 2-4% of the world's annual fossil fuel consumption [16]. A profile of the internationally registered fleet of ships greater than 100 gross tons is shown in Table 2 [17]. Transport vessels account for almost 60% of the ships and nearly 80% of the energy demand of the internationally registered fleet (not including military ships). Considered along with military ships, cargo ships account for 40% of the world fleet of vessels and 66% of world fleet fuel use. The registered fleet has approximately 84,000 four-stroke engines with total installed power of 109,000MW and some 27,000 two-stroke engines with total installed power of 164,000MW. Engines with ''unknown'' cycle types and ''turbines'' together make up only about 2.5% of total installed power for main engines.

Fuel types used in marine transportation are different from most transportation fuels. Marine fuels, or *bunkers*, can be generally classified into two categories: residual fuels and other fuels. Residual fuels, also known as heavy fuel oil (HFO) or intermediate fuel oil (IFO), are a blend of various oils obtained from the highly viscous residue of distillation or cracking after the lighter (and more valuable) hydrocarbon fractions have been removed. Since the 1973 fuel crisis, refineries adopted secondary refining technologies (known as thermal cracking) to extract the maximum quantity of refined products (distillates) from crude oil. As a consequence, the concentration of contaminants such as sulfur, ash, asphaltenes, and metals has increased in residual fuels.

Table 2. Profile of 2002 world commercial fleet, number of main engines, and main engine power.

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%

Notes: Percent of energy demand is not directly proportional to installed power because military vessels typically use much less than their installed power except during battle. Average military deployment rate is 50% underway time per year [18]; studies indicate that when underway Naval vessels operate below 50% power for 90% of the time [19]. Therefore, energy demand was adjusted in this Table to reflect these facts. The data upon which military vessel power was based specified the number of engines aboard Naval ships. This table was previously presented in other publications [16, 20]. Note: The data in the above table to not necessarily reflect the fleet profile of ships that come to California.

To reduce operating expenses, marine engines have been designed to burn the least costly of petroleum products. Residual fuels are preferred if ship engines can accommodate its poorer quality, unless there are other reasons (such as environmental compliance) to use more expensive fuels. Of the two-stroke, low-speed engines, 95% use HFO and 5% are powered by MDO [20]. Fuel consumed by 70% of the four-stroke, medium-speed engines is HFO, with the remainder burning either MDO or MGO. Four-stroke, high-speed engines all operate on MDO or MGO. The remaining engine types are small, high-speed diesel engines all operating on MDO or MGO, steam turbines powered by boilers fueled by HFO, or gas turbines powered by MGO.

The nations selling the most fuel to commercial ships are typically nations with strong interests in the cargoes or services those ships provide. Organization of Economic Cooperation and Development (OECD) nations account for roughly half of these fuel sales and provide one illustration of historical consumption trends in the overall fleet [21, 22]. Table 3 summarizes fuel quantities sold by the top nations selling international marine fuels [23, 24]. The US currently provides ~15% of the world's marine fuels, similar to the volume sold by Singapore.

Table 3. International marine fuel sales by nation [23, 24].

Percent of World Bunkers	2003		2004		2005	
World	150,568	100%	167,734	100%	175,330	100%
OECD	81,425	54%	91,326	54%	99,140	57%
OECD North America	20,873	14%	26,213	16%	27,930	16%
United States	**19,559**	**13%**	**24,828**	**15%**	**26,455**	**15%**
OECD Europe	47,860	32%	51,442	31%	53,787	31%
OECD Pacific	12,692	8%	13,671	8%	17,419	10%
Non OECD	69,143	46%	76,408	46%	76,190	43%
Singapore	20,809	14%	19,567	12%	25,479	15%

1.2.2 Marine emissions inventories

Emissions inventories for oceangoing ships can be calculated using various methodologies [20]. Figure 2 depicts cargo fleet emissions inventory estimates for various pollutants in the cargo fleet. The figure shows estimated ranges of fuel use and CO_2 emissions alongside the other pollutant emissions using a log-scale.

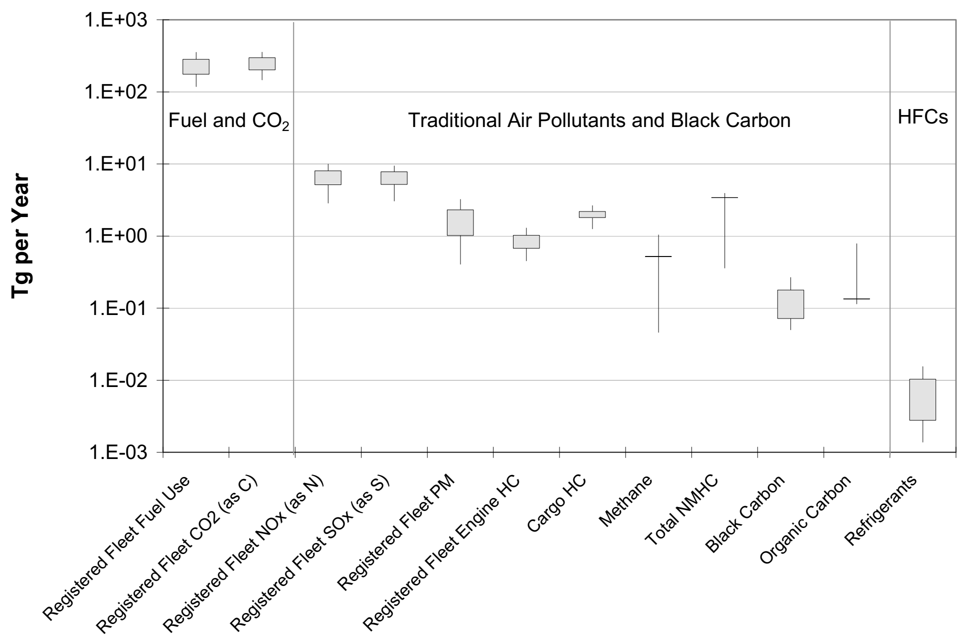


Figure 2. Summary of estimated ranges in global emissions from maritime shipping. Box-plots represent the 5th and 95th percentile results; whiskers extend to lower and upper bounds.

1.3 Shipping Emissions Health Impacts

Emissions from ships may lead to a number of human health impacts, including thousands of premature mortalities each year attributed to PM emissions from ships [25, 26]. These impacts have also been identified in work specifically focused on California. Figure 3 shows evidence for California that indicates that premature mortality from PM emissions due to shipping will soon catch up to those from trucks. Figure 4 shows where many impacts might occur globally [25].

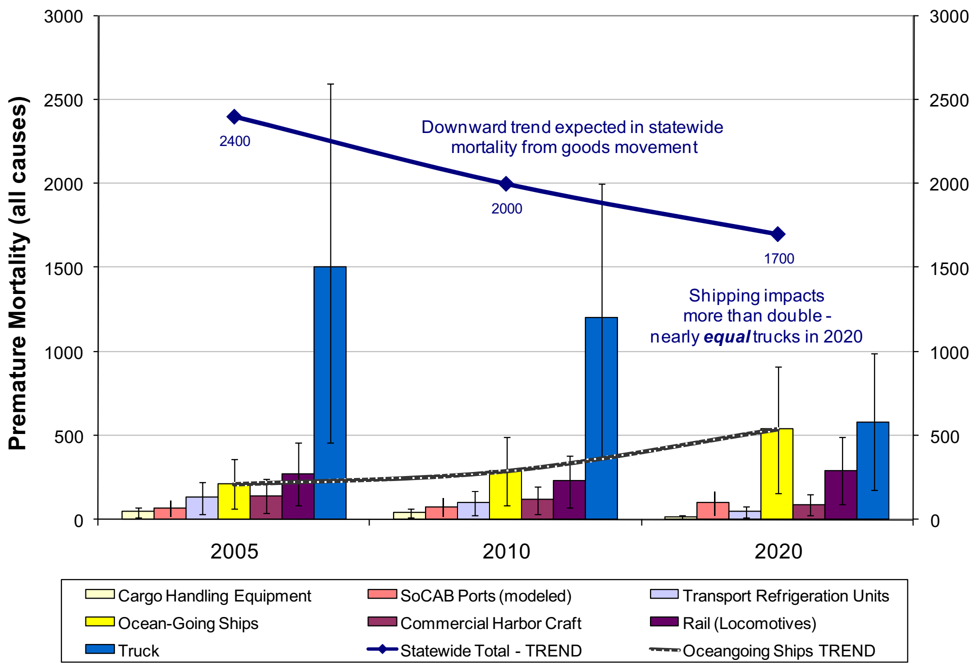


Figure 3. Premature mortality (all causes) due to freight transportation pollution projected over time. Although overall trends are downward, trends for oceangoing ships are on a upward trend and will almost equal premature mortality from trucks by 2020 [26].

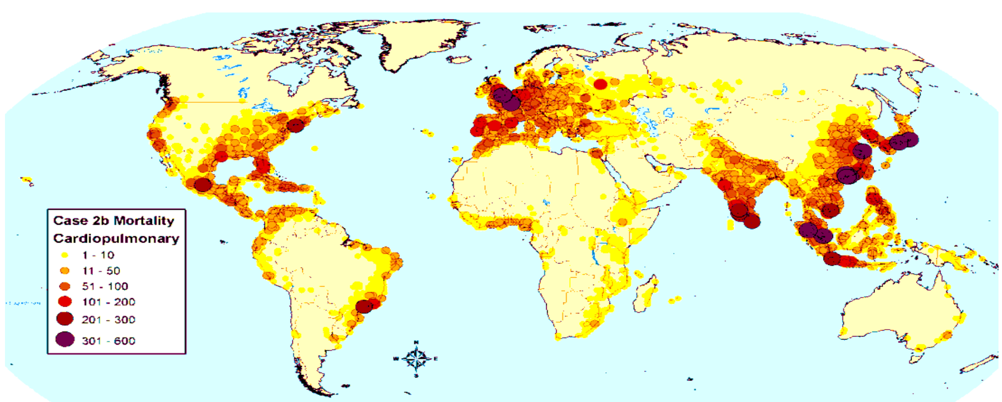


Figure 4. Map of premature mortality, geospatially depicted for one case of the recent Corbett and Winebrake (2007) study [25].

1.4 Mitigation alternatives for shipping

Reducing pollution from shipping has been well-studied, although work continues to update cost and performance of known alternatives and to quantify emerging options. Fewer studies have considered directly how to mitigate CO_2 emissions; the IMO study of greenhouse gases from ships presented a suite of alternatives for both new and existing vessels [10].

The IMO study estimated that new vessel CO_2 emissions could be reduced by 5-20% through technological measures, with hull and propeller modifications and engine optimization for efficiency (rather than power) offering the greatest potential. Other new-engine technologies offered only modest CO_2 reductions (0.5-5%), although a hypothetical combination of technological measures could achieve a maximum range of 5-30% reduction. Furthermore, the IMO study estimated that reducing CO_2 from existing vessels (e.g., through retrofit technologies) would be more challenging, with reductions from individual measures ranging from 1-7%. Some reasonable combinations put CO_2 reductions in a range of 5-12%, with a hypothetical combination of all technological measures at 5-20%.

Reduction of traditional air pollutants has received greater attention. An important consideration identified in reducing air quality pollutants through technologies and alternative fuels is that nearly all increase the energy requirements on system-basis by 1-5%, thereby increasing CO_2 emissions attributed to shipping proportionally.

The issue of emissions tradeoffs between traditional air pollutant control and GHG emissions has received special attention as the IMO, ARB, and others consider policies to require low sulfur fuels aimed at reducing SO_x and PM emissions. Producing these low-sulfur fuels requires additional energy at the refining stage of the fuel cycle. The next section discusses our analysis comparing these total fuel cycle GHG and SO_x emissions across a suite of traditional and alternative fuels.

2 Total Fuel Cycle Analysis and the TEAMS Model

2.1 TEAMS Model Description

In order to more completely assess emissions from marine transportation (and to compare these emissions across fuel alternatives and against competing land-side modes), a *total fuel life cycle* (or "total fuel-cycle") emissions analysis is needed. In such analyses, emissions are quantified along the entire fuel pathway—from feedstock extraction, to fuel processing, to delivery, and to end-use, as shown in Figure 5. We use the term "downstream" to refer to emissions occurring at the end-use technology (i.e., vessel); we use the term "upstream" to refer to emissions due to the extraction, production, and delivery of the fuel ultimately consumed in the end-use technology.

Total fuel cycle analyses (TFCA) are complicated. Process fuel consumed at each "upstream" stage (for example, in the energy-intensive activity of petroleum refining) also has its own fuel-cycle chain that must be considered. A full explanation of the methodologies used to quantify these upstream emissions is beyond the scope of this report, however there is a vast and growing literature discussing these methodological approaches [27-30].

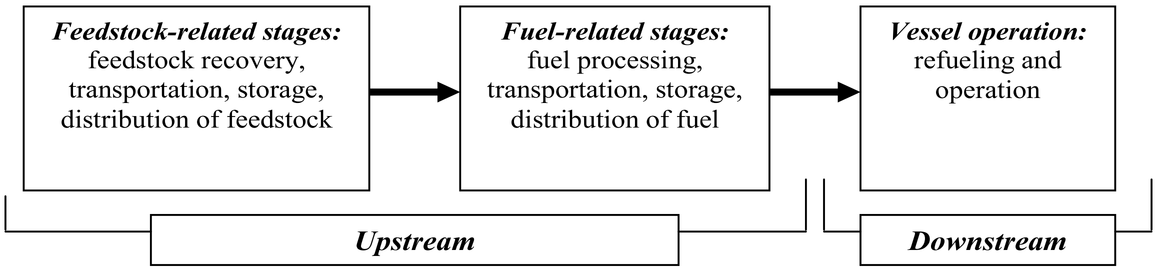


Figure 5. Diagram of total fuel cycle analysis stages for marine fuels.

To conduct our analysis, we use a modification of the peer-reviewed Total Energy & Emissions Analysis for Marine Systems (TEAMS) model, which was originally based on Argonne National Lab's GREET model [27-30]. We modified TEAMS as originally published to allow TFCA for the particular set of fuels under study (IFO, DMA, DMB) and to capture results in units more appropriate for side-by-side fuel comparisons. Our modified version of TEAMS calculates emissions in (g/MBtu) for different marine vessels by taking into account energy use and emissions of combustion and non-combustion events in the upstream and downstream stages of the total fuel-cycle. The focus in this report is on CO_2 and SO_x emissions associated with the use of IFO, DMA, and DMB marine fuels. Many of the upstream assumptions for our analysis (except those discussed below) are identical to those found in published work [31] and are available at http://www.rit.edu/~teams.

2.2 Analytical Approach

2.2.1 Marine fuels considered

This analysis considers a set of six fuels. These fuels are shown in Table 4. For each fuel, we identified four parameters of importance from a TFCA standpoint. These parameters are: (1) sulfur content; (2) energy content; (3) physical density; and (4) refining efficiency. Assumptions for these parameters are discussed in the next section.

Table 4. List of fuel types evaluated in this study.

Fuel Type	Description
IFO 380	Intermediate fuel oil with a viscosity of 380 centistokes at 50° C.
IFO 180	Intermediate fuel oil with a viscosity of 180 centistokes at 50° 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.

2.2.2 Modeling Assumptions

2.2.2.1 Sulfur content

We use fuel quality testing data provided by Det Norske Veritas (DNV) to ARB for DMA and DMB to calculate the average sulfur values and their probability distributions [32]; for IFO 380 and 180 we use previously reported sulfur levels [31]. We used best-fit probability distributions for sulfur for our distillate fuels. These probability functions were trimmed as defined by our lower and upper bounds shown in Table 5. (Note that the upper bounds reflect a small number of samples that exceeded ISO specifications of 1.5% S for DMA and 2% for DMB. In addition, fuel sulfur of less than 0.05% is reported as 0.05%--representing the lower bound testing limit--and therefore our lower bound is conservatively high). For the IFO fuels, we used a triangular distribution with lower and upper bounds as shown in the table.

Table 5. 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

2.2.2.2 Physical densities

For physical densities (g/gal), we used the same approach as described above for sulfur, except using physical density data provided by ARB based on DNV testing. The lower, mean, and upper values are shown in Table 6.

Table 6. 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	3863
IFO 180	3739	3767	3817
DMA (0.1% Sulfur)	3184	3278	3416
DMA (Global)	3127	3300	3564
DMB (0.1% Sulfur)	3172	3295	3450
DMB (Global)	3125	3355	3629

2.2.2.3 Energy content

For energy content, we applied 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 [33]. We ignore water content and ash content for this analysis, as these have a negligible effect on energy content for the fuels we evaluate.

2.2.2.4 Refinery efficiencies

Refining efficiency is an important parameter, as it helps define the amount of energy input needed to produce a given amount of refined product output. Estimated refinery efficiencies for each fuel are based on best estimates of refinery performance for a typical refinery found in industrialized countries, as reported elsewhere [34]. (No data have been uncovered suggesting that these values are not also true for refineries operating in developing countries as well). To create specific efficiencies for each fuel product, we developed a relationship between refining efficiency and sulfur content based on efficiency values for residual and low-sulfur distillate fuels as reported in TEAMS [31]. Using this relationship, we then estimated refining efficiencies for each product based on the sulfur content of the fuel, as shown in

Table 7. These estimates are a first approximation and further research is needed to evaluate efficiencies for various refinery types. However, as demonstrated later, emissions from the refining stage of the total fuel cycle only represent about 5-10% of total emissions; hence, large variations in refinery efficiencies will likely only lead to modest changes in total fuel cycle emissions results. This study makes no assumptions about the potential for refinery efficiency improvements to further offset the small net increases in CO2, although investment in increased conversion of residual to distillate may be associated with some system improvements.

Table 7. Refining efficiency by fuel used in the analysis.

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%

3 Results

3.1 Probabilistic Sensitivity Analysis Results

For our probabilistic sensitivity analysis, we placed best-fit probability distributions on our input parameters using world marine fuel sample data provided by DNV to ARB [32]. Using Monte Carlo sampling with the TEAMS model, we calculated total fuel cycle results for 10,000 trials to identify the range of results that might be expected. Our graphical results for CO_2 are shown in Figure 6. This figure identifies the most likely (peak) total fuel cycle carbon emissions for each fuel. For example, the two IFO fuels have a peak around 92,000 grams CO_2 per million BTU (gCO_2/MBtu), while the peak frequencies for distillates are shifted higher by about 0.5% to 2%, depending on fuel specifications. The graph also shows the range of values that exist for each fuel, given the possible ranges for each of our input variables discussed in section 2. The IFO fuels tend to have much tighter distributions (i.e., greater certainty with respect to total fuel cycle carbon emissions) as opposed to the distillates, which have much larger emissions ranges. Numerical values for our probabilistic analysis are shown in Table 8. Figure 7 shows our 5%-95% ranges for total fuel cycle CO_2 emissions by fuel.

3.2 Fuel Cycle Contribution to CO_2 and SO_x

Results are presented below in terms of each stage in the total fuel cycle in graphical and tabular form. Figure 8 shows the results for CO_2 for each of the analyzed fuels using sample mean input parameter values. This stacked bar chart presents expected emissions from the three general stages of the total fuel cycle: feedstock extraction, fuel processing, and operation. As shown in this figure, DMA and DMB have higher CO_2 emissions from the upstream stages of the fuel cycle compared to IFO; however, these are mostly offset by lower emissions downstream (i.e., vessel operation). Numerical results shown in Table 9 demonstrate that total emissions for these fuels are very similar.

Table 8. Descriptive TFC CO_2 emissions statistics for probabilistic sensitivity analysis for 10,000 trials reported in gCO2/MBtu.

Units: gCO_2/MBtu	DMA (0.1% Sulfur)	DMA (Global)	DMB (0/1% Sulfur)	DMB (Global)	IFO 180	IFO 380
Mean Result and % change from IFO 380	94,200 2.17%	93,300 1.19%	93,200 1.08%	92,700 0.54%	92,300 0.11%	92,200 N/A
Median Result	94,100	93,300	93,200	92,700	92,300	92,200
Standard Deviation	1,300	1,600	1,600	2,600	500	500
5^{th} Percentile	92,200	90,800	90,800	89,100	91,600	91,400
95^{th} Percentile	96,500	96,000	96,000	97,600	93,200	93,000
Minimum	91,100	88,700	89,400	86,600	91,300	91,000
Maximum	98,600	99,700	98,100	101,900	93,700	93,400

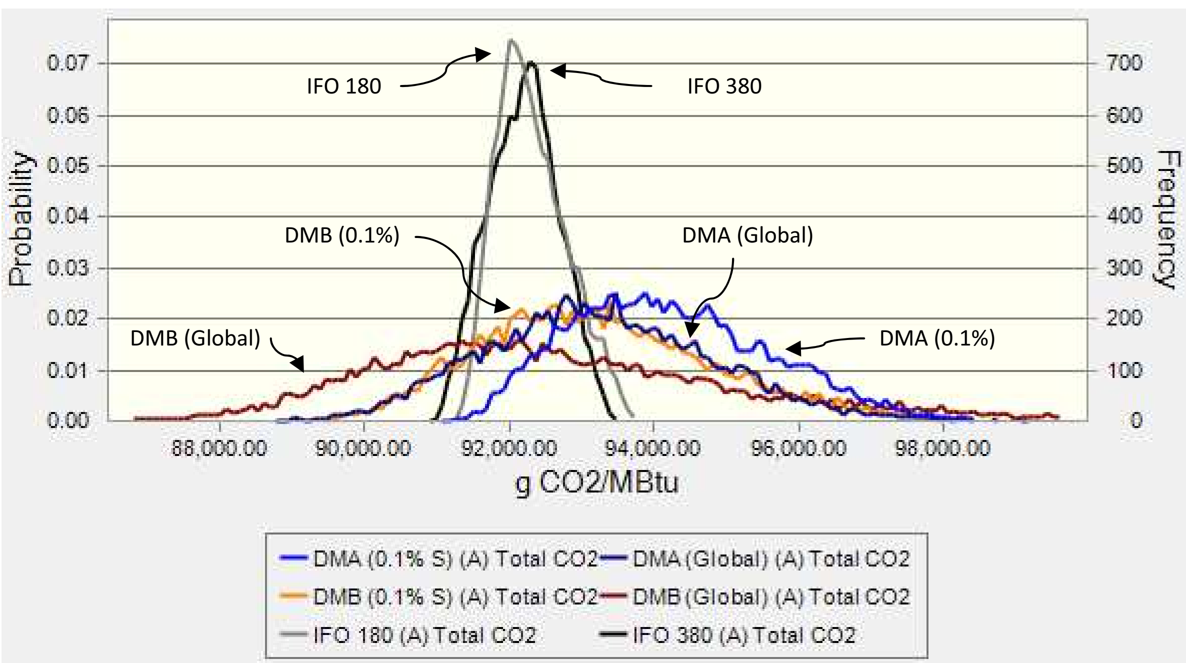


Figure 6. Probabilistic results for total fuel cycle CO_2 emissions (in gCO2/MBtu) by fuel using Monte Carlo sampling (10,000 trials).

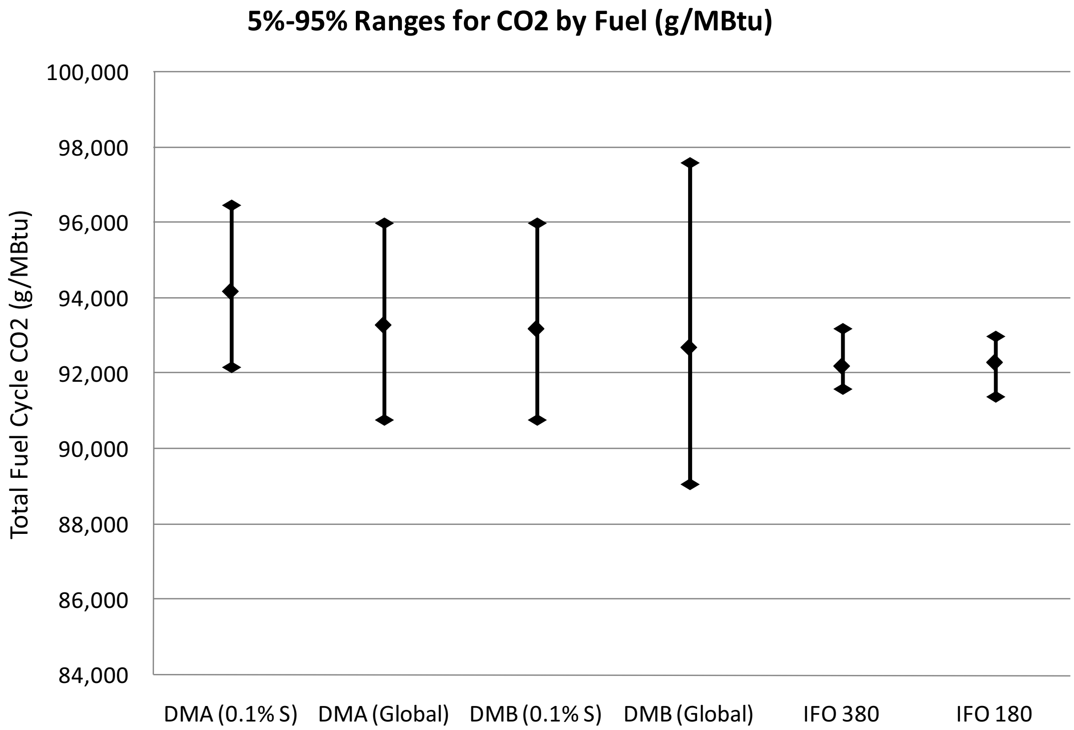


Figure 7. Ranges (5%-95%) for CO_2 total fuel cycle emissions from probabilistic sensitivity analysis. Ranges show overlap with some variation in mean values.

Figure 9 shows our total fuel cycle analysis results for SO_x, with numerical data presented in Table 10. Unlike CO_2, almost all of the SO_x emissions from these fuels occur during the downstream stage of the total fuel cycle. The tabular data also show the very significant reductions in SO_x expected from ARB-compliant fuel as compared to the IFO fuels currently in use.

Table 9. Total fuel cycle analysis results by stage for CO_2 for all fuels (gCO2/MBTU) using sample mean input values, along with percent contribution to total emissions and percent change from IFO 380.

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%

Note: Results rounded to nearest hundred; total in table may be different than total of rounded values shown and percentages may not add up to 100% due to rounding.

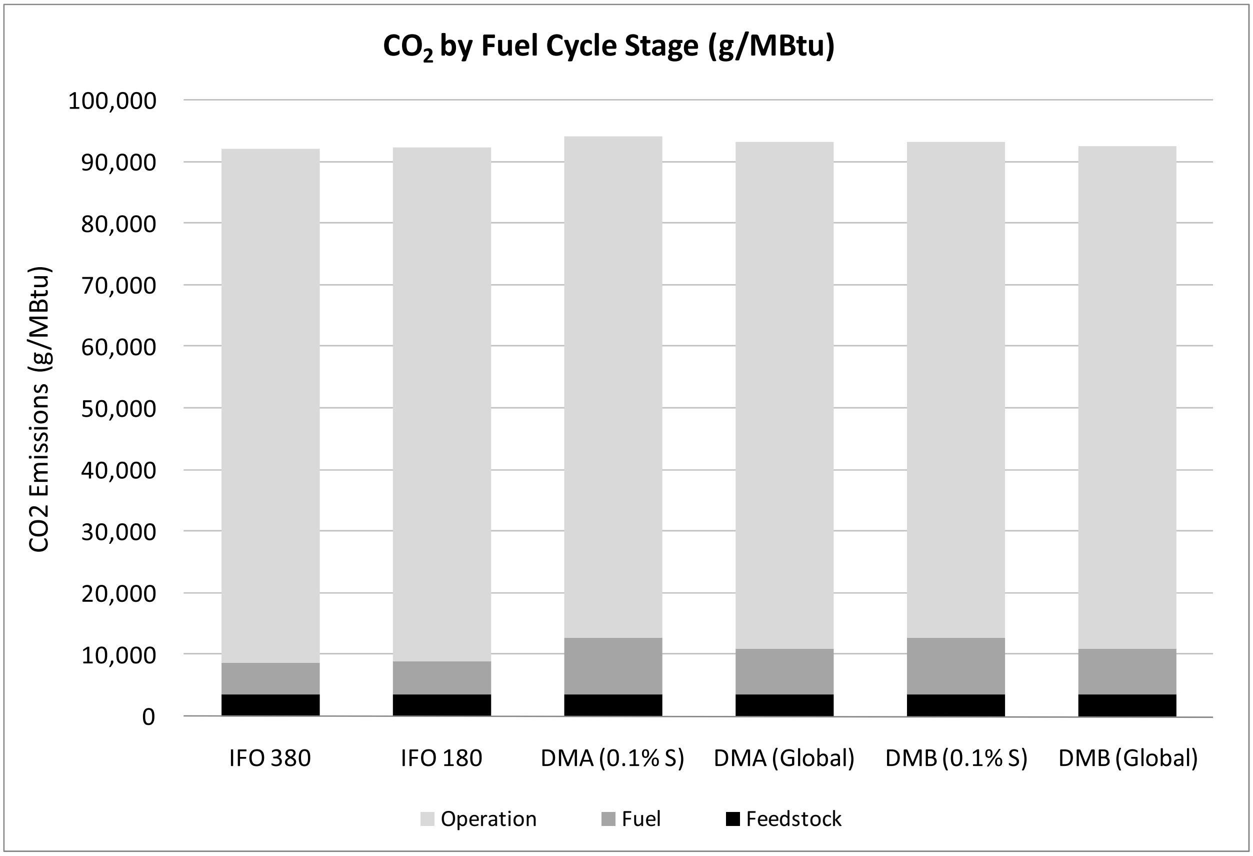


Figure 8. Total fuel cycle results for CO_2 for each of six (6) different marine fuels using sample mean input values. Results show larger upstream emissions from DMA and DMB compared to IFO fuels, but smaller emissions from operation stages.

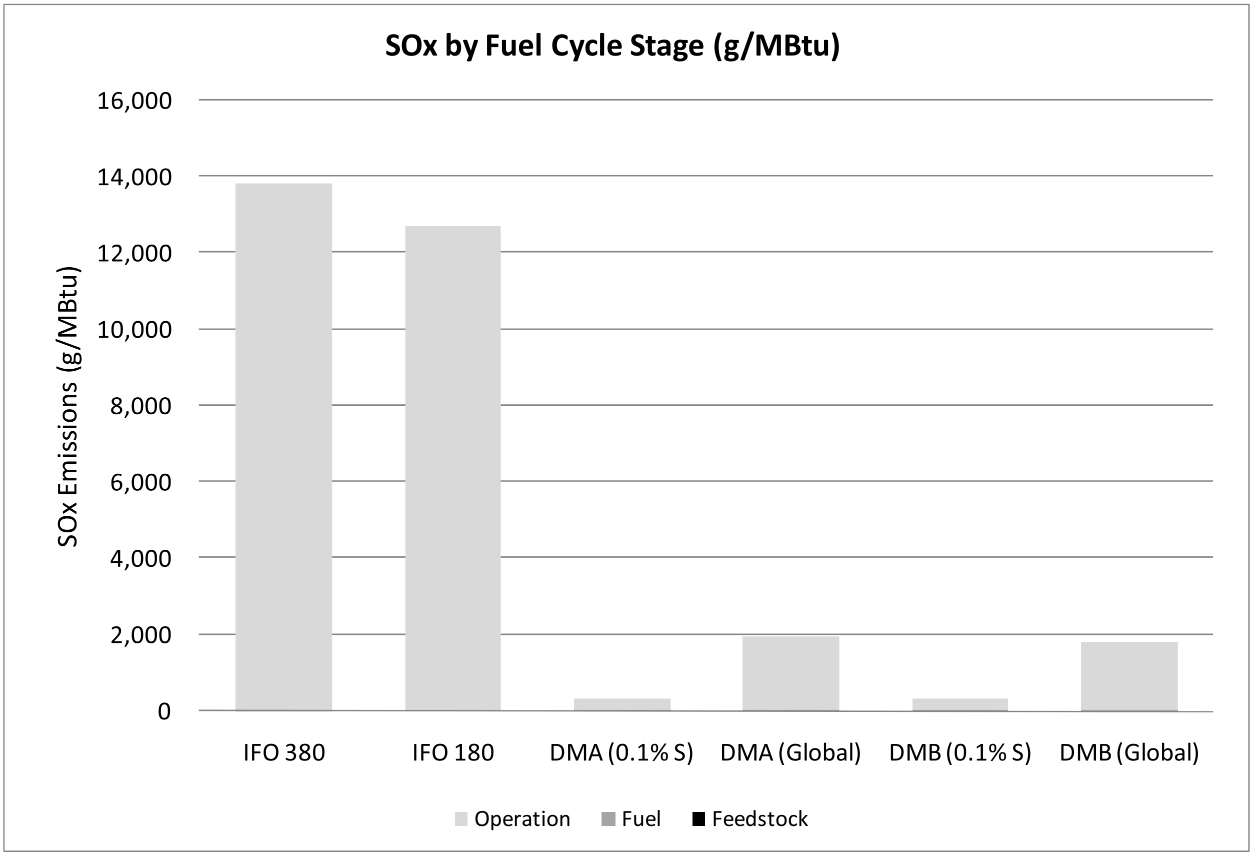


Figure 9. Total fuel cycle results for SO_x for each of six (6) different marine fuels using sample mean input values. These emissions are almost exclusively due to the downstream (i.e., operation) segments of the fuel cycle.

Table 10. Total fuel cycle analysis results by stage for SO_x for all fuels (g/MBtu) using sample mean input values, along with percent contribution to total emissions and percent change from IFO 380.

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%

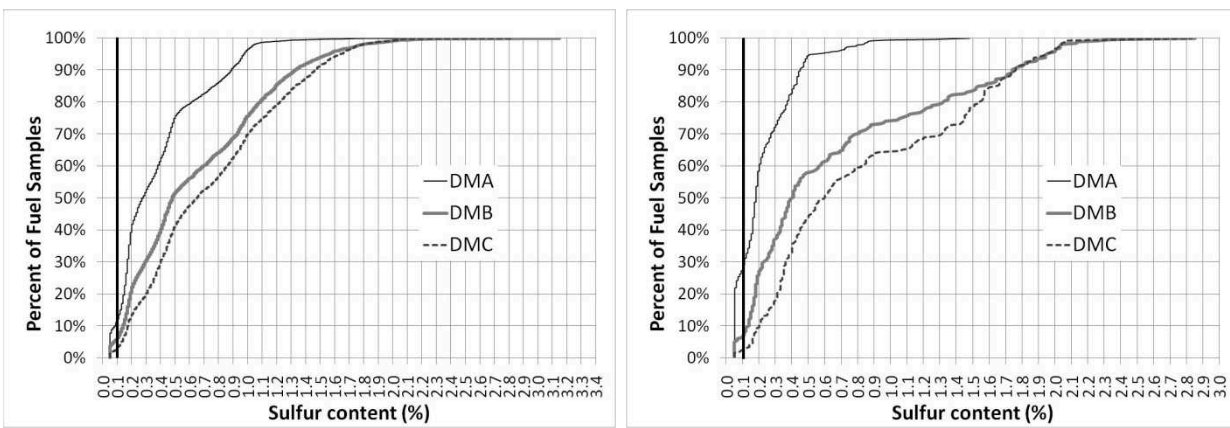
Note: Results rounded to nearest hundred; total in table may be different than total of rounded values shown and percentages may not add up to 100% due to rounding.

4 Distillate Production and Supply Constraints

4.1 Current Mix of US Marine Distillate Supply

For this report we evaluated marine distillate supply using data provided by ARB and based on fuel tests from DNV. Figure 10a and 10b display cumulative distributions of fuel samples as a function of sulfur content for three types of marine distillate fuels (DMA, DMB, and DMC) sold globally (10a) and domestically (10b). These distributions show the percentage of sampled fuel (y-axis) that met certain sulfur content levels (x-axis), based on more than 5,000 test samples of fuel sold in the US and abroad. Assuming that these samples are correlated with fuel sales volumes, these data provide at least a first-order representation of fuel quality for each type of marine distillate fuel sold. For example, the bold, vertical line in each graph of the figure identifies 0.1% sulfur fuel. As shown in Figure 10b, we would estimate that about 29% of DMA, 6.8% of DMB, and 2.3% of DMC currently sold in the US are ARB-compliant.

This section provides an initial assessment of potential fuel availability and supply constraints related to ARB's distillate rule. First, we look at global consumption trends to demonstrate general trends to replace residual fuel production in favor of light and middle distillates. Second, we analyzed available data on fuel use by ships globally and within the 24 nm region of California coastline regulated by ARB. We discuss each type of analysis in the next subsections.

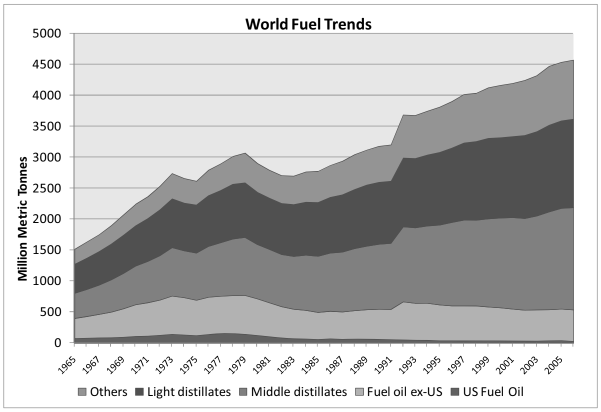


(a) (b)

Figure 10. Distribution of Sulfur Content for Marine Distillates from Fuel Samples for a) Global; b) US

4.2 Global trends in residual and distillate fuel

According to the British Petroleum *BP Statistical Review of World Energy* [35], total fuel oil (including residual fuels such as heavy home heating oil, heavy fuel for oil-fired utility power generation, and marine fuels) consumed in the US has been declining steadily since the late 1970s to less than 3.3% of total energy consumption. Of this, the marine sector has accounted for more than half of residual fuel oil demand. Moreover, over the past decade US producers have been importing more and more residual fuel oil for resale, and such imports represent over half of the residual fuel sold to ships. These trends point to a shift in global and US refinery output that now focuses primarily on meeting higher-valued demand for distillates, as shown in Figure 11.



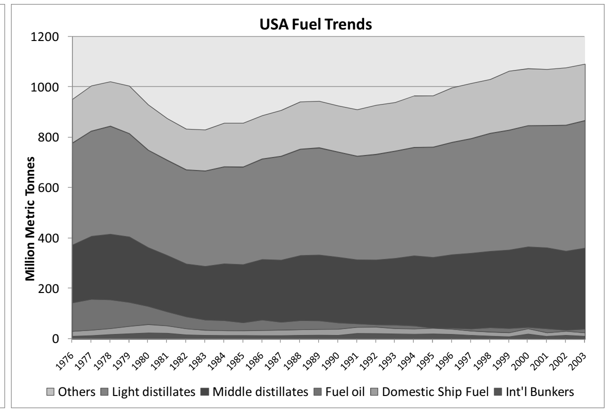


Figure 11. Global and US fuel supply trends (1976-2003) demonstrating increased consumption of light and middle distillates, and less consumption of residual fuels.

Coincident with these trends is a steady increase in demand for transportation diesel fuels, including onroad diesel products, nonroad diesel fuel, and marine distillate fuels. Department of Energy data indicate that diesel fuel used in transportation has been growing at compounding rates between 3.8% and 4.3% annually, consistent with growth in goods movement [36]. A switch to marine distillates to comply with ARB regulations would be expected to increase the growth rate to some degree. But we believe the industry is already on a steady growth path towards distillate fuels, and therefore this modest shift in demand for distillates may be accommodated by planned investment currently upgrading refining product mix. Moreover, if these investments also seek to improve energy efficiency in the refinery, they may offset the 1% to 2% net increases in total fuel cycle CO_2 emissions estimated in this report.

4.3 Distillate demand from ARB rule

We analyzed fuel demand projections produced by ARB to assess what the likely distillate demand impacts might be from a shift from residual oil to distillates within the 24 nm region considered under the rule. Our results are shown in Table 11 (and are based on the abovementioned assumption that the fuel test sampling data adequately represent the quality of fuel sold in the market). This table identifies expected HFO and ARB-compliant distillate demand under "business-as-usual" (BAU case), and with proposed ARB regulations (ARB case). The table identifies the quantities of HFO and ARB-compliant fuels that would be needed to satisfy the ARB-rule case. The table also includes estimated percentages reflecting the proportion of ARB-compliant distillate with respect to: (1) projected BAU global ARB-compliant distillate production; (2) projected BAU US ARB-compliant distillate production; and (3) projected BAU US distillate production overall (both ARB-compliant and non-ARB-compliant distillates). The results of this analysis are also reflected in Figure 10, which not only shows the data from the table, but also notes the existing levels of ARB-compliant fuel that are available on the West Coast.

5 Conclusion

A switch to lower sulfur fuels would likely reduce sulfur emissions by approximately 85-97%, while increasing total fuel cycle carbon emissions by 0.5-2.2%. The increases in carbon from low-sulfur fuels come primarily at the fuel processing (refining) stage of the fuel cycle; these emissions are offset in large part by reductions in carbon in the vessel operating stage. This study makes no assumptions about the potential for refinery efficiency improvements to further offset the small net increases in $CO2$, although investment in increased conversion of residual to distillate may be associated with some system improvements.

This report also provides a first approximation of potential fuel supply constraints due to proposed regulations requiring the use of low-sulfur distillates in the marine sector. The results indicate that new low-sulfur fuel requirements along the U.S. West Coast would generate distillate demand representing less 0.5% of the total U.S. distillate production.

Table 11. Expected distillate and heavy fuel oil (HFO) consumption (tons/year) for a business-as-usual (BAU) case and the 0.1% S case.

	Projected Fuel Consumption (tons/year)			Fuel Consumption under a BAU Case by Fuel type (tons/year)		Fuel Consumption under an 0.1% S Case by Fuel Type (tons/year)		% of Projected Global 0.1% S-compliant Distillate Supply for Marine Sector		% of Projected US 0.1% S-compliant Distillate Supply for Marine Sector		% of US Total Distillate Production
	Aux. Eng.	Aux. Boilers	Main Engines	Total HFO	Total Distillate	Total HFO	Total Distillate	BAU Case	0.1% S Case	BAU Case	0.1% S Case	0.1% S Case
2006	237,116	146,791	433,735	767,848	49,794	767,848	49,794	0.41%	0.41%	0.85%	0.85%	0.01%
2009	279,066	167,275	493,386	660,661	279,066	660,661	279,066	2.22%	2.22%	4.60%	4.60%	0.07%
2010	299,120	166,069	488,567	654,636	299,120	0	953,756	2.29%	7.31%	4.74%	15.13%	0.26%
2011	320,973	173,386	509,942	683,328	320,973	0	1,004,301	2.37%	7.40%	4.89%	15.31%	0.27%
2012	344,866	181,021	532,264	713,286	344,866	0	1,058,152	2.44%	7.50%	5.06%	15.52%	0.28%
2013	371,075	189,000	555,592	744,591	371,075	0	1,115,666	2.53%	7.60%	5.23%	15.73%	0.30%
2014	399,913	197,347	579,986	777,334	399,913	0	1,177,246	2.62%	7.71%	5.42%	15.96%	0.32%
2015	431,738	206,094	605,514	811,608	431,738	0	1,243,346	2.72%	7.83%	5.63%	16.21%	0.33%
2016	466,962	215,270	632,247	847,517	466,962	0	1,314,479	2.83%	7.96%	5.85%	16.48%	0.35%
2017	506,054	224,913	660,258	885,171	506,054	0	1,391,226	2.95%	8.10%	6.10%	16.77%	0.37%
2018	549,551	235,061	689,629	924,690	549,551	0	1,474,241	3.08%	8.26%	6.37%	17.08%	0.40%
2019	598,069	245,757	720,445	966,202	598,069	0	1,564,271	3.22%	8.42%	6.66%	17.43%	0.42%
2020	652,310	257,050	752,797	1,009,846	652,310	0	1,662,157	3.38%	8.61%	6.99%	17.81%	0.45%

6 References

1. Intertanko, Revisions of MARPOL Annex VI, the NOx Technical Code and Relevant Guidelines. IMO submittal, INTERSESSIONAL MEETING OF THE BLG WORKING GROUP ON AIR POLLUTION, 1st session, Agenda item 2: 2006.
2. IPIECA; OCIMF, Environmental Impact of SOx emissions from international shipping and considerations on the supply of low sulphur bunker fuels IMO Submittal, INTERSESSIONAL MEETING OF THE BLG WORKING GROUP ON AIR POLLUTION, 1st session, Agenda item 2: 2006; Vol. BLG-WGAP 1/2/13.
3. California Air Resources Board, DRAFT DOCUMENT: Fuel Sulfur and Other In-Use Operational Requirements for Main Propulsion Diesel Engines and Auxiliary Boilers Operated On Ocean-Going Vessels Within California Waters and 24 Nautical Miles of the California Baseline. http://www.arb.ca.gov/ports/marinevess/documents/092407ogvdraftreg.pdf, 2007.
4. Winebrake, J. J.; Corbett, J. J.; Meyer, P. E., Energy Use and Emissions from Marine Vessels: A Total Fuel Cycle Approach. *Journal of Air and Waste Management* **2007,** *57*, (January), 102-110.
5. Bureau of Transportation Statistics *National Transportation Statistics 2005*; U.S. Department of Transportation, Research and Innovation Technology Administration: Washington, DC, 2005.
6. Bureau of Economic Analysis National Income and Product Accounts Table. http://www.bea.gov/bea/dn/nipaweb/index.asp (June 12).
7. Bureau of Transportation Statistics *National Transportation Statistics 2007*; U.S. Department of Transportation, Research and Innovation Technology Administration: Washington, DC, 2007.
8. U.S. Energy Information Administration *Annual Energy Outlook 2007 with Projections to 2030*; DOE/EIA-0383; U.S. Department of Energy: Washington, DC, 2007.
9. Organisation for Economic Co-Operation and Development (OECD); Hecht, J. *The Environmental Effects of Freight*; TRANSP4; Organisation for Economic Cooperation and Development (OECD): Paris, France, 1997, 1997; p 35.
10. Skjølsvik, K. O.; Andersen, A. B.; Corbett, J. J.; Skjelvik, J. M. *Study of Greenhouse Gas Emissions from Ships (MEPC 45/8 Report to International Maritime Organization on the outcome of the IMO Study on Greenhouse Gas Emissions from Ships)*; MT Report MT00-A23-038, MEPC 45/8; MARINTEK Sintef Group, Carnegie Mellon University, Center for Economic Analysis, and Det Norske Veritas: Trondheim, Norway, 31 March 2000, presented to IMO 29 June 2000, 2000.
11. Energy Information Administration *Energy Efficiency Initiative, Volume 1: Energy Policy Analysis*; International Energy Agency: Paris France, May 1998, 1998; p 193.
12. Environmental Protection Agency *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*; EPA 430-R-05-003; U.S. Environmental Protection Agency: Washington, DC, 15 April 2005, 2005; p 432.
13. Environmental Protection Agency National Air Pollutant Emission Trends, 1970-2002. http://www.epa.gov/ttn/chief/trends/ (11 May 2005).
14. Energy Information Administration Annual Energy Outlook 2007 with Projections to 2030, Supplemental Transportation Tables. http://www.eia.doe.gov/oiaf/aeo/supplement/index.html (21 March 2008).
15. Bates, J.; Brand, C.; Davison, P.; Hill, N. *Economic Evaluation of Emissions Reductions in the Transport Sector of the EU: Bottom-up Analysis, UPDATED, Final Report*; AEA Technology Environment: Abingdon, UK, 2001.
16. Corbett, J. J., Marine Transportation and Energy Use. In *Encyclopedia of Energy*, Cleveland, C. J., Ed. Elesvier Science: San Diego, CA, 2004; Vol. 3, pp 745-748.

17. Lloyds Maritime Information System (LMIS) *The Lloyds Maritime Database*, (Level 2) ver 1.3; Lloyd's Register - Fairplay Ltd.: 2002.
18. Navy, U. S., Navy News Service Message. In Navy Media Center Publishing: 1996.
19. NAVSEA *U.S. Navy Marine Diesel Engine and Gas Turbine Exhaust Emissions*; Naval Sea Systems Command 03X31: Washington, DC, February 1994, 1994.
20. Corbett, J. J.; Koehler, H. W., Updated Emissions from Ocean Shipping. *Journal of Geophysical Research - Atmospheres* **2003,** *108*, (D20), 4650-4666.
21. International Energy Agency, *Quarterly Oil Statistics, various issues*. Organisation for Economic Cooperation and Development: Paris, France, 1977-1997.
22. Energy Information Administration World Energy Database and International Energy Annual 2001. http://www.eia.doe.gov/emeu/world/main1.html (January 2003).
23. International Energy Agency; Organisation for Economic Cooperation and Development, Oil Information 2007. In OECD/IEA: Paris, France, 2007; p 746.
24. International Energy Agency; Organisation for Economic Cooperation and Development, Energy Statistics of Non-OECD Countries, 2004-2005. In OECD/IEA: Paris, France, 2007; p 786.
25. Corbett, J. J.; Winebrake, J. J.; Green, E. H.; Kasibhatla, P.; Eyring, V.; Lauer, A., Mortality from Ship Emissions: A Global Assessment. *Environmental Science & Technology* **2007,** *41*, (24), 8233-8239.
26. California Air Resources Board *Appendix A: Quantification of the Health Impacts and Economic Valuation of Air Pollution from Ports and Goods Movement in California*; California Air Resources Board: 3/22/2006, 2006.
27. Winebrake, J. J.; Corbett, J. J.; Meyer, P. *Total Energy and Emissions Analysis for Marine Systems (TEAMS) Model*; U.S. Department of Transportation: Washington, DC, February, 2006.
28. Wang, M.; Saricks, C.; Wu, M., Fuel ethanol produced from Midwest US corn: Help or hindrance to the vision of Kyoto? *Journal of the Air & Waste Management Association* **1999,** *49*, (7), 756-772.
29. Wang, M.; Wu, Y.; Elgowainy, A. *Operating Manual for GREET: Version 1.7*; Chicago, 2005.
30. Wang, M. Q.; Huang, H. S. *A Full Fuel-Cycle Analysis of Energy and Emissions Impacts of Transportation Fuels Produced from Natural Gas*; ANL/ESD-40; Argonne National Lab: Argonne, IL, 1999.
31. Winebrake, J. J.; Corbett, J. J.; Meyer, P., Energy Use and Emissions from Marine Vessels: A Total Fuel Life Cycle Approach. *Journal of the Air and Waste Management Association* **2007,** *57*, 102-110.
32. Det Norske Veritas Petroleum Services, Marine distillate fuel sample properties. In Marine distillate fuel sample properties ed.; provided through personal communication to James J. Corbett via California Air Resources Board, Ed. Sacramento, CA, 2007.
33. ISO *Petroleum Products - Fuels (Class F) - Specifications of Marine Fuels, ISO 8217*; ISO 8217: 2005(E); International Organization for Standardization: Geneva, Switzerland, November 2005, 2005.
34. Wang, M.; Lee, H.; Molburg, J., Allocation of Energy Use in Petroleum Refineries to Petroleum Products: Implications for Life-Cycle Energy Use and Emission Inventory of Petroleum Transportation Fuels. *International Journal of Life Cycle Analysis* **2004,** *9*, (1), 34-44.
35. British Petroleum *BP Statistical Review of World Energy June 2007*; British Petroleum p.l.c.: London, June 2007, 2007; p 48.
36. Energy Information Administration *State Energy Consumption Estimates 1960 Through 2004*; DOE/EIA-0214(2004); Energy Information Administration: Washington, DC, June 2007, 2007; p 514.