SECTION 5 STATUS OF USE IN CONTAINERSHIP FLEETS

The shipping industry is facing many challenges to meet proposed and adopted regulations dealing with low sulfur marine fuels worldwide. Vessel owners are considering new and alternative strategies such as entering into low-sulfur fuel contracts now to meet future low sulfur fuel regulations and implementing trials to see how switching to low sulfur fuels will impact their engines and fuel operations. Some vessel manufacturers are incorporating requests by clients to add extra low sulfur tanks to new vessels, while marine engine manufacturers are recommending procedures for switching from higher sulfur fuel to lower sulfur fuel while engines are running. This is known as dual-fuel switching in coastal waters, as opposed to reconfiguring a ship to run on distillate instead of residual fuel all the time. Shipping lines were interviewed with regard to fuel use (Section 5.1), equipment issues associated with low sulfur fuels (Section 5.2), and operational issues (Section 5.3).

5.1 Status of Use by Fleets

In order to determine the present status of use of lower sulfur marine fuel in containership fleets and possible equipment requirements needed in the future for using lower sulfur marine diesel fuel, the major container carrier lines that service the Ports of Los Angeles and Long Beach were contacted and interviewed in coordination with Port of Los Angeles staff. The shipping lines contacted included:

- APL
- China Shipping
- CMA-CGM
- Cosco
- CP Ships
- Evergreen, including Hatsu and Lloyds CST
- FESCO
- Hapag Lloyd
- Hamburg Süd
- Hanjin
- Hyundai Merchant Marine (HMM)
- K Line
- Maersk
- Matson
- Mediterranean Shipping Company (MSC)
- Mitsui O.S.K. Lines (MOL)
- Nippon Yushen Kaisha (NYK) Line
- OOCL
- P&O Nedlloyd
- Sinotrans
- U.S. Lines
- Wan Hai
- Yang Ming
- Zim

Forty-two percent, or ten out of the 24 shipping lines contacted, responded to the inquiry. For some shipping lines, the short duration of this study did not allow enough time to gather information and obtain permission from their overseas headquarters and the vessel owners. The responses were expressed in a very general form pertaining to their fleets' fuel use and fuel system requirements. Specific percentages could not be drawn from the responses, although the majority of the respondents stated their vessels are currently using IFO 380, a residual fuel blend, for both main and auxiliary engines. Some ships had dedicated marine distillate auxiliary fueling systems. A small but unquantifiable number of vessels use residual fuel at sea and marine distillate fuel as they near the coast or at berth for their auxiliary engines.

The same kinds of shipping lines had also recently been contacted by the ARB for a similar ocean-going vessel survey to collect information for an emission inventory update in support of proposed emission reduction regulations. The ARB ship survey indicated that for approximately 20% of the vessels included in the responses would require some sort of retrofit or modification in order to be able to switch fuels during transit for the auxiliary engines.[77] Preliminary results of the ARB survey also showed 99% of the main engines use residual fuel, while 77% of the vessels are currently using residual fuel in their auxiliary engines and 23% are using marine distillate fuel in their auxiliary engines.[78] ARB's survey results for average in-use sulfur content were consistent with the sulfur content averages found in the DNV PS fuel testing data (see Section 4). The sulfur content used in engines for shipping lines calling at U.S. West Coast ports averaged 2.7% for residual fuel and 0.6% for marine distillate fuel.

5.2 Equipment Requirements

Container vessel equipment requirements for using and storing lower sulfur fuel were discussed with the shipping lines, since the fuel system design plays a role in determining what level of participation the vessels will have in using lower sulfur fuels near the coast. Typical fuel equipment on a container vessel consists of:

- Fuel storage tanks
- Fuel treatment system
- Settling tanks
- Lubricating oil storage tanks
- Supply piping system
- Service tanks

The lubricating oil storage tanks are important for fuel switching. Along with the various tanks, piping and instrumentation, there are also transfer pumps, centrifuge filters, and a bunker heating system. Vessels dedicated to residual fuel may even be equipped with a small storage tank for marine distillate fuel used for emergency purposes and during maintenance. The PWBAEI found approximately 63% of containerships equipped with separate fuel oil tanks for the auxiliary engines. This means that many containerships have the capability to

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[77] ARB 2005.

[78] Personal communication between Starcrest and Mr. Paul Milkey, California Air Resources Board, 6 April 2005.

be dual-fueled but chose to operate mainly on residual, presumably because residual is a cheaper fuel and because fuel costs are one of primary expenses of ocean transportation. Some of the shipping lines mentioned extra fuel and lubricating oil storage tanks may be needed, along with the necessary piping, should switching to lower sulfur fuels be required on dedicated ships as they near the coastline. Some shipping lines expressed concern over switching fuels for propulsion engines, from an equipment requirement and operational standpoint. Others mentioned their vessels are equipped to switch fuels for both propulsion and auxiliary engines. They also mentioned that if low sulfur fuel is required, they would consider installing additional tanks for low sulfur diesel during the design planning of new vessels. While ships have many segregated bunker tanks on board, this could involve construction of a third fuel tank type:

- Residual
- Distillate (if used for auxiliaries while at sea)
- Low sulfur distillate (for use on coastal areas such as San Pedro Bay)

The ability to use more than one fuel is related to the design of the ship. About a third of the containership fleet surveyed is dedicated residual for both the main and auxiliary engines. Another third is designed to allow residual for the main engines and distillate for the auxiliary engines. A final third can use residual for the main engines and distillate for the auxiliaries but the operators use residual for auxiliary engines by choice. As mentioned above, the exact number of those vessels that can perform true coastal dual-fuel switching for both main and auxiliary engines is not known.

Although cost estimates for modifications to vessels were not part of the scope of this study, retrofit of an existing vessel could be costly when including lost earning potential during travel time to and from the shipyard, time spent at the shipyard and the actual labor and material costs for the modification. It is likely that the modification would be timed to coincide with the existing vessel maintenance schedule since modifications would require dry -docking the ship.

5.3 Operational Issues

Propulsion power for ocean-going vessels is usually accomplished by means of a single, large, low-speed, two-stroke diesel engine. There are a few steamships and medium-speed main engines in the containership fleet but they are small in number and are either very old or very small. These engines, classified as cross head engines, can be built to deliver up to 100,000 horsepower (hp), with an average of approximately 50,000 hp (about 30,000 kilowatts, kW).

Auxiliary power for ocean-going vessels can be supplied by four-stroke, medium speed engines. These engines, classified as trunk piston engines, can be rated from several hundred to several thousand kilowatts depending on ship service power and refrigeration requirements.

Concerns with the use of low sulfur fuel can be divided into two areas: fuel delivery operations and engine operations. To research these concerns, engine manufacturers, fleet managers, and lubricant manufacturers were contacted to discuss performance issues that may arise with the use of the lower sulfur fuels in propulsion and auxiliary engines.

Based on review of the data collected during the development of the PWBAEI, the following primary propulsion and auxiliary engine manufacturers for vessels entering the Port were contacted:

- Wartsila-Sulzer
- MAN B&W
- Daihatsu
- Holeby
- Yanmar
- Hyundai
- Mitsubishi

Engine research associations such as the International Council on Combustion Engines (CIMAC) and manufacturers' websites and associated articles were also consulted. The CIMAC is considered to be the authority with regard to coastal dual-fuel switching issues, since its membership includes the manufacturers, shippers, academia, fuel and lube oil suppliers, and classification societies such as Lloyds.

CIMAC[79] lists the following concerns associated with switching between heavy fuel oil and distillate fuels with low sulfur content in coastal waters:

- *Low lubricity*: Shore-side distillate fuels have specific requirements for minimum lubricity. These requirements are usually met by inclusion of lubricity additives. Marine distillate fuels have no such requirement. According to CIMAC, there is not enough experience with low sulfur diesel use to address this issue, and more research is needed.
- *Delivery-side thermal issues*. Heavy fuel oil at the fuel pumps is about 150°C because the fuel must be heated due to its high viscosity. Marine distillate fuel, introduced at ambient engine room temperature, could cause the fuel pumps to seize if introduced too fast, due to a combination of thermal contraction and low lubricity. This could cause sudden loss of propulsion or auxiliary power.
- *Fuel compatibility*. When switching from heavy fuel to a low-aromatic distillate fuel, some of the heavier asphaltic material (asphaltenes) could be precipitated from the heavy fuel. If this happens, fuel filters could clog and fuel pumps could stick, causing sudden loss of power.

CIMAC cited the last issue as the most important, but mainly as it relates to the potential mixing of two fuels in a common tank, which can occur during fuel switching. Conversations with engine manufacturer representatives and fleet managers for the shipping lines confirm these concerns. One noted that the filter clogging due to fuel incompatibility is related to the solvent effect of diesel fuel removing deposits from fuel lines. Fleet managers mentioned the filtering system, main engine cylinder oil, fuel pumps and piston

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[79] CIMAC, Bulletin No. 1, *Use of Low Sulphur Diesel Fuels in Coastal Waters*, October 2004.

liner may stick due to difference in viscosity at the time of fuel switching. Others mentioned that moving parts wear down if exposed to lower sulfur fuels for a long period, and that there could be possible malfunction of the propulsion gear if the vessel is not properly equipped with extra tanks and electronically controlled lubricators. Another mentioned that each fuel has its own appropriate temperature and a bunker operation plan would be needed when using more than one kind of fuel.

The main issues appear to be the inherent qualities of the fuel and of the lube oil. Both relate in part to the concept of lubricity and go hand-in-hand. Drawing from a wide range of sources, including the CIMAC memorandum, the following basic concepts apply:

- In two-stroke diesel engines, large quantities of lube oil are injected into the middle and lower parts of the cylinder. The lube oil is formulated to help counteract the high sulfur levels that result in sulfuric acid formation, which can be detrimental to moving parts if not neutralized.[80]
- When converting a diesel engine to distillate fuel, the anti-corrosion properties of the lube oil can be relaxed and much less (about one-fourth as much) oil and waste oil is used, since low sulfur bunker fuel blends have less sulfur and corrosive potential. Ashing and soot formation should be lower as well.[81]
- When converting to a very low sulfur bunker fuel such as below 0.05%, the inherent "cushioning" effect of the sulfur is lost and special lube oils must be used to add lubricity and prevent carbon deposition, called lacquering.[82] The fuel itself may have to be treated to add to lubricity and anti-fouling agents. The exact point at which such corrective programs are needed is not known; the 0.05% level is not supported by any empirical evidence because there is little or no documentation of research on large, two-stroke engines having extremely low sulfur content.

For medium-speed engines such as those used for auxiliary engines, the situation is similar except that most of these engines will be four-stroke, with oil being injected only into the lower part of the cylinder, resulting in much less oil consumption. Four-stroke lube oil is usually formulated very differently from two-stroke lube oil but the principles are the same: at very low sulfur concentrations, both the fuel and lube oil need additives to prevent carbon fouling. One marine fuel products supplier recently announced it has developed a "special high performance cylinder oil with a lower Base Number" in response to concerns by ship operators over the use of lower sulfur fuels.[83]

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[80] Lube oil qualities are related to Acid Number (AN) and Base Number (BN). One of the functions of lube oil is to neutralize acid corrosion that could wear engine parts (AN). To do this, an alkaline compound is added to the oil (BN). See sources such as: *http://www.spectro-oil.com/industrysectors/marine/analysistests.html*, and *http://www.blackstone-labs.com/do_i_need_a_tbn_.html*.

[81] Groner and Gorton, 2002. 'Experience from Operation on MDO and Low Sulfur Fuel on the *M/S Turandot*,' Bunker Conference, Oslo, 25 April 2002.

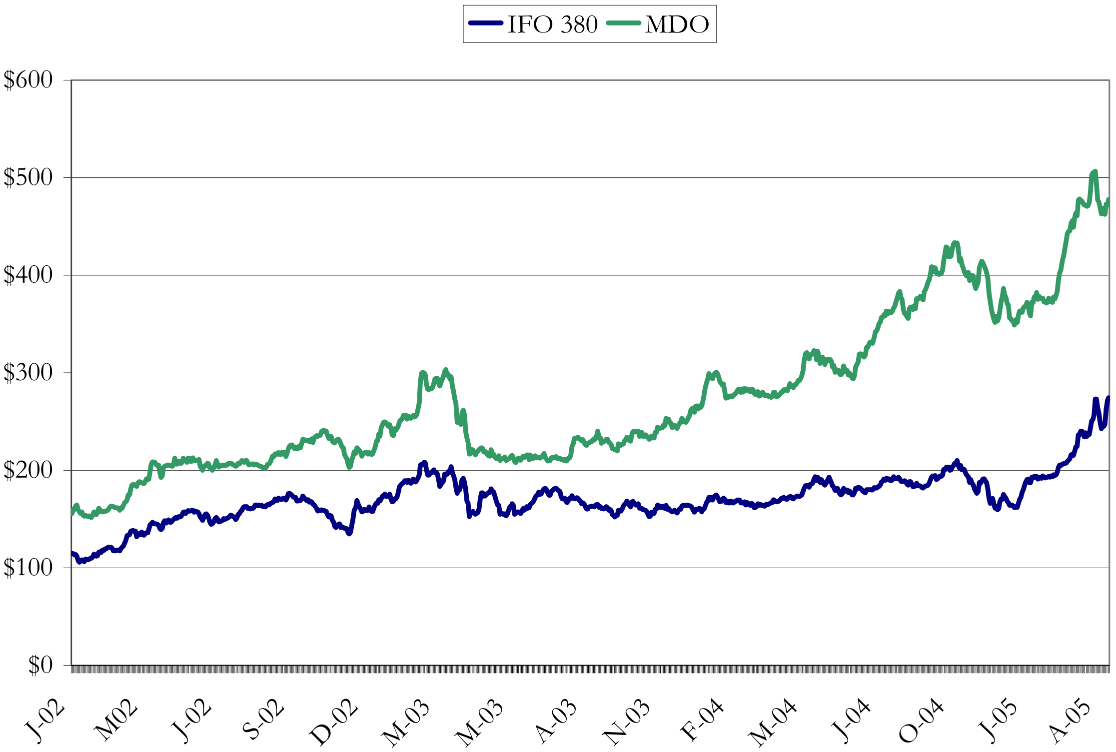
[82] Soot is formed from carbon particulate, which can cause valve problems. Lacquering is when the piston lining becomes polished with carbon deposits and prevents proper cylinder oiling; improper oiling can cause deleterious scuffing and uneven wear. See: *http://www.infineum.com/products/marine/oil/index.html,* and *http://joleguen.free.fr/imo6b.htm*.

[83] Shell Marine Products, *Shell Alexia LS – effective lubrication in a changing world,* 01 June 2005.

SECTION 6 COST EFFECTIVENESS

Cost effectiveness is defined as the dollars spent per ton of pollutant reduced as a result of the use of an emission control measure. For this study the control measure is to use lower sulfur fuels in container ships. A simplified approach to cost effectiveness is used that considers the incremental cost of the fuel as compared to its emission reduction potential. Incremental cost is the difference between the currently used marine fuel and the lower sulfur fuel grades that are available or may become available in the future. As discussed previously, residual fuel is commonly used for main propulsion engines and marine distillate fuel may be used for auxiliary engines. Figure 6.1 shows the three-year fuel cost history for the two marine fuels mostly used by ocean-going vessels: residual fuel (IFO 380, average 2.7% sulfur) and marine distillate fuel (average 0.6% sulfur). As the figure shows, the cost difference between the two marine fuels has widened over the last year as the price of oil has increased. Costs for the various fuels used in this study include a three-month average price, a three-year average and three-year maximum. This method was used in order to obtain an order of magnitude for potential cost effectiveness; prices vary from day-to-day and cannot be predicted.

Figure 6.1: Marine Fuel Cost History, 2002 to 2005



The fuels considered in the study are summarized in Table 6.1, where:

- Residual < 4.5% sulfur: baseline for main engines and some auxiliaries.
- Residual < 1.5% sulfur: may be mandated if a SECA is implemented for coastal waters of the U.S.
- MDO > 0.5% sulfur: marine distillate fuel used as a baseline for some auxiliary engines.
- MDO < 0.2% sulfur: low sulfur marine distillate fuel being considered for some EU countries.

Table 6.1: Typical Sulfur Contents for Baseline and Alternative Fuels

Fuel	Typical Sulfur Content (%)	Typical Sulfur Content (ppm)
Residual < 4.5% S	2.74%	27,400
Residual < 1.5% S	1.5%	15,000
MDO > 0.5% S	0.6%	6,000
MGO < 0.2% S	0.1%	1,000
Grade No. 2 S500	0.03%	300
CARB Diesel S500	0.015%	150
ULSD S15	0.0015%	15

Both residual and distillate fuel can have varying sulfur levels that sometimes overlap. Worldwide (as defined for purposes of this study) averages are used for residual, U.S. averages are used for the onroad fuels and California averages are used for fuels regulated in that State:

- EPA Grade No. 2 S500
- CARB Diesel S500
- ULSD S15

6.1 Methodology

Fuel costs, incremental fuel costs, emissions, emission reduction percentages, and emission reductions were used to develop cost effectiveness.

- Fuel costs: Developed from sources such as *Bunkerworld,* a leading authority on reporting fuel prices for marine bunkers, as well as Oil Price Information Services (OPIS) and the Energy Information Administration (EIA) for the land-based fuels. All costs were estimated as being dollars per tonne of fuel, which is the industry standard for pricing marine fuel.

- Incremental fuel costs: The additional cost of cleaner fuels over the baseline was estimated using the current fuel prices. For example, residual fuel (IFO 380, 2.7% sulfur) is approximately $200/tonne, high sulfur MDO (0.6% sulfur) is approximately $400/tonne, thus the cost increment is $200/tonne for an IFO/MDO fuel switch.
- Emissions were extracted from the 2001 emissions for the Port of Los Angeles as documented in the PWBAEI, except as noted:
  - NO_X
  - PM_{10}
  - SO_2
  - CO_2, estimated from ENTEC[84] emission factors
  - Fuel, estimated from ENTEC emission factors
- Emission reduction percentages: Developed in coordination with the ARB.
- Emission reductions: The product of baseline emissions multiplied by an applicable emission reduction factor.

Incremental fuel costs were estimated by multiplying the incremental fuel cost per tonne by the gross fuel tonnage estimate. Cost effectiveness was estimated by dividing the incremental fuel cost by the emission reductions in tons. Tons (2,000 pounds [lbs] per ton) are commonly used in the U.S. to estimate emissions reductions. Tonnes, also called metric tons, (2,205 lbs/tonne), are the international unit of measurement for marine fuel. The equation used to calculate cost effectiveness (CE) is:

$$CE = \frac{\text{incremental fuel cost} \times \text{fuel consumed}}{\text{emission reduction \%} \times \text{emissions}} = \frac{(\$/\text{tonne} \times \text{tonne})}{\text{tons}} = \$/\text{tons}$$

6.1.1 Emissions

To be consistent with other Port-related projects, the existing 2001 emissions data developed for the PWBAEI was used to estimate the emission reductions and the cost effectiveness. Emissions were extracted from the Port emissions model and are presented in Tables 6.2 through 6.5 for NO_X, PM_{10}, SO_2 and CO_2, respectively.

Table 6.2: NO_x Emissions, 2001, tons

NO_X						Auxiliaries	
Mode	Propulsion	Aux	Boiler	Total	Percent	RO_Aux	MDO_Aux
Cruise	4,308.56	292.20	2.38	4,603.14	66.5%	106.15	186.05
Maneuvering	155.13	199.10	0.78	355.01	5.1%	72.33	126.77
Hotelling	0.00	1,942.73	21.41	1,964.14	28.4%	705.75	1236.98
	4,463.69	2,434.03	24.57	6,922.29	100.0%	884.23	1549.80

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[84] ENTEC 2002.

Table 6.3: PM_{10} Emissions, 2001, tons

PM_{10} Mode	Propulsion	Aux	Boiler	Total	Percent	Auxiliaries RO_Aux	Auxiliaries MDO_Aux
Cruise	456.48	8.31	0.25	465.04	82.9%	4.90	3.41
Maneuvering	21.23	6.18	0.08	27.50	4.9%	3.65	2.54
Hotelling	0.00	66.01	2.26	68.27	12.2%	38.94	27.07
	477.71	80.50	2.60	560.81	100.0%	47.49	33.01

Table 6.4: SO_2 Emissions, 2001, tons

SO_2 Mode	Propulsion	Aux	Boiler	Total	Percent	Auxiliaries RO_Aux	Auxiliaries MDO_Aux
Cruise	2,742.15	122.51	10.47	2,875.12	69.9%	78.66	43.84
Maneuvering	61.77	91.90	3.42	157.10	3.8%	59.01	32.89
Hotelling	0.00	987.63	94.00	1,081.63	26.3%	634.17	353.47
	2,803.92	1,202.04	107.89	4,113.85	100.0%	771.84	430.20

Table 6.5: CO_2 Emissions, 2001, tons

CO_2 Mode	Propulsion	Aux	Boiler	Total	Percent	Auxiliaries RO_Aux	Auxiliaries MDO_Aux
Cruise	163,171.74	13,537.78	616.11	177,325.63	62.0%	4,744.13	8,793.65
Maneuvering	3,690.24	9,218.64	201.58	13,110.46	4.6%	3,230.55	5,988.09
Hotelling	0.00	89,892.93	5,533.68	95,426.61	33.4%	31,501.76	58,391.17
	166,861.98	112,649.35	6,351.38	285,862.70	100.0%	39,476.44	73,172.91

This study evaluated the cost effectiveness of using cleaner fuels for main and auxiliary engines. The boiler emissions were not considered as they are outside the scope and the emissions are almost negligible when compared to emissions from propulsion and auxiliary engines. Main engine emissions were assumed to be using residual fuel, based on information obtained from the shipping lines. In the last two columns, total auxiliary emissions were split into residual (RO_Aux) and distillate (MDO_Aux) subtotals to reflect the auxiliary engines using both fuels. As previously discussed, the average sulfur content was assumed for the baseline residual fuel (2.7% sulfur) and baseline marine distillate fuel (0.6% sulfur).

The PWBAEI reflects a micro-scale evaluation of both emissions and fuel consumption within the same model framework, using inbound and outbound estimates for each ship type and terminal destination for:

- Hotelling
- Harbor maneuvering
- Precautionary zone transiting
- 10-, 15-, and 20-mile segments for four shipping routes

- At-sea segments for four shipping routes that may extend 40 miles from the harbor, past the 20-mile radius

Specific fuel consumption (SFC) was estimated in a similar manner to the pollutants, since there were emissions factors from ENTEC that could be input to the Port of Los Angeles emissions model.

The Port of Los Angeles is expected to have significant growth, particularly in containership activity; it was assumed that as the amount of ship calls increase, both the emissions and fuel consumption would increase at the same rate. Therefore, the cost effectiveness is assumed to be the same in future years. As large containerships are being built and replacing the older steamships and smaller vessels in the fleet, the fuel consumption per container or TEU will lower. Engine efficiency is at a plateau for new ships and the next set of improvements in fuel efficiency will require additional cost at the new build stage.

Table 6.6 summarizes the results for fuel consumption.

Table 6.6: Fuel Consumption by Mode and Ship Source, 2001, tonnes

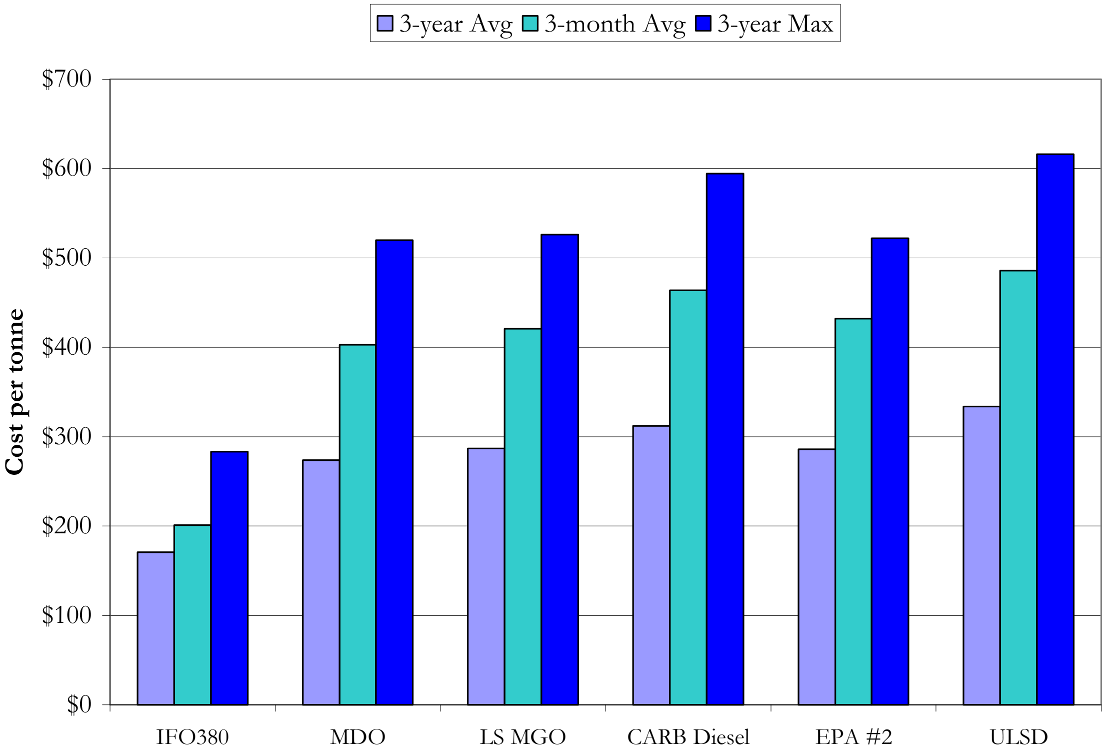
SFC Mode	Propulsion	Aux	Boiler	Total	Percent	Auxiliaries RO_Aux	Auxiliaries MDO_Aux
Cruise	46,176.85	3,865.06	21.63	50,063.54	62.4%	1,354.46	2,510.60
Maneuvering	1,648.75	2,631.87	7.08	4,287.70	5.3%	922.30	1,709.57
Hotelling	0.00	25,663.17	194.24	25,857.41	32.2%	8,993.31	16,669.86
	47,825.60	32,160.10	222.94	80,208.64	100.0%	11,270.07	20,890.03

6.1.2 Incremental Costs

The incremental costs for three-month average, three-year average, and three-year maximum were applied to the fuel consumption volumes above. Prior to calculating the incremental costs, fuel costs were obtained. Since fuel prices change on a constant basis and the market has seen an increase in prices, cost data for the last three years was used along with the latest three-month average in 2005. For the marine fuels, the fuel prices were obtained for Singapore from *Bunkerworld* for January 2002 to mid-April 2005. The cost for low sulfur residual fuel (IFO <1.5% sulfur) is based on estimates from conversations with marine fuel experts from *Bunkerworld*, fuel suppliers and a shipping line in Europe. The onroad fuel prices were obtained from EIA data for January 2002 to mid-April 2005. The onroad fuel costs were converted from cents/gallon to U.S. dollars/tonne since the marine fuels prices are given in U.S. dollars/tonne. The three-month average prices are based on 1 January 2005 through 31 March 2005.

Figure 6.2 shows the 2005 three-month average, three-year average and three-year maximum fuel costs for the various fuels.

Figure 6.2: Fuel Prices, $/tonne



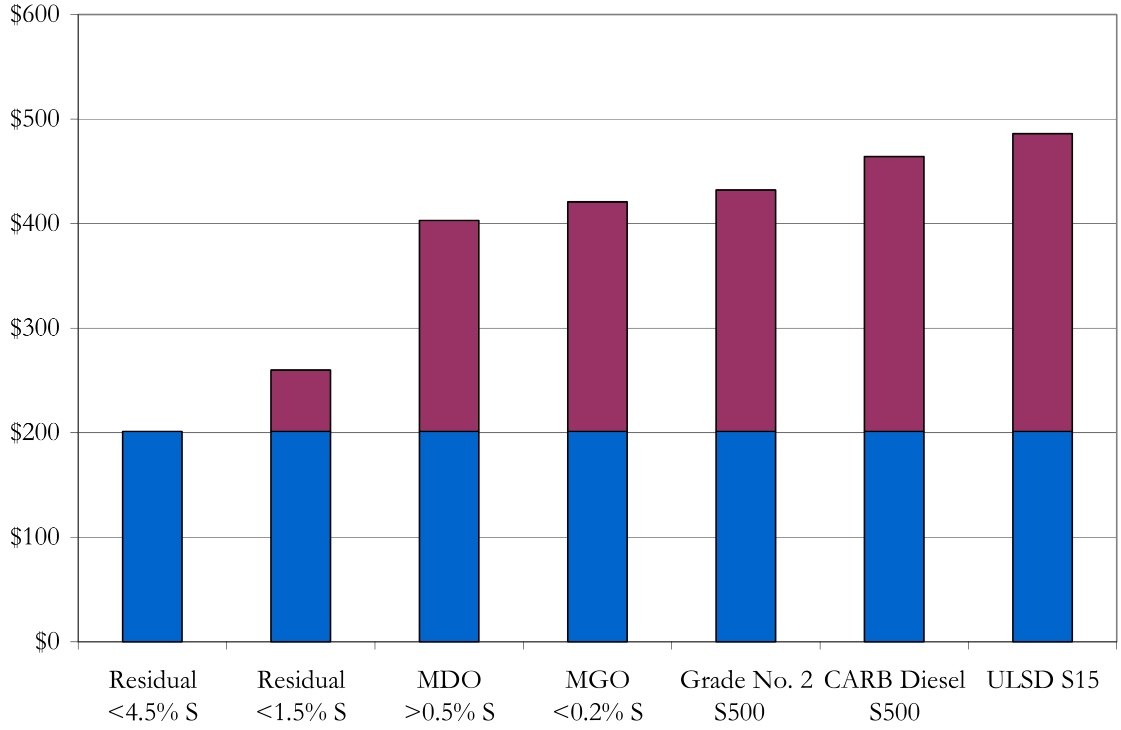
The prices for each fuel were then subtracted from the base residual fuel price for IFO 380 and the base distillate fuel price for regular marine distillate oil. Table 6.7 and Figure 6.3 present the incremental cost for the three-month average prices in 2005 for the various fuels studied.

Table 6.7: Incremental Fuel Cost for 3-month Average Price

Fuel	3-month Avg Fuel Cost $/tonne	(2.7% S) Residual Base $/tonne	(0.6% S) MDO Base $/tonne
Residual < 4.5% S	$201		
Residual < 1.5% S	$260	$59	
MDO > 0.5% S	$403	$202	
MGO < 0.2% S	$421	$220	$18
Grade No. 2 S500	$432	$231	$29
CARB Diesel S500	$464	$263	$61
ULSD S15	$486	$285	$83

The shaded areas indicate where comparisons are not possible because residual is assumed to be a baseline fuel and for some auxiliary engines, MDO is also a baseline fuel. The baseline fuels are listed in the columns, while reductions, costs, and cost effectiveness are entered for each possible entry in a row.

Figure 6.3: Incremental Fuel Cost, 3-month Average



The blue portion of the bar in this figure represents the base price for residual fuel for the exmple price used.

6.1.3 Emission Reductions Percentages

Reduction percentages were applied to the baseline emissions for each pollutant. Reductions for NO_X and SO_2 are considered relatively easy to verify because they are either based on known emission factors or the percent fuel sulfur. By contrast, PM is the most complicated and subject to uncertainty because PM emission factors and emission reductions vary widely depending on the source and because the emission reduction estimates involves the use of an equation based on an estimate of the sulfur to sulfate conversion rate. To help estimate the PM reductions, ARB staff was consulted.[85]

Tables 6.8 through 6.11 show the control factors or reduction percentages for each pollutant considered, including NO_X, PM_{10}, SO_2, and CO_2, respectively. The tables are set up to read starting with the starting fuel (residual fuel for main engines, residual fuel for auxiliary engines, and marine diesel fuel for auxiliary engines) on a column heading and moving down the rows to find the reduction for a different fuel.

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[85] Mr. Paul Milkey, California Air Resources Board, April 2005.

Table 6.8: Reduction Percentages for NO_X

Main Engines	% Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	0%	0%	
MDO > 0.5% S	0.62%	10%	10%	
MGO < 0.2% S	0.11%	10%	10%	0%
Grade No. 2 S500	0.03%	10%	10%	0%
CARB Diesel S500	0.015%	15%	15%	6%
ULSD S15	0.0015%	15%	15%	6%

Table 6.9: Reduction Percentages for PM_{10}

Main Engines	% Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	18%	18%	
MDO > 0.5% S	0.6%	58%	58%	
MGO < 0.2% S	0.1%	65%	65%	17%
Grade No. 2 S500	0.03%	68%	68%	24%
CARB Diesel S500	0.015%	74%	74%	38%
ULSD S15	0.0015%	75%	75%	40%

Table 6.10: Reduction Percentages for SO_2

Main Engines	% Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	45%	45%	
MDO > 0.5% S	0.6%	78%	78%	
MGO < 0.2% S	0.1%	96%	96%	83%
Grade No. 2 S500	0.03%	99%	99%	95%
CARB Diesel S500	0.015%	99%	99%	98%
ULSD S15	0.0015%	100%	100%	100%

Table 6.11: Reduction Percentages for CO_2

Main Engines	% Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	0%	0%	
MDO > 0.5% S	0.6%	5%	5%	
MGO < 0.2% S	0.1%	5%	5%	0%
Grade No. 2 S500	0.03%	5%	5%	0%
CARB Diesel S500	0.015%	5%	5%	0%
ULSD S15	0.0015%	5%	5%	0%

6.1.4 Emission Reductions

Estimation of mass emission reductions included applying these factors to the existing 2001 emissions developed for the PWBAEI, as is shown in Tables 6.12 through 6.15 for NO_X, PM_{10}, SO_2, and CO_2, respectively:

Table 6.12: NO_X Reductions, 2001, tons

Main Engines	% Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	0.00	0.00	
MDO > 0.5% S	0.62%	446.37	88.42	
MGO < 0.2% S	0.11%	446.37	88.42	0.00
Grade No. 2 S500	0.03%	446.37	88.42	0.00
CARB Diesel S500	0.015%	669.55	132.63	92.99
ULSD S15	0.0015%	669.55	132.63	92.99

Table 6.13: PM_{10} Reductions, 2001, tons

Main Engines	% Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	85.99	8.55	
MDO > 0.5% S	0.6%	277.07	27.54	
MGO < 0.2% S	0.1%	310.51	30.87	5.61
Grade No. 2 S500	0.03%	324.84	32.29	7.92
CARB Diesel S500	0.015%	353.51	35.14	12.54
ULSD S15	0.0015%	358.28	35.62	13.20

Table 6.14: SO_2 Reductions, 2001, tons

Main Engines	% Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	1,268.93	349.30	
MDO > 0.5% S	0.62%	2,189.92	602.82	
MGO < 0.2% S	0.11%	2,701.59	743.67	358.50
Grade No. 2 S500	0.03%	2,773.22	763.39	408.69
CARB Diesel S500	0.015%	2,788.57	767.62	419.45
ULSD S15	0.0015%	2,802.38	771.42	429.13

Table 6.15: CO_2 Reductions, 2001, tons

Main Engines	% Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	0.00	0.00	
MDO > 0.5% S	0.6%	8,563.30	5,324.64	
MGO < 0.2% S	0.1%	8,563.30	1,865.95	0.00
Grade No. 2 S500	0.03%	8,563.30	1,865.95	0.00
CARB Diesel S500	0.015%	8,563.30	1,865.95	0.00
ULSD S15	0.0015%	8,563.30	1,865.95	0.00

6.2 Results

As indicated above, cost effectiveness is defined as the incremental cost of the fuel divided by the reductions. Reducing sulfur in fuels mainly affects SO_2 and PM. Findings for SO_2 show a clear trend where cleaner fuel grades cost more investment per ton of air pollution reduced. Trends for PM are not as clear. A pattern similar to that of SO_2 would have been expected because PM reductions are attributed to a portion of the sulfur being converted to sulfate. Trends for NO_x and CO_2, are completely incidental and independent from any fuel sulfur reductions. The NO_x reductions are due to:

- Switching from residual to a distillate removes fuel-borne nitrogen compounds
- California fuel blends call for changes in aromatic content and cetane levels, which can lower NO_x levels to a small degree

Finally, any CO_2 reductions are only from changes in fuel economy, since all fuels tend to have about the same proportion of carbon, and CO_2 emissions are a function of the carbon content of the fuel. The fuel economy of distillate (185 g/kW-hr) is about 5% better than that of residual (195 g/kW-hr). These estimates are theoretical; it has not been established that there are any fuel savings in actual use.

The following tables present cost effectiveness for each of the pollutants using three-month average, three-year average, and three-year maximum incremental prices, respectively. The higher the dollar amount in the table, the less cost effective the control measure is for that pollutant.

The cost effectiveness for the EPA Grade No. 2 fuel (500 ppm) is different from the CARB diesel (500 ppm) in large part due to the different emission reduction percentages for the two fuels and the difference in cost. The CARB diesel has lower aromatics and higher cetane which will give lower NO_X emissions. For PM and SO_X, the emission reductions vary between the two fuels due to their respective national average sulfur contents of 150 ppm for CARB diesel and about 300 ppm for EPA.

For comparison, the California *Carl Moyer* program requires a $12,000/ton of NO_X reduced (or better) cost effectiveness in order for projects that use cleaner marine vessel and other heavy duty diesel engines to be eligible for funding.[86]

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[86] ARB, *The Carl Moyer Program: Incentives for Lower Emission Heavy-Duty Engines, Frequently Asked Questions*, December 2004. See: *http://www.arb.ca.gov/msprog/moyer/faq.htm#9*.

Tables 6.16 through 6.18 summarize cost effectiveness for NO_X.

Table 6.16: NO_x Cost Effectiveness, 3-month Average, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$21,643	$25,746	
MGO < 0.2% S	0.1%	$23,572	$28,040	
Grade No. 2 S500	0.03%	$24,750	$29,442	
CARB Diesel S500	0.015%	$18,786	$22,347	$13,704
ULSD S15	0.0015%	$20,357	$24,217	$18,646

Table 6.17: NO_x Cost Effectiveness, 3-year Average, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$10,929	$13,001	
MGO < 0.2% S	0.1%	$11,679	$13,893	
Grade No. 2 S500	0.03%	$12,322	$14,657	
CARB Diesel S500	0.015%	$10,072	$11,981	$8,761
ULSD S15	0.0015%	$11,643	$13,850	$13,704

Table 6.18: NO_x Cost Effectiveness, 3-year Maximum, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$25,393	$30,207	
MGO < 0.2% S	0.1%	$26,036	$30,972	
Grade No. 2 S500	0.03%	$25,607	$30,462	
CARB Diesel S500	0.015%	$22,214	$26,426	$16,624
ULSD S15	0.0015%	$23,786	$28,295	$21,567

Tables 6.19 through 6.21 summarize cost effectiveness for PM_{10}.

Table 6.19: PM_{10} Cost Effectiveness, 3-month Average, \$/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$34,867	$82,655	
MGO < 0.2% S	0.1%	$33,885	$80,326	$67,010
Grade No. 2 S500	0.03%	$34,009	$80,621	$76,472
CARB Diesel S500	0.015%	$35,581	$84,347	$101,593
ULSD S15	0.0015%	$38,043	$90,184	$131,321

Table 6.20: PM_{10} Cost Effectiveness, 3-year Average, \$/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$17,606	$41,737	
MGO < 0.2% S	0.1%	$16,788	$39,798	$26,059
Grade No. 2 S500	0.03%	$16,931	$40,136	$34,281
CARB Diesel S500	0.015%	$19,076	$45,220	$64,953
ULSD S15	0.0015%	$21,758	$51,579	$96,513

Table 6.21: PM_{10} Cost Effectiveness, 3-year Maximum, \$/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$40,909	$96,977	
MGO < 0.2% S	0.1%	$37,427	$88,724	$22,337
Grade No. 2 S500	0.03%	$35,187	$83,414	$5,274
CARB Diesel S500	0.015%	$42,075	$99,742	$123,244
ULSD S15	0.0015%	$44,451	$105,373	$151,890

Tables 6.22 through 6.24 summarize cost effectiveness for SO_2.

Table 6.22: SO_2 Cost Effectiveness, 3-month Average, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	$1,157	$990	
MDO > 0.5% S	0.6%	$3,705	$3,172	
MGO < 0.2% S	0.1%	$3,909	$3,346	$1,748
Grade No. 2 S500	0.03%	$4,021	$3,442	$1,878
CARB Diesel S500	0.015%	$4,577	$3,919	$3,949
ULSD S15	0.0015%	$4,910	$4,203	$4,334

Table 6.23: SO_2 Cost Effectiveness, 3-year Average, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	$392	$336	
MDO > 0.5% S	0.6%	$1,871	$1,601	
MGO < 0.2% S	0.1%	$1,937	$1,658	$680
Grade No. 2 S500	0.03%	$2,002	$1,713	$842
CARB Diesel S500	0.015%	$2,454	$2,101	$2,525
ULSD S15	0.0015%	$2,808	$2,404	$3,185

Table 6.24: SO_2 Cost Effectiveness, 3-year Maximum, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%	$1,274	$1,091	
MDO > 0.5% S	0.6%	$4,347	$3,721	
MGO < 0.2% S	0.1%	$4,317	$3,696	$583
Grade No. 2 S500	0.03%	$4,160	$3,561	$129
CARB Diesel S500	0.015%	$5,413	$4,634	$4,791
ULSD S15	0.0015%	$5,737	$4,911	$5,013

Tables 6.25 through 6.27 summarize cost effectiveness for CO_2.

Table 6.25: CO_2 Cost Effectiveness, 3-month Average, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$1,128	$428	
MGO < 0.2% S	0.1%	$1,229	$1,329	
Grade No. 2 S500	0.03%	$1,290	$1,395	
CARB Diesel S500	0.015%	$1,469	$1,588	
ULSD S15	0.0015%	$1,592	$1,721	

Table 6.26: CO_2 Cost Effectiveness, 3-year Average, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$570	$216	
MGO < 0.2% S	0.1%	$609	$658	
Grade No. 2 S500	0.03%	$642	$695	
CARB Diesel S500	0.015%	$787	$852	
ULSD S15	0.0015%	$910	$984	

Table 6.27: CO_2 Cost Effectiveness, 3-year Maximum, $/ton reduced

	Typical % Sulfur	(2.7% S) Residual Main	(2.7% S) Residual Aux	(0.6% S) MDO Aux
Residual < 4.5% S	2.74%			
Residual < 1.5% S	1.5%			
MDO > 0.5% S	0.6%	$1,324	$502	
MGO < 0.2% S	0.1%	$1,357	$1,468	
Grade No. 2 S500	0.03%	$1,335	$1,444	
CARB Diesel S500	0.015%	$1,737	$1,878	
ULSD S15	0.0015%	$1,860	$2,011	

The fuel switching scenario most likely to occur in the near future is the adoption of the ARB draft rulemaking for auxiliary diesel engines operated on ocean-going vessels in

California coastal waters, which could require MGO with <0.2% sulfur. For illustrative purposes, reductions for switching to MGO with <0.2% sulfur, as compared to selected fuel grades, were taken from the relevant preceding tables and converted to bar charts as illustrated in Figures 6.4 through 6.6 for the three-month, three-year average and three-year maximum incremental prices, respectively. In these charts, there are no cost effectiveness bars for NO_X and CO_2 when comparing 0.6% sulfur MDO to the 0.2% sulfur MGO because there are no associated NO_X or CO_2 reductions.

It should be noted that the PM cost effectiveness estimates for the auxiliary engines are different from ARB's recent cost effectiveness values cited at the May 2005 Ship Auxiliary Engine Workshop. The difference may be due to the different PM emission factors used in the 2001 PWBAEI and ARB's current estimated emission factor for auxiliary engines using residual fuel. ARB's cost effectiveness estimate for auxiliary engines ($30,000 per ton of PM reduced) is much lower than this report's estimated $67,000 per ton of PM reduced and it may be due to the higher emission factor used to estimate emissions.

Figure 6.4: Cost Effectiveness for MGO <0.2% Sulfur using 3-month Average Prices

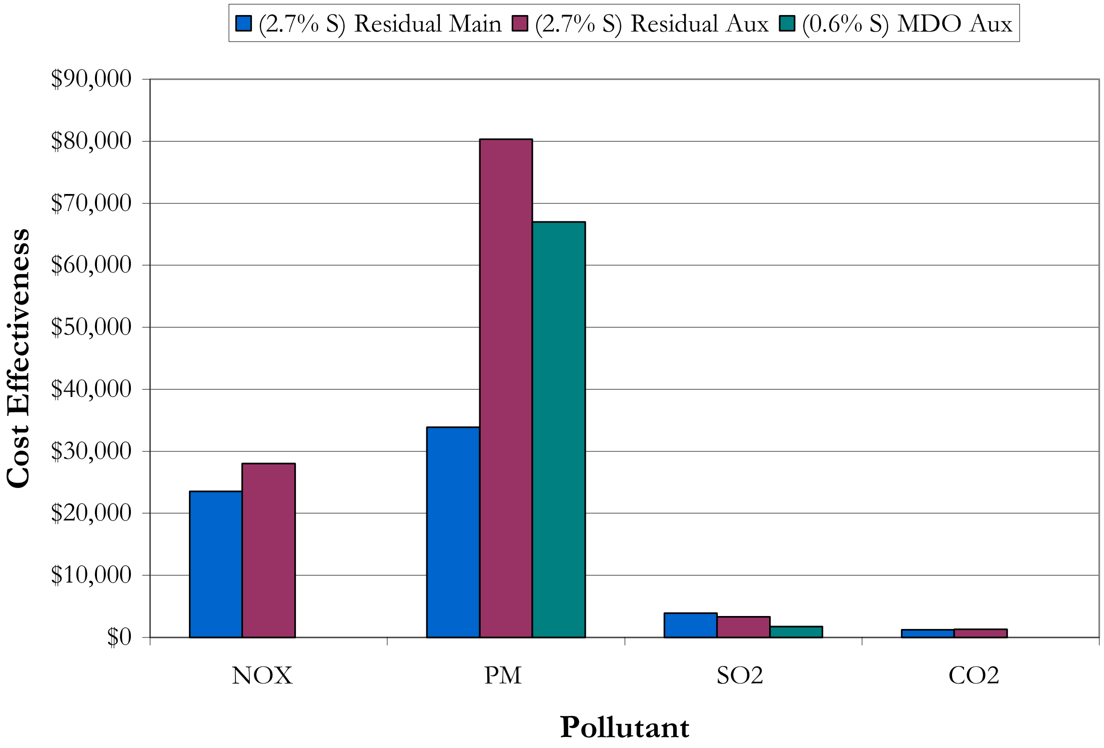


Figure 6.5: Cost Effectiveness for MGO <0.2% Sulfur using 3-year Average Prices

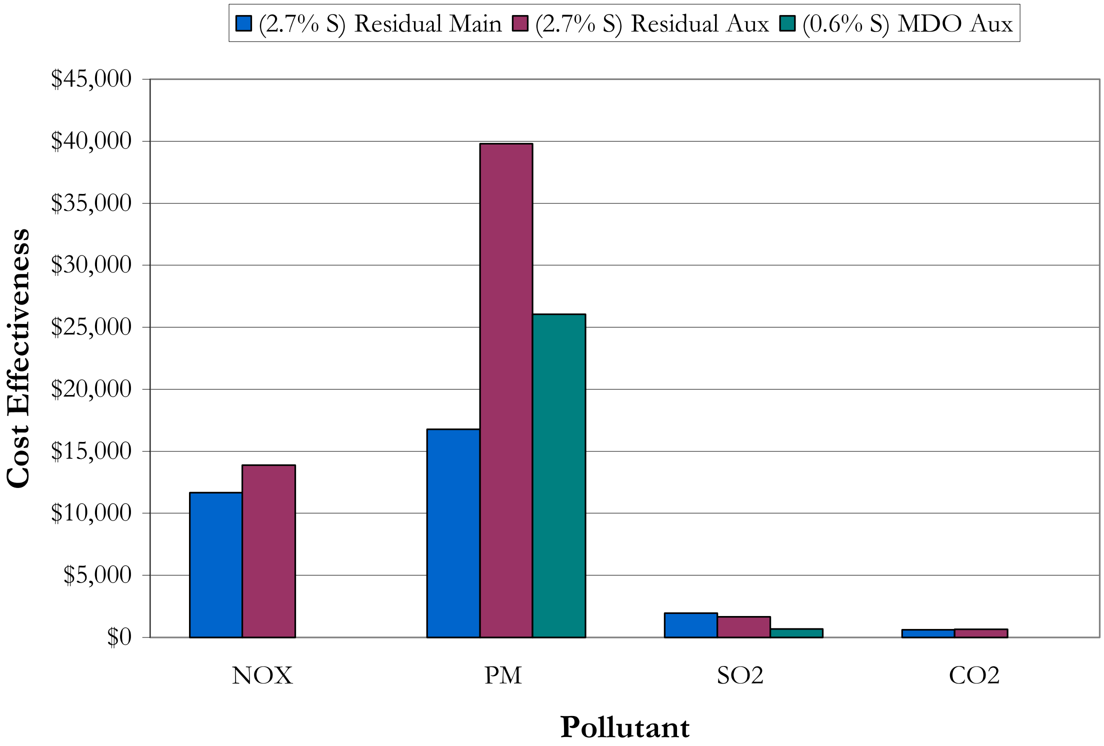
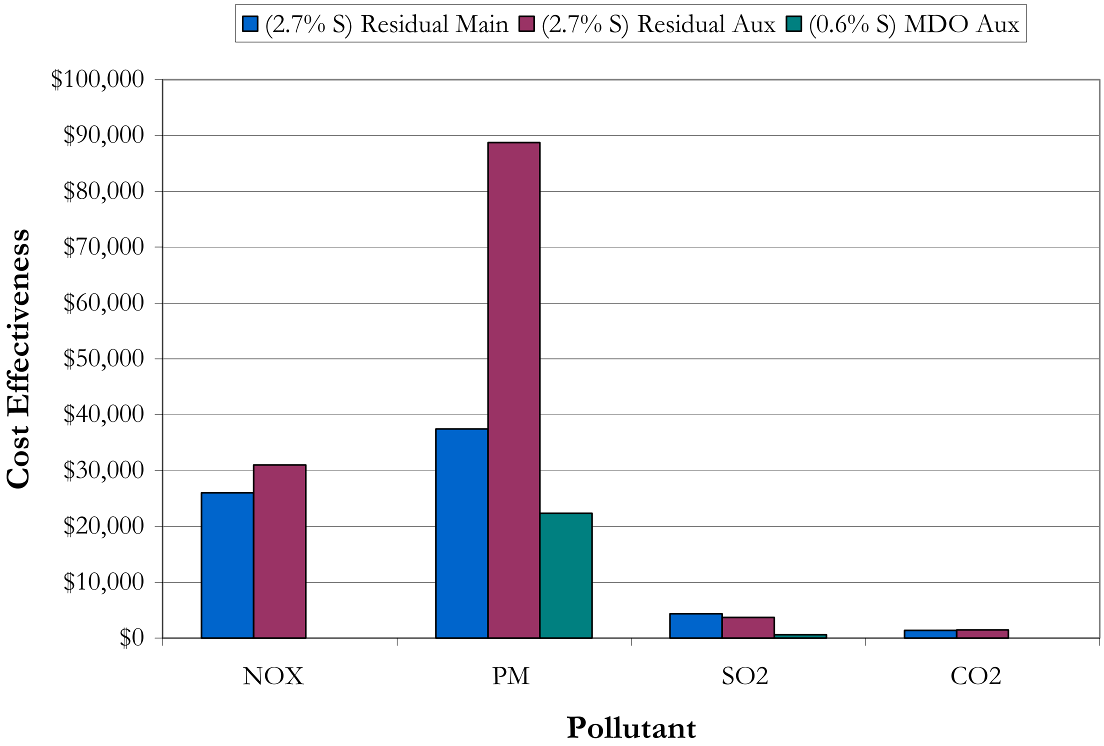


Figure 6.6: Cost Effectiveness for MGO <0.2% Sulfur using 3-year Maximum Prices



SECTION 7 CONCLUSION

This study evaluated the availability of fuel with 2,000 ppm or less sulfur for use in the propulsion and auxiliary engines of commercial container vessels. Based on the recent ARB survey earlier cited, main engines are almost exclusively powered by residual oil, and more than three quarters of the vessels use residual oil in their auxiliary engines as well. Eighty percent of these ships could use marine distillate fuel for their auxiliary engines as currently configured. However, there are a number of operational issues associated with attempting to switch main engine residual fuel to a marine distillate. Vessel configurations vary considerably even within the same shipping line's fleet; extra fuel and lubricating oil storage tanks may be needed, along with the associated piping, should fuel switching to lower sulfur fuels be required. Other issues relate to lubricity requirements, fuel temperature requirements, and fuel compatibility.

Low sulfur (≤0.2% sulfur) residual oil is not available, and low sulfur marine distillate (≤0.2% sulfur), if supplied at all, costs more than twice what residual oil costs. Two-thirds of the ports of call or origination for vessels serving the Port of Los Angeles are in Asia, however, the Asian ports, other than Singapore, are those least likely to be able to supply marine distillate with ≤0.2% sulfur content. Vessels transiting European ports (there were none included in this study) and vessels calling on North American ports en route to the Port of Los Angeles could have access to marine distillates ≤0.2% sulfur on a case-by-case basis. Based on DNV PS test data and supplier responses, marine distillates ≤0.2% sulfur is available as follows in the subject ports:

- *Available* – France: Le Havre; the Netherlands: Rotterdam
- *Some availability* – Canada: Vancouver; U.S.: Los Angeles, New York, San Francisco, Seattle; Singapore
- *Little availability* – Mexico: Acapulco; Panama Canal; U.S.: Charleston, Honolulu, Norfolk, Savannah; China: Guangzhou, Hong Kong, Qingdao, Shanghai, Xingang; Japan: Nagoya, Tokyo Bay; Malaysia: Port Klang; Taiwan: Keelung
- *No availability* – China: Xiamen; Japan: Kobe; Malaysia: Tanjung Pelepas; South Korea: Busan; Taiwan: Kaohsiung

Under current pricing (based on a three-month average as described in Section 6), and using the Carl Moyer program $12,000/ton NO_X reduced cost effectiveness threshold, it would not be cost effective in the current market to switch from residual oil to MGO ≤0.2% sulfur, at a rate of $23,600 to $28,000/ton NO_X reduced (operational and technical feasibility aside). If, however, three-year average pricing is used, fuel switching becomes much more cost effective, at $11,700 to $13,000/ton NO_X reduced. Even at this level of cost effectiveness, however, it is unlikely that a shipping line would convert its propulsion engines to MGO <0.2% sulfur due to cost and operational issues, or even its auxiliary engines, without monetary incentives or subsidies, or regulatory requirements to do so.

Although the onroad fuels (Grade No. 2 S500, CARB Diesel S500, and ULSD S15) were included in this study and in the cost effectiveness section, these fuels are not required to meet the flashpoint requirement for marine fuels, have not been tested on ocean-going vessels' engines, and are not currently supplied by marine suppliers for large-volume bunker sales. It should be noted, that CARB Diesel, which is subject to a minimum 52°C flashpoint, is currently available to many harbor craft in California and will be required for use in all harbor craft in California starting in 2007. Some of these harbor craft may be subject to the marine fuel regulation, so CARB Diesel meeting the 60°C flashpoint will be available at California ports in the near future.

As new regulations arise for low sulfur marine distillate and residual fuels, it is recommended there be:

- additional research for trial use of lower sulfur fuel in marine engines,
- actual emissions testing of the various pollutants, especially particulate matter,
- fuel quality testing,
- fuel switching procedures development similar to those already in place by vessels that routinely switch fuels,
- consideration given to other alternatives in lowering emissions, such as gas scrubbers and cleaner engines.