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U.S.-Mexico Demonstration of Fuel Switching on Ocean Going Vessels in the Gulf of Mexico

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Disclaimer

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available and were collected through this project. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for EPA action.

Table of Contents

List of Tables

List of Figures

Executive Summary

EPA engaged the U.S. Maritime Administration, the Port of Houston Authority, two maritime shipping companies and government representatives from Mexico, including local, municipal, state and federal agencies, such as the State of Veracruz, SEMARNAT (Secretaría de medio ambiente y recursos naturales, Mexico's Ministry of Environment and Natural Resources) and PEMEX (Mexico's state-owned petroleum company) to conduct the first-ever EPA fuel switch demonstration in the Gulf of Mexico. The project focused on illustrating the effectiveness of fuel switching on ocean going vessels to reduce impacts to the Gulf of Mexico and its coastal populations. Vessels switched from heavy fuel oil (HFO) to marine gas oil (MGO) within 24 nautical miles (nm) of one U.S. and several Mexican Gulf ports. EPA also sought to raise awareness about the environmental benefits of the upcoming North American Emission Control Area (NA ECA) effective in August 2012, which will require that ships use lower sulfur fuels within 200 nautical miles of the majority of U.S. and Canadian Atlantic and Pacific coastal waters, French territories off the Canadian Atlantic coast, the U.S. Gulf Coast, and the main, populated islands of Hawaii. The NA ECA phases in lower sulfur fuels starting in 2012, requiring 0.1 per cent sulfur fuel content by 2015. The NA ECA was established under the auspices of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL Annex VI), a treaty developed by the International Maritime Organization.

This project demonstrated the benefits of the fuel sulfur provision of the NA ECA. It showed that fuel switching to MGO with a fuel sulfur content of less than 0.1 percent in the Gulf of Mexico on two ocean going vessels leads to large emission reductions of sulfur oxide (SOx) and particulate matter (PM) emissions and small emission reductions in nitrous oxide (NOx), as observed through on-board emission sampling corroborated by calculated emission reductions. Human exposure to these pollutants results in serious health impacts such as premature mortality and aggravation of heart and lung disease. Atmospheric inputs related to emissions from fossil fuel combustion and other sources of strong acids (such as nitric (HNO_3) and sulfuric (H_2SO_4) acids) alter surface seawater alkalinity, pH, and inorganic carbon storage which can disrupt natural biogeochemical cycles. This is expected to have the greatest impact in near-coastal waters, where the ecosystem responses to ocean acidification most affect human populations.

During the demonstrations, the test vessels encountered no operational issues of concern due to fuel switching.

Emission measurements were taken on one test vessel while steaming between, approaching, and hotelling at the Ports of Houston, Veracruz and Alta Mira. It was found that switching from HFO (with a 3.79 % sulfur content) to MGO (with a 0.01% sulfur content) achieved significant reductions in emissions of SOx and PM (2.5 micron in size) and small reductions in NOx – 89, 80 and 5 percent respectively – at a 2 percent increase in vessel operating costs, due to the higher cost of lower-sulfur fuel.

Ship emission inventories were developed for the Ports of Houston, Veracruz and Alta Mira using vessel port call data together with Lloyd's Register of Ships data. Emissions were

estimated on both HFO with a sulfur content of 3.0 percent[1] and MGO with a sulfur content of 0.1 percent. Emission calculations were based on EPA's Best Practice Guidance Document[2]. Annual emissions by ship type, ship operating mode (e.g., maneuvering, hotelling, etc.), fuel type and fuel switching zone boundary were calculated for each port. Tankers contributed most to annual emissions in Houston, whereas containers were the largest sources of annual emissions for Veracruz and Alta Mira. At all ports, the "cruise" operating mode contributed the most to total annual ship emissions. At all ports calculated annual emissions reductions of NOx, PM and SOx achieved through fuel switching within a 24 nm fuel switching zone were over 5, 75 and 80 per cent respectively. EPA found a three to five-fold increase in emissions reductions using a 200 nm fuel switching zone boundary versus a 24 nm boundary.

Dispersion modeling was conducted for the Port of Veracruz using the calculated emission inventory. The modeling showed a large reduction in impacts of ship emissions on port area air quality and sensitive reefs due to fuel switching within 24 nm of the port. Only emissions from ships were modeled. The study did not include the impact of other sources on air quality, such as those from all other activities at the port as well as all other regional sources. Air quality modeling showed a seven-fold reduction in 24-hour average and annual average $PM_{2.5}$ concentrations and a 24- to 25-fold reduction in 24-hour average and annual average SO_2 concentrations. This study has indicated that local concentrations of $PM_{2.5}$ pollution could be reduced as much as 43 to 88 percent over the entire modeling domain by moving to a fuel-switching mode for ships calling on the Port of Veracruz. Deposition modeling showed a 99 per cent reduction of SO_2 deposition to sensitive reef areas off the coast of Veracruz.

While acknowledging that this study has not quantified the effects of fuel switching on overall concentrations or deposition of air pollutants, the reductions of PM and SOx concentrations associated with fuel switching imply that similar results could be achieved in Mexico through reduced use of HFO fuel in shipping.

[1] This sulfur content for HFO was used for inventory calculations for the Gulf Region because SEMARNAT used 3.0% in their inventory calculations for Mexican ports. 3.0% is assumed to be conservative for the Gulf Region based upon the two demonstration projects. HFO had a sulfur content of 3.37% and 3.79% for the Maersk and Hamburg Süd demonstrations, respectively. In addition, SEMARNAT indicates average HFO used in Mexico is 3.8% sulfur. Larger reductions should be expected if the sulfur fuel levels are greater than the 3.0% assumed here..

[2] ICF International, *Current Methodologies in Preparing Mobile Source Port Related Emission Inventories,* Final Report, April 2009. Available at http://www.epa.gov/sectors/sectorinfo/sectorprofiles/ports/ports-emission-inv-april09.pdf.

1. Introduction

Ocean going vessels (OGVs) are used to transport the majority of goods (measured by weight and value) globally. These vessels are a significant source of air pollution, affecting populations and ecosystems especially near coastal areas[3] [4]. EPA's modeling also shows potential impacts far inland[5]. This project focused on the impact of OGV emissions in the Gulf of Mexico, where they contribute to air pollution at ports throughout the Gulf region, and also adversely affect Gulf ecosystems. One method of significantly reducing emissions from OGVs is to switch from a high sulfur marine heavy fuel oil (HFO) (also known as bunker fuel or residual oil) to lower sulfur marine gas oil (MGO) (also known as marine distillate fuel or marine diesel oil). . Switching from HFO to MGO can dramatically reduce ship particulate matter (PM) and sulfur oxides (SOx) emissions as well as achieving moderate reductions in nitrous oxide (NOx) emissions. These and other pollutants emitted from ships are related to human and environmental health impacts, including asthma, increased cancer risk, regional haze/smog, and, via aquatic deposition, acidification and hypoxia. The Port of Houston, three key Gulf Ports in Mexico – Progreso, Alta Mira and Veracruz -- and the Port of Houston's Sister port in Brazil – Santos -- have all been targeted through this project, which involved switching to lower sulfur marine fuel in ships approaching the U.S., Mexican and Brazilian coasts. EPA did not estimate or measure emissions reductions at the Port of Santos for this report.

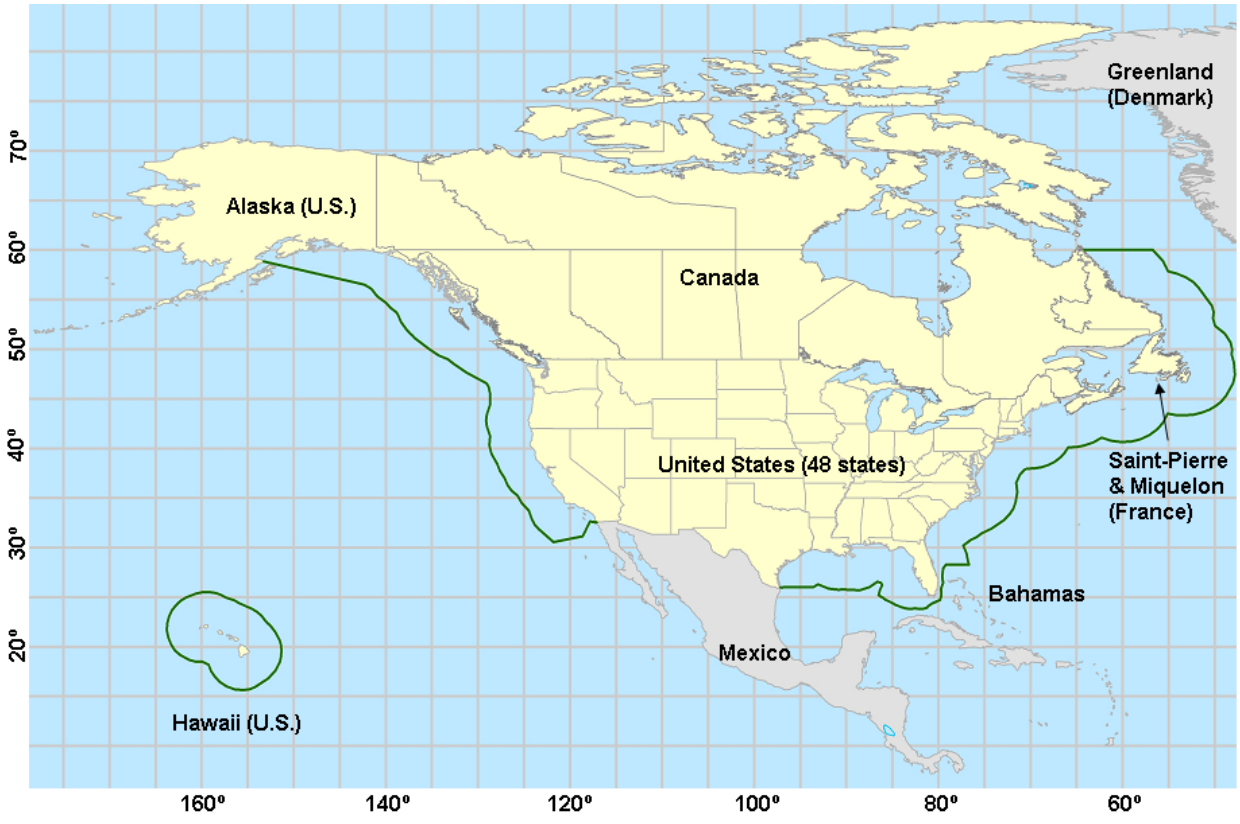
The United States Government, together with Canada and France, has established a North American Emission Control Area (NA ECA) that will put in place lower sulfur marine fuel standards and other requirements beginning in August 2012. The ECA was established under the auspices of Annex VI of the International Convention for the Prevention of Pollution from Ships ((MARPOL Annex VI), a treaty developed by the International Maritime Organization. This ECA will require use of lower sulfur fuels in ships operating within 200 nautical miles of the majority of the U.S. and Canadian coastline, including the U.S. Gulf Coast (see Figure 1). The fuel switching demonstration project sought to demonstrate the benefits of the NA ECA provision requiring 0.1 per cent fuel sulfur by 2015. This project also sought to raise awareness throughout the Gulf of Mexico about the environmental and human health benefits associated with implementing lower sulfur fuel content requirements, such as those of the NA ECA.

[3] Corbett, J. et al. (2007), *Mortality from Ship Emissions: A Global Assessment*, Environ. Sci. Technol. 41(24):8512-8.

[4] Dalsøren, S. B., et al. (2009), *Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports*, Atmos. Chem. Phys., 9, 2171-2194.

[5] U.S. Environmental Protection Agency, *Regulatory Impact Analysis: Control of Emissions of Air Pollution from Category 3 Marine Diesel Engines,* EPA Report EPA-420-R-09-019, December 2009. Available at http://www.epa.gov/otaq/regs/nonroad/marine/ci/420r09019.pdf

Figure 1: North American Emission Control Area



2. Project Goals and Partners

This international project was the result of a partnership between the U.S. EPA, the Port of Houston Authority, the Mexican federal government, the U.S. Maritime Administration, Maersk Line, a Danish-based shipping company, and Hamburg Süd, a German-based shipping company. Additionally, ICF International managed the technical elements of the program with the University of California-Riverside performing the emission measurements on the Hamburg Süd vessel.

EPA's fuel switch demonstration engaged the maritime shipping industry and government representatives from Mexico, to raise awareness about the feasibility of fuel switching and the environmental benefits of implementing fuel sulfur marine fuel requirements and the upcoming North American ECA in August 2012. The fuel switching demonstration along with the emission reduction estimates and dispersion modeling were intended, in particular, to inform policy makers in the Gulf of Mexico of the potential health and environmental benefits of fuel switching.

EPA and the Mexican federal government conducted a technical workshop in April 2010 at the Port of Veracruz in Mexico to launch the fuel switching demonstration. The workshop also provided Mexican government and industry stakeholders an opportunity to learn first-hand about this issue and to gather information on how to address marine emissions. It was well attended by officials from local, municipal, state and federal agencies, including the State of Veracruz, SEMARNAT[6] and PEMEX[7]. This report presents the results of the fuel switching demonstration, emission inventory development and emissions dispersion modeling. The fuel switching demonstration enabled the documentation of any operational issues related to fuel switching, the calculation of emissions reductions based on fuel use, and the direct measurement of air pollutant reductions. The emission inventory was developed using port call data at the Ports of Veracruz, Alta Mira and Houston. The dispersion modeling used the emission inventory data to calculate air concentrations and loadings to the Gulf. This report and a fuel switching outreach video are tools to help raise the awareness of stakeholders of the benefits of fuel switching. In 2011 the video will also be available via the Gulf Coastal Ecosystem Learning Centers and the National Oceanic and Atmospheric Administration's Oceans Today Kiosk through the Smithsonian Institution. For resources and more information see the project web site: www.epa.gov/international/fuelswitch.html.

[6] The Ministry of Environment and Natural Resources (*Secretaría de Medio Ambiente y Recursos Naturales*, Semarnat) is a federal government agency which main purpose is to promote the protection, restoration and conservation of ecosystems and natural resources, as well as environmental goods and services, in order to promote their sustainable use and development.

[7] Petróleos Mexicanos or Pemex is a Mexican state-owned petroleum company.

3. Benefits of Fuel Switching

Fuel switching can produce significant emission reductions in coastal areas with benefits potentially extending to inland areas. To quantify these reductions in the Gulf of Mexico, port emission inventories were developed for the Port of Houston as well as the Ports of Alta Mira and Veracruz in Mexico. In addition, dispersion modeling of PM and SOx emissions was done at the Port of Veracruz to see the reduction in deposition on the city of Veracruz and the surrounding sensitive reef areas.

The North American ECA will come into effect in August 2012 and will require the NOx and fuel sulfur reductions shown in Table 1. This project focused on demonstrating the benefits of the fuel sulfur provision.

Table 1: North American ECA Requirements

Requirements	Outside ECA	Inside ECA
NOx	20% reduction in new vessels by 2011	80% reduction in new vessels by 2016
Fuel Sulfur (%)	– *2012: 3.50%* – *2020: 0.50%* – The 2020 fuel standard could be delayed to 2025; subject to 2018 fuel availability review	– *2010-14: 1.00%* – *2015: 0.10%*

These NOx and fuel sulfur reductions will lead to substantial reductions in ozone and PM2.5 emissions and Sulfur depositions well into the interior of the U.S. as shown in Figure 2, Figure 3, and Figure 4, respectively.

Figure 2: 2020 Potential ECA Ozone Reductions

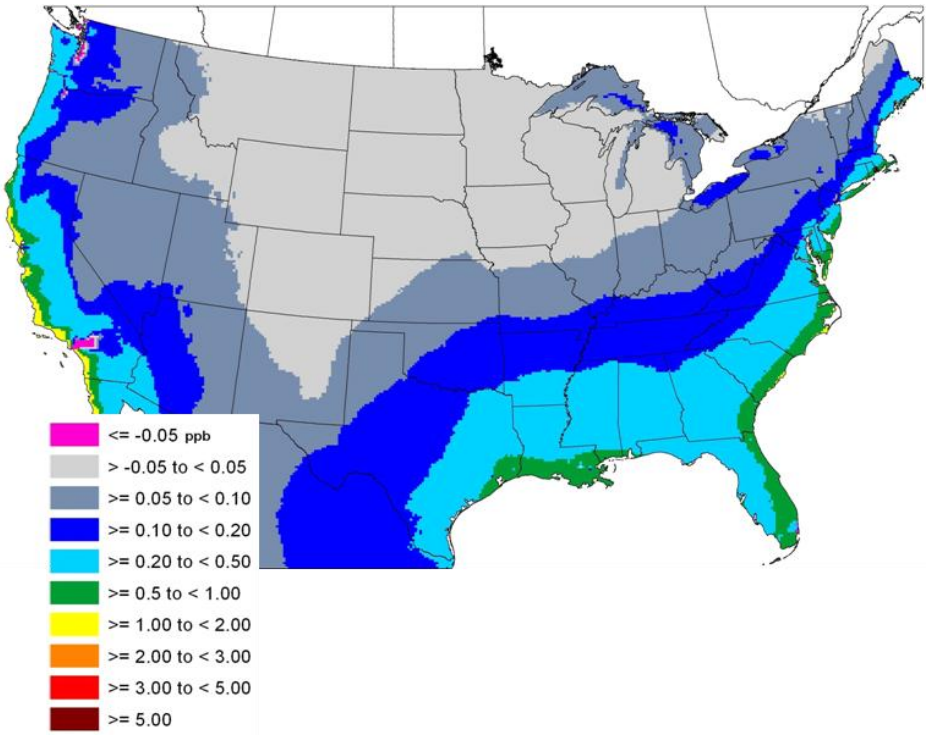


Figure 3: 2020 Potential ECA $PM_{2.5}$ Reductions

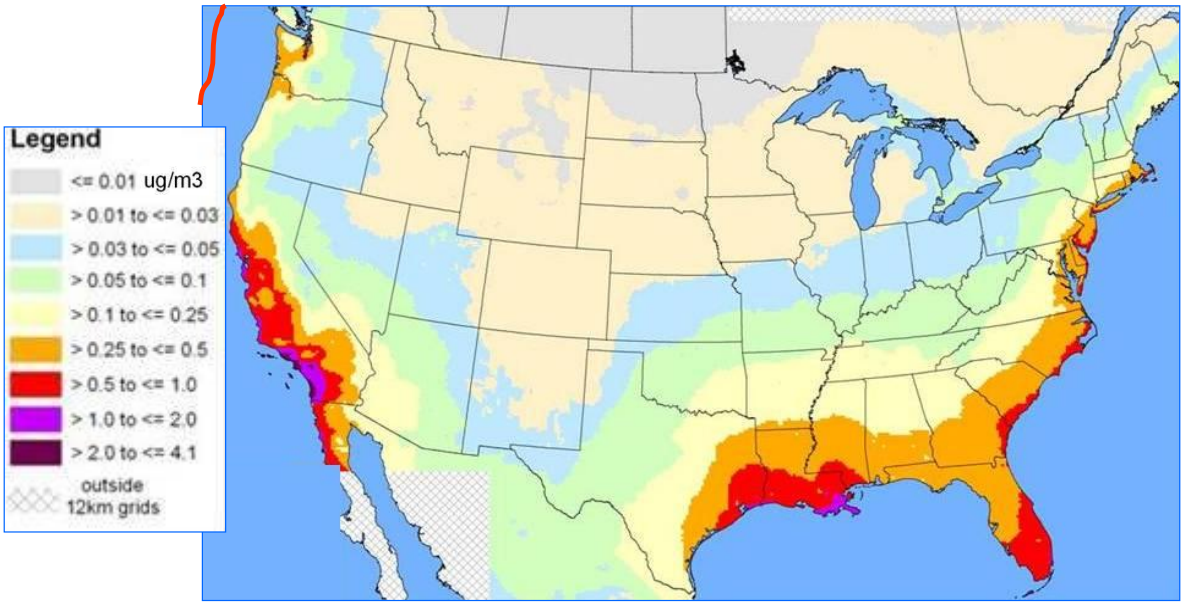
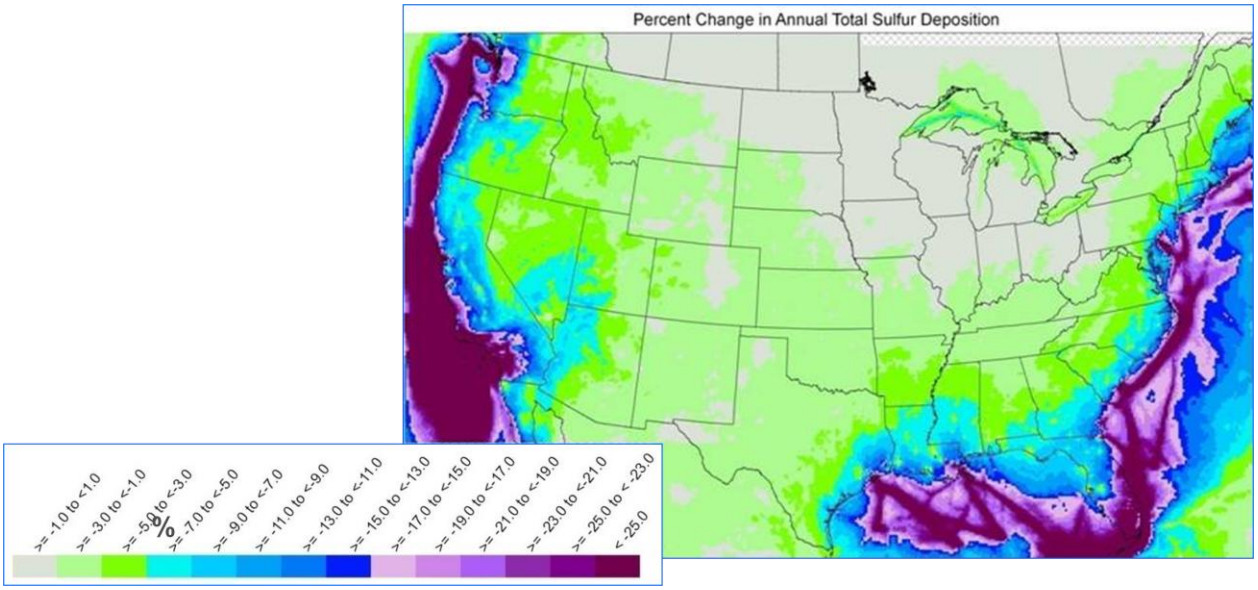


Figure 4: 2020 Potential Sulfur Deposition



As a result of these reductions, the health benefits in the United States are substantial. In 2020, EPA expects to save 5,500 to 14,000 lives and provide respiratory relief for 5 million people. The monetized health benefits exceed $47 to $110 billion dollars annually. The cost per tonne[8] of emission reduction from ships compares favorably with land-based emission control programs as shown in Table 2.[9]

Total costs for ECA implementation in 2020 were estimated at $3.2 billion. These costs included hardware costs for NOx controls, fuel system modifications and operating costs for using lower sulfur fuel. Taking the monetized health benefits (as cited in the above paragraph) and comparing to these total costs, the health benefit to cost ratio is substantial – ranging from 15:1 to 30:1.

Table 2: Cost per tonne of emission reduction for NA ECA

Pollutant	ECA	Land-Based
NOx	$2,600/tonne	$200 - $12,000/tonne
$PM_{2.5}$	$11,000/tonne	$2,000 - $50,000/tonne
SOx	$1,200/tonne	$200 - $6,000/tonne

[8] Tonne is used here to denote metric tons.

[9] U.S. Environmental Protection Agency, *Proposal to Designate an Emission Control Area for Nitrogen Oxides, Sulfur Oxides and Particulate Matter,* Report EPA-420-R-10-013, August 2010. Available at http://www.epa.gov/otaq/regs/nonroad/marine/ci/420r10013.pdf

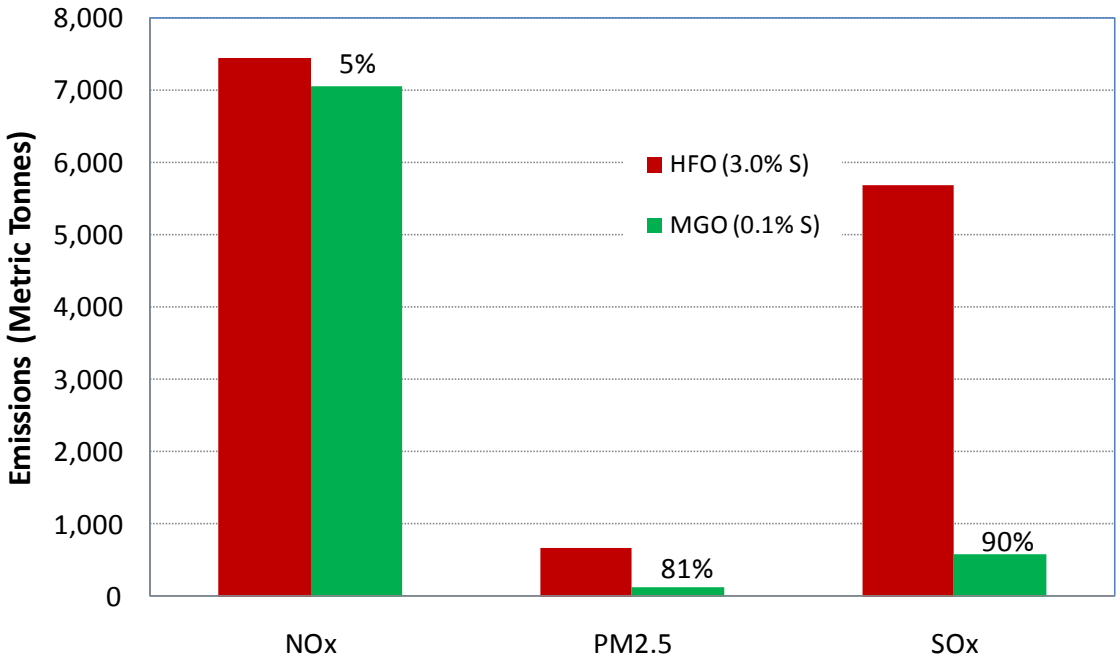
3.1. Port Emissions Inventories

Port emission inventories of three ports were developed using vessel port call data together with Lloyd's Register of Ships data. Emissions were estimated on both residual fuel with a sulfur content of 3.0 percent[10] (HFO) and distillate fuel with a sulfur content of 0.1 percent (MGO). Emission calculations were done following EPA's Best Practice Guidance Document[11] and are discussed in detail in Appendix A.

Port of Houston, USA

Using the methodology described in Appendix A, emissions on HFO and MGO were calculated for 2007 if all ships entering or leaving the Port of Houston used that fuel within 24 nm of the U.S. coastline. Fuel switching was assumed to occur prior to the 24 nm boundary. Comparisons of port emissions for Port of Houston are shown in Figure 5. As shown in the figure, NOx emissions are reduced by 5 percent, $PM_{2.5}$ by 81 percent and SOx by 90 percent by switching from HFO to MGO within 24 nm of port. This amounts to 402 metric tonnes of NOx, 544 metric tonnes of $PM_{2.5}$, and 5,116 metric tonnes of SOx.

Figure 5: Port of Houston Emissions Assuming a 24 nm Fuel Switching Zone



[10] 3.0 percent sulfur was used for inventory calculations for the Gulf Region because SEMARNAT used 3.0% in their inventory calculations for Mexican ports. 3.0% is assumed to be conservative for the Gulf Region based upon the two demonstration projects. HFO had a sulfur content of 3.37% and 3.79% for the Maersk and Hamburg Süd demonstrations, respectively. In addition, SEMARNAT indicates average HFO used in Mexico is 3.8% sulfur. Larger reductions should be expected if the sulfur fuel levels are greater than the 3.0% assumed here.

[11] ICF International, *Current Methodologies in Preparing Mobile Source Port Related Emission Inventories,* Final Report, April 2009. Available at http://www.epa.gov/sectors/sectorinfo/sectorprofiles/ports/ports-emission-inv-april09.pdf.

Based upon the emission inventory using the methodology described in Appendix A, emissions for all ships operating on HFO in the various modes are shown in Figure 6. The largest emissions are during the 24 nm cruise followed by emissions generated during transit down the Houston Ship Channel and hotelling. Figure 7 shows emissions of $PM_{2.5}$ and SOx by ship type. Tankers produce the highest emissions across all modes followed by container ships. Tanker ships made 3002 calls at the Port of Houston while container ships only made 783 calls in 2007.

Figure 6: Port of Houston Emissions by Mode

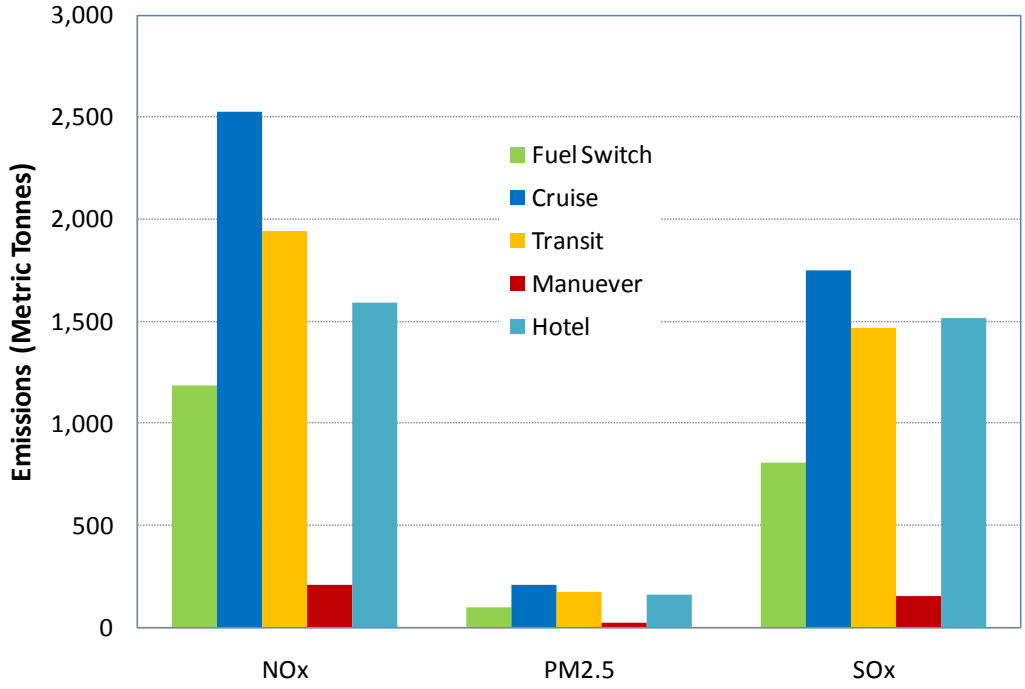
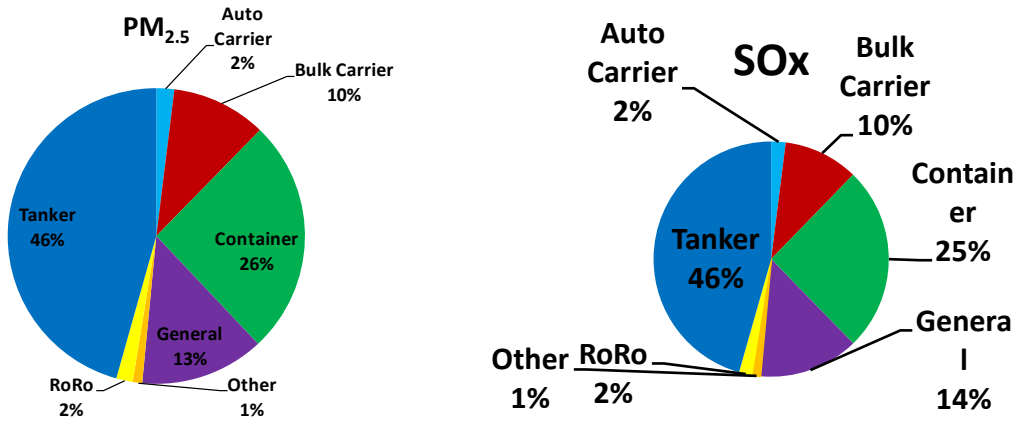


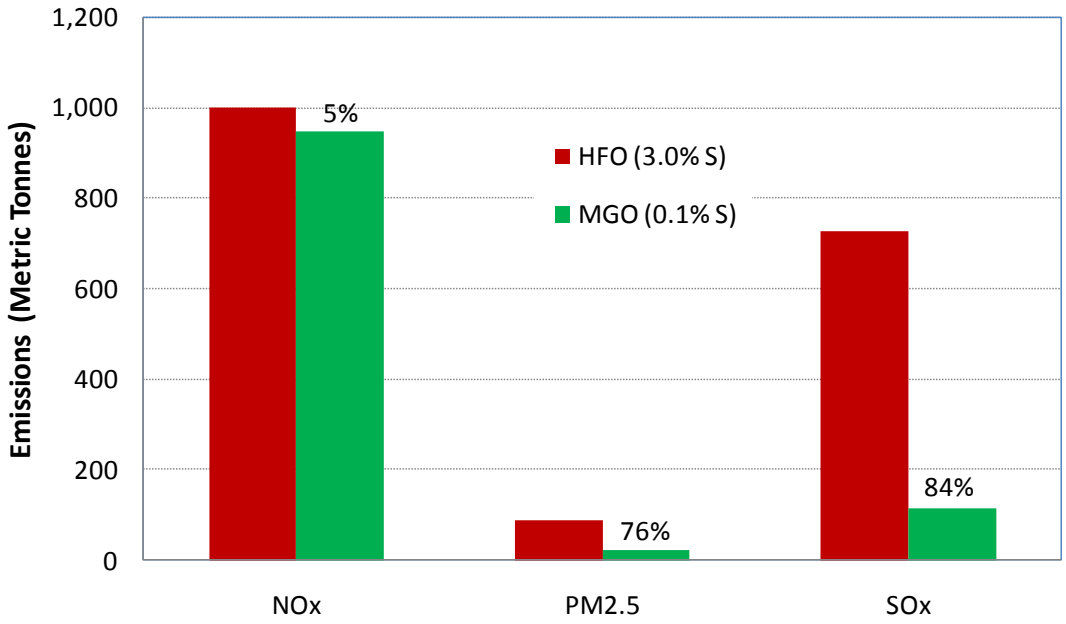
Figure 7: Port of Houston Emissions by Ship Type



Port of Alta Mira, Mexico

Using the methodology described in Appendix A, emissions on HFO and MGO were calculated for 2005[12] if all ships entering or leaving the Port of Alta Mira used that fuel within 24 nm of the Mexican coastline. Fuel switching was assumed to occur prior to the 24 nm boundary. Comparisons of port emissions for Port of Alta Mira are shown in Figure 8. As shown in the figure, NOx emissions are reduced by 6 percent, $PM_{2.5}$ by 76 percent and SOx by 84 percent by switching from HFO to MGO within 24 nm of port. This amounts to 51 metric tonnes of NOx, 66 metric tonnes of $PM_{2.5}$, and 615 metric tonnes of SOx. These emissions reductions are lower than those for the Port of Houston due to the fact that total annual calls at the Port of Alta Mira were 1,138 compared to Port of Houston's 5,778 calls.

Figure 8: Port of Alta Mira Emissions Assuming a 24 nm Fuel Switching Zone



Based upon the emissions inventory prepared using the methodology in Appendix A, emissions for all ships operating on HFO in the various modes are shown in Figure 9. The largest emissions are during the 24 nm cruise followed by emissions generated during hotelling. Figure 10 shows emissions of $PM_{2.5}$ and SOx by ship type. Container ships produce the highest emissions at the port.

[12] 2005 was used for the Mexican port inventories because call data at the Mexican ports was only available for 2005.

Figure 9: Port of Alta Mira Emissions by Mode

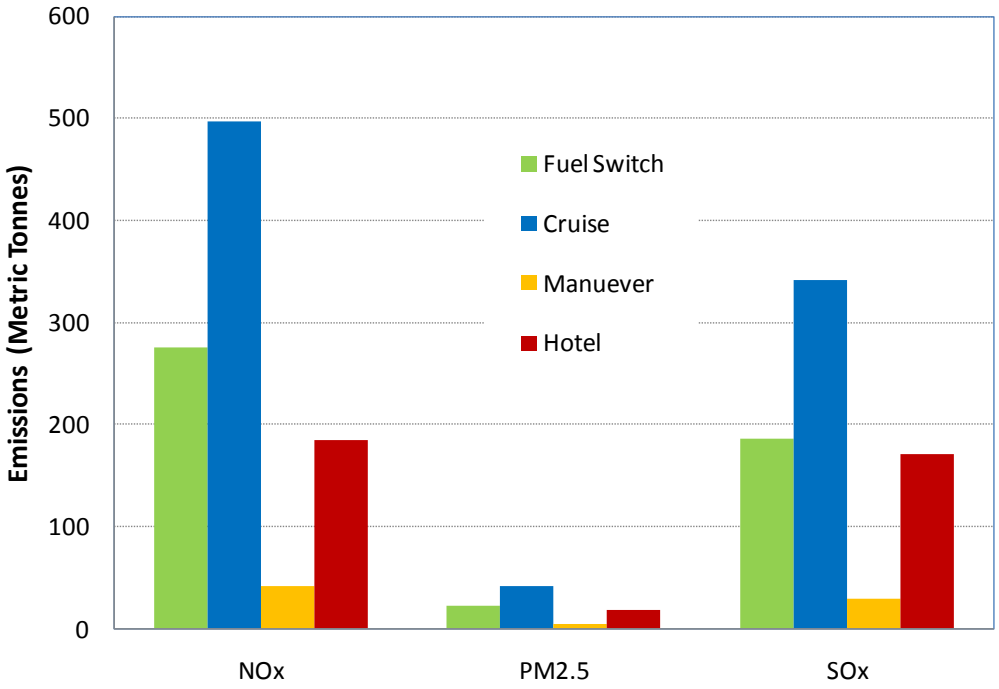
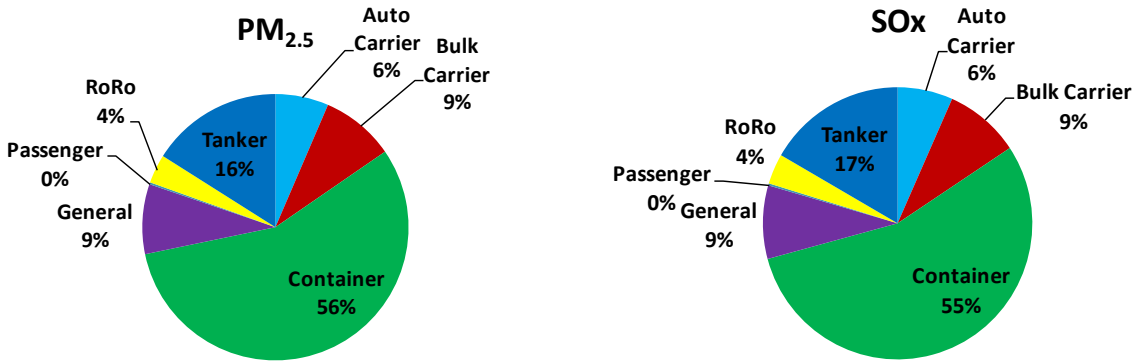
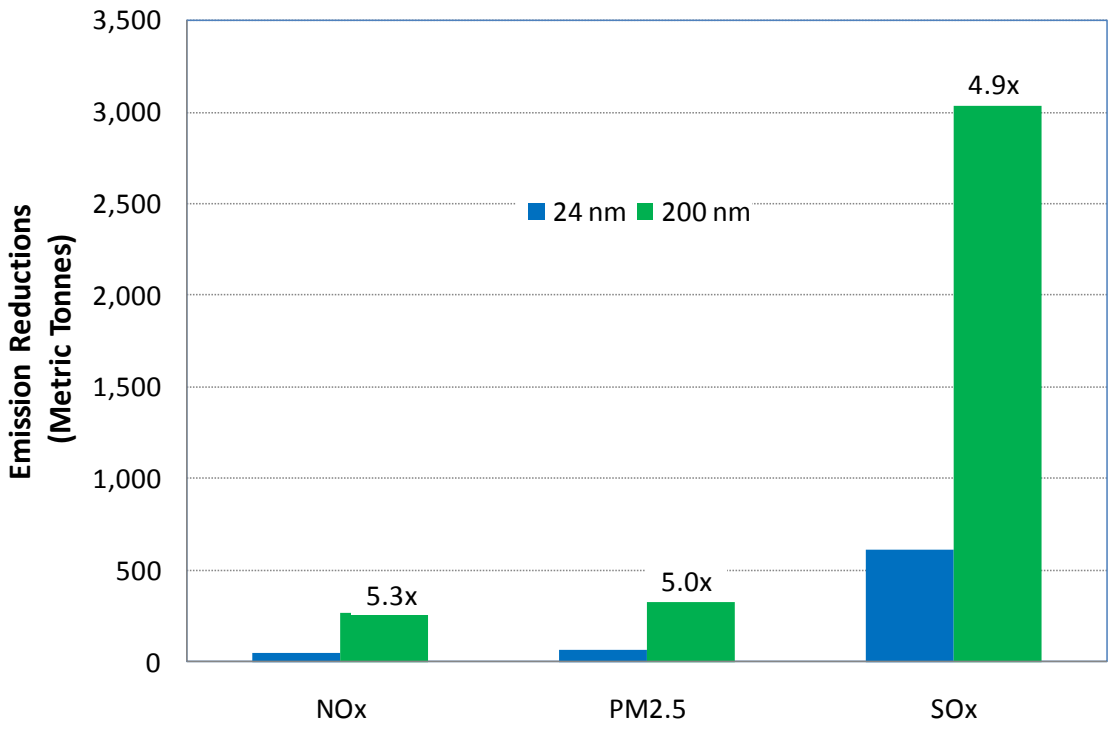


Figure 10: Port of Alta Mira Emissions by Ship Type



Emission reductions possible by extending a low-sulfur fuel switching zone out to 200 nm instead of 24 nm is shown in Figure 11. As shown in the figure, emission reductions can be increased by a factor of 5 by increasing a fuel switching zone from 24 nm as specified in this study to a 200 nm boundary, such as that established by the North American ECA.

Figure 11: Effect of Fuel Switching Zone Distance for Port of Alta Mira



Port of Veracruz, Mexico

Using the methodology described in Appendix A, emissions on HFO and MGO were calculated for 2005[12] if all ships entering or leaving the Port of Veracruz used that fuel within 24 nm of the Mexican coastline. Fuel switching was assumed to occur prior to the 24 nm boundary. Comparisons of port emissions for Port of Alta Mira are shown in Figure 12. As shown in the figure, NOx emissions are reduced by 6 percent, $PM_{2.5}$ by 78 percent and SOx by 87 percent by switching from HFO to MGO within 24 nm of port. This amounts to 70 metric tonnes of NOx, 94 metric tonnes of $PM_{2.5}$, and 892 metric tonnes of SOx. These comparatively lower emissions reductions are due to the fact that total annual calls at the Port of Veracruz were 1,446 compared with 5,778 calls at the Port of Houston.

Based upon the emissions inventory prepared using the methodology in Appendix A, emissions for all ships operating on HFO in the various modes are shown in Figure 13. The largest emissions are during the 24 nm cruise followed by emissions generated during hotelling. Figure 14 shows emissions of $PM_{2.5}$ and SOx by ship type. Container ships produce the largest contribution of emissions at the port.

Figure 12: Port of Veracruz Emissions Assuming a 24 nm Fuel Switching Zone

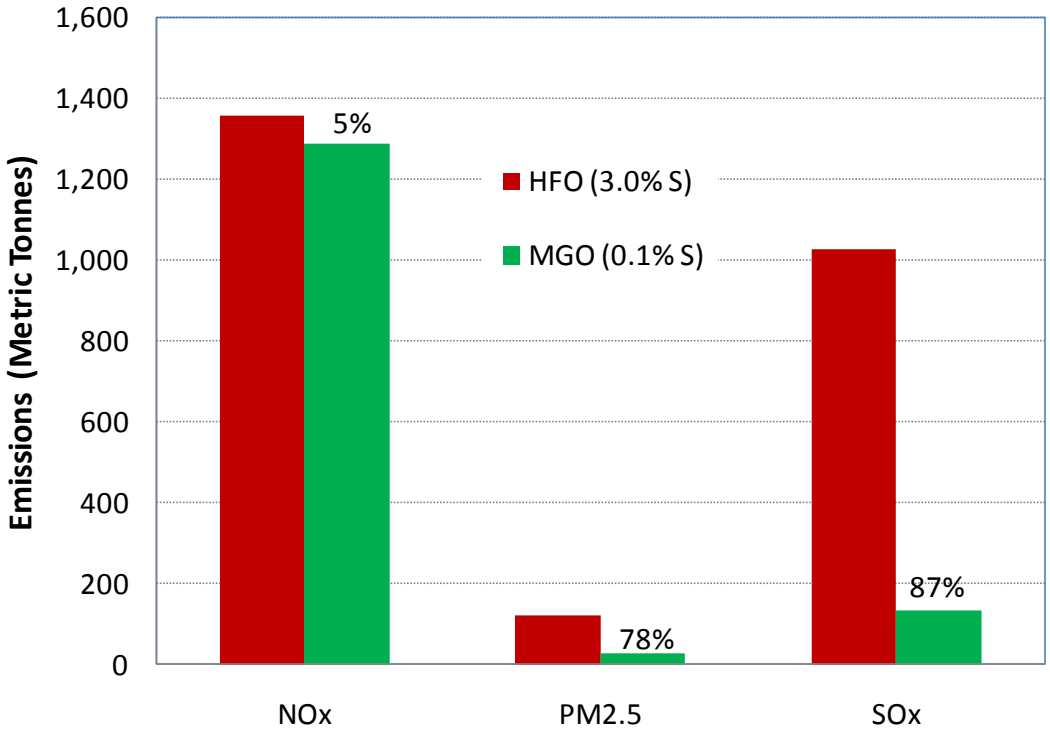


Figure 13: Port of Veracruz Emissions by Mode

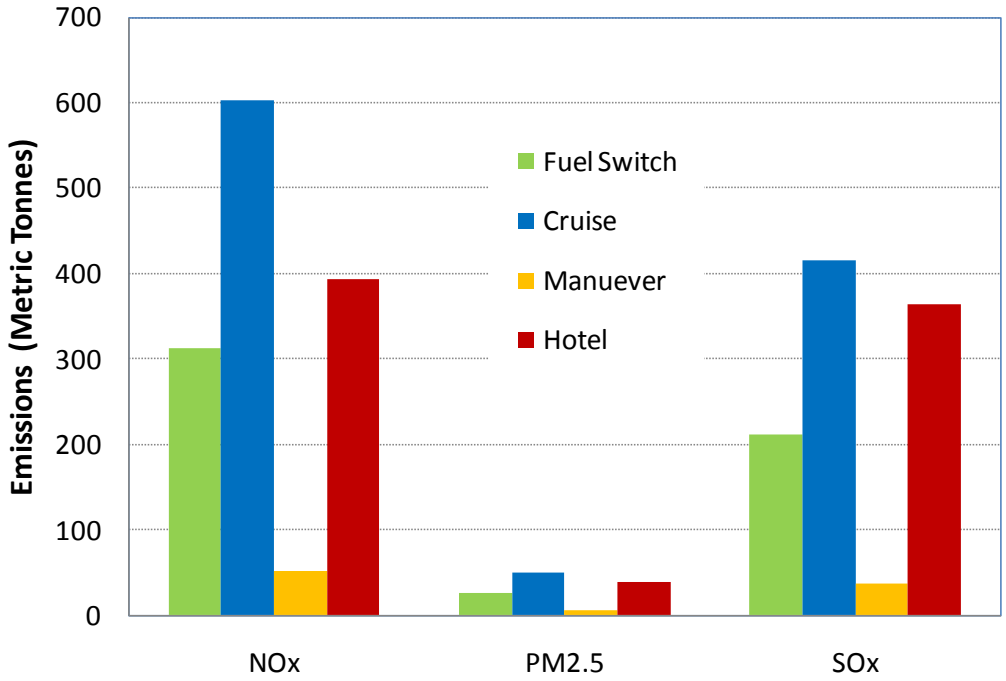
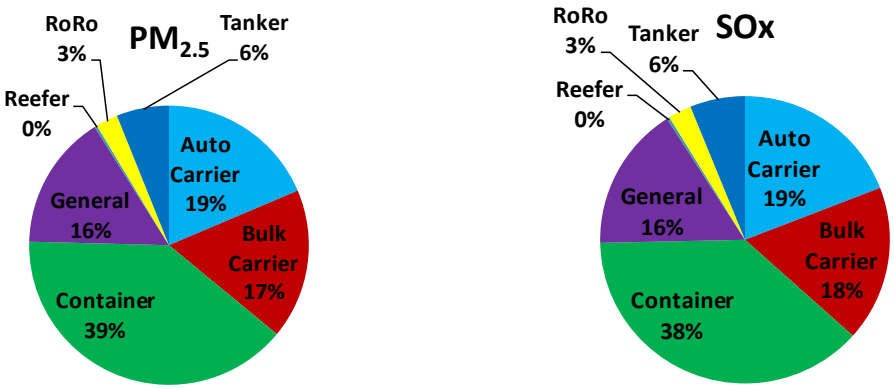
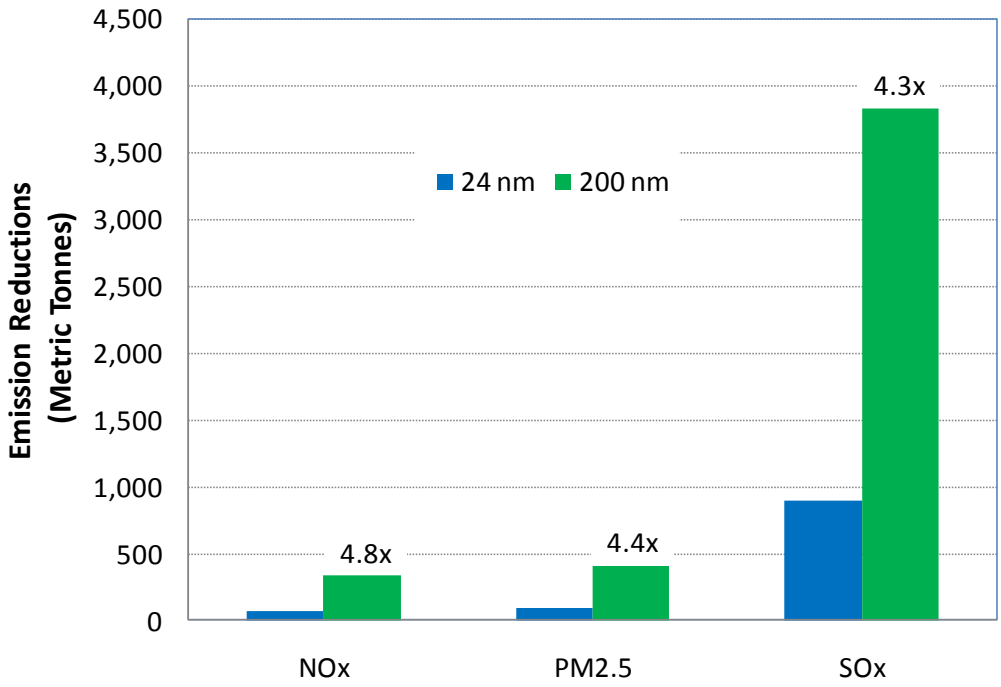


Figure 14: Port of Veracruz Emissions by Ship Type



Emission reductions possible by extending a low-sulfur fuel switching zone out to 200 nm instead of 24 nm is shown in Figure 15. As shown in the figure, emission reductions can be increased by a factor of 4 by increasing a fuel switching zone from 24 nm as specified in this study to a 200 nm boundary, such as that established by the North American ECA.

Figure 15: Effect of Fuel Switching Zone Distance for Port of Veracruz



3.2. Dispersion Modeling

In order to perform a screening-level assessment of health and ecosystem risk associated with fuel switching at a port in Mexico, the emissions calculations of Section 3.1 were used to estimate the air dispersion of key pollutants and their deposition to key sensitive ecosystem

areas – coral reefs that are within a designated National Sea Park area near the Port of Veracruz. The process of obtaining necessary meteorological data is discussed first, followed by an overview of the modeling methodology and then a discussion of results. Technical details are presented in Appendix Band then a discussion of results. Technical details are presented in Appendix B.

Methodology Overview

Meteorology

Necessary meteorological data for the AERMOD model is prepared with the AERMET preprocessor to incorporate the needed planetary boundary layer turbulence structure. Minimum required inputs for AERMET include hourly surface wind speed and direction, temperature, sky cover, and morning upper air sounding. Other inputs include various measurements of pressure, humidity, cloud coverage, surface heat/radiation flux, and afternoon sounding data.

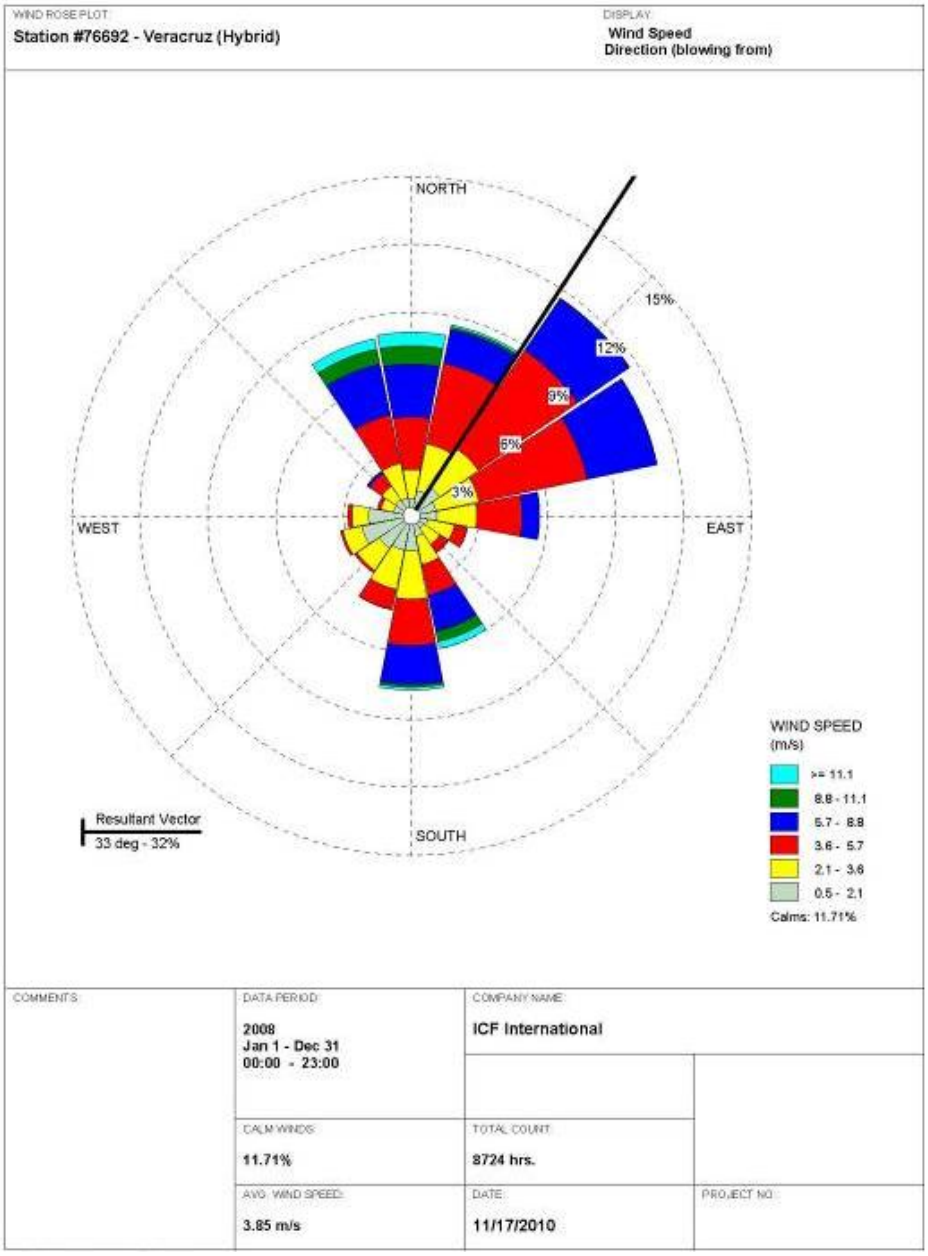
Obtaining this information required contacting numerous sources within various US and Mexican agencies. Appendix B documents the sources contacted and the information available from each. Ultimately, a variety of sources were compiled together into a single meteorological record from February 2008 through February 2009, providing one year of relevant meteorological data.[13]

Figure 16 shows a wind rose for the resulting annual meteorological record. This represents the meteorology driving the dispersion simulations. It is clear that the dominant wind direction is from the northeast, which is an on-shore direction for Veracruz. That is, there is a tendency for pollution emitted at and approaching the port to be blown toward land, increasing the potential for emissions to impact air quality and human health.

[13] All analysis here is performed following US EPA guidance as much as practicable. As such, Appendix W to 40 CFR Part 51, November 9, 2005, Section 8.3.1.2 states that, "Five years of representative meteorological data should be used when estimating concentrations with an air quality model. Consecutive years from the most recent, readily available 5-year period are preferred. The meteorological data should be adequately representative, and may be site specific or from a nearby NWS station. Where professional judgment indicates NWS-collected ASOS (automated surface observing stations) data are inadequate {for cloud cover observations}, the most recent 5 years of NWS data that are observer-based may be considered for use." However, this data was not available for the current study location, and one year of composite data was created.

It is common to have different meteorological record years than emission years, typically to average out inter-annual variability in meteorological records. However, an extended record was not available here. While an extended record may produce more "typical" results, that hypothesis is untestable until a longer record becomes available. Instead, all available data was employed. That this results in different years for emissions and meteorology is immaterial, as the results are meant to show general impacts of fuel switching in the present time-frame, not those specific for any particular year. Further discussion appears both below and in Appendix B

Figure 16: February 2008 through January 2009 Composite Record Wind Rose



Ship Emissions

The emissions inventory, prepared as discussed above, includes emissions estimated for the Port of Veracruz and two other ports for each of the four ship operating modes (cruise, approach, maneuvering, and hotelling) under both a business as usual case – using only HFO – and a fuel-switching case – using a combination of HFO and MGO. Annual emissions are considered, from all vessels calling on each of the Ports for calendar year 2005. This is discussed in Section 3.1, under the "Port of Veracruz" heading. The difference in these two cases estimates the annual emission reductions achievable if all vessels included in the inventory were to switch from high- to low-sulfur fuel.

Dispersion Model, Settings, and Other Inputs

To estimate the corresponding annual reduction in air pollutant concentration and deposition, the ship emission quantities were used in an air dispersion model. Emissions from all four operating modes were included. The individual results allow a demonstration of the fate of these pollutants emitted from ships calling on the Port of Veracruz, while the difference between them indicates the corresponding reduction in pollutant concentrations.

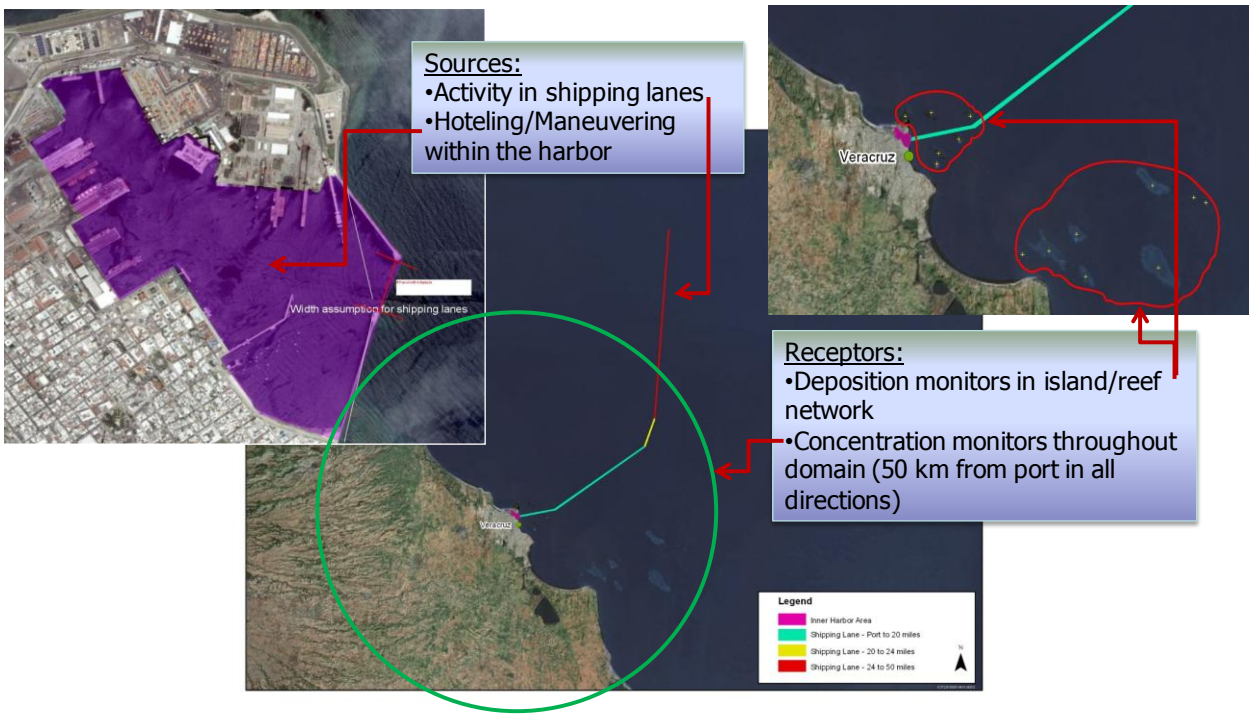
All modeling was conducted using U.S. EPA's AERMOD[14] model. This allows current state-of-the-science characterization of dispersion at a regional scale while balancing the resolution required with the amount of input data. A domain with a radius of 50 km from the Port area was characterized with the model.

Geolocation of ship activity was assigned using a GIS application. The port and ship channel were modeled as a series of area sources. This was done by mapping the four operating modes to four operating areas. Hotelling and maneuvering were assigned to the harbor area. The shipping lane out to 24 nm from the harbor area was assigned the cruise emissions. The shipping lane beyond 24 nm was assigned the fuel switch operating mode emissions, plus a portion of the HFO cruise emissions to account for the operation on that fuel.

Receptors were assigned in a radius of 50 km from the harbor area, in increments of 10 degrees angularly and from 0.5 to 2.5 km radially, with decreasing resolution further from the harbor area. Additionally, receptors were placed at the reef and island network near the harbor to characterize deposition to those areas. Figure 17 shows the modeling domain, including the various source and receptor locations.

[14] AERMOD is a next generation dispersion model designed as the successor to the prior ISCST3. It is formulated as a steady-state Gaussian plume model, but with updated PBL turbulence parameterization, and was added to Appendix W to 40 CFR Part 51 as the preferred/recommended model for most modeling applications, including single and multi source simulations of most types of emissions, including on- and off-road mobile and stationary sources in most environments, and domains up to 50 km from a source.

Figure 17: Dispersion Modeling Sources and Receptors



Local terrain effects on the dispersion calculations were also included. A commercial source[15] of data for the local topography was used and processed using the AERMAP terrain preprocessor.

All emissions were assumed to be released at 50 m above the ground with an initial vertical dimension of 23 m[16]. All receptors were taken at a breathing height of 1.8 m. The former will lead to significantly diluted concentrations at ground level as pollutants are dispersed in the air. The latter produces virtually identical concentrations to those at ground level. Effects of both dry and wet removal of pollutants was considered. Also, all sources were modeled as area sources. This method was used because the precise locations of the emission releases that occur in the harbor area could not be determined, and the shipping lanes represent a non-steady state emission source. Instead, area sources, with vertices of each source determined using the digitized "footprint" of the harbor area and emissions distributed uniformly (horizontally) throughout the areas was used. This will somewhat dilute the effects of emissions relative to treatment of them as point sources, but is required given the uncertainty in ship location.

Emissions were characterized in terms of the official standards for air quality in Mexico, "NORMA Oficial Mexicana NOM-0xx-SSA1-yyyy", where xx represents the pollutant and yyyy the year of its implementation. Each has both a chronic (i.e., long term exposure) and acute

[15] www.mapmart.com

[16] As determined in the California Air Resources Board's (ARB) "Diesel Particulate Matter Exposure Assessment Study for the Ports of Los Angeles and Long Beach", April 2006. This height was determined as, "...the average ship stack height is about 43 m tall. When the emissions are released from the top of a ship's exhaust stack, there is a plume rise that occurs which was estimated to average to be about 7 meters. This results in an average release height of 50 meters."

reference level. As for US NAAQS, the acute values are not defined in terms of peak concentrations, but relative to a certain permissible number of exceedances per year. The model was set to determine these "design values". Table 3 shows the standards for the pollutants considered here, and the definition of the design value reported by the model. As only a single year of meteorological data was available, the values represent those from this one year.

Table 3: NORMA Oficial Mexicana for Modeled Pollutants

Contaminante	Norma	Valores de Concentración Máxima				
		Exposición Aguda			Exposición Crónica	
		Concentración y tiempo promedio	*Frecuencia máxima aceptable*	*As Applied Here*	*Concentración y tiempo promedio*	*As Applied Here*
Bióxido de azufre (SO_2)	NOM-022-SSA1-1993	0.13 ppm (24 Horas)	1 vez al año	2nd Highest High 24-Hour Concentration < 130 ppb	0.03 ppm (media aritmética anual)	Annual Average Concentration < 30 ppb
Partículas fracción gruesa (PM_{10})	NOM-025-SSA1-1993	120 µg/m^3 (24 Horas)	2% de las mediciones de 24 horas al año[2]	98th Percentile of Annual 24-Hour Concentrations < 120 □g/m^3	50 µg/m^3 (media aritmética anual)	Annual Average Concentration < 50 µg/m^3
Partículas fracción fina ($PM_{2.5}$)	NOM-025-SSAI-1993	65 µg/m^3 (24 Horas)	2% de las mediciones de 24 horas al año[2]	98th Percentile of Annual 24-Hour Concentrations < 65 □g/m^3	15 µg/m^3 (media aritmética anual)	Annual Average Concentration < 15 µg/m^3

Results

Concentration of Pollutants

The emissions, meteorology, and other inputs discussed above were included in the dispersion model to predict downwind concentrations. Figure 18 shows the resulting values of $PM_{2.5}$ for the 98th percentile of all 24-hour average concentrations reported at each receptor location when operating on HFO. Figure 19 shows similar $PM_{2.5}$ values, but with all ships undergoing fuel switching.[17]

Note that the same background image is used in Figure 18 through Figure 25, with concentrations shown in color overlapping the background image. The coastline generally runs from the north-northwest to the south-southeast, facing east. The Port of Veracruz is centered in each image, with the inner harbor shown in pink.

[17] Note that although Figure 19 is labeled "MGO", it actually includes operations on both MGO within 24 nm of the port and HFO beyond 24 nm.

Figure 18: Estimated 24-hour Average Concentrations of $PM_{2.5}$ on HFO

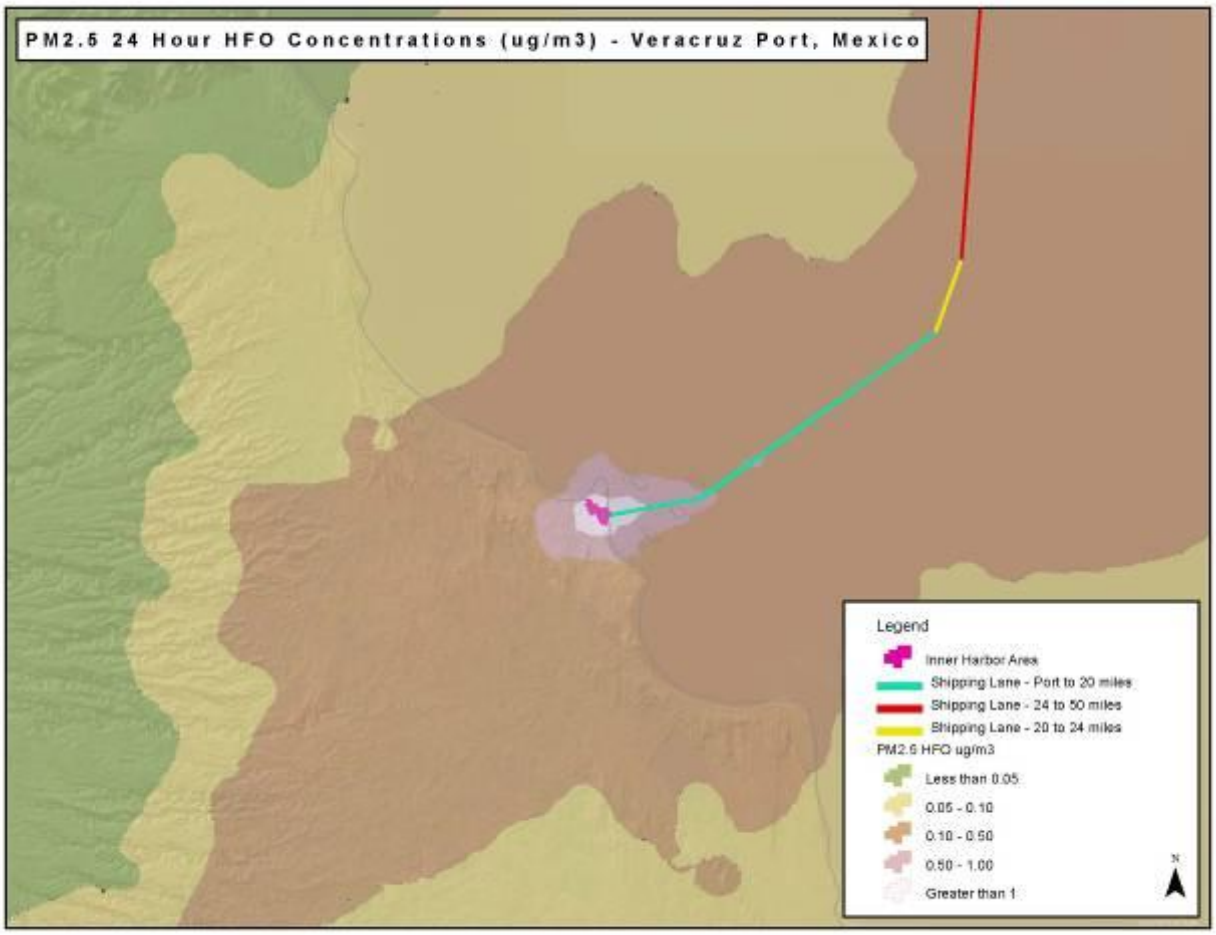
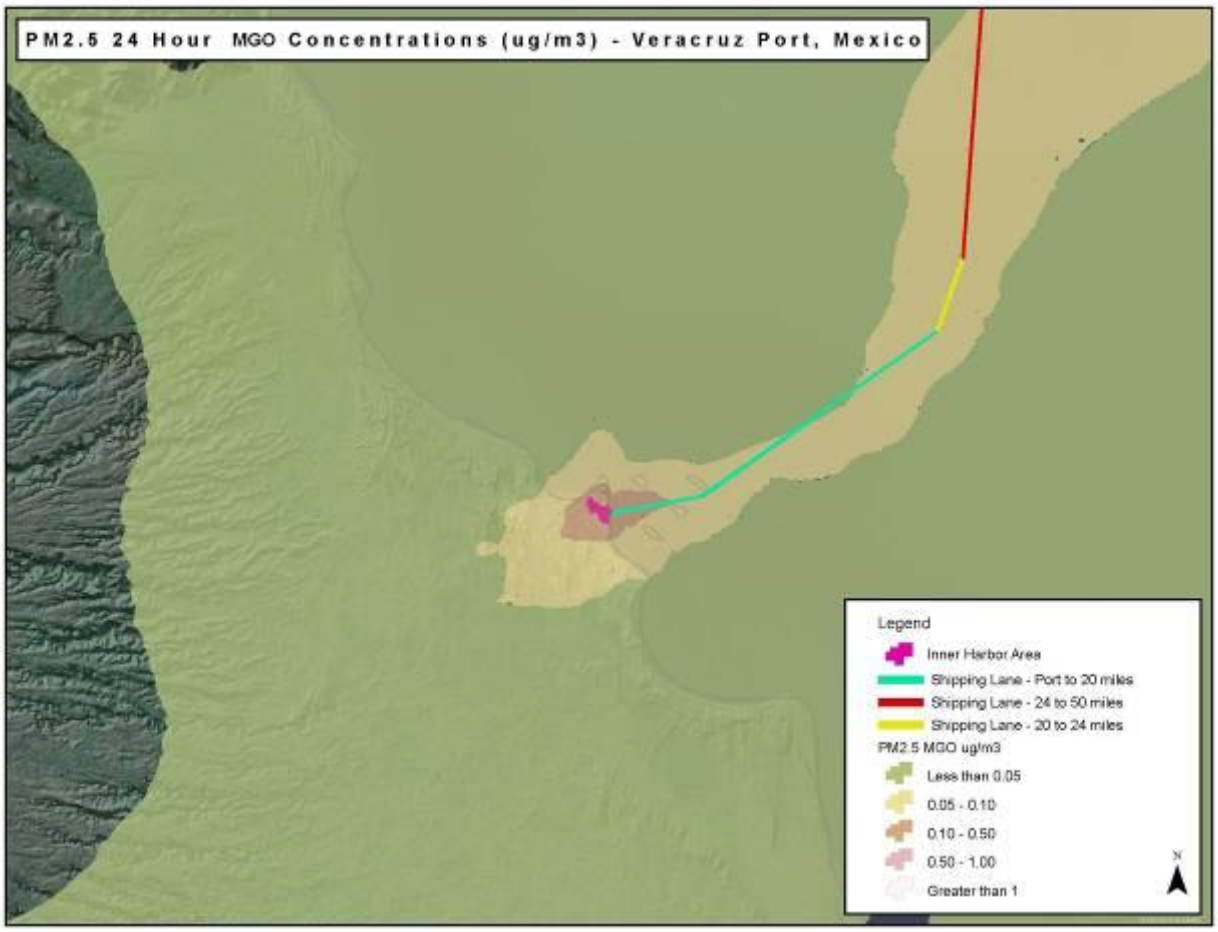


Figure 19: Estimated 24-hour Average Concentrations of $PM_{2.5}$ with Fuel Switching



Comparison of these two figures show how concentrations (at appropriate "design values" – those quantities relevant for achieving legal standards of air quality) may be reduced when moving from operations under a traditional approach (using only HFO fuel) to that of a fuel switching approach (i.e., use of 0.1% sulfur MGO within 24 nm of shore). To further quantify the potential reductions, we investigated concentrations within a circle of diameter 2 km centered on the port. This area includes a significant portion of the city of Veracruz and is predicted to experience some of the highest concentrations. The average design value for 24-hour average $PM_{2.5}$ in this area is about 1.4 $\mu g/m^3$ for the HFO case and about 0.2 $\mu g/m^3$ for the fuel switching case. This represents a seven-fold reduction in 24-hour average $PM_{2.5}$ concentrations.

Note the concentrations shown here include only emissions from ships. For comparison to air quality standards, all background concentrations, including those from all other activities at the port as well as all other regional activities, would also need to be added to these values. However, these modeling results provide a first look at the potential impact of ship emissions on coastal areas and sensitive ecosystems.

Figure 20 and Figure 21 show similar results to Figure 18 and Figure 19, but for annual average $PM_{2.5}$ concentrations.

Figure 20: Estimated Annual Average Concentrations of $PM_{2.5}$ on HFO

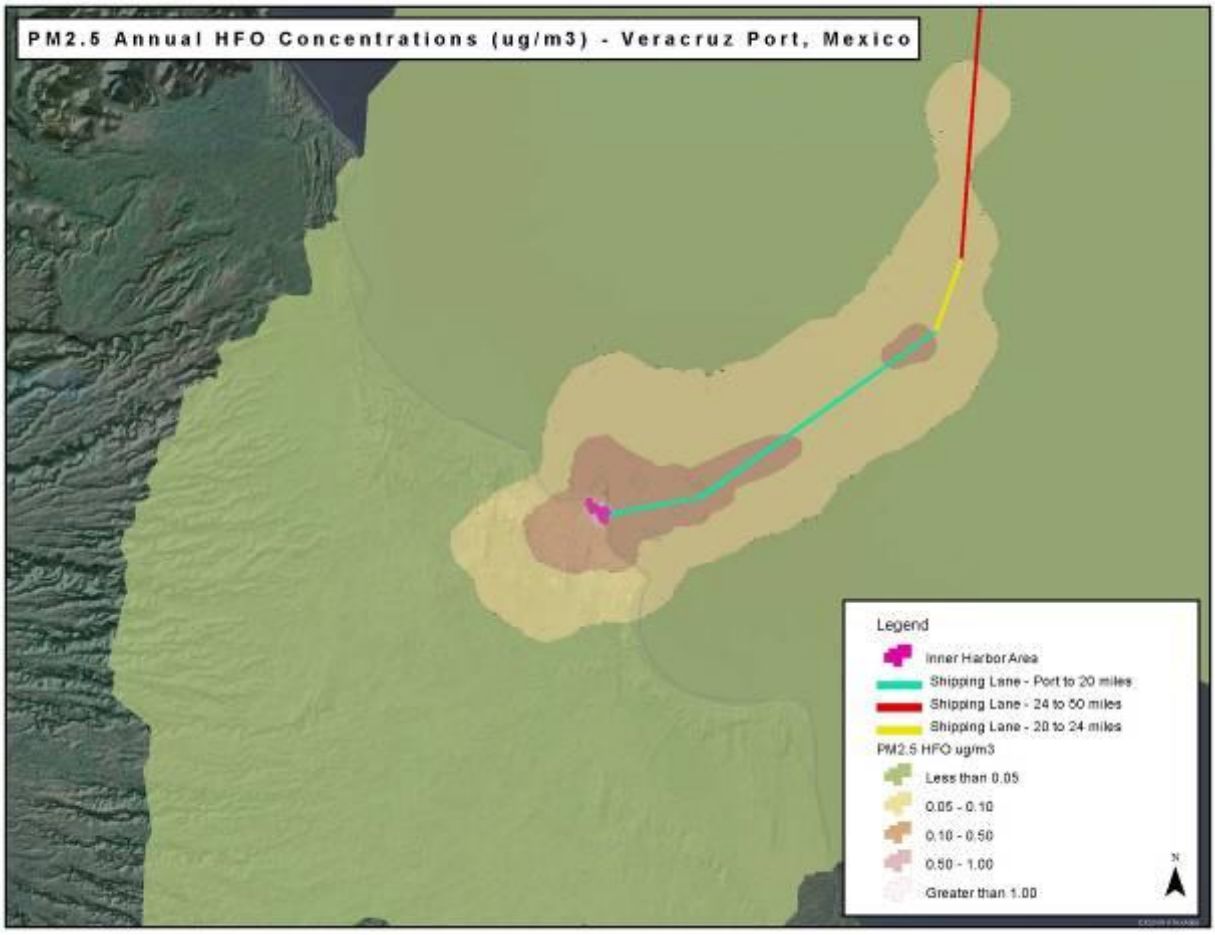
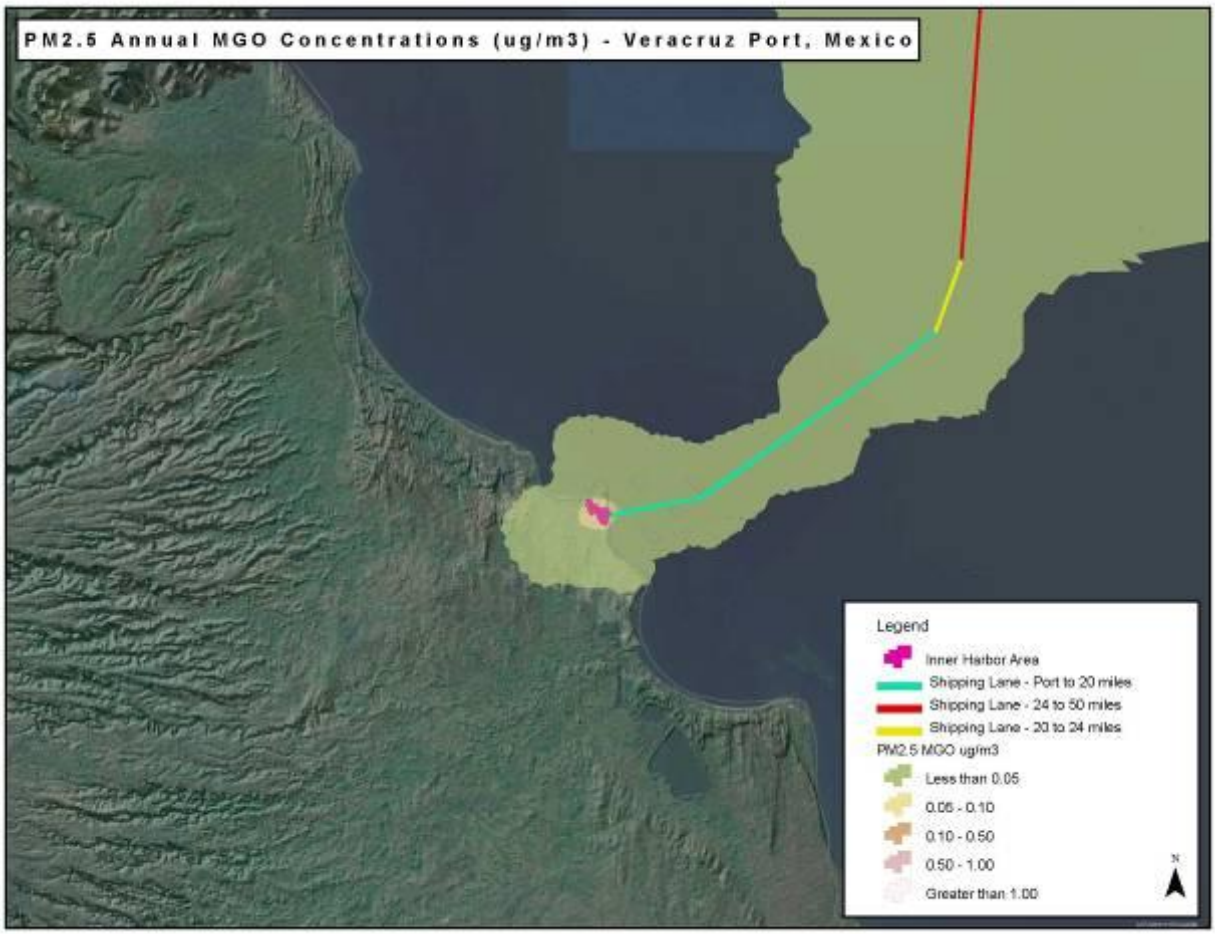


Figure 21: Estimated Annual Average Concentrations of $PM_{2.5}$ with Fuel Switching



As above, with a 2 km radius of the Port's center annual average concentrations are reduced seven-fold under the fuel switching scenario, from an average concentration of 0.47 to 0.06 $\mu g/m^3$.

Figure 22 shows the resulting values for the 24-hour average concentrations of SO_2 from ships operating solely on HFO fuels for the modeled year. As described in Table 3, these represent the 24-hour SO_2 design value, which is the 2nd highest high of the series of 24-hour average SO_2 concentrations at each receptor location. Similarly, Figure 23 shows the 24-hour concentrations of SO_2 from ships operating in a fuel switching mode.

Figure 22: Estimated 24-hour Average Concentrations of SO_2 on HFO

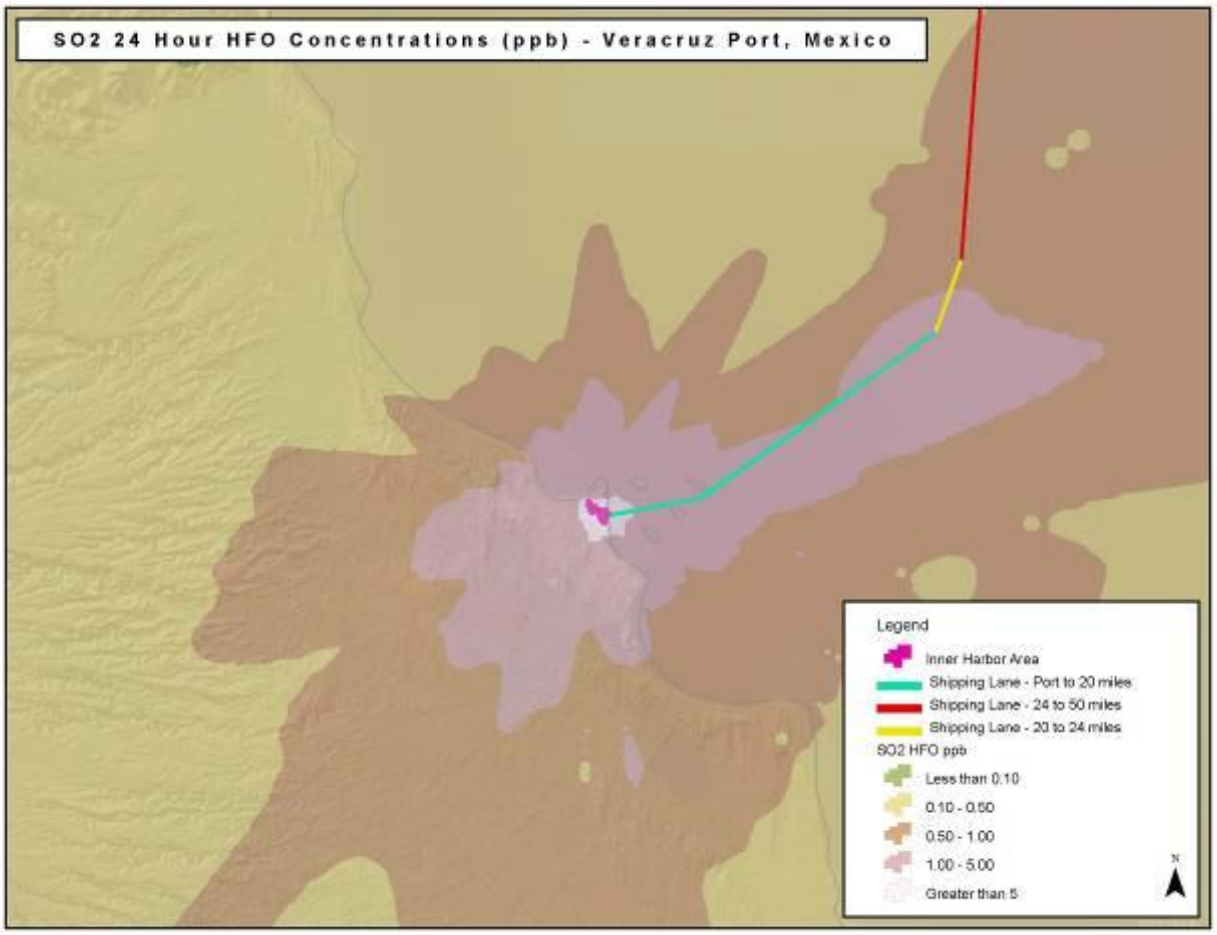


Figure 23: Estimated 24-hour Average Concentrations of SO_2 with Fuel Switching

Comparison of these two figures shows a dramatic reduction of SO_2 concentrations throughout the entire domain. Similar to the PM concentrations discussed above, average concentrations within a circle of radius 2 km centered on the Port were determined. In this circle, the average of the 24-hour SO_2 design value concentrations are reduced 24-fold under the fuel switching scenario, from an average concentration of 6.3 to 0.3 ppb.

Figure 24 shows the resulting values for the annual average concentrations of SO_2 from ships operating solely on HFO fuels for the modeled year, while Figure 25 shows the annual average concentrations of SO2 from ships operating in a fuel switching mode.

Figure 24: Estimated Annual Average Concentrations of SO_2 on HFO

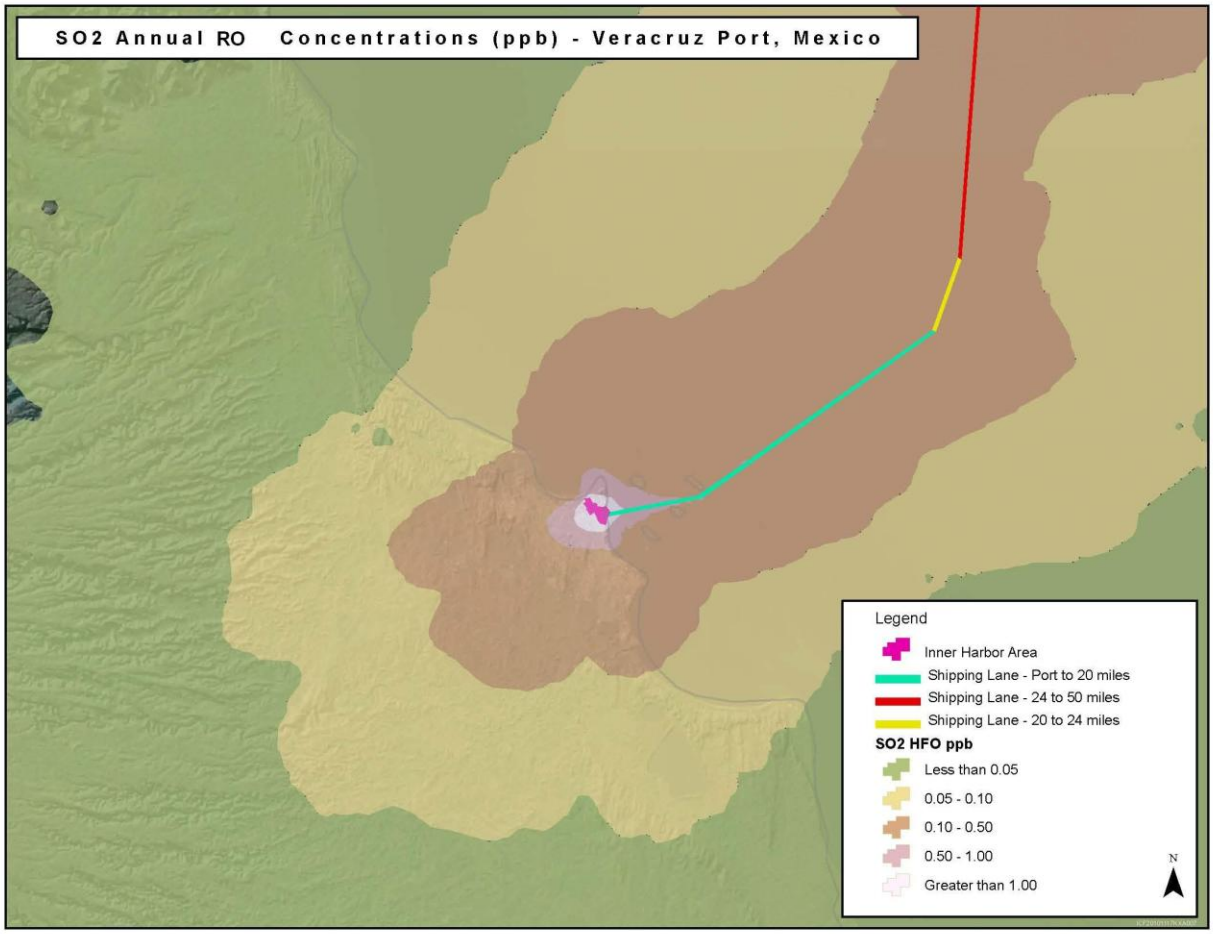


Figure 25: Estimated Annual Average Concentrations of SO_2 with Fuel Switching

As above, there are extensive pollutant reductions visible from moving to a fuel-switching regime. Within a 2 km radius of the Port's center, annual average concentrations of SO_2 are reduced 25-fold under the fuel switching scenario, from an average concentration of 1.5 to 0.06 ppb.

Deposition of Pollutants

Deposition of pollutants from ship exhaust can also impact sensitive ecosystems, including areas of natural productivity, critical habitats and areas of cultural and scientific significance. The same dispersion modeling discussed above was also used to estimate the reduction in deposition of sulfur (as SO_2) to the local waters of the Gulf of Mexico. This deposition includes both from dry and wet settling of SO_2 from ship exhaust.

Figure 17 shows a series of receptors established to characterize the impact to the island and reef network off the coast of Veracruz. The deposition at each of these receptors was calculated with the AERMOD model. The total deposition was then calculated for each of the two reef/island areas under both the HFO fuel usage case and the fuel switching case. Figure 26

shows the total deposition to each of the areas in each case under the assumption that all vessels in each inventory either switched from high- to low-sulfur fuel within 24 nm of shore or operate solely on HFO. Table 4 tabulates these values.

Figure 26: Estimated Annual Deposition of SO_2

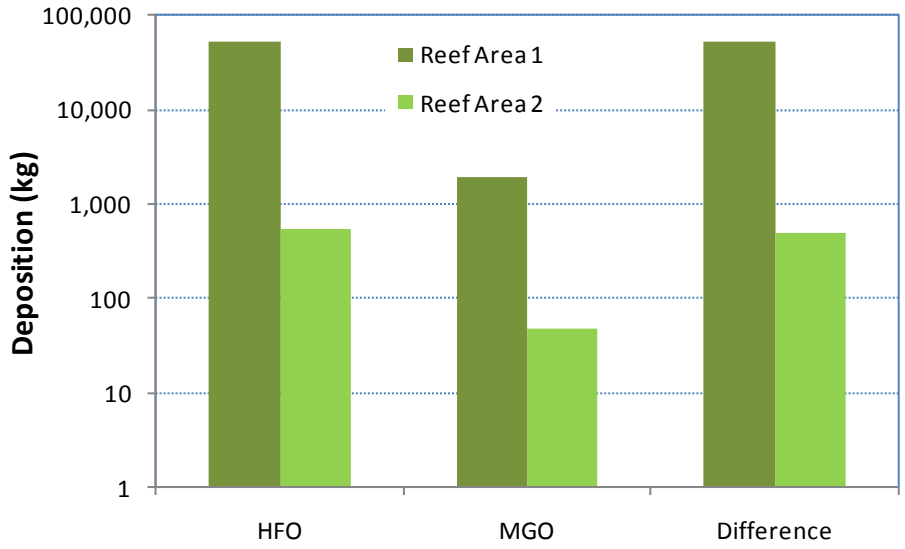


Table 4: Estimated Annual Total Deposition of SO_2[18]

Reef		Units	HFO	MGO	Difference	Percent Reduction
Reef Area 1	Area	m^2	283,474,477			
	Total Annual SO_2 Flux	g/m^2	0.19	0.01	0.18	
	Total Annual Deposition	kg	53,000	1,900	52,000	96%
Reef Area 2	Area	m^2	57,673,276			
	Total Annual SO_2 Flux	g/m^2	0.0093	0.00081	0.008	
	Total Annual Deposition	kg	540	47	490	91%
Total	**Total Annual SO_2 Deposition**	**kg**	**54,000**	**2,000**	**52,000**	**96%**

These results indicate that about 52,000 kg (or 96 percent of the baseline value) of SO_2 deposition could be avoided to the reef and island network surrounding Veracruz if all vessels calling on the Port were to move to a fuel switching regime within 24 nm of shore.

Health and Environmental Effects

In its Proposal to the IMO regarding the Designation of a North American Emission Control Area to Reduce Emissions from Ships[19], the US EPA indicated that ships "generate emissions that

[18] Values may not sum correctly due to rounding.

[19] *Proposal to Designate an Emission Control Area for Nitrogen Oxides, Sulphur Oxides and Particulate Matter*, Submitted by the United States and Canada to the International Maritime Organization (IMO) Marine Environment Protection Committee, 2 April 2009, especially *Annex 1*. Available at http://www.epa.gov/oms/oceanvessels.htm.

elevate on-land concentrations of harmful air pollutants such as $PM_{2.5}$ and ozone, as well as SO_x and NO_x. Human exposure to these pollutants results in serious health impacts such as premature mortality and aggravation of heart and lung disease."

The US EPA has indicated[20] that particle pollution generally, and fine particles ($PM_{2.5}$) particularly, consist of solids and liquids in such microscopic sizes that they are easily inhaled deeply into the lungs where they can cause serious health problems. These health problems include:

- Respiratory effects, such as irritation of the airways, coughing, or difficulty breathing
- Decreased lung function
- Aggravated asthma
- Development of chronic bronchitis
- Irregular heartbeat
- Heart attacks,
- Premature death, and
- More subtle indicators of cardiovascular disease.

People with heart or lung diseases, children and older adults are considered particularly sensitive to particulate air pollution, although all people may experience temporary symptoms from exposure to elevated levels of particle pollution.

In addition to direct human health effects, PM2.5 is responsible for other "welfare" effects, including a degraded environment. Environmental effects of $PM_{2.5}$ include:

- *Visibility reduction*: Fine particles ($PM_{2.5}$) are the major cause of reduced visibility (haze)
- *Environmental damage*. Particles can be carried long distances before settling to ground or water surfaces where they can acidify lakes and streams, alter the aquatic nutrient balance, deplete nutrients from the soil, damage forests and crops, and affect ecosystem diversity.
- *Aesthetic damage*: Particle pollution can also stain and damage stone and other materials, including culturally important objects such as statues and monuments.
- *Climate change*: Particles can influence the radiative balance and influence climate. Although, globally, particles are thought to cool the planet through both direct and indirect effects, some species, such as black (elemental) Carbon act as warming agents.[21]

In addition to the general PM health effects, EPA and other agencies have noted that exposure to particulate matter from diesel exhaust (DPM) has also been associated with additional

[20] http://www.epa.gov/air/particlepollution/health.html

[21] See, for example, http://www.ipcc.ch/ipccreports/tar/wg1/index.php?idp=160

adverse health effects. Marine diesel engines emit DPM, a complex mixture of particulate compounds that consists of fine particles (< 2.5µm), including a subgroup with a large number of ultrafine particles (< 0.1 µm) that adsorb organic compounds, are easily respirable, and consist of several organic compounds that have mutagenic and carcinogenic properties. In EPA's 2002 Diesel Health Assessment Document (Diesel HAD), inhalation of diesel exhaust was classified as a likely human carcinogen. Some studies also investigate the impact of ship emissions on climate and air quality, including through characterizing emissions of black carbon[22,23].

This study has indicated that local concentrations of $PM_{2.5}$ pollution could be reduced as much as 43 to 88 percent over the entire modeling domain by moving to a fuel-switching mode for ships calling on the Port of Veracruz.

The US EPA has indicated that there is significant scientific evidence linking short-term human exposures to concentrations of SO_2 in the air to an array of adverse respiratory effects. (Note that several of these effects are interrelated to sulfate exposure through particulate matter.) These health effects include bronchoconstriction and increased asthma symptoms, and are particularly important for asthmatics, especially during episodes of elevated breathing (such as during exercise). Short-term exposures to SO_2 are correlated to increased hospital admissions for respiratory illnesses, particularly for children, the elderly, and asthmatics.

Environmental effects of increased concentrations of SO_2 include acidification of lakes and streams through deposition, accelerated corrosion of buildings and monuments, and reduced visibility.

Note that adverse effects are also attributable to other gaseous sulfur oxides (e.g. SO_3), which are also linked to exhaust emissions. However, they tend to be at concentrations much lower than that of SO_2. Thus the primary effects can be determined by studying SO_2 concentrations alone.

Studies have shown that atmospheric inputs related to emissions from fossil fuel combustion and other sources of strong acids (such as nitric (HNO_3) and sulfuric (H_2SO_4) acids) alter surface seawater alkalinity, pH, and inorganic carbon storage which can disrupt natural biogeochemical cycles. This is expected to have the greatest impact in near-coastal waters, where the ecosystem responses to ocean acidification most affect the human population.[24]

Sulfate emission in particular, and thus Sulfuric acid deposition, may be mitigated with switching to lower sulfur fuels. This study has indicated that annual SO_2 concentrations over the entire modeling domain could be reduced 46 to 96 percent by moving to a fuel-switching mode for all

[22] E.g.: Lack et al., *Particulate emissions from commercial shipping: Chemical, physical and optical properties,* J. Geophys. Res., vol 114, 2009.

[23] E.g.: Lauer et al., *Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget,* Atmos. Chem. Phys., vol. 7, 2007, p5061-5079.

[24] E.g.: Doney et al., *Impact of Anthropogenic Atmospheric Nitrogen and Sulfur Deposition on Ocean Acidification and the Inorganic Carbon System*, Proc. Nat. Acad. Sci., September 11, 2007, vol. 104, no. 37, p14580–14585.

vessels calling on the Port of Veracruz. Similarly, deposition of SO_2 to sensitive reefs and islands off the coast could be reduced 96 percent, or by about 52,000 kg annually.

In its IMO application, the US and Canadian Governments concluded that emissions from ships contribute to a large number of adverse human health impacts and that designation of the proposed ECA would reduce the risk of premature mortality and contribute to the avoidance of many morbidity-related health impacts. While acknowledging that this study has not quantified the effects of fuel switching on overall concentrations of air pollutants, as noted on Page 23, the reductions of PM and SOx concentrations associated with fuel switching imply that similar results could be achieved in Mexico through reduced use of HFO fuel in shipping.

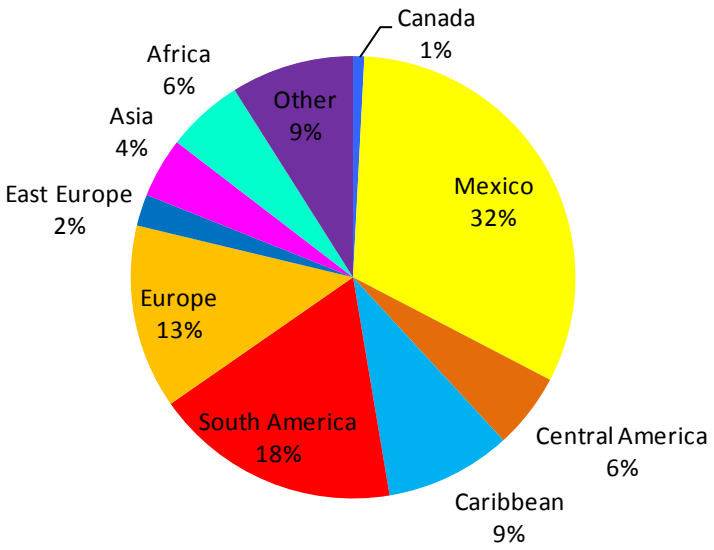
4. Fuel Switching Demonstrations

EPA partnered with two maritime shipping companies (Maersk Line and Hamburg Süd) to demonstrate fuel switching on two container ships which regularly travel between the Port of Houston and Mexico. The first fuel switch demonstration was conducted on the Maersk Roubaix in November 2009. The second fuel switching demonstration was conducted on the Hamburg Süd Cap San Lorenzo in April 2010 and a third was conducted on this ship at the Port of Santos in August 2010. EPA did not estimate or measure emissions reductions at the Port of Santos for this report.

4.1. Demonstration Design

The first component of the demonstration design was the identification of the vessel type to include in the study. EPA identified vessels most representative of the shipping fleet calling on the Port of Houston and Mexican Gulf ports and thus potentially contributing the most to ship emission affecting those areas. As can be seen from Figure 7, the most common ship types which call at Port of Houston were tankers followed by container ships. As shown in Figure 27, 32 percent of the ships that stopped at Port of Houston travelled to Mexico.

Figure 27: Ship Destinations from Port of Houston



Of the ships that went to Mexico from Port of Houston, 43 percent went to Alta Mira and 18 percent went to Veracruz as show in Figure 28. Typically container ships travel to Alta Mira and Veracruz while tankers tend to go to Cayo Arcas, which is an oil terminal in the Gulf over 90 miles from shore. As the project goal was to demonstrate the impact of ship emissions reductions near land, EPA chose to test fuel switching on container ships which typically go into ports on the coast and thus – all other things being equal – would tend to have greater impacts on coastal and inland air quality.

The general fuel switching demonstration design included switching from HFO to MGO before reaching 24 nautical miles from the coast line and traveling into and out of the port, operating at least the main and auxiliary engines on MGO as shown in Figure 29.

Figure 28: Mexican Port Destinations from Port of Houston

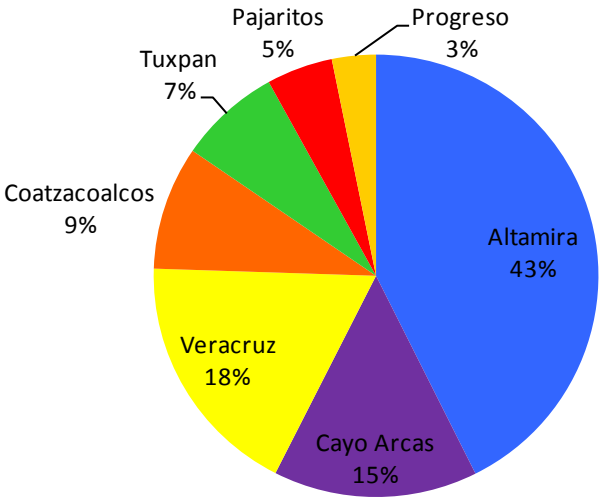
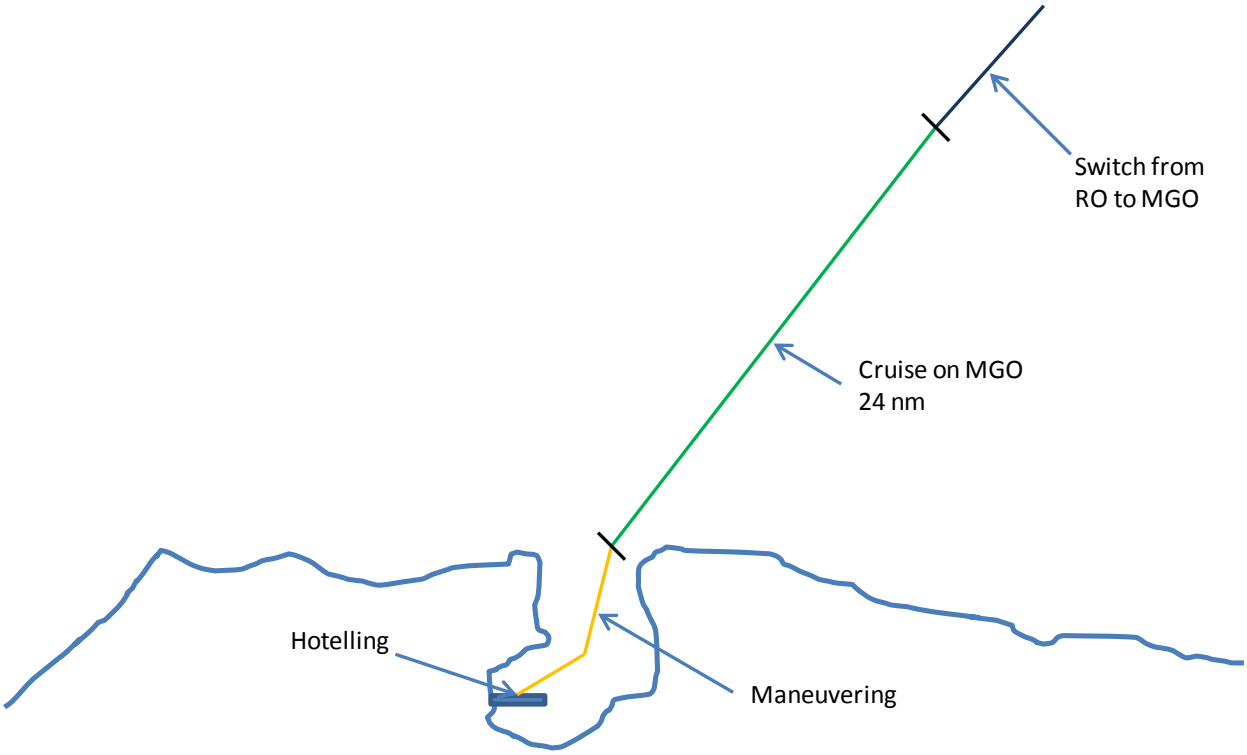


Figure 29: Schematic of Fuel Switching Demonstration Design



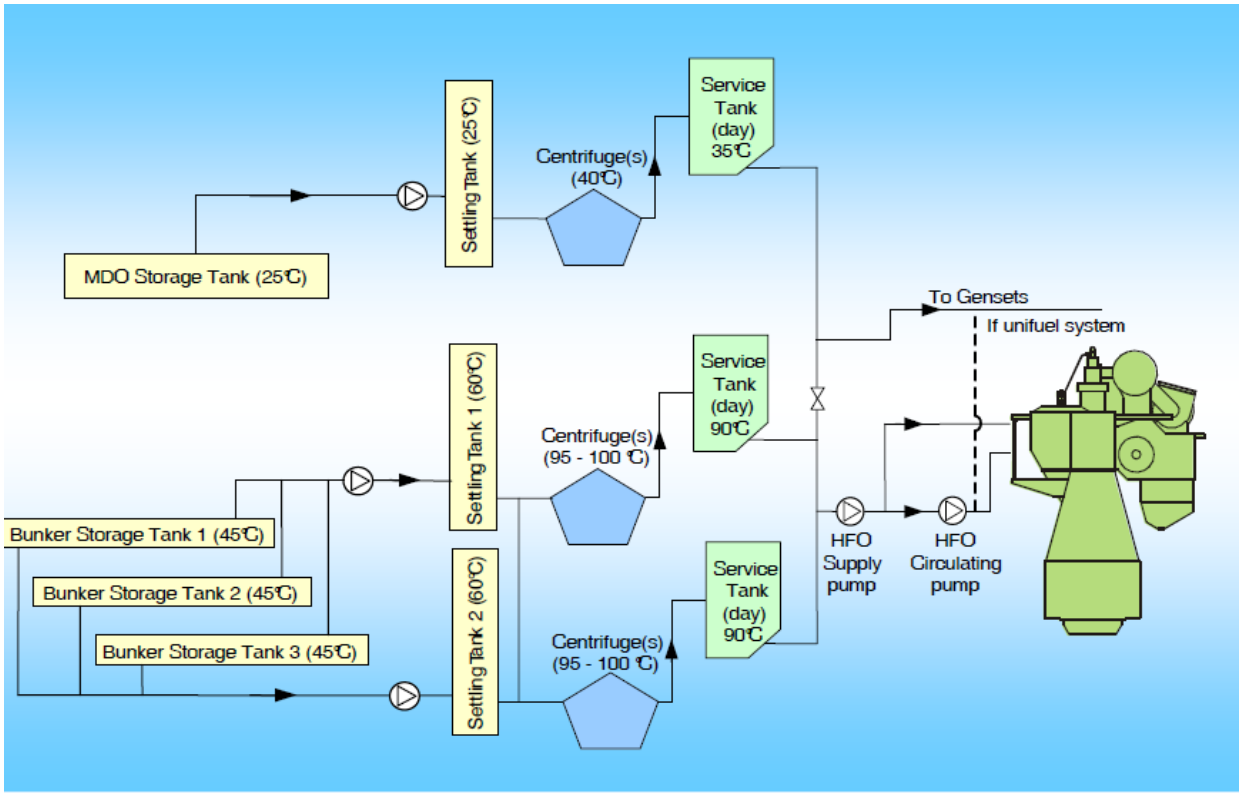
4.2. Fuel Switching Logistics

Ship Operation on HFO

Since HFO may contain contaminants and other components that would reduce the reliability of the fuel injectors, these materials must be separated or removed from the fuel oil prior to use. Additionally there is a viscosity specification for the fuel oil to ensure proper operation of the fuel pumps. Equipment is on a vessel to clean the fuel oil and maintain the proper viscosity. Although, generally heavier fuels require more complex fuel treatment systems, all systems prevent heavy fuel oils from solidifying in the fuel system, improve operational efficiency, and maintain the fuel circulation, injection, and combustion systems. These systems consist of storage and settling tanks, filters, and purifiers.

As shown in Figure 30, fuel is transported from storage tanks to the settling tank by transfer pumps. Settling tanks hold enough fuel for approximately 2 days of travel and have coils to heat the fuel. If heating is not maintained, the fuel will become too viscous to pump. In the settling tanks, heavy fuel solids settle to the bottom while fuel to be burned is drawn from the top of the tank. Fuel is then pumped from the settling tank through a pre-heater and into one or more centrifugal separators by feed pumps. This fuel is then pumped to the service (day) tank, where approximately one day's reserve of pre-treated and cleaned fuel is maintained at an appropriate temperature to maintain fuel viscosity for use in the engine. The engine fuel supply system then draws fuel beyond that necessary for combustion from the day tank to the injection system and circulates the additional fuel back to the day tank to prevent solidification throughout the supply system. Sets of supply and circulating pumps pressurize the system and transfer fuel from the day tank, the final engine fuel filter, and injectors while a pre-heater and viscosity meter maintain fuel viscosity throughout the fuel system.

Figure 30: Vessel Fuel System

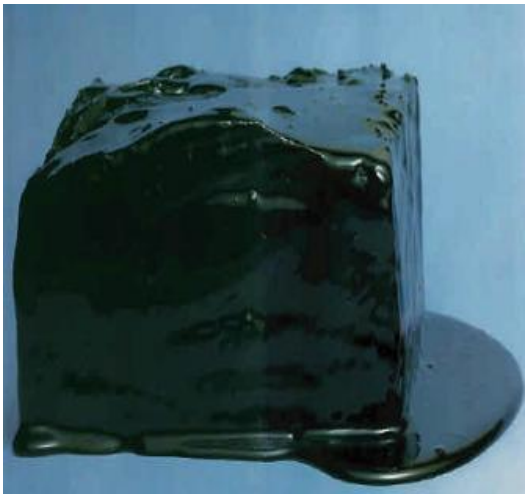


Source: MAN B&W Diesel[25]

Most ships carry both residual and distillate fuels on board. Older ships would use distillate fuels in their auxiliary engines while operating the main engine on HFO. Newer ships operate both main and auxiliary engines on HFO but keep a supply of distillate fuel for fuel line cleaning and startup. Because of the viscous nature of residual fuels (see Figure 31), they need to be heated to a minimum of 95°C to be liquid enough to pump and be injected into the engine cylinder. Distillate fuels are significantly less viscous and can be pumped and injected at around 40°C. Thus when fuel switching from HFO to MGO, the fuel temperature must be reduced from a minimum of 95°C to 40°C to make sure the fuel's viscosity does not get too low for the fuel pumps.

[25] MAN B&W, Operation on Low-Sulphur Fuels Two-Stroke Engines, available at: http://www.manbw.com/article_005271.html

Figure 31: Residual Fuel Unheated



Switching from HFO to MGO

When switching from HFO to MGO, the fuel temperature must be lowered slowly (~2°C per minute) to prevent thermal shock to the fuel system. In addition, due to the solvent nature of MGO, initial use of the fuel will tend to pick up solids and cat fines (catalyst material left in residual fuel from the refinery process) which may plug fuel filters. Once the fuel system is flushed, however, this should not be a problem. Also systems used to operating on HFO may tend to leak initially when switching to MGO. This can usually also be remedied quickly.

Although all the above mentioned concerns are legitimate, it should be noted that Maersk[26] illustrated that all its vessels switch both main and auxiliary engines to MDO with less than 0.2 percent sulfur within 24 nautical miles of their California destination port for main engines and within 24 nautical miles of the California border for auxiliary engines. They have noted no problems from this program to date after over 1700 port calls.

The Maersk study included 111 vessels and over 1000 fuel switches consuming 29.4 MT of MDO per switch from April 2006 to January 2009. The resulting total emissions reduction has been calculated at almost 900 tons per year, including a 95 percent SOx, 86 percent PM, and 12 percent NOx reduction (which includes low-NOx auxiliary mode). These reductions are greater than anticipated by the program. In the Maersk study, all vessels used separate service tanks for high- and low-sulfur fuels (DMA and DMB, with DMX for lifeboat engines and emergency generator use) to minimize compatibility issues. Also, as all fuel switching in this program is considered short term, they made no cylinder lube oil BN[27] change. Maersk noted that fuel switching is considered "normal engineering practice" and provides no special training for its crews.

[26] *Maersk Line's Fuel Switch Experiences in California Waters*, presentation by A.P. Moller-Maersk Group, Regulatory Affairs, Maersk Marine Technology, April 27, 2010.

[27] Base Number (BN or TBN) is a measure of the cylinder lube oil's ability to neutralize acid.

4.3. Maersk Roubaix Demonstration

The Maersk Roubaix (IMO 9332688) is a 1,118 TEU[28] container ship and is pictured in Figure 32. It was built in 2006. Specific ship details are provided in Table 5. Its regular route during the demonstration is shown in Table 6. For this project, the Maersk Roubaix switched fuels at two ports on this route – the Ports of Houston and Progreso.

Figure 32: Maersk Roubaix

Table 5: Maersk Roubaix Specifications

Ship Specifications
Container Ship – 1,118 TEUs
Main Engine – MAN 7L58/64 – 9730 kW MSD
Auxiliary Engines – 3 x MAN 6L16/24 connected to 570 kW 440/220 V generators 1 x 1400 kW 440/220V shaft generator
Service Speed – 19.6 knots Maximum Speed – 21.0 knots
Controllable pitch (CP) propeller
Fuel Capacity – 180 tonnes MGO – 1000 tonnes HFO

[28] A TEU is a twenty foot equivalent unit used to measure container capacity. Standard containers like those shown in Figure 32 are typically 2 TEUs.

Table 6: Estimated Schedule for Maersk Roubaix

Port Name	Country	Arrival Date	Departure Date
Houston	USA	11/9/2009 7:00	11/9/2009 23:00
New Orleans	USA	11/11/2009 13:00	11/12/2009 0:01
Mobile	USA	11/13/2009 8:00	11/13/2009 14:00
Progreso	Mexico	11/15/2009 23:00	11/16/2009 14:00
Santo Tomas De Castilla	Guatemala	11/18/2009 6:00	11/18/2009 15:00
Belize	Belize	11/19/2009 5:00	11/19/2009 18:30
Puerto Cortes	Honduras	11/20/2009 6:00	11/20/2009 19:30
Manzanillo	Panama	11/23/2009 6:00	11/23/2009 21:00
Cartagena	Columbia	11/26/2009 2:00	11/26/2009 16:30
Barranquilla	Columbia	11/27/2009 1:00	11/27/2009 21:00
Manzanillo	Panama	11/28/2009 18:00	11/29/2009 6:30
Puerto Limon	Costa Rica	11/29/2009 20:30	11/30/2009 11:00
Puerto Cortes	Honduras	12/2/2009 7:00	12/2/2009 22:00
Santo Tomas De Castilla	Guatemala	12/3/2009 6:00	12/3/2009 14:30
Houston	USA	12/7/2009 7:00	12/7/2009 23:00

The Maersk Roubaix switched fuels from HFO to MGO before 24 nm from the entrance to the Houston Ship Channel. The HFO had a sulfur content of 3.37% while the MGO had a sulfur content of 0.14%[29]. The ship entered the Houston Ship Channel and docked at Barbour's Cut on November 10, 2009. It left Barbour's Cut and the Houston Ship Channel on November 11, 2009. The ship then switched fuels back to HFO upon leaving the 24 nm boundary. On November 16th, the Roubaix travelled to Progreso, Mexico, switching fuel back to MGO before 24 nm from the Port of Progreso. It left the same day and switched back to HFO once outside the 24 nm boundary. The main and auxiliary engines and boilers were all operating on MGO when the ship was within the 24 nm boundary at the Ports of Houston and Progreso.

No emission measurements were made, but emission reductions were calculated as discussed in Appendix A. Total emission reductions due to fuel switching at the Port of Houston are shown in Figure 33. Emission reductions due to fuel switching at the Port of Progreso are shown in Figure 34. Emissions reduced at the two ports are 0.12 metric tonnes of NOx (6%), 0.24 metric tonnes of $PM_{2.5}$ (87%) and 2.05 metric tonnes of SOx (94%) with a differential fuel cost of $6,456, which represents only 2% of the total fuel costs for a round trip voyage shown in Table 6.

Fuel Price

Fuel prices were estimated at $460/metric tonne for HFO and $740/metric tonne for MGO base upon Bunkerworld.com prices for Houston on September 15, 2010.

[29] Per documentation submitted to EPA by Maersk.

Figure 33: Estimated Emissions for Fuel Switch at Port of Houston

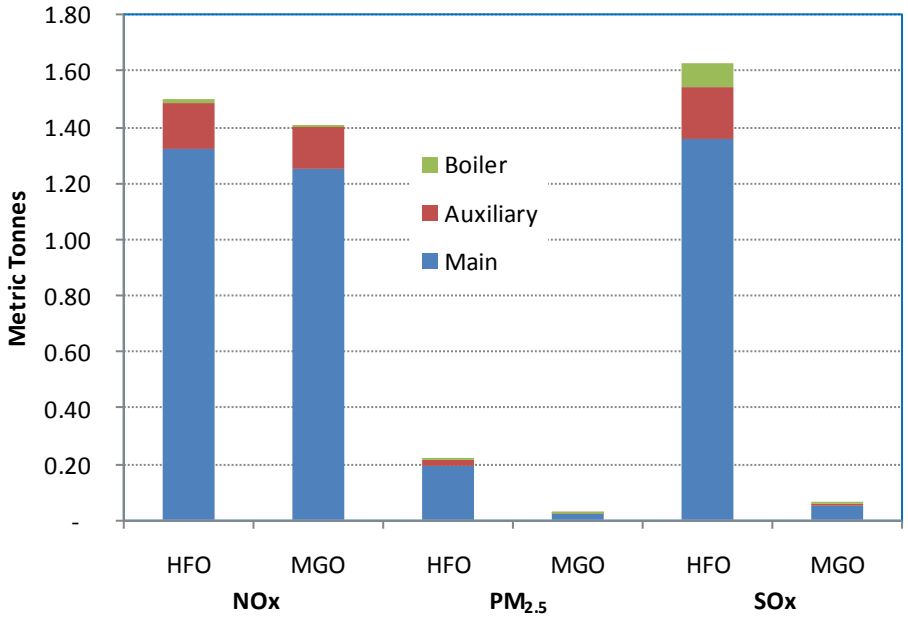
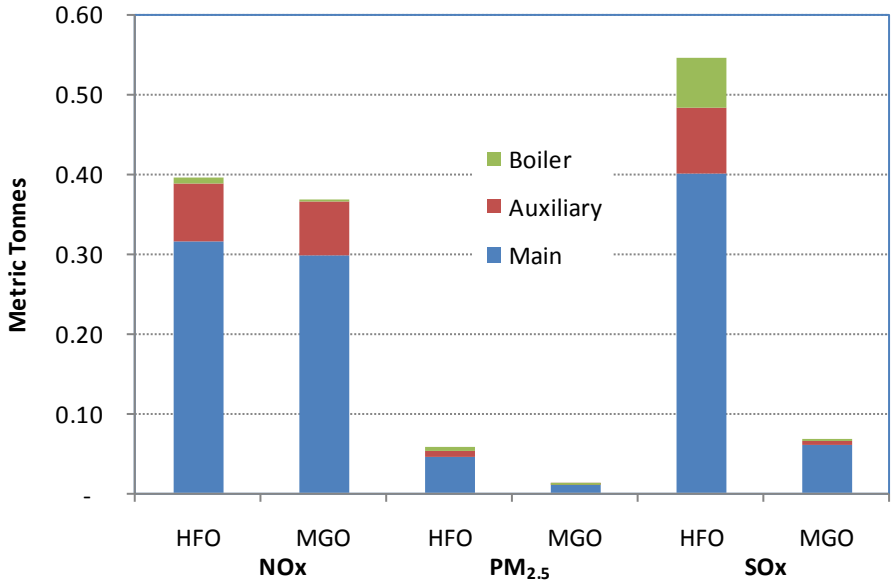


Figure 34: Estimated Emissions for Fuel Switch at Port of Progreso



Operational Issues

Maersk indicated no operational issues when switching from one fuel to the other.

4.4. Hamburg Süd Demonstration

The Cap San Lorenzo (IMO 9215684) is a 3,739 TEU container ship and is pictured in Figure 35. It was built in 2001. Specific ship details are provided in Table 7. Its schedule during the demonstration period is shown in Table 8. Fuel switches were conducted while at the Ports of Veracruz, Alta Mira and Houston from April 14-16, 2010. The fuel switch at the Port of Santos in Brazil occurred during a port call in late August 2010.

Figure 35: Hamburg Süd Cap San Lorenzo

Table 7: Cap San Lorenzo Specifications

Ship Specifications
Container Ship – 3,739 TEUs
Main Engine – Sulzer 7RTA84 – 28,760 kW SSD
Auxiliary Engines – 4 x MAN 9L28/32 connected to 1890 kW 440/220 V generators
Service Speed – 22.5 knots Maximum Speed – 23.9 knots
Fixed pitch (FP) propeller
Fuel Capacity – 349 tonnes MGO – 6,062 tonnes HFO

Table 8: Estimated Cap San Lorenzo Schedule

Port	Country	Arrive	Depart
Veracruz	Mexico	4/16/2010 0:00	4/16/2010 12:00
Altamira	Mexico	4/17/2010 5:00	4/17/2010 23:00
Houston	USA	4/19/2010 6:00	4/20/2010 18:00
Cartagena	Columbia	4/24/2010 22:00	4/26/2010 22:00
Suape	Brazil	5/4/2010 0:00	5/4/2010 12:00
Santos	Brazil	5/7/2010 7:00	5/7/2010 22:00
Rio Grande	Brazil	5/9/2010 19:00	5/10/2010 9:00
Navegantes	Brazil	5/11/2010 15:00	5/12/2010 7:00
Paranagua	Brazil	5/11/2010 17:00	5/13/2010 7:00
Santos	Brazil	5/13/2010 20:00	5/14/2010 20:00
Rio de Janeiro	Brazil	5/15/2010 10:00	5/15/2010 22:00
Salvador	Brazil	5/17/2010 17:00	5/18/2010 5:00
Puerto Cabello	Venezuela	5/24/2010 5:00	5/28/2010 15:00
Cartagena	Columbia	5/30/2010 1:00	5/31/2010 13:00
Veracruz	Mexico	6/4/2010 0:00	6/4/2010 12:00

The Cap San Lorenzo switched fuels from HFO to MGO upon entering the Port of Veracruz. The HFO had a sulfur content of 3.79% while the MGO had a sulfur content of 0.01%[30]. The ship left Veracruz on April 17, 2010. It then entered and left the Port of Alta Mira on April 18, 2010. It entered the Houston Ship Channel and docked at Barbour's Cut on April 20, 2010. The Cap San Lorenzo also demonstrated fuel switching while calling at the Port of Santos, Brazil from August 27 to 29, 2010.

Emission Sampling Methodology

During the Cap San Lorenzo voyage from Veracruz to Houston, stack emissions were measured from both the main and auxiliary engines while operating on MGO and HFO at several engine loads and speeds. In addition, emissions were measured while the vessel switched fuels. The methods for sampling and analysis of the gases and particulate matter (PM) conformed to the requirements of ISO 8178-1.[31]

Testing Fuels

Testing was performed on both the residual and distillate marine fuels. The heavy fuel oil (HFO) met ISO 8217:2005 specifications[32] and this is the fuel that the engine typically operates on the

[30] Per documentation submitted to EPA by Hamburg Süd – see Appendix C for Fuel Certificates of Analysis.

[31] International Standards Organization. IS0 8178-1, Reciprocating internal combustion engines: Exhaust emission measurement. Part 1: Test-bed measurement of gaseous particulate exhaust emissions, First edition 1996-08-l5

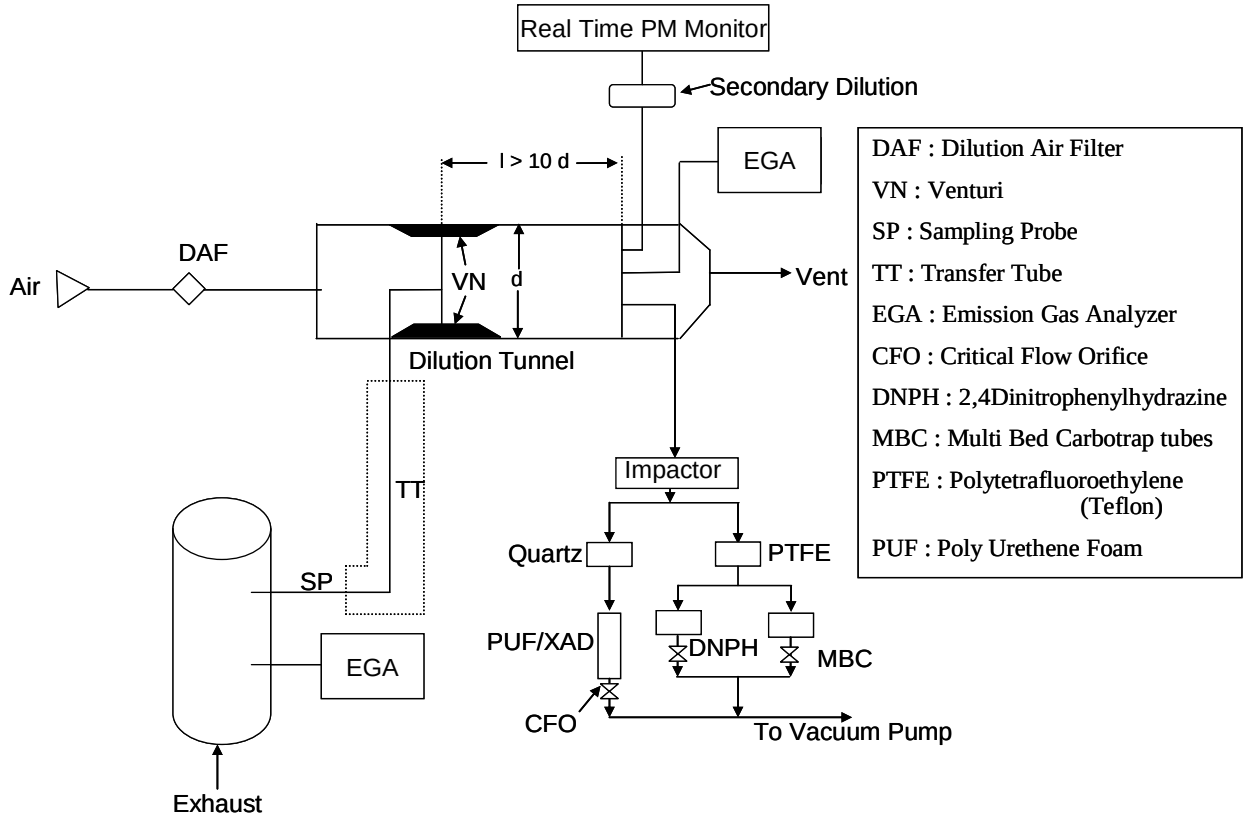
[32] International Standards Organization. ISO 8217. *Petroleum products: Fuels (class F), Specifications of marine fuels.* ISO 8217: 2005(E), 2005

open seas. The Certificate of Analysis (CoA) for the HFO and distillate fuels was obtained and a one-liter sample was drawn from the main engine and auxiliary engine final filter drains, immediately upstream of the injector rail, for subsequent analysis. Appendix C shows these fuel documents.

Engine Testing

Engine sampling involved the use of a partial flow dilution system with single venturi (see Figure 36). The concentrations of CO_2 or NOx were measured in the raw exhaust gas and diluted gas streams using an exhaust gas analyzer. The dilution ratio was determined from both the CO_2 and NOx raw and dilute concentrations, and the dilution ratios agreed within 5%, as specified in the reference method.[31] PM was measured both continuously using a Nephelometer (TSI DustTrak 8520) and during specified speed and load points with discrete filter samples. Filter samples were later analyzed for elemental carbon (EC) and organic carbon (OC).[33] SO_2 is calculated from fuel measurements. Figure 37 shows the engine room sampling system. Additional details are below.

Figure 36: Schematic of the Emission Sampling System



[33] EC (elemental carbon) represents dry particulates. When measuring ship emissions, OC is typically made up of unburned fuel or oil that surrounds the EC. (BC – black carbon – is measured by a specific absorption method and is typically used synonymously with EC.)

Figure 37: Emission Sampling of Main Engine Exhaust

Operating Conditions of the Auxiliary Engine While Measuring Emissions

Auxiliary engine testing was done at port with the engine operating according to the 5-modes of the ISO-8178 D2 cycle. Since the operating system of the vessel only allows operation up to 75% before a second generator set will turn on, the resulting emissions factors are weighted for each mode achieved. Setting up the lab and measuring the modal emissions at 3 modes in triplicate for 2 fuels was done within a 12 hour period.

Operating Conditions of the Main Engine While Measuring Emissions

Since the testing was carried out at sea, it was difficult to match "in-use" engine operating conditions with the operating conditions specified for the four modes in the ISO 8178 E-3 (Table 9) marine certification test. For example, the vessel was not operated at 100% power and data for that point were instead collected for a limited time at 85% power. All other test modes were incorporated into the vessel operation schedule.

Table 9: Engine Operating Conditions for the ISO 8178 E-3 Cycle

	Rated speed	Intermediate speed		
Speed, %	100	91	80	63
Power, %	100	75	50	25
Weighting factor	0.2	0.5	0.15	0.15

Due to constraints such as voyage time, sea current, wave pattern, wind speed/direction, and cargo load, the ISO 8178 E-3 load points were approximated as shown in Table 10.

Table 10: Operating Engine Load

HFO		MGO	
Engine RPM	Load (%)	Engine RPM	Load (%)
27	1.4	27	1.5
52	11.7	52	11.8
66	23.7	66	23.7
92	59.3	92	62.0

This project has a focus on the emissions benefits of switching to a cleaner burning fuel when entering a port. Thus the project was designed to measure emission benefits at operating modes used in approaching or departing a harbor, not necessarily only at the ISO load points. The four operating modes sampled included measurement of both HFO and distillate fuel at:

1) Cruise mode measurements during the 24 nautical miles prior to the entrance of the Houston Ship Channel
2) Operation within any reduced speed zones and within the Houston Ship Channel
3) Maneuvering operations from the port entrance to the dock
4) Operations at dock at the Port of Houston

Engine Performance Measurements during Testing

On-board engine performance testing was done in accordance with Chapter 6 of the NTC.[34] This included measurements of the variables listed in Table 11 as well as other engine settings necessary to define engine-operating conditions, such as waste-gate, charge air bypass, and turbocharger status.

[34]International Maritime Organization, Marine Environment Protection Committee: Prevention Of Air Pollution From Ships; Report of the Working Group on Annex VI and the NOx Technical Code (MEPC 57/Wp.7/Add.2 3) April 2008.

Table 11: Engine Parameters Measured during Testing

Symbol	Parameter	Dimension
n_d	Engine speed	min^{-1}
p_C	Charge air pressure at receiver	kPa
P	Brake power (as specified below)	kW
P_{aux}	Auxiliary power (if relevant)	kW
T_{sc}	Charge air temperature at receiver (if applicable)	K
T_{caclin}	Charge air cooler coolant inlet temperature (if applicable)	K
$T_{caclout}$	Charge air cooler coolant outlet temperature (if applicable)	K
T_{Sea}	Seawater temperature (if applicable)	K
q_{mf}	Fuel oil flow (as specified below)	kg/h

Gaseous emissions following the Simplified Measurement Method (SMM)

Onboard measurements followed the general requirements of Chapter 5 of the NTC in order to perform tests safely and with minimal interference to the engine. This includes arrangements for the sampling of the exhaust gas and transfer of the sample through properly heated lines to the analyzers. The concentrations of gases in the raw exhaust and the dilution tunnel were measured with a Horiba PG-250 portable multi-gas analyzer, which can continuously and simultaneously measure up to five separate gas components. Table 12 details the gases and ranges sampled with the Horiba instrument. Additionally, a JUM THC Analyzer HFID 3-200 was used to measure total hydrocarbons. Both instruments meet all the specifications of the NTC. For quality control, Appendix 4 *Calibration of the Analytical and Measurement Instruments* of the NTC was followed and analyzer checks were carried out periodically with calibration gases.

Table 12: Detector Method and Concentration Ranges for Gaseous Monitoring

Component	Detector	Ranges
Nitrogen Oxides (NO_x)	Heated Chemiluminescence Detector (HCLD)	0-25, 50, 100, 250, 500, 1000, & 2500 ppmv
Carbon Monoxide (CO)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, 2000, & 5000 ppmv
Carbon Dioxide (CO_2)	Non dispersive Infrared Absorption (NDIR)	0-5, 10, & 20 vol%
Sulfur Dioxide (SO_2)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, & 3000 ppmv
Oxygen	Zirconium oxide sensor	0-10, & 25 vol%
Total Hydrocarbons	Heated Flame Ionization Detector (HFID)	0-10; 100; 1,000; 10,000 ppm

Gaseous Measurements using a Portable Emission Measurement Systems (PEMS)

In addition to SMM sampling, gaseous emission concentrations were also monitored with a Portable Emission Measurement System (PEMS). This system was set up in compliance with 40 CFR Part 1065 and sampled raw gases from the same location in the exhaust conduit as used for the SMM using a transfer line meeting the NTC.

Particulate Matter (PM) Mass Emissions Measurements

A raw particulate sampling probe was fitted close to and upstream of the raw gaseous sample probe in the exhaust. In order to measure PM, a sampling probe was inserted into the end of the dilution tunnel (>10 diameters downstream) and directed to a PM sample splitter that allowed up to three samples to be collected. A cyclone separator, sized to remove particles >2.5um was fit into the stream. From the separator, two lines were added with 47 Gelman filter holders, one for collecting PM on a Teflon filter and the other for collecting PM on a quartz filter. Thus the flow in the dilution tunnel was split into two fractions, a smaller flow for measuring PM mass and PM properties and a much larger flow that was vented outside the vessel. With the partial dilution approach for measuring gases and PM, it is critical for the dilution ratio be determined accurately.

Simultaneous Teflon and quartz filters were collect at each operating mode and analyzed according to standard procedures. The simultaneous collection of quartz and Teflon filters allows an internal quality check of the PM mass. Teflon filters used to acquire PM mass are weighted following the procedure of the Code of Federal Regulations (CFR) (40 CFR Part 86). Total PM was collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflo filters and weighed using a Cahn (Madison, WI) C-35 microbalance. Before and after collection, the filters were conditioned for 24 hours in an environmentally controlled room (RH = 40%, T = 25 °C) and weighed daily until two consecutive weight measurements were within 3 µg. PM samples were also collected in parallel on 2500 QAT-UP Tissuquartz Pall (Ann Arbor, MI) 47 mm filters that are preconditioned at 600°C for 5 h. A 1.5 cm^2 punch is cut out from the quartz filter and analyzed with a Sunset Laboratory (Forest Grove, OR) Thermal/Optical Carbon Aerosol Analyzer according to the NIOSH 5040 reference method (NIOSH 1996). All PM filters were sealed in containers immediately after sampling, and kept chilled until analyzed.

Measuring the Real-Time Particulate Matter (PM) Emissions

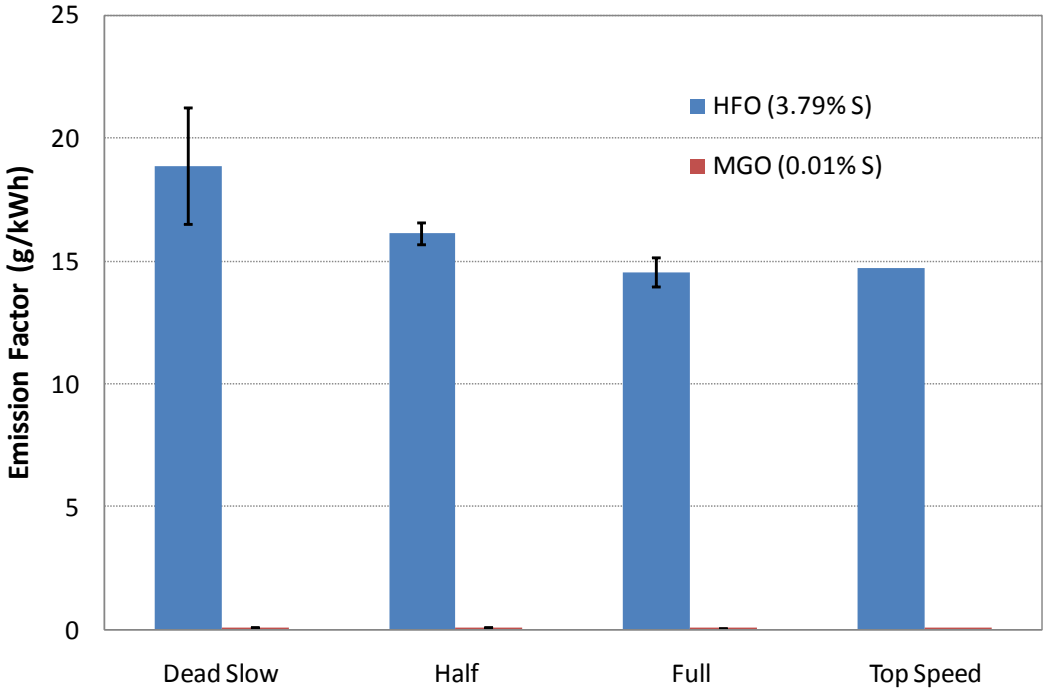
In addition to the PM mass measurements, UCR used a Nephelometer (TSI DustTrak 8520) to monitor transient PM emissions. The DustTrak measures the light scattered by the aerosols and provided real-time data on the stability of the PM stream while the filter mass is accumulating. Because this method is strongly dependent on particle size and refractive index, it is not considered a Federal Reference Method (FRM). In this project the DustTrak was calibrated against the discrete mass samples on the Teflon filters to provide real-time measurements.

Emission Sampling Results

The main (propulsion) engine was tested at four different speeds, typically dead slow (1.4% load, 5.8 knots), half speed (11.7% load, 11.7 knots), full speed (23.7% load, 14.7 knots) and top speed (59.3% load, 20.1 knots). SO_2 emissions at the various load points show a 99.7% reduction in SO_2 emissions as a result of fuel switching (Figure 38). NOx emissions at the various load points is show a 1 to 6 percent reduction depending on speed as a result of fuel switching although the reductions are not statistically significant (Figure 39). $PM_{2.5}$ emissions at the various load points show a 47% to 71% reduction due to fuel switching (Figure 40).

Speciated PM emission results[35] show a significant decrease in sulfates (H_2SO_4) while OC tends to increase particularly at half speed (Figure 41). Hamburg Süd engineers believe this increase was due to increased amounts of unburned fuel being picked up by the MGO as this was the first time the vessel had switched fuels for any length of time. In comparison, half speed emission sampling for two other ships are compared in Figure 42. These ships have been undergoing fuel switching regularly when entering California waters and show that typically OC should stay the same or show a reduction when switching from HFO to MGO. Thus once the Cap San Lorenzo starts regular fuel switching as part of the North American ECA, it is likely that the OC on MGO should be similar to that on HFO.

Figure 38: Propulsion Engine SO_2 Emissions



[35] Speciated PM emissions include elemental carbon (EC), organic carbon (OC) and sulfates (H_2SO_4). EC is typically soot or dry carbon particles also considered black carbon. OC is typically unburned oil or fuel that attaches to the EC. Sulfates are formed from the fuel sulfur.

Figure 39: Propulsion Engine NOx Emissions

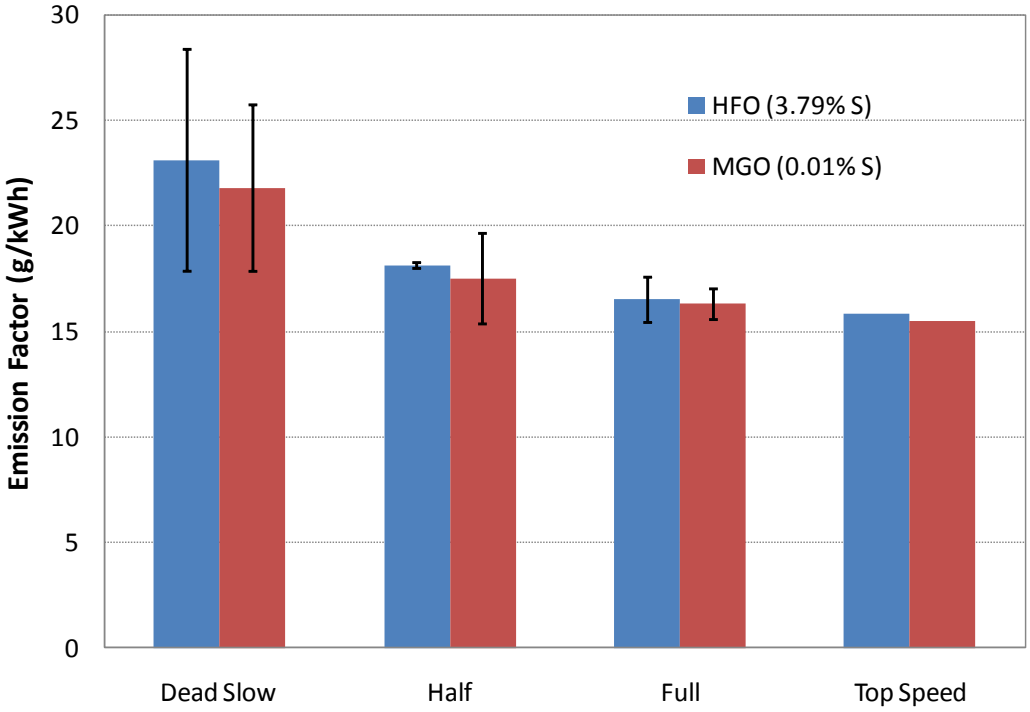


Figure 40: Propulsion Engine $PM_{2.5}$ Emissions

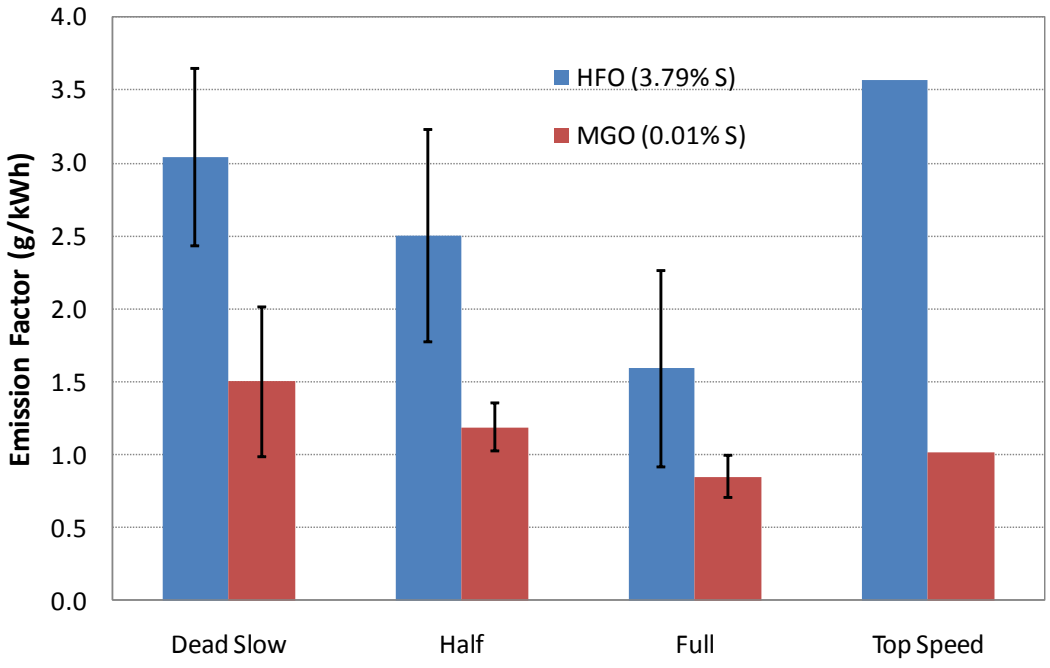


Figure 41: Propulsion Engine Speciated $PM_{2.5}$ Emissions

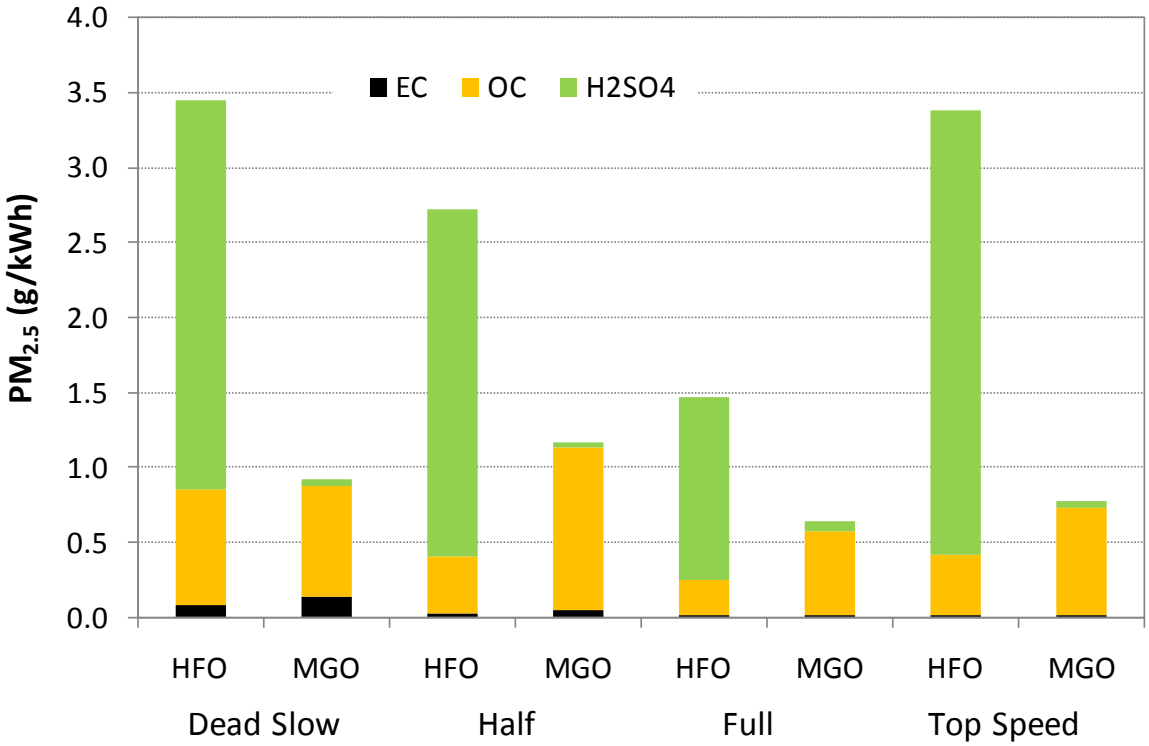
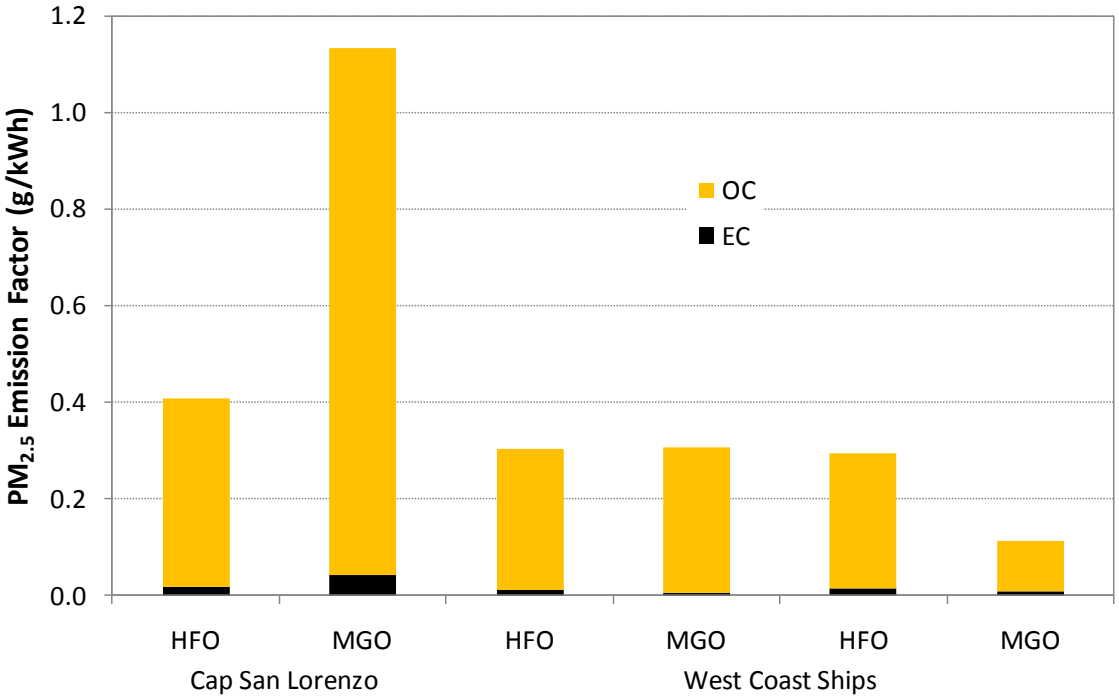


Figure 42: Speciated $PM_{2.5}$ Emissions Comparisons with Other Ships



Auxiliary engine emission measurements were made at 25%, 50% and 75% load. SO_2 emissions at the various load points show a 99.7% reduction as a result of fuel switching (Figure 43). NOx emissions at the various load points is show an 11% reduction at 25% load but a 19% increase at 50% load (Figure 44). In addition, the NOx emission factors are considerably lower than the expected 13.7 g/kWh expected for Category 2 medium speed diesel engines. This might be indicative of an older engine not running at peak performance. $PM_{2.5}$ emissions at the various load points show a 52% to 67% reduction due to fuel switching (Figure 45). Speciated PM emission results (Figure 46) show a significant decrease in sulfates (H_2SO_4) while OC tends to increase particularly at 75% load. Again this is likely due to the MGO picking up unburned fuel due to the fact that this was the first time the vessel had switched fuels for any length of time.

Figure 43: Auxiliary Engine SO_2 Emissions

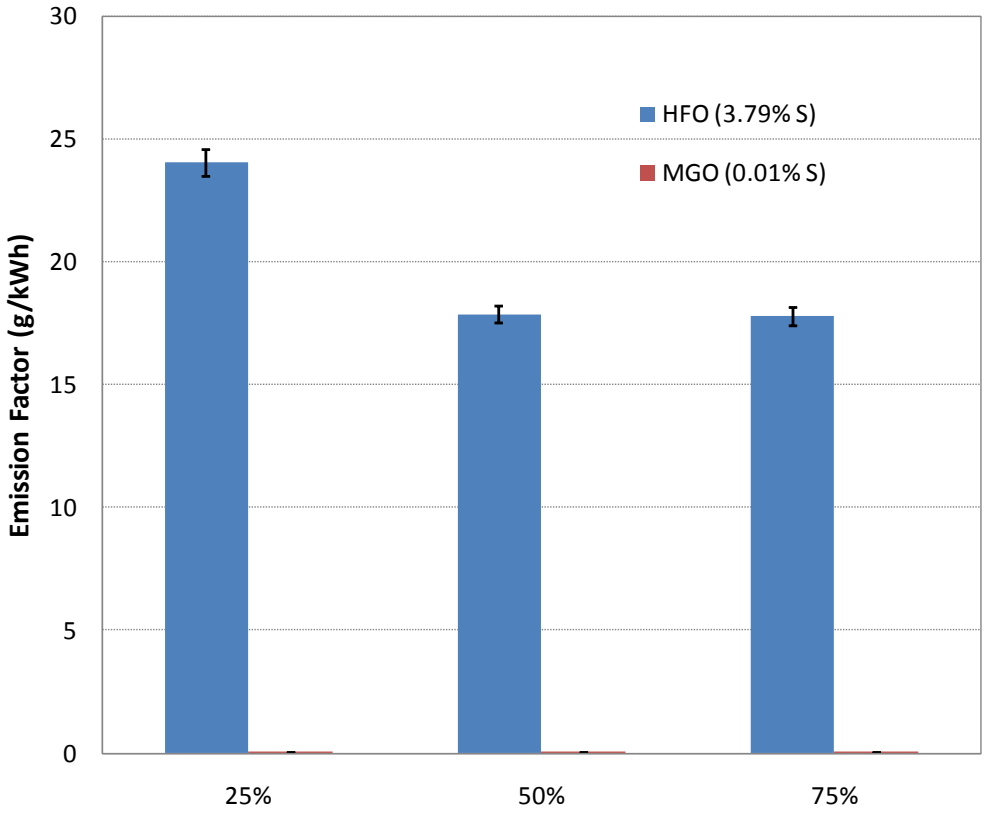


Figure 44: Auxiliary Engine NOx Emissions

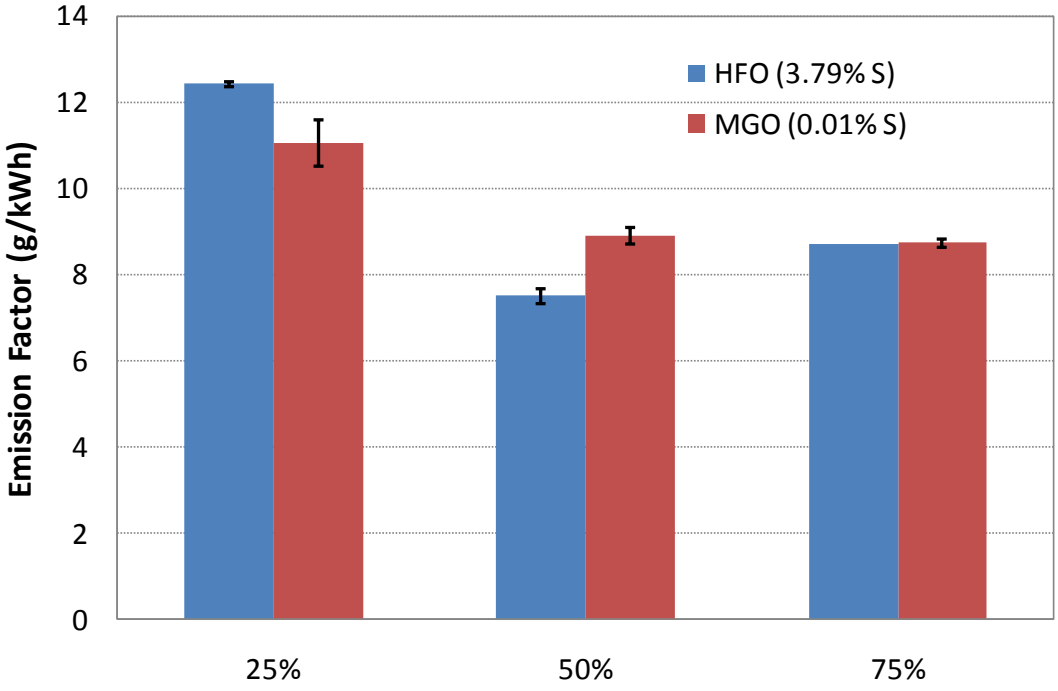


Figure 45: Auxiliary Engine $PM_{2.5}$ Emissions

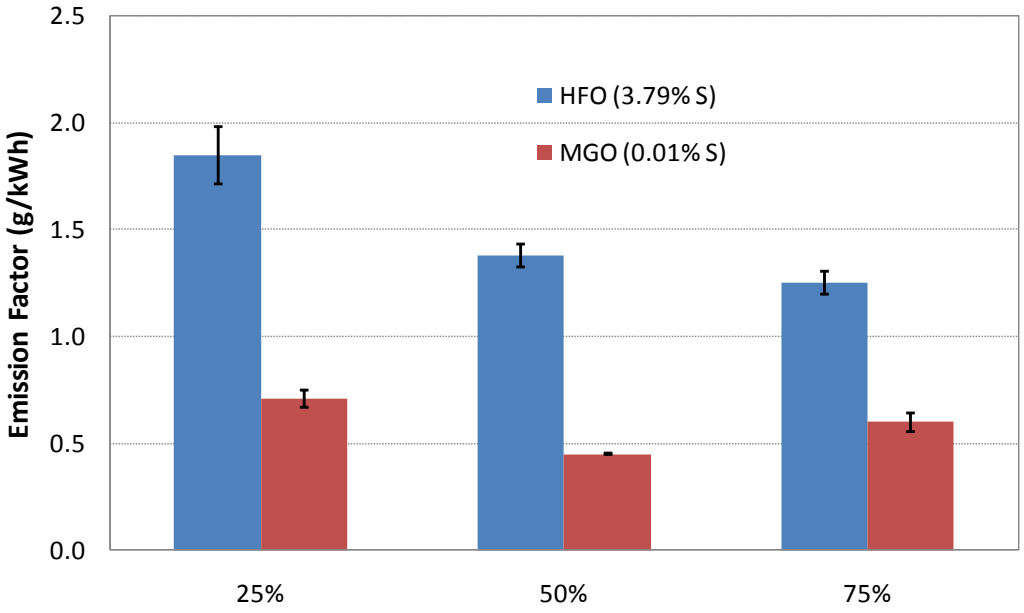
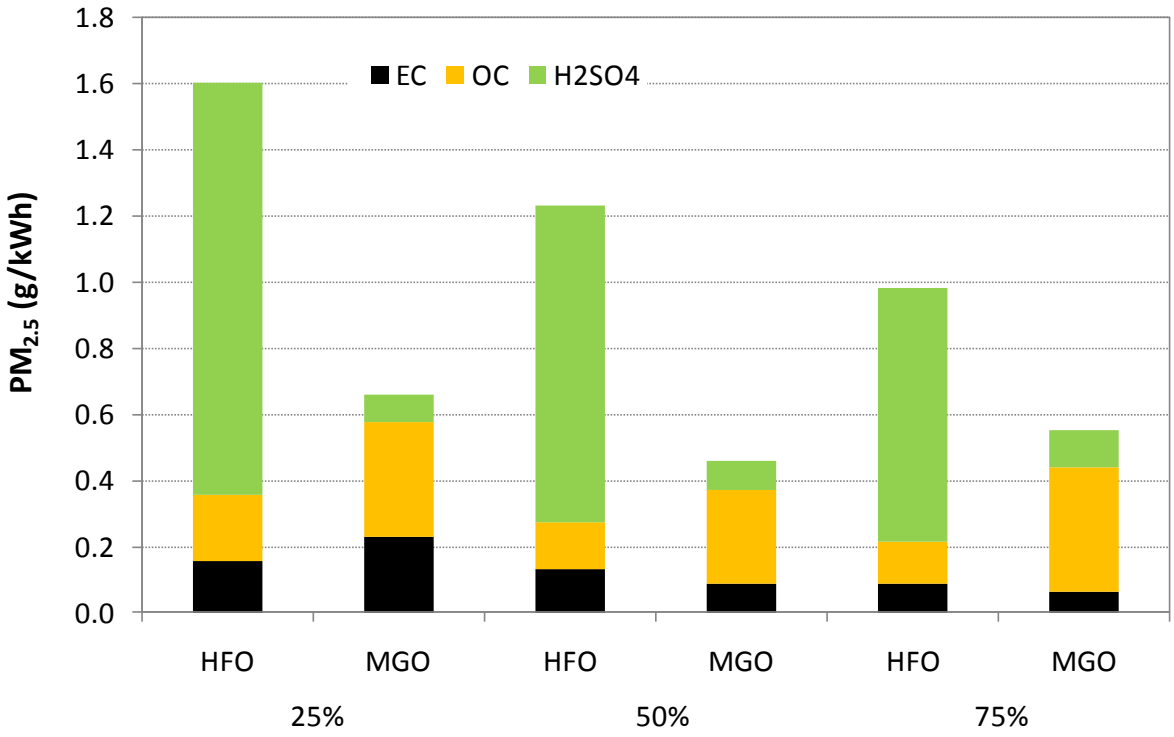


Figure 46: Auxiliary Engine Speciated $PM_{2.5}$ Emissions



Operational Issues

For the work performed during this study and along the test demonstration vessel route, the 0.01% MGO used was available only at the Port of Houston. According to the superintendent in charge of the Cap San Lorenzo, the fuel switching process is simple and is part of normal engine operational procedures. No special training is needed. He reported that the Cap San Lorenzo's engines and fuel supply systems ran normally during the fuel switching exercise and no difficulties were encountered. Tank capacity was sufficient to carry the needed lower sulfur fuel for the demonstration (300 metric tonne capacity, 40 metric tonnes needed for the demonstration).

The average sulfur level of the HFO available in Mexico was 3.8%[36] which is higher than and the global average which is estimated to be 2.7%.

Estimated Fuel Switching Emission Reductions

Using the emission factors determined from emission sampling, emission reductions at the three ports were calculated using the methodology in Appendix A. Emission reductions due to fuel switching at the Port of Veracruz are shown in Figure 47. Emission reductions due to fuel

[36] SEMARNAT, Experiencias en México relacionadas con las emisiones de grandes buques, presented in Veracruz, Mexico on April 16, 2010. Available at http://www.epa.gov/international/air/workshopreport/AnnexIII.pdf.

switching at the Port of Alta Mira are shown in Figure 48. Emission reductions due to fuel switching at the Port of Houston are shown in Figure 49. Emissions changes due to fuel switching at the three ports are an increase of 0.01 metric tonnes of NOx (0%), 0.17 metric tonnes of $PM_{2.5}$ (54%) and 3.13 metric tonnes of SO_2 (99.7%) with a differential fuel cost of $10,171. This is approximately 2% of the voyage fuel costs for the round trip shown in Table 8.

Figure 47: Estimated Emissions for Fuel Switch at Port of Veracruz

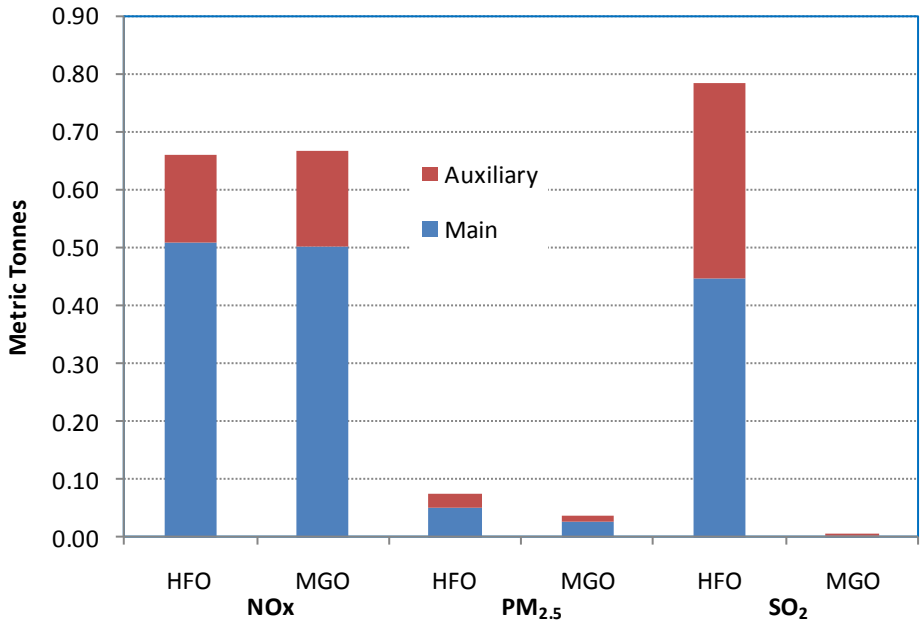


Figure 48: Estimated Emissions for Fuel Switch at Port of Alta Mira

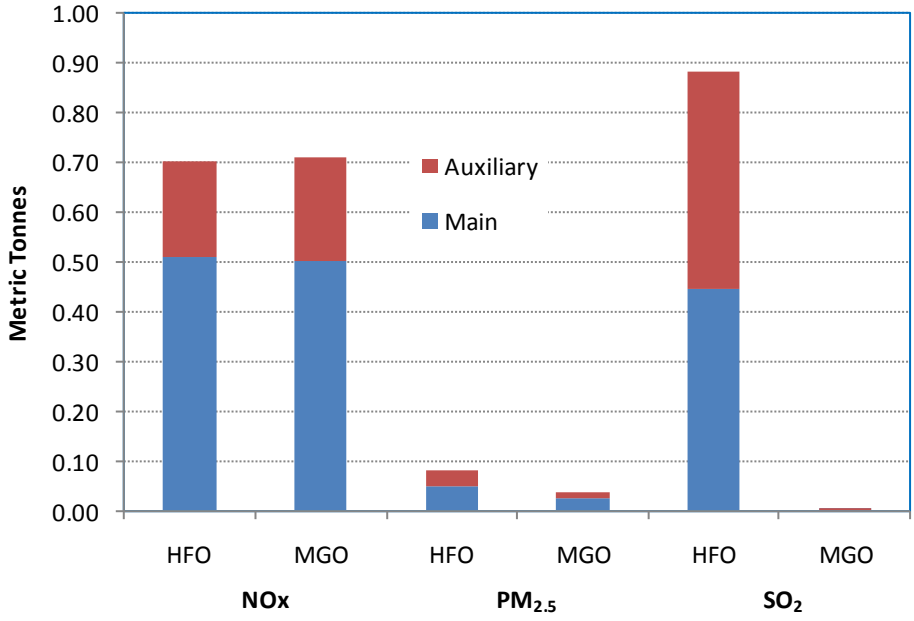
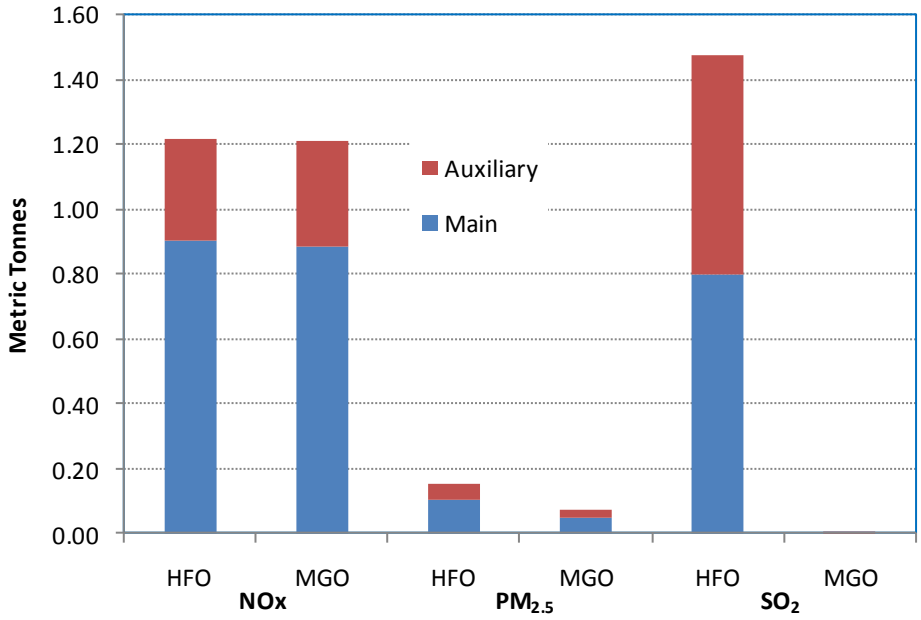


Figure 49: Estimated Emissions for Fuel Switch at Port of Houston



5. Summary of Key Findings

This project demonstrated that fuel switching in the Gulf of Mexico can lead to large emission reductions of both PM and SOx emissions, as observed through on-board emission sampling and corroborated by calculated emission reductions. Dispersion modeling showed a large reduction in impacts on port area air quality and sensitive reefs due to fuel switching. While acknowledging that this study has not quantified the effects of fuel switching on overall concentrations or deposition of air pollutants, the reductions of NOx, PM and SOx concentrations associated with fuel switching imply that similar results could be achieved in Mexico through reduced use of HFO fuel in shipping.

Emissions monitoring showed that switching to low-sulfur marine fuel achieved significant reductions in emissions of SOx and PM (2.5 micron in size) and small reductions of NOx – 89, 80 and 5 percent respectively – at a 2 percent increase in vessel operating costs, due to the higher cost of lower-sulfur fuel.

Ship emission inventories were developed for the Ports of Houston, Veracruz and Alta Mira using vessel port call data together with Lloyd's Register of Ships data. Annual emissions by ship type, ship operating mode (e.g., maneuvering, hotelling, etc.), fuel type and fuel switching zone boundary were calculated for each port. Tankers contributed most to annual emissions in Houston, whereas containers were the largest sources of annual emissions for Veracruz and Alta Mira. At all ports, the "cruise" operating mode contributed the most to total annual ship emissions. At all ports annual emissions reductions of NOx, PM and SOx achieved through fuel switching within a 24 nm fuel switching zone were calculated. For the Port of Houston NOx, PM and SOx reductions were 5, 81 and 90 percent respectively; for Alta Mira NOx, PM, and SOx reductions were 5, 76, and 84 percent respectively; and for Veracruz NOx, PM, and SOx reductions were 5, 78, and 87 percent respectively. For the Port of Veracruz there was over a four-fold increase in annual emissions reductions using a 200 nm fuel switching zone boundary versus a 24 nm boundary. And for the Port of Alta Mira this increase in fuel switching boundary resulted in a 5-fold increase in annual emissions reductions.

Dispersion modeling was conducted for the Port of Veracruz using the calculated emission inventory. The modeling showed a large reduction in impacts of ship emissions on port area air quality and sensitive reefs due to fuel switching within 24 nm of the port. Only emissions from ships were modeled. The study did not include the impact of other sources on air quality, such as those from all other activities at the port as well as all other regional sources. Air quality modeling showed a seven-fold reduction in 24-hour average and annual average $PM_{2.5}$ concentrations and a 24- to 25-fold reduction in 24-hour average and annual average SO2 concentrations. This study has indicated that local concentrations of $PM_{2.5}$ pollution could be reduced as much as 43 to 88 percent over the entire modeling domain by moving to a fuel-switching mode for ships calling on the Port of Veracruz. Deposition modeling showed a 99 per cent reduction of SO2 deposition to sensitive reef areas off the coast of Veracruz.

Some key lessons learned from this project are listed below:

- Operational issues: During the demonstrations, the test vessels encountered no operational issues of concern due to fuel switching.
- Fuel Storage: The fuel tank capacity used for MGO was sufficient to accommodate the fuel needed for the fuel switching demonstration.
- Meteorological data availability for impact assessment: One of the most challenging aspects for analysis of air quality impacts was obtaining the requisite meteorological data.

Appendix A – Port Inventory Methodology

Estimating emission inventories generally involves applying emission factors[37] to measures of port activity across a range of activity sectors. The U.S. Environmental Protection Agency (EPA) has developed a guidance document regarding the development of port emission inventories.[38] This appendix first summarizes the general methodology used for all ports then discusses the specific methodology for each port.

General Methodology

The current practice to calculate emissions from OGVs is to use energy-based emission factors together with activity profiles for each vessel. The emission factor is in terms of emissions per unit of energy from the engine; emissions are the product of the emission factor and the power needed to move the ship in a particular activity. The bulk of the work involves determining representative engine power ratings for each vessel and the development of activity profiles for each ship call. Using this information, emissions per ship call and mode can be determined using the equation below.

$$E = P \times LF \times A \times EF$$

Where **E** = Emissions (grams [g])
P = Maximum Continuous Rating Power (kilowatts [kW])
LF = Load Factor (percent of vessel's total power)
A = Activity (hours [h])
EF = Emission Factor (grams per kilowatt-hour [g/kWh])

Various data sources are available to those preparing port emission inventories. These include Marine Exchange/Port Authority (MEPA) data, U.S. Army Corps of Engineers (USACE) entrances and clearances data, Lloyd's Register of Ships (Lloyd's Data), and Pilot data. The importance and use of each are discussed below and shown in Figure 50.

OGVs vary greatly in speed and engine sizes based on ship type as described in Table 13. Various studies break out vessel types differently, but it makes most sense to group vessel types by the cargo they carry. Other characteristics that should be determined from Lloyd's Data are the propulsion engine power and engine speed, maximum vessel speed, and engine speed. Generally auxiliary engine power is not readily available but can be estimated from the Port of Houston Port Air Emissions Inventory.[39] Calculated auxiliary to propulsion power ratios by ship type can be found in Table 14.

[37] An emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Marine emission factors are usually expressed as the weight (commonly measured in grams) of pollutant divided by the energy (commonly measured in kilowatt-hours (kWh)) of the engine used to produce that emission.

[38] ICF International, *Current Methodologies in Preparing Mobile Source Port Related Emission Inventories,* Final Report, April 2009. Available at http://www.epa.gov/sectors/sectorinfo/sectorprofiles/ports/ports-emission-inv-april09.pdf.

[39] Starcrest Consulting Group, *2007 Goods Movement Air Emissions Inventory at the Port of Houston.* Final Draft, January 2009. Available at http://www.portofhouston.com/pdf/environmental/PHA-GM-AirEmissions-07.pdf.

Figure 50: Data Sources and their Uses

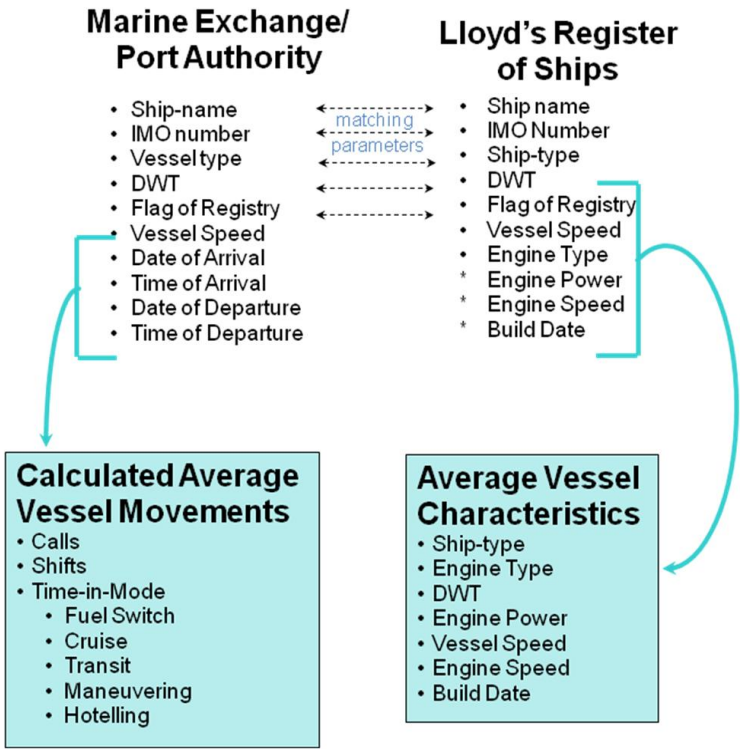


Table 13: Oceangoing Vessel Ship Types

Ship Type	Description
Auto Carrier	Self-propelled dry-cargo vessels that carry containerized automobiles.
Bulk Carrier	Self-propelled dry-cargo ship that carries loose cargo. Heavy load (HL) carriers and self-unloaders (SU) are further defined.
Container Ship	Self-propelled dry-cargo vessel that carries containerized cargo.
General Cargo	Self-propelled cargo vessel that carries a variety of dry cargo.
Miscellaneous	Category for those vessels that do not fit into one of the other categories or are unidentified.
Passenger	Self-propelled passenger ships
Reefer	Self-propelled dry-cargo vessels that often carry perishable items.
Roll-on/Roll-off (RORO)	Self-propelled vessel that handles cargo that is rolled on and off the ship, including ferries.
Tanker	Self-propelled liquid-cargo vessels including chemical tankers, petroleum product tankers, liquid food product tankers, etc.
Tugs	Self propelled ocean going tugs.

Table 14: Auxiliary Engine Power Ratios

Ship Type	Auxiliary to Propulsion Power Ratio
Auto Carrier	0.472
Bulk Carrier	0.248
Bulk Carrier, HL	0.390
Bulk Carrier, SU	0.401
Container 0-1000 TEUs	0.220
Container 1000-2000 TEUs	0.220
Container 2000-3000 TEUs	0.224
Container 3000-4000 TEUs	0.127
Container 4000-5000 TEUs	0.253
Container 5000-6000 TEUs	0.154
Container 6000-7000 TEUs	0.152
General Cargo	0.236
Miscellaneous	0.094
Passenger Ship	0.278
RORO	0.706
Reefer	0.281
Tanker 0-30K DWT	0.356
Tanker 30-60K DWT	0.200
Tanker 60-90K DWT	0.212
Tanker 90-120K DWT	0.207
Tanker > 120K DWT	0.169
Tugs	0.018

Fuel type also is instrumental in determining emission factors and should be determined for each port. It is assumed as a baseline that all OGVs operate their main propulsion and auxiliary engines on heavy fuel oil (HFO). It is also assumed that both the main and auxiliary engines are switched from HFO to marine gas oil (MGO) before they reach 24 nautical miles (nm) from the coastline. Fuel switching times are estimated based upon total ship propulsion power as shown in Table 15.

Table 15: Fuel Switching Times

Total Propulsion Power	Fuel Switching Time
0-10,000 kW	0.50 hr
10,000-30,000 kW	0.75 hr
> 30,000 kW	1.00 hr

Ship activity during a typical port call is best accomplished by breaking down the call into sections that have similar speed characteristics. Vessel movements for each call are described by using five distinct time-in-mode calculations. A call combines all modes. Each time-in-mode is associated with a speed and, therefore, an engine load that has unique emission characteristics. While there will be variability in each vessel's movements within a call, these time-in-modes allow an average description of vessel movements at each port. Time-in-modes should be calculated for each vessel call occurring in the analysis year over the waterway area near the port. The time-in-modes are described in Table 16.

Table 16: Vessel Movements and Time-In-Mode Descriptions

Activity	Description
Fuel Switch	This is time during which the ship is switching fuels. This mode is modeled as operating half the time on distillate fuel and half the time on residual fuel. Fuel switching is estimated to occur at service speed. Fuel switching times are determined by total vessel propulsion power.
Cruise	Time at service speed considered to be 94 percent of maximum speed and 83 percent of MCR. Calculated for 24 nm from the finish of fuel switching to the coastline.
Transit	For the Port of Houston, transit time is calculated for movements within the Houston Ship Channel. There is no transit for the two Mexican ports.
Maneuver	Time in the port area between the breakwater and the dock. Maneuvering within a port is assumed to occur at 3 knots on average.
Hotelling	Hotelling is the time at the dock when the vessel is operating auxiliary engines only. Auxiliary engines are operating at some load conditions the entire time the vessel is manned, but peak loads will occur after the propulsion engines are shut down. The auxiliary engines are then responsible for all onboard power or are used to power off-loading equipment, or both.

Load factors are expressed as a percent of the vessel's total propulsion or auxiliary power. At service or cruise speed, the propulsion load factor is assumed to be 83 percent. At lower speeds, the Propeller Law should be used to estimate ship propulsion loads, based on the theory that propulsion power varies by the cube of speed as shown in the equation below.[40]

$$\mathbf{LF = (AS/MS)^3}$$

Where **LF** = Load Factor (percent)
AS = Actual Speed (knots)
MS = Maximum Speed (knots)

Load factors for auxiliary engines vary by ship type and time-in-mode. Auxiliary engines are on all of the time, with the largest loads occurring during hotelling. Auxiliary engine load factors for OGVs are given in Table 17.

[40] When ships move against significant river currents, the actual speed in the above equation should be calculated based upon the following: for vessels traveling with the river current, the actual speed should be the vessel speed minus the river speed; for vessels traveling against the river current, the actual speed should be the vessel speed plus the river speed.

Table 17: Auxiliary Engine Load Factor Assumptions

Ship Type	Cruise	Transit	Maneuver	Hotel
Auto Carrier	0.15	0.30	0.45	0.26
Bulk Carrier	0.17	0.27	0.45	0.10
Bulk Carrier, HL	0.17	0.27	0.45	0.10
Bulk Carrier, SU	0.17	0.27	0.45	0.10
Container 0-1000 TEUs	0.16	0.25	0.55	0.16
Container 1000-2000 TEUs	0.16	0.25	0.55	0.16
Container 2000-3000 TEUs	0.16	0.25	0.55	0.16
Container 3000-4000 TEUs	0.16	0.25	0.55	0.16
Container 4000-5000 TEUs	0.16	0.25	0.55	0.16
Container 5000-6000 TEUs	0.16	0.25	0.55	0.16
Container 6000-7000 TEUs	0.16	0.25	0.55	0.16
General Cargo	0.17	0.27	0.45	0.22
Miscellaneous	0.17	0.27	0.45	0.22
Passenger Ship	0.80	0.80	0.80	0.64
RORO	0.15	0.30	0.45	0.26
Reefer	0.15	0.30	0.45	0.32
Tanker 0-30K DWT	0.13	0.24	0.33	0.26
Tanker 30-60K DWT	0.13	0.24	0.33	0.26
Tanker 60-90K DWT	0.13	0.24	0.33	0.26
Tanker 90-120K DWT	0.13	0.24	0.33	0.26
Tanker > 120K DWT	0.13	0.24	0.33	0.26
Tugs	0.17	0.27	0.45	0.22

Emission factors for OGV propulsion are given in Table 18 for slow speed diesel engines (SSD), medium speed diesel engines (MSD), gas turbines (GT) and steam turbines (ST) and are the most generally accepted. [41]

The International Maritime Organization (IMO) adopted NOx limits in Annex VI to the International Convention for Prevention of Pollution from Ships in 1997. These NOx limits apply for all marine engines over 130 kilowatts (kW) for engines built on or after January 1, 2000, including those that underwent a major rebuild after January 1, 2000. The required number of countries ratified Annex VI in May 2004 and it went into force for those countries in May 2005. Most manufacturers build engines to emit well below the standard. EPA determined the effect of the IMO standard to be a reduction in NOx emissions of 11 percent below engines built before 2000.[42] Therefore for engines built in 2000 and later, a NOx factor of 0.89 should be applied to

[41] Entec UK Limited, *Quantification of Emissions from Ships Associated with Ship Movements between Ports in the European Community*, prepared for the European Commission, July 2002. Available at http://www.europa.eu.int/comm/environment/air/background.htm

[42] Conversation with Michael Samulski of EPA, May 2007.

the calculation of NOx emissions for both propulsion and auxiliary engines. Since this standard only applies to diesel engines, the factor is not applied to either steam turbines or gas turbines.

Table 18: Emission Factors for OGV Main Engines, g/kWh

Fuel	Stroke	Sulfur	NOx	PM_{10}	$PM_{2.5}$	SOx	BSFC
HFO	MSD	3.00%	14.0	1.53	1.41	12.49	213
	SSD		18.1	1.52	1.39	11.44	195
	STM		2.1	1.61	1.48	17.89	305
	GT		6.1	1.61	1.48	17.89	305
MGO	MSD	0.10%	13.2	0.19	0.17	0.40	203
	SSD		17.0	0.19	0.17	0.36	185
	STM		2.0	0.17	0.15	0.57	290
	GT		5.7	0.17	0.15	0.57	290
During Fuel Switch	MSD	Varies	13.6	0.86	0.79	6.44	208
	SSD		17.6	0.85	0.78	5.90	190
	STM		2.1	0.89	0.82	9.23	298
	GT		5.9	0.89	0.82	9.23	298

Emission factors are considered to be constant down to about 20 percent load. Below that threshold, emission factors tend to increase as the load decreases. This trend results because diesel engines are less efficient at low loads and the BSFC tends to increase. Thus, while mass emissions (grams per hour) decrease with low loads, the engine power tends to decrease more quickly, thereby increasing the emission factor (grams per engine power) as load decreases. Low load adjustment factors should be multiplied by emission factors when the propulsion load factor is less than 20 percent. Low load adjustment factors are given in Table 19.

No low load adjustment factor should be applied to diesel electric or gas turbine electric engines for loads below 20% MCR because several engines are used to generate power, and some can be shut down to allow others to operate at a more efficient setting.

As with propulsion engines, the most current set of auxiliary engine emission factors comes from Entec. Table 20 provides these auxiliary engine emission factors. There is no need for a low load adjustment factor for auxiliary engines, because they are generally operated in banks. When only low loads are needed, one or more engines are shut off, allowing the remaining engines to operate at a more efficient level.

Fuel prices were estimated at $460/metric tonne for HFO and $740/metric tonne for MGO[43].

Inventory development specific to each port is discussed below.

[43] Bunkerworld.com prices for Houston as of September 15, 2010.

Table 19: Calculated Low Load Multiplicative Adjustment Factors

Load	NOx	PM	SO_2	Fuel
1%	11.47	19.17	5.99	5.82
2%	4.63	7.29	3.36	3.28
3%	2.92	4.33	2.49	2.44
4%	2.21	3.09	2.05	2.01
5%	1.83	2.44	1.79	1.76
6%	1.60	2.04	1.61	1.59
7%	1.45	1.79	1.49	1.47
8%	1.35	1.61	1.39	1.38
9%	1.27	1.48	1.32	1.31
10%	1.22	1.38	1.26	1.25
11%	1.17	1.30	1.21	1.21
12%	1.14	1.24	1.18	1.17
13%	1.11	1.19	1.14	1.14
14%	1.08	1.15	1.11	1.11
15%	1.06	1.11	1.09	1.08
16%	1.05	1.08	1.07	1.06
17%	1.03	1.06	1.05	1.04
18%	1.02	1.04	1.03	1.03
19%	1.01	1.02	1.01	1.01
20%	1.00	1.00	1.00	1.00

Table 20: Auxiliary Engine Emission Factors (g/kWh)

Fuel	Sulfur	NOx	PM_{10}	$PM_{2.5}$	SOx	BSFC
HFO	3.00%	14.7	1.54	1.42	13.31	227
MGO	0.10%	13.9	0.18	0.17	0.42	217
During Fuel Switch		14.3	0.86	0.79	6.87	222

Port of Houston

The specific methodology for the Port of Houston inventory development is discussed below.

Call Data

U.S. Army Corps of Engineers Entrances and Clearances data[44] for 2007 was used to develop the port emissions inventory for the Port of Houston. The Maritime Administration (MARAD) maintains the Foreign Traffic Vessel Entrances and Clearances database, which contains statistics on U.S. foreign maritime trade. Data are compiled during the regular processing of statistics on foreign imports and exports. The database contains information on the type of vessel, commodities, weight, customs districts and ports, and origins and destinations of goods. IMO number was used to link the Call Data to Lloyd's data to determine ship characteristics.

[44] http://www.ndc.iwr.usace.army.mil//data/dataclen.htm

Transit Times and Distances

All ships except containers, passenger ships and tankers were assumed to dock at the Port of Houston turning basin, 51.2 nm down the Houston Ship Channel. Bulk carriers, general cargo and RoRos travelled that distance at an average speed of 8.2 knots. Auto carriers and reefers travelled the distance at an average speed of 10.1 knots. Passenger ships were assumed to stop at the Bayport facility which is 35 nm down the Houston Ship Channel at an average speed of 11.5 knots. All container ships except those operated by CMA CGM and MSC were assumed to stop at Barbour's Cut, 32 nm down the Houston Ship Channel at an average speed of 12 knots. Container ships operated by CMA CGM and MSC were assumed to stop at Bayport with an average speed down the Houston Ship Channel of 11.5 knots. Tankers were assumed to stop at the Jacintoport Terminal, 41.5 nm down the Houston Ship Channel at an average speed of 8.9 knots. All distances and speeds were derived from the Port of Houston 2007 emissions inventory.[45]

Maneuvering Times

Maneuvering times were estimated from the Port of Houston 2007 emissions inventory[45]. The maneuvering times per call used in the inventory calculations in this report are shown in Table 21. All maneuvering was assumed to occur at an average of 3 knots.

Table 21: Port of Houston Maneuvering Times per Call

Ship Type	Hrs per Call
Auto Carrier	1.5
Bulk Carrier	2.0
Container Ship – Barbour's Cut	1.0
Container Ship – Bayport	0.5
General Cargo	2.0
Passenger Ship	0.5
Reefer	1.5
RoRo	2.0
Tanker	1.0

Hotelling Times

Average hotelling times were also taken from the Port of Houston 2007 emissions inventory[45]. The hotelling times per call used in this report are shown in Table 22.

[45] Starcrest Consulting Group, *2007 Goods Movement Air Emissions Inventory at the Port of Houston.* Final Draft, January 2009. Available at http://www.portofhouston.com/pdf/environmental/PHA-GM-AirEmissions-07.pdf

Table 22: Port of Houston Hotelling Times per Call

Ship Type	Hours per Call
Auto Carrier	21.0
Bulk Carrier	71.3
Bulk Carrier, HL	63.3
Bulk Carrier, SU	71.3
Container 0-1000 TEUs	36.5
Container 1000-2000 TEUs	36.5
Container 2000-3000 TEUs	38.4
Container 3000-4000 TEUs	41.6
Container 4000-5000 TEUs	44.2
Container 5000-6000 TEUs	73.7
Container 6000-7000 TEUs	66.1
General Cargo	49.2
Miscellaneous	46.5
Passenger Ship	12.1
Reefer	28.9
RoRo	31.1
Tanker 0-30K DWT	28.3
Tanker 30-60K DWT	34.2
Tanker 60-90K DWT	45.9
Tanker 90-120K DWT	29.9
Tanker > 120K DWT	34.6
Tugs	21.8

Mexican Ports

The specific methodology for the Ports of Alta Mira and Veracruz inventory development is discussed below.

Call Data

Port call data for 2005[46] was obtained from SEMARNAT and used to develop the port emissions inventory for the Ports of Alta Mira and Veracruz. Compared with Houston, port calls at Alta Mira and Veracruz are relatively low --- 1,138 and 1,446 compared to 5,778 at Houston. Call data included ship name, general ship type, DWT, and date and time of arrival and departure. IMO number was assigned based upon the ship name and DWTs. IMO number was used to link the Call Data to Lloyd's data to determine ship characteristics.

Maneuvering Times

Maneuvering times per call for both ports were assumed to be 1 hour.

[46] Only 2005 call data was available for Mexican Ports.

Hotelling Times

Hotelling times for each ship call were calculated from the arrival and departure times. These were used in the calculation of hotelling emissions. Average hotelling times for the two ports are shown in Table 23 by ship type.

Table 23: Average Hotelling Times for Alta Mira and Veracruz

Ship Type	Average Hotelling Time per Call (hrs)	
	Alta Mira	Veracruz
Auto Carrier	14.7	30.3
Bulk Carrier	68.0	105.5
Container	13.2	16.0
General Cargo	39.2	73.2
Passenger	15.5	--
Reefer	--	95.6
RoRo	13.1	17.3
Tanker	30.3	34.9

Appendix B – Dispersion Modeling Methodology Details

Sources of Meteorological Data

One of the most challenging tasks for analysis of air quality impacts was obtaining the requisite meteorological data. Over the course of two months, we contacted numerous individuals in several US and Mexican government agencies to obtain adequate data. The key individuals who assisted us in our research include:

- Norma Angélica Tepoz Ortega (CONAGUA) – 3-hour data of Precipitation, Winds, and Cloud Cover for years 2001-2010, somewhere in Veracruz
- Emmanuel Álvarez Ramírez (SMN) – 10 minute EMA[47] data of Winds, Precipitation, Temperature, Humidity, Pressure, Solar Radiation for 2008 and 2009 in C. Previsión and Alvarado
- Antonio Luna Díaz Peón - April 2008 detailed hourly data from Veracruz. All needed fields but only one month
- Alfredo Ruiz-Barradas (U. Md.) – Provided contacts for SMN and Sr. Luna
- Jorge Zavala (UNAM) – 10 minute tide gauge data of Winds, Pressure, Humidity, Temperature[48]
- Dan Thompson, Caroline Corvington, Dan Beardsley (NOAA) – provided contacts within CONAGUA
- Martin Medina (NOAA) – provided contacts within CONAGUA
- Juana María Tavarez Nieto (CONAGUA) – January 2009 detailed hourly data from Veracruz, All needed fields but only one month.

Throughout this, we were not able to identify an existing "perfect" data set for modeling. The closest dataset to what was needed were the observations taken in Veracruz and provided by Sra. Tavarez and Sr. Luna. These records had all required fields, and we understood they were available for three years, from 2007 to 2009. However, when we requested the remaining files we learned they were damaged – most likely by Hurricane Karl, which struck Veracruz during the Autumn of 2010 – and it was unclear if they would be available. Table 24 lists the various data sources collected

[47] Estación Meteorológica Automatica. Data available at: http://smn.cna.gob.mx/index.php?option=com_content&view=article&id=106:estaciones-automaticas&catid=6:slider

[48] Servicio Mareográfico Nacional, Universidad Nacional Autónoma de México, Instituto de Geofísica. More information is available at www.mareografico.unam.mx

Table 24: Meteorological Data Record Sets

	Record					
	0	1	2	3	4	5
Required						
Time span	all	Apr-08	Feb, Mar 09	8/07-12/09	1/01-12/09	Jan-09
Time step	~0, 12Z	hourly	10 min	10 min	3-hour	hourly
Source			tide gauge station in Veracruz (http://www.mareografico.unam.mx)	EMA via SMN at Alvarado and C. Previsión (http://smn.cna.gob.mx/)		
Location	Mérida and Ciudad Victoria		19°11'31.42" N 96° 7'24.79" W	Prev.: 96°06'41", 19°08'34"; Alv.: 95°37'57", 18°42'54"	EST	
Surface wind speed		Uspd_m/s	vto_vel	WSK_kph, WSMK_kph	VTOVEL	Uspd_m/s
Surface wind direction		Udir	vto_dir	Dir_deg, WSMDir_deg	VTODIR	Udir
Wind observation height			8 m			
Temperature		Td	temp_atm	AvgTemp_C		Td
Temperature observation height						
Total sky and/or cloud cover		cld coverage, type (at levels), tot_sky_coverage		*(NA. estimated from AvgSR)*	NUBOCT	cld coverage, type (at levels), tot_sky_coverage
Humidity		Tw, RH	hum_rel	AvgRh_pct *(but corrected)*		Tw, RH
Precipitation		Pcp_mm		Rain_mm	PRE24, PRETPO, PRELAM	Pcp_mm
Morning upper air sounding						
Other useful data						
Pressure		StPres, SLP	pres_atm	AvgBP_mbar		StPres, SLP
Cloud height		CltHt			NUBBAJ	CltHt
Heat/radiation flux		insol_hrs, min		AvgSR_Wm2		insol_hrs, min
Afternoon sounding data						
Additional provided						
		vis				vis
		Ugst_m/s				Ugst_m/s
		Uavg_m/s				Uavg_m/s

0	NOAA GSD Sounding database (http://esrl.noaa.gov/raobs/)
1	Antonio Luna Díaz Peón - April 2008 – detailed hourly data from Veracruz, all needed fields but only one month
2	Jorge Zavala (UNAM) – Feb, Mar 2009 – 10 minute tide gauge data of Winds, Pressure, Humidity, Tempera
3	Emmanuel Álvarez Ramírez (SMN) – 1/2008-12/2009 (Alvarado), 8/2007-12/2009 (C. Previsión) – 10 minute EMA data of Winds, Precipitation, Temperature, Humidity, Pressure, Solar Radiation
4	Norma Angélica Tepoz Ortega (CONAGUA) – 2001-2010 – 3-hour data of Precipitation, Winds, and Cloud Cover for 10 years , somewhere in Veracruz
5	Juana María Tavarez Nieto - Jan 2009 - detailed hourly data from Veracruz, same as #1

Meteorological Data Record Details

Since a single data set was not available that both covered a sufficient amount of time and contained all required fields, we created one from the various pieces available. This included the following:

- April 2008 and January 2009 were taken directly from the provided CONAGUA records. These were provided in Excel™ spreadsheets with a single tab for each day of the month. These data were aggregated to a single file for each month, translated to text files, translated into a SAMSON-type data record which the AERMET model can read, and then processed with AERMET for the AERMOD model.
- Other fields were taken from the 10-minute EMA station at Alvarado. These were processed from monthly records into a single annual file, then processed from 10-minute to hourly average values in the SAMSON[49] format. This record provided all other required fields except cloud cover and relative humidity.[50] For those, the following was done:
  - Relative humidity was instead taken from the EMA observations at C. Prevision. In the few cases where RH was invalid at both stations, it was estimated from the range of valid measurements at other times with a random component
  - Cloud cover was taken from the 3-hour records provided by Sra. Tepoz. These records were interpolated into hourly values.

  A complete set of these variables for 2008 from these sources was aggregated, processed, quality assured, translated to the SAMSON format, and processed through AERMET.

The full 2008, mixed source, AERMOD-ready, surface and upper air files were then combined with the independently processed January 2009 and April 2008 data files. This has the

[49] http://www1.ncdc.noaa.gov/pub/software/cdrom/samson/format.txt

[50] RH actually is included, but clearly incorrect for the Alvarado station for this period.

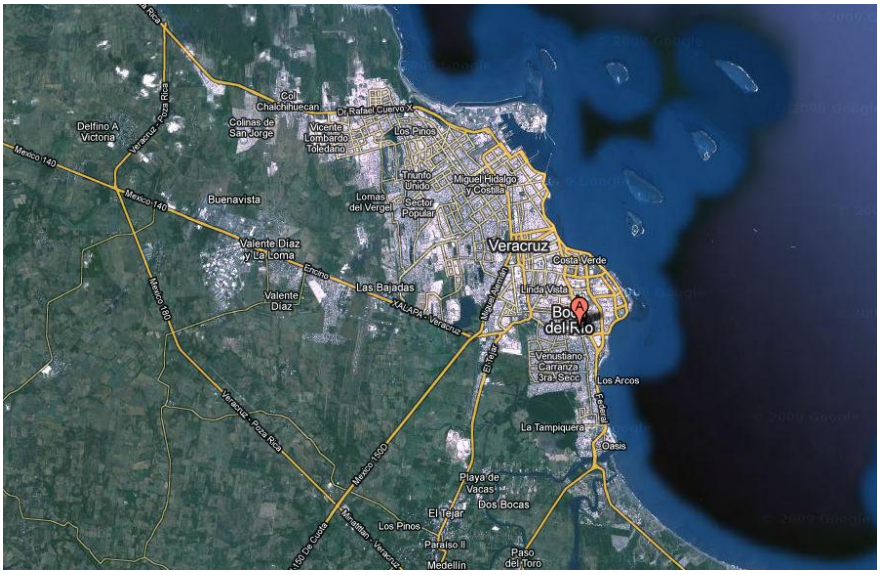
advantage of having each processed separately with the AERMET tool, which allows different surface characterization in each case.

Surface characteristics were determined by sectors within a 1 km radius of each meteorological location. As detailed observations of land use were not available, it was estimated using Google Earth. From images of the sites, sectors were apportioned and typical land use within each sector approximated. Corresponding values of Bowen ratio (β_0), albedo (α), and roughness (z_0) were then taken from the AERMET User's Guide.[51] Although somewhat less precise than the analyses from AERSURFACE, this approach is reasonable given the amount of data available and the relatively homogenous and distinct land uses in the vicinity of each station (typically farmland, wetlands, or water). Note that all stations lie inland by at least 1 km.

2008 and 2009 upper air data was taken from nearby Mérida station. Observations are provided by NOAA Global Systems Division (GSD).

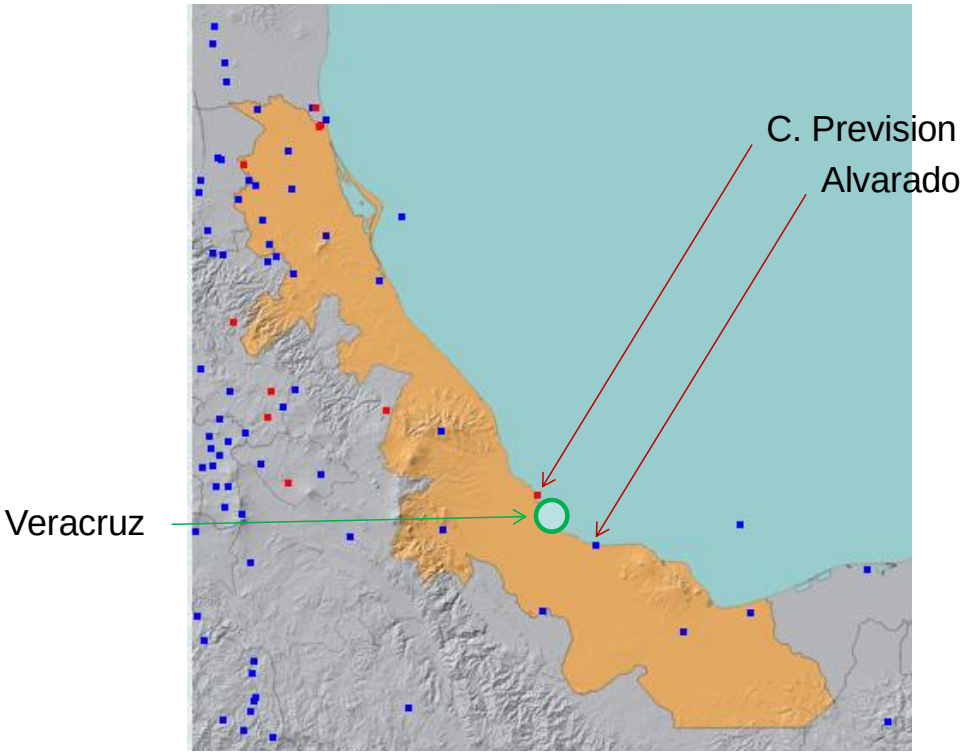
Figure 51 shows the location of the observations within Veracruz for January 2009 and April 2008. These are data sets 1 and 5 from Table 24. Figure 52 shows the location of the two EMA stations used for the remaining data other than cloud cover and upper air observations.

Figure 51: Location of Hourly Meteorological Observations in Veracruz



[51] USER'S GUIDE FOR THE AERMOD METEOROLOGICAL PREPROCESSOR (AERMET), U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Emissions, Monitoring, and Analysis Division, Research Triangle Park, North Carolina 27711, November 2004, EPA-454/B-03-002.

Figure 52: Location of 10-Minute EMA Meteorological Observations near Veracruz



For the modeling, the January 2009 observations were relabeled as 2008. This is evident in Figure 16, which shows a wind rose from the entire modeling period, but is labeled January to December, 2008. This is to avoid technical issues in the modeling with input meteorological data spanning multiple years. The January 2009 records were processed as if they actually represented January 2008, then combined with the records from February through December 2008. This is functionally equivalent to having records from a single year for all averaging periods.

The discussion in Section 3.2 focuses primarily on the wind field. Other meteorological fields also influence the dispersion of pollutants once emitted, but have a less direct influence than winds. These are discussed above, although precipitation is worth noting separately as it may significantly influence deposition. Table 25 shows the total precipitation from the composite record used in the dispersion modeling compared to the climatological average. The composite, annual record shows nearly twice the annual rainfall as the climatological average for Veracruz, although it is unknown if this is due solely to inter-annual variation and accurate for Veracruz for that year or is an artifact of the quality of the meteorological data collected or the disparate locations included. For example, reliance on stations not in the immediate vicinity of the city could have greater overall rainfall than Veracruz due to terrain or other local effects.

Table 25: February 2008 through January 2009 Composite Precipitation

Month	Mean Total Rainfall[52] (mm)	Total Rainfall from Modeling Record (mm)		Month	Mean Total Rainfall (mm)	Total Rainfall from Modeling Record (mm)
Jan	24.1	33.5		Aug	323.1	178.8
Feb	16.0	89.1		Sep	358.6	1214.6
Mar	14.5	54.6		Oct	152.9	682.4
Apr	17.4	22.9		Nov	59.6	429.5
May	48.2	62.7		Dec	24.4	74.1
Jun	298.3	332.5				
Jul	419.9	316.7		**Total**	**1757.0**	**3491.5**

Other Model Inputs

The AERMOD model was run for each pollutant separately to accommodate the varying emissions strengths when the ship was operating on high and low sulfur fuels. Emissions occurring within the harbor were considered urban sources, with a corresponding regional population of 702,394, while emissions in all other locations approaching and departing the port in open water were considered rural. Polygon area sources were used to represent all emissions, and were considered steady in time, with hourly emission densities showing no seasonal or diurnal variation and fixed by the total annual emissions strength.

Both dry and wet deposition for gases and particles was employed. Particle deposition was considered via AERMOD's "METHOD_2" option. For PM_{10} the fine fraction was estimated at 92 percent and the mass mean diameter as 0.77 μm. For $PM_{2.5}$ the fine fraction is, by definition, 1 and the mass mean diameter was estimated at 0.51 μm. Gas dry and wet deposition parameters were determined for SO_2. In that case, gas diffusivity in air and water were determined following Weseley[53], with values of D_a = 0.1246 cm^2/sand D_w = 5.74E-6 cm^2/s. The Henry's Law constant for SO_2 is 121.59 Pa m^3/mol.[54] Cuticular resistance for SO_2 is taken as 30 s/cm.[55] Sectors for gas deposition properties were estimated by looking out 50 km radially from the center of the port and establishing predominate land use from Google Earth™ , while the season for gas deposition was assumed to be lush tropical summer all year. Terrain data for the region was determined by processing SRTM DEM1-type commercial data through the AERMAP preprocessor to determine elevation and hill height scales. This was obtained from www.mapmart.com.

[52] Source: WMO. Record available at http://worldweather.wmo.int/179/c01302.htm.

[53] M. L. Wesely, P. V. Doskey, and J. D. Shannon, Deposition Parameterizations for the Industrial Source Complex (ISC3) Model, ANL/ER/TR-01/003, DOE/xx-nnnn, Argonne National Laboratory, June 2002.

[54] R. Sander, Compilation of Henry's Law Constants for Inorganic and Organic Species of Potential Importance in Environmental Chemistry, Available at: http://www.mpch-mainz.mpg.de/~sander/res/henry.html

[55] Baldocchi, A Multi-Layer Model For Estimating Sulfur Dioxide Deposition To A Deciduous Oak Forest Canopy, Atmospheric Environment Vol. 22, No. 5, pp. 869-884, 1988.

Model Execution

Each of these inputs was assembled into appropriate AERMOD input files following current implementation guidelines[56] and processed with the most recent version of the AERMOD model (version 09292). Appropriate design values were determined within the model using the model's PLOTFILE option and exported to a GIS application for plotting.

[56] Addendum to the User's Guide for the AMS/EPA Regulatory Model – AERMOD (EPA-454/B-03-001, September 2004), U.S. EPA, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina 27711, October 2009

Appendix C – Monitoring Methodology

Testing was performed on both the residual and distillate marine fuels. Figure 53 shows the certificate of analysis (CoA) for the HFO sample. Figure 54 shows the certificate of analysis (CoA) for the MGO sample. Figure 55 shows the fuel audit results.

Figure 53: HFO Fuel Certificate of Analysis

```
FROM
VISWA LAB


TO
COLUMBUS SHIPMANAGEMENT GmbH
ATTN: MR. CHRISTOPH GESSNER


Fuel Sample               CAP SAN LORENZO
VLC Log No.               F100308663  Date 03/05/10
Bunk. Port and Date       HOUSTON, USA - 03/03/10
Place and Date Sent        -
Supplier                  CHEMOIL
Date Received at VLC      03/05/10
Sample Type per Customer  IFO 380
Grade                     RMG 380
Tamper Proof              0198357 : Sealed

Customer furnished data:
Density                 986.8 kg/m3
Viscosity              357   cSt
Quantity                  1800  M.Tons

SPECIFIED PARAMETERS FOR RMG 380

Density @ 15 degC     987.2  kg/m3  (991.0  Max)
API Grade              11.75        ( 11.20 Min)
Viscosity @  50 degC  344.00 cSt    (380.00 Max)
Viscosity @ 100 degC   33.0  cSt    ( 35.0  Max)
Upper Pour Point        6    degC   ( 30    Max)
Carbon Residue        17.34  %wt.   (18.00  Max)
Ash                    0.040 %wt.   ( 0.150 Max)
Water                  0.10  %vol.  ( 0.50  Max)
Sulfur                 3.19  %wt.  ( 4.50  Max)
Sediment               0.01  %wt.   ( 0.10  Max)
Vanadium                194  wt.ppm (  300  Max)
Al + Si                   7  ppm    (   80  Max)
Flash Point            > 70  degC   (   60  Min)

ADDITIONAL PARAMETERS

SI          5 ppm
AL          3 ppm
Na         16 ppm
Ca          3 ppm
Fe         12 ppm
Pb        < 1 ppm
Ni         14 ppm
P         < 1 ppm
Zn        < 1 ppm
Mg        < 1 ppm
CCAI               849
Calorific value     40.18 MJ/kg
Minimum Transfer Temperature                  42 degC
Injection Temperature (For 13 cSt Viscosity) 133 degC
Engine Friendliness Number (EFN: 1-100)       54

GRADE CONFORMANCE
The fuel sample tested conforms to grade RMG 380.
```

```
COMMENTS

SUGGESTIONS & RECOMMENDATIONS TO SHIP OWNERS/OPERATORS/TECHNICAL STAFF
_____________________________________________________________________

Temperature for injection viscosity 10 is 144=B0C.
Temperature for injection viscosity 15 is 127=B0C.

CARBON RESIDUE

Observation:  Though within limit, carbon is high.
--------------------
Improve purification efficiency through reduction of throughput and
maintaining temperature around 98=B0C in purifier heater. Higher air charge
temperature (within-limits) can reduce deposit formation. Inspect exhaust
passages and turbo charger and wash down if necessary.

POUR POINT

Observation:
---------------------------------
Heat and store this fuel at 10=B0C above the measured pour point temperatur=
e.

CCAI

Observation:  Ignition delay is indicated by CCAI greater than 840 for
medium-speed engines and greater than 870 for low-speed engines.

OVERALL QUALITY:

Engine Friendliness Number (EFN) is a unique bench-mark of fuel quality
evaluated by VISWA LAB from the point of view of engine wear and tear
resulting from the use of this fuel. Based on EFN, which is calculated from
the analysis results listed in this report, the quality of this fuel is
above average.

NOTE:  The conformance of this fuel to the contracted specifications may
have no relationship to the evaluation of this fuel based on EFN.


*************************************************************************=
*
**
WITH EFFECT FROM 20TH FEB 2010, KINDLY FORWARD SAMPLES BUNKERED IN ROTTERDA=
M
AND ANTWERP TO OUR LAB IN SINGAPORE USING THE APPROPRIATE AIR WAYBILLS
INCLUDED IN THE SAMPLE KIT BOX. THIS INSTRUCTION SUPERSEDES THAT GIVEN IN
THE WORLD MAP ENCLOSED IN THE KIT. IF THE FUEL IS PART OF A MACHINERY
PROBLEM INVESTIGATION, KINDLY FORWARD TO VISWA LAB HOUSTON. IF YOU HAVE ANY
QUESTIONS, PLEASE CONTACT US.
*************************************************************************=
*
**
You can view this and earlier reports online at
http://www.viswalab.com/vlclogin.htm
Questions? Call Dr. R.Vis,
Tel(713)-842-1985 Fax(713)-842-1981
REPORT PREPARED Ms K Vis
```

Figure 54: MGO Fuel Certificate of Analysis

FROM
VISWA LAB

TO COLUMBUS SHIPMANAGEMENT GmbH
ATTN: MR. CHRISTOPH GESSNER

Fuel Sample CAP SAN LORENZO
VLC Log No. F100308631 Date 03/05/10
Bunk. Port and Date HOUSTON, USA - 03/03/10
Place and Date Sent -
Supplier ADA
Date Received at VLC 03/05/10
Sample Type per Customer MGO
Grade DMA LS
Tamper Proof 0198351 : Sealed

Customer furnished data:
Density 860.1 kg/m3
Viscosity 3 cSt
Quantity 40 M.Tons

SPECIFIED PARAMETERS FOR DMA LS

Density @ 15 degC 853.0 kg/m3 (890.0 Max)
API Grade 34.30 (27.40 Min)
Viscosity @ 50 degC cSt (Max)
Viscosity @ 100 degC cSt (Max)
Viscosity @ 40 degC 2.63 cSt
Upper Pour Point -9 degC (0 Max)
Carbon Residue 0.01 %wt. (0.30 Max)
Ash 0.003 %wt. (0.010 Max)
Water < 0.01 %vol. (0.00 Max)
Sulfur 0.02 %wt. (0.10 Max)
Sediment 0.00 %wt. (0.00 Max)
Vanadium 4 wt.ppm (0 Max)
Al + Si < 1 ppm (0 Max)
Flash Point > 70 degC (60 Min)

ADDITIONAL PARAMETERS

SI < 1 ppm
AL < 1 ppm
Na < 1 ppm
Ca 1 ppm
Fe 3 ppm
Pb < 1 ppm
Ni < 1 ppm
P < 1 ppm
Zn < 1 ppm
Mg < 1 ppm
CCAI
Calorific value 42.99 MJ/kg
Minimum Transfer Temperature degC
Injection Temperature (For 13 cSt Viscosity) degC
Engine Friendliness Number (EFN: 1-100)

GRADE CONFORMANCE
The fuel sample tested conforms to grade DMA LS.

COMMENTS
DENSITY WAS CONFIRMED BY REPEATED ANALYSIS. PLEASE NOTE THAT BUNKER DENSITY IS HIGHER THAN THE LAB MEASURED DENSITY.

VISUAL APPEARANCE - CLEAR AND BRIGHT
****
******
**
WITH EFFECT FROM 20TH FEB 2010, KINDLY FORWARD SAMPLES BUNKERED IN ROTTERDAM AND ANTWERP TO OUR LAB IN SINGAPORE USING THE APPROPRIATE AIR WAYBILLS INCLUDED IN THE SAMPLE KIT BOX. THIS INSTRUCTION

SUPERSEDES THAT GIVEN IN THE WORLD MAP ENCLOSED IN THE KIT. IF THE
FUEL IS PART OF A MACHINERY PROBLEM INVESTIGATION, KINDLY FORWARD TO
VISWA LAB HOUSTON. IF YOU HAVE ANY QUESTIONS, PLEASE CONTACT US.
****
******
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You can view this and earlier reports online at
http://www.viswalab.com/vlclogin.htm
Questions? Call Dr. R.Vis,
Tel(713)-842-1985 Fax(713)-842-1981
REPORT PREPARED Ms K Vis

Figure 55: Fuel Audit Results

SOUTHWEST RESEARCH INSTITUTE®

6220 CULEBRA RD. 78238-5166 • P.O. DRAWER 28510 78228-0510 • SAN ANTONIO, TEXAS, USA • (210) 684-5111 • WWW.SWRI.ORG

July 22, 2010

Charles Bufalino
University of California, Riverside
1084 Columbia Avenue
Riverside, CA 92507
Phone No.:(951) 781-5784
Fax: (951) 781-5790

Re: Fuel Analyses – PO# RT10297667
1.08.05 11831.01.001
SWRI WO # 53432

Dear Mr. Bufalino:

Analyses of your samples for Density and Sulfur by various methods have been completed, as requested. The two samples were received in 1 L containers on July 14, 2010 and were in good condition. Sample Identifications and test results are shown in the attached table.

Test aliquots were taken in accordance with ASTM test procedures. Analyses were performed in accordance with the test procedure with no deviations or modifications. The analyses pertain only to the sample(s) received by Southwest Research Institute and represent only a sampling of this batch. This report shall not be reproduced except in full without the express written permission of Southwest Research Institute. If you have any questions please call me at (210)-522-6920.

Sincerely,

Melissa T. Legg
Senior Research Scientist
Petroleum Products Research Department
Office of Automotive Engineering – Div. 08

OMTLBGV0
Page 1 of 2

HOUSTON, TEXAS (713) 977-1377 • WASHINGTON, DC (301) 881-0226

DATA SUMMARY FOR U.C. Riverside
July 22, 2010
SWRI WORKORDER #53432

D 4052 Density (API by Meter) at 60°F

Sample ID	MDO	HFO
API @ 60 F (15.5C)	34.2	11.7
Specific Gravity @ 60 F	0.8541	0.9879
Density @ 15.5C	0.8536	0.9872

D 2622 Sulfur - Wavelength Dispersive X-Ray Florescence

Sample ID	MDO	HFO
Sulfur, Weight %	0.01092	3.78968
Sulfur, ppm	109.2	37896.8

No uncertainties have been determined for these results, but ASTM repeatability may be referenced.

OMTLBGV0
Page 2 of 2

Engine testing

Since emission factors have to be determined after the emissions are stable for a few minutes and then sampling continues for up to 5 minutes or longer as required by the ISO- 8178 protocol, the University of California at Riverside (UCR) was not able to achieve meaningful emission factors at some of the operating modes, such as the maneuvering modes. Further the vessel does not normally change fuels during maneuvering or within the channel due to safety concerns so emission factors with statistical significance would be difficult to achieve. Instead, trends were obtained based on calculations, such as by comparing the fuels emission factors on different fuels at some of the modes of the ISO protocol and certain operating modes, although not necessarily in the same locations to allow a rough comparison of emission benefits.

GASEOUS EMISSIONS FOLLOWING THE SIMPLIFIED MEASUREMENT METHOD (SMM)

The concentrations of gases in the raw exhaust and the dilution tunnel were measured with a Horiba PG-250 portable multi-gas analyzer, which can continuously and simultaneously measure up to five separate gas components. Major features of the PG-250 include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. EPA ETV program.

For quality control, UCR followed Appendix 4 *Calibration of the analytical and measurement instruments* of the NTC and carried out analyzer checks with calibration gases before and after each set of tests. Instrument drift was held to less than 2%. Because the instrument measures the concentration of five gases, the calibration gases will be a blend of several gases (super-blend) made to within 1% specifications by Praxair (Los Angeles, CA). Specifications of the Horiba instrument are provided in Table 26; JUM is similar.

Table 26: Quality Specifications for the Horiba PG-250

Repeatability	±0.5% F.S.(NOx : ≦100ppm range CO : ≦1000ppm range) ±1.0% F.S.
Linearity	±2.0% F.S.
Drifft	±1.0% F.S./day(SO_2: ±2.0%F.S./day)

PEMS monitoring was done in parallel with the SMM. In cases where test durations for a given mode were less than 60 minutes, the auto zero function on the PEMS was turned off.

CALCULATION OF EMISSION FACTOR

The emission factor at each mode was calculated from the measured gaseous concentration, the reported engine load in kilowatts (kW) and the calculated mass flow in the exhaust. An overall single emission factor representing the engine is determined by weighting the modal data according to the ISO 8178 -E-3 and ISO 8178- D2 requirements and summing them. The equation used for the overall emission factor is as follows:

$$A_{WM} = \frac{\sum_{i=1}^{i=n} (g_i \times WF_i)}{\sum_{i=1}^{i=n} (P_i \times WF_i)}$$

Where:

A_{WM} = Weighted mass emission level (HC, CO, CO_2, $PM_{2.5}$, or NO_x) in g/kW-hr

g_i = Mass flow in grams per hour at the i^{th} mode,

P_i = Power measured during each mode, including auxiliary loads, and

WF_i = Effective weighing factor.

The calculated emission factor is strongly dependent on the mass flow of the exhaust. Exhaust flow rate was calculated as described below.

Calculation of the Exhaust Flow Rate Assuming the Engine as an Air Pump

This method has been widely used for calculating exhaust flow rate in diesel engines, especially stationary diesel engines. This method assumes the engine is an air pump, and the flow rate is determined from displacement of the cylinder, recorded rpm, with corrections for the temperature and pressure of the inlet air. This method assumes the combustion air flow equals the total exhaust flow. However, for low-speed, two stroke engines, there could be scavenger air flow while the piston is expanding and the exhaust valve is still open. This scavenger air would not be included in the air pump calculation leading to under predicting the total exhaust flow and the emission factors. The method works best for four stroke engines or for two-stroke engines where there the scavenger air flow is much smaller than the combustion air.

Appendix D – Related Information

U.S.EPA Fuel Switching Project Site: www.epa.gov/international/fuelswitch.html

U.S.EPA Ocean Vessels and Large Ships Site: www.epa.gov/oms/oceanvessels.htm

U.S.EPA National Clean Diesel Campaign Site: http://www.epa.gov/cleandiesel/

California Air Resources Board Commercial Marine Vessel Site: http://www.arb.ca.gov/ports/marinevess/marinevess.htm

American Petroleum Institute: API Fuel Switching Practices: http://www.klgates.com/FCWSite/ballast_water/air_emissions/API_Fuel_Switching.pdf