# Assessment of Remote Airborne Monitoring to Control Sulfur Emissions from Ocean-Going Vessels

**FINAL REPORT**

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## TABLE OF CONTENTS


**Abstract** 2

**Introduction** 3

**Research** 5

1 . Assessment of Associated Health Burdens 5

1.1 Introduction 5

1.2 Methods 6

1.2.1 WRF-Chem Model 6

1.2.2 BenMAP - Health Impacts 7

1.3 Results & Discussion 9

1.3.1 $SO_X$ emissions 10

1.3.2 $PM_{2.5}$-associated mortality 14

1.3.3 $O_3$ concentrations 17

1.4 Conclusions 17

1.5 Future Recommendations 19

2 . Cost-Benefit Analysis 20

2.1 Introduction 20

2.2 Methods 21

2.2.1 BenMAP - Economic Valuation of Improved Health Outcomes 21

2.2.2 Data Acquisition 23

2.2.3 Methods and Assumptions for Cost-Benefits 25

2.2.4 Methods for Sensitivity Analysis 29

2.3 Results & Discussion 30

2.4 Conclusions 33

3 . Fundraising & Support Campaign 35

3.1 Introduction 35

3.2 Methods 35

3.3 Results 36

3.4 Conclusion 38

4 . Activities to Support Field Experiments 39

4.1 Overview of Experimental Needs 39

**References** 41

**Appendix A: Air Quality & Health Burdens Report** 45

**Appendix B: Cost-Benefit Analysis Database** 63

**Appendix C: Database of Partners: Financial & In-Kind Support** 67

# Abstract

The transportation industry depends heavily on petroleum fuels. While legislation and alternative energy sources and fuels are gradually driving a departure from oil usage on land, ocean-going vessels (OGVs), or ships, remain heavily dependent on petroleum-derived products. As of 2014, the California Air Resources Board (CARB) enacted the California Sulfur Rule which aims to limit the sulfur content of fuels used by ships to 0.1% within 24 nautical miles of California's shorelines. Yet, faced with partial scrutiny and near- trivial consequences for non-compliance, OGVs face strong financial incentives to continue burning "bunker fuels" – the bottom of the barrel, sulfur-rich, noxious sludge that remains after petroleum processing. Current methods to test sulfur fuel content, which takes place only at berth, are limited and untargeted and have proven to be only partially effective. To facilitate the achievement of the public health benefits which empower these regulatory efforts, this project's primary focus was to investigate the use of sensor packages carried by Unmanned Aerial Vehicles (UAVs) to improve the efficacy of the inspection process via detecting and targeting non-compliant OGVs while still at sea. By mapping and modeling the health impacts, direct cost, and monetized benefits associated with the implementation of UAV and sensor payload technology; galvanizing interest in the affected communities; and pursuing support (e.g. financial, in-kind, and expressions of support), this Practicum team has materially aided The ADEPT Group, Inc., achieve its goal- which was to provide evidence supporting the necessity for full compliance with the California Sulfur Rule. To that end, the Practicum Team assessed the feasibility and cost associated with such UAV monitoring systems, as well as reviewed the science and novel technologies to be employed during applied research sea trials in October 2020.

# Introduction

The transportation industry depends heavily on petroleum fuels. While increasingly stringent legislation and alternative energy sources and fuels are slowly driving a departure from oil usage on land, ocean-going vessels (OGVs), or ships, remain heavily dependent on petroleum derived products. The continued reliance on fossil fuels has negative human health consequences. Exposure to sulfur-rich emissions from oil combustion correlates with long-lasting and severe health issues including asthma, pulmonary disease, lung cancer, and even death. Portside communities such as San Pedro and Wilmington in southern Los Angeles County, which are heavily populated by lower-income and ethnic minority groups, are disproportionately impacted by pollution from OGVs sailing in and out of the Ports of Long Beach and Los Angeles, the busiest port complex in North America.

As of January 1, 2020, new international regulations mandate that OGVs can no longer burn fuels exceeding 0.5% in sulfur content by weight. The California Sulfur Rule further limits the sulfur content of OGV fuels to 0.1% within 24 nautical miles of shorelines. Yet, faced with partial scrutiny and near- trivial consequences for non-compliance, OGVs have strong financial incentives to continue burning "bunker fuels" – the bottom of the barrel, sulfur-rich, noxious sludge that remains after petroleum processing. Current methods of testing sulfur fuel content, which take place once ships are at pier are only partially effective. Promising, novel tools are in development to cost-effectively extend the range of emission monitoring capabilities to detect marine cheats at sea, before they can significantly impact the health of those who live and work in or near California's commercial ports.

This project carries out research into the many environmental and human health consequences attributed to OGV high sulfur fuel combustion as well as analyzes the effectiveness of UAVs equipped with sensor payloads to ensure regulatory compliance. Current emission regulations lack effectiveness if they are not properly enforced. To achieve better public health outcomes, as intended by regulatory efforts, the primary focus of this project is to investigate the use of Unmanned Aerial Vehicle (UAV) sensor packages to improve detection of OGV non-compliance at sea. The hope is that a judicious implementation of these recent technological advances will cause a positive OGV behavior modification that results in the: (i) lifting of a significant health burden imposed on vulnerable coastal communities, (ii) redressing of directly linked environmental injustices, and (iii) setting a precedent for non-Californian ports to follow.

The report addresses six research questions, each discussed in its corresponding section:

(1) What is the distribution and magnitude of health burdens resulting from particulate matter and sulfur -- among other chemical species -- emitted by OGVs on communities in and around the San Pedro Bay ports? In particular, what are estimates for associated premature deaths and diseases in two compliance scenarios: (a) 100% compliance and (b) 10% cheating? (Section 1)

(2) What is the monetary value of preventing the health impacts associated with non-compliant OGV emissions? (Section 2)

(3) What are the methods and protocols for ship emission monitoring in European Union countries? What are their costs, benefits, and limitations? What are the costs to replicate a variant of such programs near California's commercial ports? (Section 2)

(4) What additional public and private funding resources/agencies can be incentivized to co-fund emission testing of OGVs sailing in sea traffic lanes in and out of the Bays of San Francisco and San Pedro? What are the best strategies to approach said funding institutions? (Section 3)

(5) What are potential outreach avenues (media coverage, public forum, community events, etc.) to galvanize interest in such a project and to attract co-funding partners? (Section 3)

(6) What is the best technology available to measure the distance- reliably and cost-effectively- from a UAV to an OGV smokestack in real-time? (Section 4)

By mapping and modeling health impacts, analyzing drone technology, and galvanizing interest in the affected communities as well as pursuing support (e.g. financial, in-kind, and expressions of support), this Practicum team has materially helped The ADEPT Group, Inc., achieve its goal to co-fund and conduct a specific set of at-sea scientific trials. It is anticipated that such tests can rapidly lead to more cost effective as well as more impactful enforcement that will subsequently engender greater OGV compliance with regional, national, and international air quality regulations. These UAV and sensor package tests are anticipated to also aid other entities within the US to enforce air quality regulations.

This project aims to increase the risk of non-compliance by helping to implement enhanced targeting and monitoring system that is rapid, effective, and impactful.

# Research

## 1. Assessment of Associated Health Burdens

### *1.1 Introduction*

On January 1st, 2020, IMO's new global sulfur cap regulations came into effect, declaring 0.50% as the new global limit for sulfur content in marine fuel oil (IMO, 2020). In IMO designated Emission Control Areas (ECAs), this limit is further reduced to 0.10% sulfur content by mass. Prior to January 1, 2020, OGVs were allowed to burn high sulfur "bunker fuels" -- which were first capped at 4.50% and then later at 3.50% sulfure content by mass. Since 2014, the 'California Sulfur Rule' has required the use of low sulfur marine fuels, currently at or below 0.10% sulfur by mass within 24 nautical miles of the California coastline (Fuel Sulfur and Other Operational Requirements for Ocean-going Vessels within California Waters and 24 Nautical Miles of the California Baseline, 2008). While past iterations of these regulations were implemented to reduce environmental and health burdens worldwide, challenges to their full enforcement continue to exist.

The combustion of non-compliant marine fuel oil contributes to highly localized emissions of dangerous pollutants, most importantly the oxides sulfur ($SO_X$). More than 13% of global $SO_X$ emissions, 15% of global $NO_X$ emissions, and 3% of global $CO_2$ emissions are attributed to OGVs and these emissions are expected to reduce by up to 77% under the most recent mandates (IMO, 2020). $SO_X$ encompasses gaseous sulfur oxides such as sulfur monoxide (SO), sulfur dioxide ($SO_2$), sulfur trioxide ($SO_3$), or secondary particular sulfates ($SO_4^{2-}$), and sulfites ($SO_3^{2-}$).

Secondary particulate sulfites consist of a combination of sulfuric acids, ammonium bisulfate, and ammonium sulfate, and are formed through transformations of sulfur dioxide emissions either through gaseous or aqueous pathways. For the former, sulfur oxides react with hydroxyl radicals to form hydrogen sulfite, which then reacts with oxygen and water vapour to form gaseous sulfuric acid (Transportation Research Board, 2002; Lin *et al.*, 2011).

$$SO_{2(g)} + OH\bullet + M \Rightarrow HOSO_2\bullet + M \quad (1)$$
$$HOSO_2\bullet + O_{2(g)} \Rightarrow HO_2\bullet + SO_{3(g)} \quad (2)$$
$$SO_3 + H_2O_{(l)} + M \Rightarrow H_2SO_{4(g)} + M \quad (3)$$

This gas has two possible endpoints: condensation on existing particles as a sulfuric acid droplet or neutralization to ammonium sulfate or bisulfate in the presence of ammonia gas. Sulfur dioxides can also directly condense in foggy or cloudy conditions, and then oxidize with ozone or hydrogen peroxide to form sulfuric acid without intermediate products thereby resulting in acid rain (Transportation Research Board, 2002; Lin *et al.*, 2011).

$$HSO_3^-{}_{(aq)} + H_2O_{2(aq)} \Leftrightarrow SO_2OOH^-{}_{(aq)} + H_2O_{(l)} \quad (4)$$
$$O_{3(aq)} + SO_3^{2-}{}_{(aq)} \Rightarrow O_{2(g)} + SO_4^{2-}{}_{(aq)} \quad (5)$$

These secondary sulfates have been proven to represent up to 100% of atmospheric sulfate measured and are a major contributor to mass fractions of fine particulate matter ($PM_{2,5}$, particles with aerodynamic diameters less than or equal to 2.5 μm). Atmospheric concentrations of secondary sulfates can increase up to 68% at sites of combustion- such as near OGV smokestacks- compared to pre-combustion levels, within 20 km of the combustion source (Buzcu *et al.*, 2006).

There is a myriad of health issues associated with inhalation of $SO_X$ emissions and associated exposure to $PM_{2.5}$, both of which result from the burning of high sulfur content fuels in OGVs (EPA & OTAQ, 2010). Clinical, epidemiological, and toxicological studies indicate that there exists a causal relationship between short-term exposure to atmospheric emissions and respiratory morbidity (WHO, 2013). Sulfur dioxide, or sulfur oxides in general, "irritate the mucous membranes of the eyes, nose, throat, and lungs" and can cause a host of symptoms including inflammation, difficulty in breathing, and reduced lung and heart function (NPS, 2018). Nitrogen oxides similarly irritate the respiratory and cardiovascular systems. They are also associated with abdominal pain, fertility issues, and genetic mutations in future generations (U.S. National Library of Medicine, n.d.).

It is important to reiterate the contribution that the transformation of sulfur oxides to secondary sulfate particles has on the rising concentrations of atmospheric $PM_{2.5}$. $SO_X$ and $PM_{2.5}$ concentrations are positively correlated. As such, the increase in $PM_{2.5}$ concentrations as a result of an increase in atmospheric $SO_X$ species can be quantified. These fine particulates are *most* closely associated with oxidative stress, airway hyper-responsiveness, respiratory distress, and decreases in lung function contributing to premature deaths, even more so than $NO_X$ and $SO_X$ (Guarnieri & Balmes, 2014).

Air pollution can affect human health in both the short and the long-term and is linked with premature mortality and reduced life expectancy from lung cancer, asthma attacks, respiratory infections, and long-term respiratory and heart disease (Kampa & Castanas, 2008).

The objective was to first model the differences in atmospheric concentrations of $SO_X$ species and $PM_{2.5}$ and then quantify the associated health burdens measured in the number of cases of lower respiratory symptoms, acute bronchitis, mortality (all causes), cough and asthma exacerbation for two distinct scenarios. The first scenario assumes 100% compliance to the California Sulfur Rule while the second assumes a 10% non-compliance rate. This model was chosen as an approximation based on reports from OGV emissions monitoring and enforcement by the European Union Sulfur Directive. These EU efforts show that there was a range of non-compliance rates from 5-15% at sea, but 5% at port. This latter figure was considered to also apply regionally from an interview with expert Alex Barber, a California Air Resource Board (CARB) inspector, who reported an average 96.5% compliance based on inspections conducted at Californian ports since 2009. However, since the intent of the research at hand was to assess the effectiveness of extending the OGV inspection range from just port-side to actual at-sea assessments of smokestack emissions, a non-compliance scenario of the average of the reported 5-15% range was used (e.g. 10%).

## *1.2 Methods*

### *1.2.1 WRF-Chem Model*

To understand air quality differences between the 100% compliance and the 10% non-compliance scenarios, the Weather Research and Forecasting (WRF) model coupled with Chemistry was used. This WRF-Chem modeling system simulates emissions, transport, mixing, and reacting of chemical constituents, particularly trace gases and aerosols, in various meteorological conditions.

The simulation ran over a domain that covered the western U.S. in grids at a resolution of 4km x 4km. The vertical scale of the simulation, from surface level to 100 hPa, was divided into 24 layers. Over the ocean, the surface layer is approximately 37m thick and there are nine layers within 1km. Thus, the model adequately captures the mixing layer and has subsequently been used in multiple studies for similar assessments such as Wang, *et al.*, (2019).

Meteorological data over this 3D domain was gathered from the Final Operational Global Analysis data (ds083.2) of the National Center for Environmental Protection. Anthropogenic emissions are from the CARB emissions inventory with the Southern California domain replaced by emission from the South Coast Air Quality Management District (SCAQMD) where shipping lanes are explicitly resolved. Here, the data used was for the month of July 2012.

The model was run for an observation period, from 1st July to 1st August 2012 with 6 hour intervals such that four grid outputs were generated per day. In addition, a 6-day spin-up period was run from June 26th to July 1st. This was to minimize the effect of initial conditions or perturbations on the results of the simulation. To generate a grid of emissions it is important to understand how the chemicals are speciated and mapped over California, the simulation domain. A complete list of specifications is found in Wang, *et al.*, (2019).

Scaling of shipping emissions was achieved using data derived from CARB's Access Database. This database has two outputs which can be used to create a general snapshot of the net OGV emissions when OGVs are exclusively burning either high sulfur fuel oils or compliant low sulfur fuel oils. As this is a binary view of emissions, 10% non-compliance was calculated by using a weighted average of the two database emission factors. The first was multiplied by 0.10 and the second was multiplied by 0.90. The sum of these provided a 2.2 scaling factor to sulfur emissions from shipping which was needed to calculate air quality results for the 10% non-compliance case. The assumption has been made that the effects, in terms of the amounts of $SO_x$ generated, of the relative gravity of the OGV violations- which can range from slightly over 1.3% sulfur (likely an unintended violation) to 3.0% sulfur (gross cheating)- is already accounted for in the modeling tools to which the team was directed and utilized. For non-sulfur species, changes in emissions were estimated using the in-built WRF-Chem equations which summarize how other atmospheric chemical species concentrations change with respect to perturbations in sulfur species.

#### *1.2.2 BenMAP - Health Impacts*

Health Impact Functions (HIFs) were derived from epidemiological studies that associate air pollutant concentrations with targeted health effects. A HIF incorporates four key parameters: population data, air quality data, baseline mortality and morbidity rates, and a health risk estimate. Three health endpoints among different age groups are of particular interest.

The Environmental Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE) is an open-source software developed by the US Environmental Protection Agency (EPA). It calculates estimates for the number of air pollution-related morbidity and mortality cases over a specified spatial domain. The program provides a navigable graphical user interface (GUI) with pre-loaded databases that supplement the user-required data inputs in quantifying health impacts of air pollution.

There were six datasets required in the setup to calculate air pollution-related health impact estimates of interest. This included the grid definitions, pollutant attributes, monitoring data, incidence rates, population data, and the HIF. While some datasets were user-required inputs, others were provided by the BENMAP50.FDB and POPSIMDB.FDB databases of the software program.

Grid definitions identify geographic cells to which the air quality data, population data, incidence rates, and health impact functions will be assigned. The primary grid definition was provided by Wang *et al.,* (2019), and specified the region intended for analysis. The attribute table included two integer fields specified as Column and Row, with each polygon of the shapefile containing a non-repeating combination of values for the two fields. This allowed for a direct association between the shapefile grid definition, incidence/prevalence data, and the air quality modeling data. A crosswalk between the primary grid definition and all other pre-loaded grid definitions in the setup was then created. This step allowed BenMAP-CE to aggregate population data, incidence/prevalence rates, health impact functions, and other datasets at the geographic resolution of our analysis.

The pollutant of primary interest was $PM_{2.5}$, which is correlated with atmospheric $SO_X$ concentration. Its air quality metrics were subsequently defined. The main metric was D24HourMean, which describes a daily average of the hourly measurements taken to observe pollutant concentrations. The seasonal metric was defined as QuarterlyMean, which allowed aggregation of the daily pollutant concentration values over a specified period of time within the year. In this case, it was the observation period for which the WRF-Chem model was run: July 1st to August 1st.

The BENMAP50.FDB database provided baseline incidence and prevalence rates data required for the HIFs. BenMAP-CE provided census block population data that included over 200 age, gender, and race-specific variables. Population data was required to estimate exposure to specified health endpoints and adverse health impacts due to the change in air quality and pollutant concentrations.

BenMAP provided a database with a library of HIFs derived from multiple peer-reviewed epidemiological studies. The HIFs and corresponding health endpoints chosen for this analysis were sourced from the EPA Standard Health Functions dataset.

Following the setup modifications, the second stage involved creating the air quality surfaces, which have a grid structure that allows uniform grid cells to be populated with average pollutant concentration values in order to estimate population exposure. BenMAP-CE is dependent on air quality inputs from external modeling software or monitoring data. Our project employed the Model Direct approach to create the baseline and control air quality grids, which represented 90% and 100% compliance to the California Sulfur Rule scenarios respectively. The air quality input files were formatted to include the following variables: column, row, metric, seasonal metric, annual metric, and values.

The $PM_{2.5}$ concentration data from the WRF-Chem model was interpolated onto the primary grid definition to align the air pollution values with the unique column and row values assigned. Prior to importing the baseline and control air quality grids, the previously loaded shapefile grid definition was specified as the grid type. After the files passed the validation tests, an air quality delta air quality grid (baseline - control) was generated.

A BenMAP configuration file was built to estimate the incidence of adverse health effects due to the change in $PM_{2.5}$ concentration values. This file contained the parameters required for analysis, including the air quality grids, health impact functions, and population data, among others.

The chosen population dataset and year was the United States Census from 2012, which corresponded to the WRF-Chem modeled data. Incidence in BenMAP is defined as the "total number of adverse health effects avoided due to a change in air pollution levels," (U.S. EPA, 2015). Three representative health endpoints from the EPA Standard Health Functions Dataset were chosen. The first health endpoint was Mortality, All Cause among 30 to 99-year olds with the HIF derived from an epidemiological study by Krewski *et al*., (2009). The second health endpoint was Asthma Exacerbation, Cough among 6 to 18-year olds with the HIF derived from an epidemiological study by Ostro *et al*., (2001). The third health endpoint was Acute Bronchitis among 8 to 12-year olds with the HIF derived from an epidemiological study by Dockery *et al*., (1996). Incidence outputs are ttributed to $PM_{2.5}$ emissions associated with $SO_X$ emissions from OGVs as modelled in this paper and are thus free from confounding environmental factors or background industrial activities.

**Table 1-1:** Health Burdens Due to 10% Non-Compliance to the California Sulfur Rule; Generated by BenMAP

| Incidence* Categories | Affected Age Groups | Health Impact Function (HIF) | Incidence* |
|---|---|---|---|
| Acute Bronchitis | 8 to 12 years old | $\left(1 - \frac{1}{(1-I)\, e^{(\beta*\Delta Q)+I)}}\right) * I * \mathrm{P}$ | 40 |
| Asthma Exacerbation | 6 to 18 years old | $\left(1 - \frac{1}{(1-\mathrm{A})\, e^{(\beta*\Delta Q)+A)}}\right) * \mathrm{A} * \mathrm{P} * \mathrm{R}$ | 618 |
| Mortality (All Causes) | 30 to 99 years old | $\left(1 - \frac{1}{e^{(\beta*\Delta Q)}}\right) * I * \mathrm{P}$ | 24 |

*Incidence defined as the total number of adverse health effects (cases) avoided due to compliance with the California Sulfur Rule

$\beta$ : coefficient for the health impact function; typically represents the percent change in a given adverse health impact per unit of pollution

$\Delta Q$ : absolute air quality change in $PM_{2.5}$ concentrations between the baseline scenario (90% compliance) and control scenario (100% compliance)

$I$ : health baseline incidence rate; estimate of the average number of people who die (or suffer from an adverse health effect) in a given population over a given period of time

$P$ : exposed population; number of people affected by the reduction in air pollution

$R$ : prevalence rate; percentage of individuals in a given population who already have a given adverse health condition

$A$ : parameter from epidemiological study by Ostro et al.; weighted average of the daily prevalence of cough among 8 to 13 year olds

## *1.3 Results & Discussion*

The WRF-Chem model was run with the specifications described in the previous section to estimate the concentrations of various chemical species as a result of a 100% compliance (baseline scenario) and 10% non-compliance to the California Sulfur Rule during the month of July 2012. The results in this section include plots showing the absolute difference in chemical species concentrations between the 100% compliance and 10% non-compliance scenarios. In addition to these are maps of the ratio of this difference to the baseline 100% compliance scenario. This latter map delineates the effect that non-compliance can have with respect to the ambient air quality that can be expected when inland businesses and industries continue their activities as per their norm but with the California Sulfur Rule in place. For example, if a point on this map takes the value of *x*, then this means that the difference in species concentration at that point is *x*% of the baseline concentration. As observed, $x$ is greater than 100 for many of the chemical species in question. Together, these two interpretations of the results provide a picture of the degree and spatial extent of air quality changes because of 10% non-compliance to the California Sulfur Rule (see Table 1-2).

**Table 1-2:** Emission Changes at Hotpots$^{\Psi}$ Due to 10% Non-Compliance to the California Sulfur Rule, as Generated by WRF-Chem

| Species | Difference from Baseline* | Increase as a Percent of Baseline* |
|---|---|---|
| | $\mu g\ m^{-3}$ | % |
| Sulfur Dioxide ($SO_2$) | 0 - 4 | 80 - 120 |
| Sulfate ($SO_4^{2-}$) | 0.3 - 0.5 | 20 - 35 |
| Ammonium ($NH_4^+$) | 0.05 - 0.1 | 8 - 12 |
| Particulate Matter ($PM_{2.5}$) | 0.3 - 0.5 | 1 - 3 |

$^{\Psi}$ Hotpots spatially correlated with shipping lane and Ports of LA & Long Beach
* Baseline being ambient chemical species concentration during July 2012 as a result of 100% compliance with the California Sulfur Rule

### *1.3.1 $SO_X$ emissions*

The most direct improvement in ambient air quality that the California Sulfur Rule aims to achieve is a reduction in $SO_X$ emissions, particularly in and around ports and coastal communities. To understand the extent of such improvements, the following species were analyzed: $SO_2$, $SO_4^{2-}$, and $NH_4^+$. The objective is to show how $SO_2$ concentrations change when non-compliant OGVs burn fuels that contain more sulfur than is permitted, in addition to how atmospheric chemistry then encourages the formation of ammonium sulfate as described in Equation (5). In Figure 1-1, on the left, it is noted that the absolute difference in $SO_2$ concentrations is dampened over land by a spike of 14 $\mu gm^{-3}$ that is observed immediately off the coast of the Port of Long Beach. This suggests that the impact of $SO_2$ emissions because of OGV non-compliance is highly concentrated on communities in and near ports and along a narrow strip along the coast. Notably, the difference itself can reach 14 $\mu gm^{-3}$ and that the spatial extent of this peak is dependent on meteorological conditions which have only been modeled for a single month. Conclusions from over a longer period of observation and in varying environmental conditions have yet to be drawn.

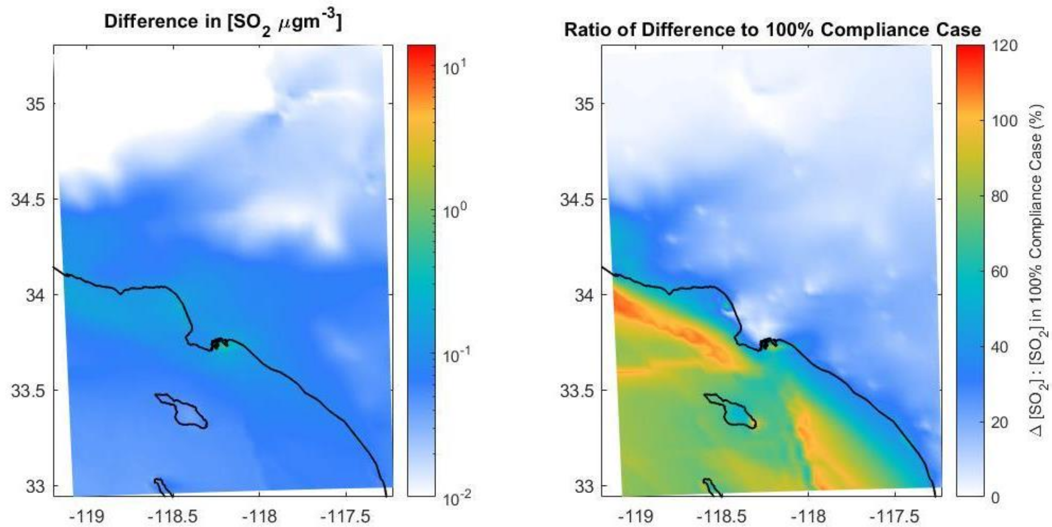



**Figure 1-1:** *Plot of: the difference in concentration of $SO_2$ between the two compliance scenarios (left); ratio of the difference in concentration of $SO_2$ to the concentration of $SO_2$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

Interestingly, the plot on the right of Figure 1-1 shows that the impact of the change in $SO_2$ concentrations as a result of non-compliance is substantial over the ocean when it is viewed as relative to concentrations of $SO_2$ in the baseline case. During the month-long simulation, it is clear that the change in $SO_2$ concentrations is between 100% to 120% of the baseline concentrations along the shipping lanes, which are markedly red-yellow in the plot. This can lead to several localized repercussions. A study of $SO_2$ emissions and their impact on marine ecosystems may be worth investigating to grasp a complete picture of some of these implications, particularly those which bring into question the sensitivity of marine species and ecosystems to perturbations of this magnitude. Additionally, it is important to note that, as a result of the shipping lines running close to the coast and extending both north and south of the ports, $SO_2$ concentrations directly along the coast can potentially increase by an average of 30% of the baseline concentrations if 10% of OGVs are non-compliant, a non-linear relationship further discussed after Figure 1-4.

The contribution of non-compliance in increasing $SO_2$ concentrations decreases further inland but is highest at the Port of Long Beach, where the increase in $SO_2$ concentration is around 80% the baseline concentration. As such, the change in $SO_2$ concentrations as a result of non-compliance is dramatic when compared to the baseline, even if the absolute increase in concentrations is relatively small.

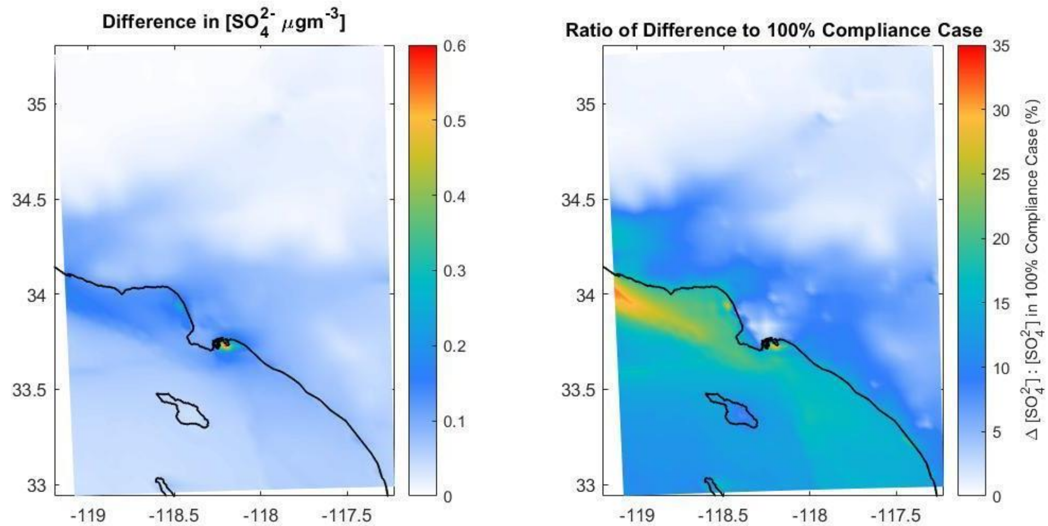



**Figure 1-2:** *Plot of: the difference in concentration of $SO_4^{2-}$ between the two compliance scenarios (left); ratio of the difference in concentration of $SO_4^{2-}$ to the concentration of $SO_4^{2-}$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

When analyzed in the context of $SO_4^{2-}$ concentrations, a very different view of $SO_X$ emissions is gained. Figure 1-2 shows that $SO_4^{2-}$ concentrations increase by a much smaller amount but that the increase is reflected across a wide spatial extent. Concentrations are expected to increase by around 0.5 μgm$^{-3}$ over the ocean, particularly along the shipping lines to the north and to the west of the Bay of San Pedro. This is consistent with the plot on the right, where, along the same shipping lines, the increase in $SO_4^{2-}$ concentrations is around 30% of the baseline concentrations. On the other hand, concentrations of $SO_4^{2-}$ along the coast and even a few miles inland are expected to increase by only around 0.1 μgm$^{-3}$. The most concentrated increase, once again, is right over the Port of Long Beach, where an increase in $SO_4^{2-}$ concentrations of almost 0.6 μgm$^{-3}$ is observed.

The increase in $SO_4^{2-}$ concentration relative to the baseline concentrations that can be expected is substantial, even many miles inland. As is shown on the right of Figure 1-2, much of the land along the coast can experience an increase in $SO_4^{2-}$ concentrations up to 10% of the baseline concentration. However, the closer one gets to the ports, the further inland this increase can be experienced. Further north and south of the port, the increase in $SO_4^{2-}$ concentration is only localized to a thin stretch along the coast. This means that, as was the case in Figure 1-1, the baseline concentrations of $SO_4^{2-}$ are low; however, the change that can occur as a result of just 10% non-compliance is a sizable fraction of ambient level and particularly exacerbated around the ports. This observation is useful when assessing the sensitivity of the populations and ecosystems to changes in such factors.

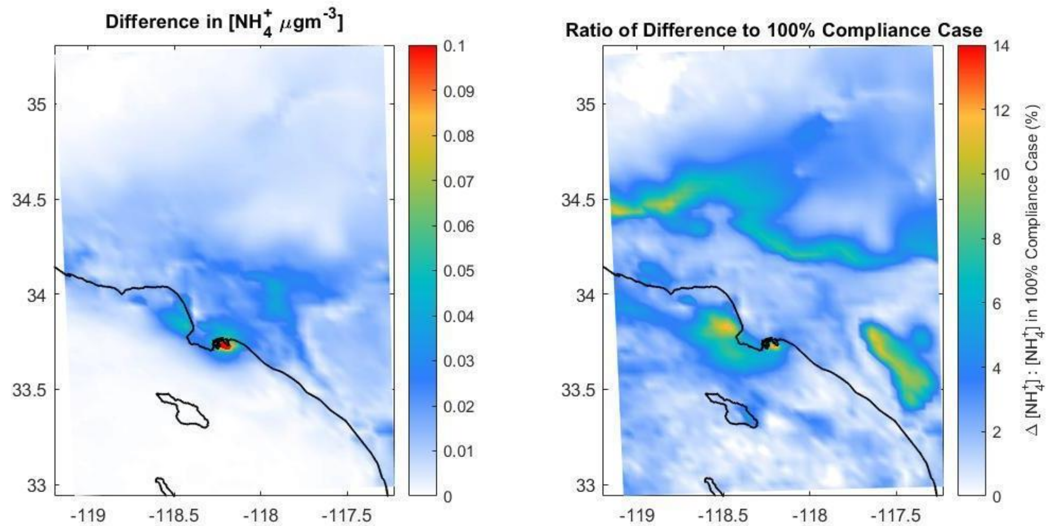



**Figure 1-3:** *Plot of: the difference in concentration of $NH_4^+$ between the two compliance scenarios (left); ratio of the difference in concentration of $NH_4^+$ to the concentration of $NH_4^+$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

It is important to note that atmospheric $SO_4^{2-}$ is often in the form of ammonium sulfate. For this reason, it is necessary to look at the spatial distribution of $NH_4^+$ concentrations under the same simulation. Atmospheric $NH_4^+$ has both natural and anthropogenic sources, including ammonia-based fertilizers, animal by-products, and some industrial processes (Behera *et al*., 2013). This explains why the absolute difference in $NH_4^+$ between the two cases is minimal and on the order of 0.05 $\mu gm^{-3}$ except just off the coast of the Port of Long Beach where it is 0.1 $\mu gm^{-3}$. Looking at the plot of the ratio of the difference to the baseline, a "plume" is observed in and around the ports, but which extends mainly off the coast rather than inland. Here, the difference in $NH_4^+$ concentrations is between 8 to 12% the baseline concentrations. Two additional "plumes" are noted much further inland. One is located southeast of the ports while the other forms a band that is directly north of the ports. These "plumes" are hypothesized to visualize how the mountain ranges surrounding the LA basin trap pollutants and can result in the accumulation of pollutants and chemical species in areas far away from their sources. To better analyze such movements and trapping that can occur under different environmental conditions a longer period of observation is required.

$NO_3^-$ is another chemical species that is associated with fuel emissions and often competes with $SO_4^{2-}$ to chemically bind with atmospheric $NH_4^+$. Thus, a spatial understanding of $NO_3^-$ concentrations illuminates which of the two species is limited and how they contribute to $PM_{2.5}$ concentrations over land or over the ocean. In Figure 1-4, there is an overall decrease in $NO_3^-$ concentrations over the ocean due to non-compliance. This is particularly true along the shipping lanes where there is a decrease of between 0.1 and 0.2 $\mu gm^{-3}$. Here, $NO_3^-$ decreases where $SO_4^{2-}$ concentrations increase. This shows that over the ocean, where $NH_4^+$ concentrations are limited, $NO_3^-$ is displaced by $SO_4^{2-}$, thereby resulting in a minimal change in $PM_{2.5}$ concentrations (Figure 1-5). Over land and particularly along the coast, $NH_4^+$ is no longer limiting, as seen in Figure 1-3. Here, $PM_{2.5}$ concentrations increase as both $NO_3^-$ and $SO_4^{2-}$ can chemically bind with the ambient $NH_4^+$ contributing to particulate matter. A map of $PM_{2.5}$ concentrations is used to understand the effect of atmospheric composition on portside communities.

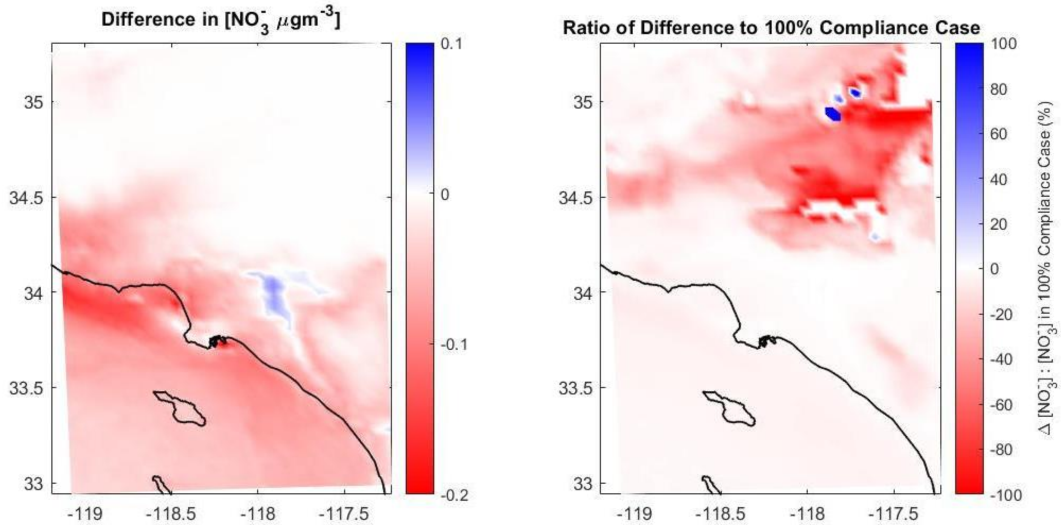



**Figure 4:** *Plot of: the difference in concentration of $NO_3^-$ between the two compliance scenarios (left); ratio of the difference in concentration of $NO_3^-$ to the concentration of $NO_3^-$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

### *1.3.2 $PM_{2.5}$-associated mortality*

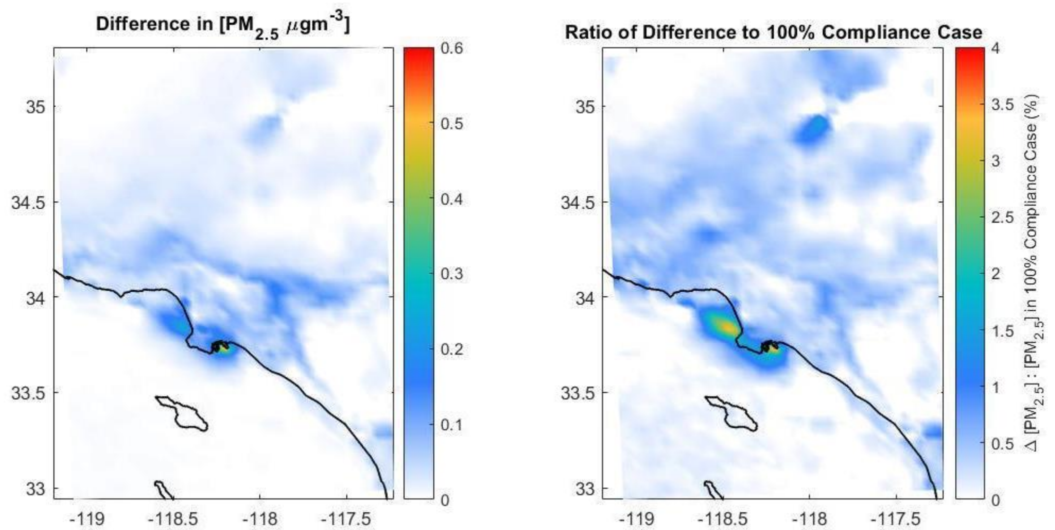



**Figure 1-5:** *Plot of: the difference in concentration of $PM_{2.5}$ between the two compliance scenarios (left); ratio of the difference in concentration of $PM_{2.5}$ to the concentration of $PM_{2.5}$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

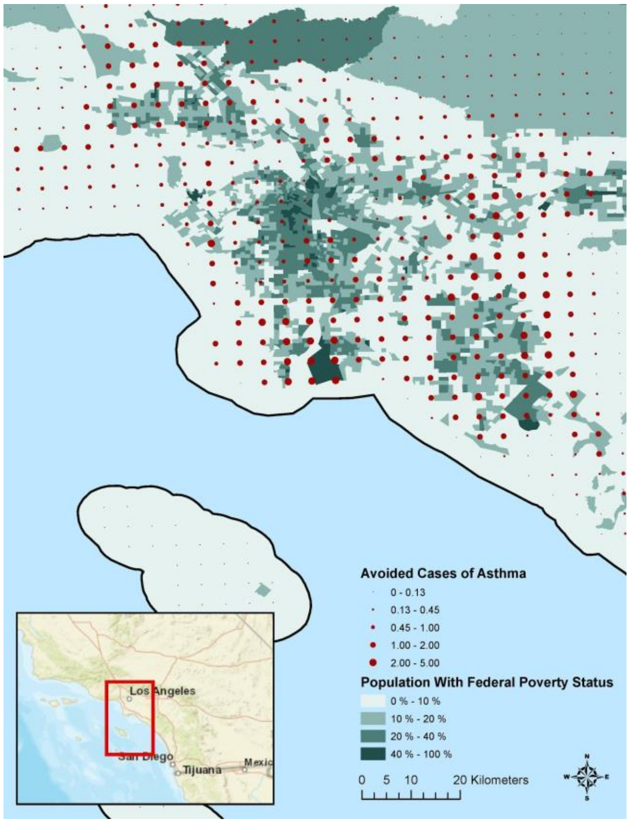
The WRF-Chem results for $PM_{2.5}$ concentrations were used as inputs in the health impact analysis that was completed on BenMAP. Spatially, concentrations of $PM_{2.5}$ are greatest in and around the Ports of LA and Long Beach. The peak in absolute difference is well correlated with the location of peaks in $SO_X$ concentrations: they are all observed just off the coast of the Port of Long Beach. In addition, it was noted that the change in concentration around the port is at most 3.5% of the baseline concentration of $PM_{2.5}$. From Figure 1-2, the change in $SO_4^{2-}$ concentration was increased by 10% of the baseline concentration of $SO_4^{2-}$ in the same region. In Figure 1-1, increases in $SO_2$ concentrations directly along the coast was 30% of the baseline concentration. This shows that $SO_2$ and $SO_4^{2-}$ contribute significantly to the rise in $PM_{2.5}$.

Visualizations for Figure 1-6 were modeled in ArcGIS: shapefiles with incidence values were sourced directly from BenMAP-CE; poverty data per census tract, and TIGER/Lines shapefiles were downloaded from the U.S Census Bureau.

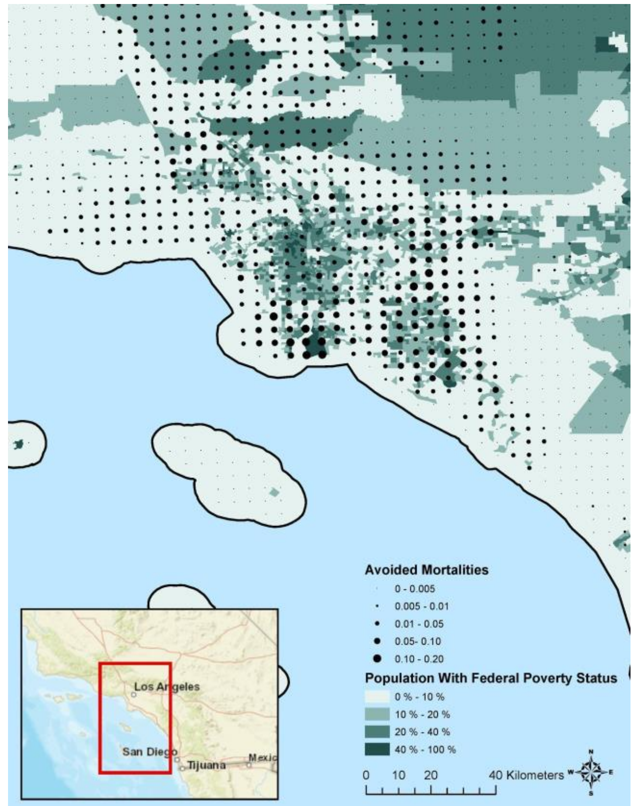
These maps visualize the spatial distribution of the total 24 deaths among 30 to 99 year olds and multiple hospitalizations: 618 cases of asthma exacerbation among 6 to 18 year olds, and 40 cases of acute bronchitis among 8 to 12 year olds caused by $PM_{2.5}$ exacerbation due 10% noncompliance. High incidence rates for all three categories: asthma exacerbation, acute bronchitis, and all-cause mortality, are concentrated in hotspots where $PM_{2.5}$ concentrations are greatest -- near the coast closest to the Port of LA and Long Beach and also at the eastern end of the basin around Riverside and San Bernardino where secondary pollutants accumulate.

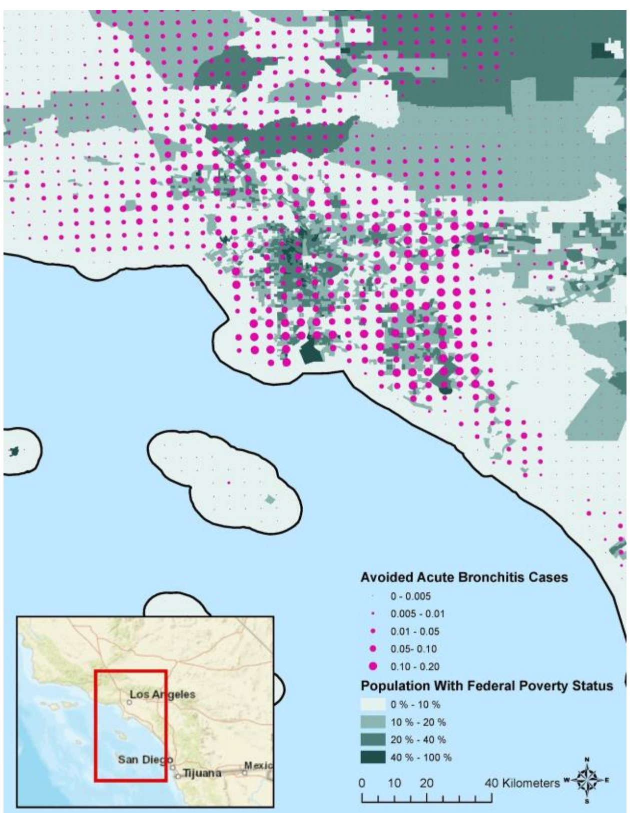
As seen in the maps, when overlayed on poverty, there is a spatial correlation where higher incidence rates for asthma exacerbation, acute bronchitis, and all-cause mortality are highly correlated with census tracts where populations have extremely high percentages of poverty. This has important environmental justice implications, since the burden of health risks is laid on those in poverty who are often disenfranchised and without health care.

**A.**




**B.**




**C.**

**Figures 1-6A-C:** *Maps visualizing geographical distributions of the change in morbidity and mortality incidence/prevalence rates due to* $PM_{2.5}$ *emissions (***A***: Asthma Exacerbation,* **B***: All Cause Mortality,* **C***: Acute Bronchitis) overlayed on top of populations with poverty status. Incidence rate magnitudes are represented by the size of dots (larger meaning more incidence) visualizing the number of annual avoided cases when compliance with California Sulfur Rule regulations increases from 90% to 100%; or in reverse, the cases caused by OGV* $PM_{2.5}$ *emissions due to 10% non-compliance. Poverty was determined by federal determination for poverty status in 2018, where darker hues represent higher percentages of the census tract population with poverty status.*

### 1.3.3 $O_3$ concentrations

An increase in $O_3$ concentrations is observed as a result of non-compliance. This rise is reflected east of the ports and continues significantly inland. As $O_3$ concentrations and speciation was not directly influenced by the WRF-Chem model which simulated non-compliance, this increase in $O_3$ concentrations is likely attributed to atmospheric chemistry and other processes that are stimulated by the change in atmospheric $SO_X$ species concentrations. It is also difficult to relate stratospheric chemical reactions, where $O_3$ usually accumulates, to changes in tropospheric compositions, even though the two layers are interrelated in many ways. It is still important to note, however, that the increase in concentrations of $O_3$ is up to 0.20 ppb directly east of the Ports and that this “plume” continues a little ways inland as well. The “plume” has a well-defined edge on its northern side, where topological features such as mountains encourage its accumulation and increase its longevity. In addition, it seems that the increase is small relative to ambient $O_3$ concentrations as the simulation only increases $O_3$ concentrations by 0.5% of the baseline concentration. Proportionally, the greatest increase is observed just inland of the Port of Long Beach, showing that the contribution of sulfurous OGV emissions is still measurable.

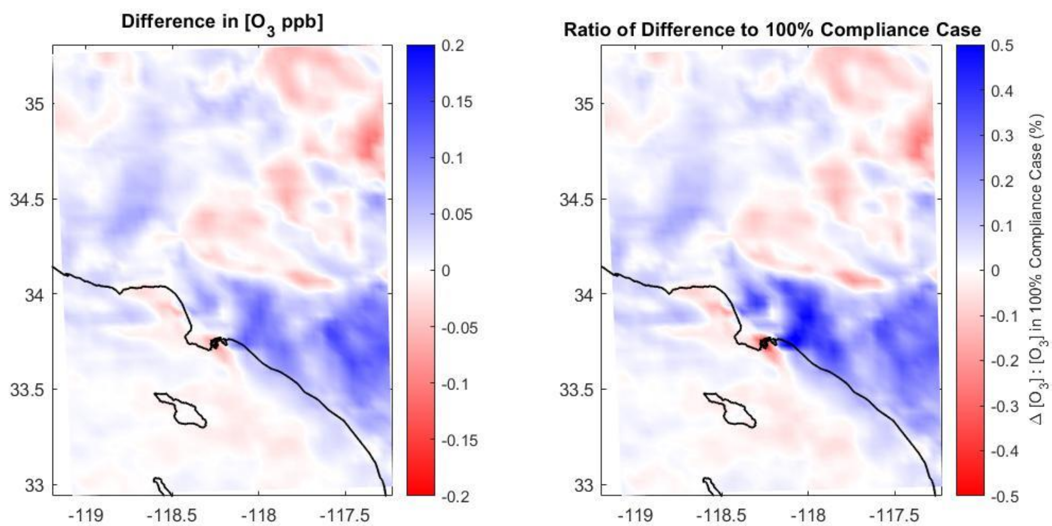



***Figure 1-7:*** *Plot of the difference in concentration of $O_3$ between the two compliance scenarios (left). Ratio of the difference in concentration of $O_3$ to the concentration of $O_3$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

## 1.4 Conclusions

While it is well documented that OGVs burning high-sulfur fuel have a drastic effect on public health, especially in Southern California where intense port-related activities create both occupational and public risks, air quality regulatory entities can benefit from better tools to enforce full OGV compliance with the California Sulfur Rule.

There is strong economic motivation to flout this rule due to several factors which include- though may not be limited to: (i) a difference over $200 per ton of clean fuel versus low sulfur fuel, (ii) a relatively low, non-targeted inspection rate of approximately 4 - 12 %, and (iii) the fact that these inspections can only be conducted at pier with a limited number of trained staff. Coupled with the fact that there is no checking for compliance while leaving the ports and that there is a known inspection pattern, it is clear that the levied penalties are minimal in comparison to the potential gain from non-compliance. There are convincing arguments that the pursuit of a more aggressive penalties structure for non-compliant OGVs can go a long way towards rapidly achieving the desired behavior modification.

A 10% non-compliance rate -- and its associated sulfur emissions -- has been modeled to account for an additional 24 deaths among 30 to 99-year olds and multiple hospitalizations each year, 618 cases of asthma exacerbation/coughs among 6 to 18-year olds, and 40 cases of acute bronchitis among 8 to 12-year olds, ceteris paribus.

As evident from the modeling results, there do exist emission hotspots associated with ports and shipping lanes; however, the degree of emission exacerbation in these hotspots cannot be proven to perfectly reflect real-world conditions, as exact conditions of compliance are unknown.

As with any model, unassailable conclusions on emission differences, nor their associated health burdens, can be drawn. However, results from past studies show that an 80% reduction in the sulfur content of OGV fuels from 2.7% to 0.5% sulfur by weight results in a 50% reduction in premature mortalities while a further 80% reduction from 0.5% to 0.1% sulfur by weight results in a 30% reduction in premature mortalities (Winebrake, *et al.*, 2009). Thus, it can be posited that the relationship between sulfur content of OGV fuels and the resultant health burdens is non-linear. As such, it is important to first understand the degree of non-compliance of OGVs in and around the Ports of LA and Long Beach so that the underlying assumptions in this study can be tuned to better capture the real-world conditions. This, in turn, will more clearly illuminate how the reduction in fuel sulfur content truly correlates with mitigating health burdens.

Approximately 40% of Americans live within coastal counties. This number grows to 60%, or 26.5 million people, in California (NOAA, 2016). Populations in many of the coastal counties are either heavily employed in or rely on the shipping industry, thus making research on the health impacts contributed by marine commercial activity highly relevant (Coker & Sok, n.d). Looking at the case of Southern California, it is known that OGV activity at large ports, such as the Ports of LA and Long Beach, endangers the health of nearby communities in Long Beach, Belmont Shore, the Westside, San Pedro, Harbor, Wilmington, West Carson, and Lomita as seen during spatial visualization of aforementioned health burdens. Based on proximity to loading and unloading docks, it is acknowledged that these regions are vulnerable to public health harms caused by emissions from the combustion of sulfur-rich fossil fuels. What has not been acknowledged to date are the additional "hidden" ill health effects from unreported sulfur emissions from yet to be recognized non-compliant OGVs. If these suspected health effects continue to be ignored, the necessary mitigating measures are unlikely to be taken to protect human health and lives.

Quantifying the incidence and progression of mortality and human health endpoints is a critical component of regional health risk assessments and the policy decision-making process of air pollution-based regulatory agencies such as the California Air Resources Board (CARB) and the South Coast Air Quality Management District (SCAQMD). Despite legislation that mandates a reduction in the sulfur content of fuels, OGVs and their emissions will still account for approximately 250,000 deaths and 6.4 million childhood asthma cases each year globally (Sofiev, *et al.,* 2018). Thus, it is hoped that this research will galvanize interest in enhancing the existing inspection practices -- specifically frequency and range -- to explore the full potential of implementing aerial monitoring and active targeting systems at a level similar to that of Unmanned Aerial Vehicles (UAVs) being used in the EU. The expectation is that such enhanced aerial monitoring will yield less pollution and greater fines from sulfur rule violators. Of note is that in Norway, aerial monitoring has reportedly paid for itself in one year from the collected fines.

This research indicates that deploying a small number of UAVs, suitably equipped with sensor package payloads, can significantly help to identify and catch non-compliant OGVs on a real-time basis, and thus discourage non-compliance. This can greatly lower negative health effects from the suspected OGV non-compliance highlighted in this study, resulting in significant air quality improvement, a drop in air pollution-related morbidity and mortality, and an overall rise in the quality of life for disadvantaged communities in and around the ports.

### *1.5 Future Recommendations*

While the spatial analysis examined general regions where the incidence of health effects was localized, a more substantial manipulation of data with ArcGIS could assess the aforementioned health impacts for individual communities and cities, galvanizing local interest in enhanced UAV based enforcement- which can result in additional program co-funding. AB 617 clearly mandates the allocation of financial gains from emissions fines towards lowering air pollution in California's disadvantaged communities, attributing mortalities and hospitalizations (asthma, acute bronchitis, lower respiratory symptoms) to these communities. Putting forth incidences of morbidity and mortality due to the lack of tools to fully document the level of non-compliance could help promote and enact projects leading to at-sea aerial monitoring solutions for both medium and long-range compliance assessments.

Furthermore, this significant quantification of statistics on health impacts -- which so far are limited only to $PM_{2.5}$-associated health burdens -- should be extended to $NO_X$, $SO_X$, and ozone species and for longer than a one-month snapshot. Of note is that this extension in the scope of research would require more initial WRF-Chem models to be run- specifically with more current emission data than July 2012 (2014 onward). As of 2014, California passed more stringent regulations, stating that sulfur content cannot exceed 0.1% by mass within 24 nautical miles off the state coast, which is likely to affect ambient OGV emissions and thus model conclusions.

# 2 . Cost-Benefit Analysis

## *2.1 Introduction*

A Cost-Benefit (C-B) Analysis was undertaken to assess the relative cost-effectiveness of implementing Unmanned Aerial Vehicles (UAVs) with sensor monitoring systems to help meet air quality goals set by the California Air Resources Board (CARB) as per the California Sulfur Rule. Both the California Sulfur Rule and new IMO regulations (implemented January 1st, 2020) were enacted to address air quality issues via mandated use of low-sulfur fuels. The current dilemma involves a record of non-compliance and a deficiency in the existing OGV monitoring protocol for full enforcement of the California Sulfur Rule and SECA conditions. To CARB's credit, its current practices to monitor vessels at port have greatly improved since the enforcement program's origin in 2010. However, because of the high number of OVGs that routinely enter and exit the San Pedro Bay ports, it is not feasible for CARB to monitor every ship. Due to budget limitations, the choice of which vessel is to be inspected is based on the chronology and frequency of its port visits. If a vessel has been monitored within the previous year, it is unlikely to be retested within 9 to 12 months. CARB inspectors opt instead to test OGVs that have not yet been inspected within a year. Penalties for OVGs range from $1,000 - $10,000 per day of non-compliance. The concept of UAVs with sensor payloads seeks to fill current monitoring gaps by both CARB and the US Coast Guard.

To properly conduct this analysis, numerous factors at play were considered. A key aspect is the cost to implement a UAV based system. The Practicum Client, the ADEPT Group Inc. (ADEPT) chose the AEROMON BH-12 emission measuring solution because: (i) its sensor suite can map and measure several critical gaseous compounds including $CO_2$, NO, $NO_2$, PM, $SO_2$, along with other critical parameters, (ii) its approach frequently recalibrates the sensor suite, (iii) it offers a more cost-effective solution, and (iv) its scientifically collaborative attitude.

Another aspect of the analysis attempted to quantify the value of the benefits gained in the Year 2023, under two implementation options. The first option is where CARB owns the UAV system and contracts UAV pilots separately. The second is where CARB does not own the UAV systems, instead hiring UAV pilots who provide their own UAVs. The C-B analysis took into account: current cost in the EU to monitor sulfur compliance based on equipment, labor, and enforcement; net financial saving in medical expenses from countries who already apply ship emission monitoring programs, monetary value affixed to avoided morbidity and mortality as modelled by BenMAP, cost of operation per ship monitored per country, port infrastructure, and current CARB average inspection rate and collected penalties.

To conduct the C-B analysis of UAV plus AEROMON BH-12 emission monitoring technologies, published regulatory literature for cost estimates was reviewed, a joint WRF-Chem and BenMAP model was run (as discussed in Section 1, "Assessment of Associated Health Burdens"), and, when necessary, dialogs were conducted with responsible public and private sector representatives in the European Union (EU) where UAV + sensor payloads enhanced enforcement has been in use for at least three years. Those surveyed included: Maria Kousa - CEO of AEROMON; Stephanie Seddon-Brown - Senior Project Officer for the European Maritime Safety Agency (EMSA); Roger Strevens - Global Sustainability Chair for Trident Alliance; Ward Van Roy - Aerial Surveillance Operator for the Royal Belgian Institute of Natural Sciences; and Cptn. J. Kip Louttit, Executive Director, Marine Exchange of Southern California.

Ultimately, the C-B analysis effort provided a range of the estimated value to be gained in the communities in and near San Pedro Bay through the year 2023 from the deployment of UAV based monitoring of OGV emissions. This value was estimated for two scenarios: one where CARB owns the UAV systems and separately contracts drone operators, and another where CARB contracts UAV pilots who supply their own UAV systems.

## *2.2 Methods*

### *2.2.1 BenMAP - Economic Valuation of Improved Health Outcomes*

The Environmental Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE) estimates the economic value of the incidence, or total number of adverse health effects avoided due to a change in air pollution levels (U.S. EPA, 2015). Monetizing the economic benefits of a reduction in air pollutant concentrations and the corresponding health incidences involves valuation approaches such as Willingness to Pay (WTP), Cost of Illness (COI), and Value of a Statistical Life (VSL).

As mentioned above, BenMAP-CE provides pre-loaded databases that supplement the user-required data inputs in quantifying the economic benefits of health incidence results. There were three datasets required in the setup to estimate these economic values. This includes inflation data, valuation functions, and income growth adjustment data.

The United States setup provided an EPA Standard Inflators dataset, which contains All Goods Index values, Medical Cost Index values, and Wage Index values per year. This pre-loaded inflation dataset has a value of 1 for the year 2015. The U.S. setup also provided an EPA Standard Valuation Function dataset, which contains an extensive library of valuation functions that convert the reduction in risk of adverse health impacts and corresponding air pollutant concentrations into quantifiable economic benefits. These valuation functions are dependent on unit values from epidemiological studies and vary by health endpoint. Finally, an EPA Standard Income Growth dataset was also provided by BenMAP, which includes an adjustment factor per endpoint group per year. Income Growth Adjustment involves modifying valuation functions to reflect an increase in real income over a period of time, which also implies an increase in the willingness to pay.

An Aggregation, Pooling, and Valuation (APV) configuration file stores user preferences and selections required to generate valuation results. The first process to create the APV file involved selecting the aggregation level at which valuation results will be reported. The primary grid definition provided by Wang *et al.,* (2019) was the chosen spatial scale of analysis for health incidence and was also selected to be the aggregation level for economic valuation.

The second process involved pooling, which is the combination of different sets of data through various pooling methods. Since BenMAP-CE only permits the pooling of incidence results and corresponding study-specific economic benefit estimates for the same health endpoint group, the pooling function was not utilized for this project due to the three different endpoint groups of the health impact analysis, (Asthma Exacerbation, Mortality, and Acute Bronchitis). Therefore, each incidence result was added to a separate pooling window.

The third and final process involved specifying the valuation functions and methods that determine how to assign an economic value to the health incidence results. The primary valuation approach used for calculating the value of avoided cases of Acute Bronchitis and Asthma

Exacerbation was WTP, while the value of avoided Mortality cases was calculated using VSL. In addition to the pre-loaded inflation dataset, income growth adjustment dataset, and valuation function dataset provided by BenMAP the United States setup, the EPA Standard Variables dataset contained other relevant data such as income and poverty statistics.

The Willingness to Pay (WTP) valuation approach used for Acute Bronchitis had a unit value of $490. This was derived by multiplying the original unit value of $81.63 (value in 2015) from the EPA by the representative number of days that symptoms of Acute Bronchitis are observed. In economic benefit analyses performed by the EPA, the unit value of Acute Bronchitis reflects a 6 to 7-day period. The estimation of WTP to avoid a case of Acute Bronchitis is specifically based on estimates to avoid the observable symptoms.

**Table 2-1:** Unit Value for WTP based on Contingent Valuation studies

| Health Endpoint | Basis for Estimate | Age Range | | Unit Value (2015$) | Distribution of Unit Value | Parameters of Distribution | |
|---|---|---|---|---|---|---|---|
| | | Min | Max | | | P1 | P2 |
| Acute Bronchitis | WTP: 6 day illness, CV studies | 0 | 17 | $490 | Uniform | 144.60 | 834.98 |

Source : U.S. EPA BenMAP User Manual (2015) Appendix H-6

The Willingness to Pay (WTP) valuation approach for Asthma Exacerbation, Cough had a unit value of $221 for children based on evidence from Dickie and Ulery (2002). This unit value was derived from a lognormal distribution and was additionally multiplied by 0.973811 to account for a mean household income difference between the study participants and the general U.S. population.

**Table 2-2:** Unit Value for WTP based on study by Dickie and Ulery (2002)

| Health Endpoint | Basis for Estimate * | Age Range | | Unit Value | Unit Value Distribution | Parameters of Distribution | |
|---|---|---|---|---|---|---|---|
| | | Min | Max | | | P1 | P2 |
| Asthma Attacks; Cough; | 1 symptom-day, Dickie and Ulery (2002) | 0 | 17 | $221 | Lognormal | 5.39 | 0.0925 |

Source : U.S. EPA BenMAP User Manual (2015) Appendix I-9

The Value of a Statistical Life (VSL) as the valuation approach for Mortality, All Cause was based on the contingent valuation works of Mrozek and Taylor (2002) and Viscusi and Aldy (2003). This alternative has a mean value of $7.6 million (value in 2015) with a normal distribution of unit values.

**Table 2-3:** Unit Value for VSL based on Contingent Valuation studies

| Basis for Estimate * | Age Range at Death | | Unit Value (VSL) (2015$) | Distribution of Unit Value | Parameters of Distribution | |
|---|---|---|---|---|---|---|
| | Min | Max | | | P1 | P2 |
| VSL, based on 2015$ range from $1.38 million to $13.76 million – 95% CI of assumed normal distribution | 0 | 99 | 7,570,229 | Normal | 3,160,172 | – |

Source : U.S. EPA BenMAP User Manual (2015) Appendix I-1

**Table 2-4:** Economic Benefits by BenMAP Due to 10% Non-Compliance to the California Sulfur Rule

| Health Endpoint Group | Incidence* | Valuation Function* | Valuation Method | Estimated Economic Value |
|---|---|---|---|---|
| Acute Bronchitis | 40 | A*AllGoodsIndex | Willingness to Pay (WTP)* | $20,560 |
| Asthma Exacerbation | 618 | A*B*AllGoodsIndex | Willingness to Pay (WTP) | $141,050 |
| Mortality | 24 | A*AllGoodsIndex | Value of a Statistical Life (VSL)* | $210,435,480 |

*Incidence : the total number of adverse health effects avoided due to a change in air pollution levels

*Valuation Function : used by BenMAP-CE to estimate the economic values of changes in the incidence of health effects

*Willingness to Pay (WTP) : the willingness of individuals to pay for a good or service, such as a reduction in the risk of illness; economists tend to view an individual's WTP for an improvement in environmental quality as the appropriate measure of the value of a risk reduction

*Value of a Statistical Life (VSL) : the aggregate dollar amount that a large group of people would be willing to pay for a reduction in their individual risks of dying in a year, such that we would expect one fewer death among the group during that year on average

*A* : Medical costs over *x* years

*B* : Opportunity cost over *x* years

All Goods Index can be used to adjust the value of generic goods

After the APV Configuration file was saved, an APV Results file was generated. Within the Pooled Valuation Results report, the Point Estimate values represented the economic value of the aggregated health incidence results for each endpoint per grid cell in the primary grid definition. The sum of these values produce an economic value estimate of $20,560 for the 40 avoided cases of Acute Bronchitis among 8 to 12 year old's, $141,050 for the 618 avoided cases of Asthma Exacerbation among 6 to 18 year olds, and $210,435,480 for the 24 avoided cases of Mortality among 30 to 99 year old's.

### *2.2.2 Data Acquisition*

#### ***UAV Devices and Pilots***

Cost estimates related to UAV devices and pilots were obtained through discussions with Flying Lion, Inc., a Southern California-based Unmanned Aerial System (UAS) consulting firm specialized in on-demand aerial assessments, UAS equipment, ground control, training, and consulting services for Public Safety agencies. The cost to buy a single hybrid drone is approx. $45,000, with an additional $13,500 for cameras (video and infrared), $2,500 for spare parts (including motors and propeller blades), and $2,000 to $3,000 for extra batteries. Annual maintenance costs were taken to be 100% of the UAV cost. UAVs in active use have a lifetime of about two years due to rapid developments in UAV software and sensor technology and the lack of certified UAV parts. At a minimum, for the envisioned research to validate their use in the contemplated field, two UAV devices must be available on site to ensure that OGV monitoring can be performed without interruption (e.g. one active UAV and one back-up). For a single UAV pilot working eight-hours per day for 150 days each year, two separate estimates were provided: (1) $1,600 per day for the pilot and related ground services, where the enforcement agency separately purchases its own UAV devices, and (2) $2,100 per day for the pilot and related ground services, where the pilot provides their own UAV. These UAV pilot estimates include insurance for potential damage sustained by the UAV. At a minimum, two UAV pilots are required at any given time to control the UAV and provide line of sight data. UAV and pilot costs were provided for the purposes of cost-benefit modeling and should not be interpreted as official or exact quotations.

### *Aeromon BH-12 Devices and Operator*

Costs related to the AEROMON BH-12 system + operator were provided by AEROMON Oy, a Finnish provider of UAS-assisted emission monitoring and detection sensor technology. Annual cost estimates include – and are not limited to: one active BH-12 system, one back-up BH-12 system, AEROMON Cloud Service (ACS) licenses for fuel sulfur content operations (one license per BH-12 system), sensor modules, calibration gases, remote support in operation planning and preparations, fuel sulfur content data quality control through ACS, on-site support, and training of the BH-12 and maritime emission monitoring for the UAV pilots and BH-12 operator. Training costs are incurred only in the first year. Consumables include: (1) sensor modules for $CO_2$, $SO_2$, NO, and $NO_2$, which must be replaced approximately every six months, and (2) calibration gases, where approximately six sets per year are needed to perform 25 calibrations and 25 calibration-level checks for the 150 days of BH-12 device operation. AEROMON provides the necessary spare parts and automatically delivers new sets of calibration gases. Estimates were provided following the model currently in use for fuel sulfur content measurement campaigns in the EU. The cost of one BH-12 operator working eight-hours/day for 150 days/year was estimated from $540/day (year 1) to $625/day (year 3). The BH-12 systems and operator costs were provided for the purposes of cost-benefit modeling and are not to be interpreted as official or exact quotations.

### *Marine Exchange Software*

Estimates for Marine Exchange ship traffic software and reports were obtained via dialog with the Marine Exchange of Southern California. These services' value was roughly estimated at $450/month. It includes and may not be limited to the following services: "The Tug Operator Package," "Access on Web," and "Telephone Service." Another $450/month is allocated for similar services from the Marine Exchange of the San Francisco Bay Region.

### *Chase Boat*

The cost to contract one chase boat for 150 days per year was estimated at $2,100/ day. This includes the cost of the crew, vessel, fuel, and insurance coverage. The chase boat should be able to sustain a speed of at least 20 knots and have at a minimum a 25-foot deck from which UAVs can be launched and retrieved. Two separate chase boats will be contracted, one in San Pedro Bay and one in San Francisco Bay, such that the combined number of days contracted equals 150 days per year.

### *CARB Enforcement*

CARB enforcement data was obtained from: (1) CARB Annual Enforcement Reports, 2015 through 2018, (2) case settlement agreements from 2015 through 2019 for fuel sulfur content violations available online through CARB's Enforcement Case Settlements section; and (3) discussions with CARB Air Pollution Specialist and Fuel Sulfur Content Inspector.

### *2.2.3 Methods and Assumptions for Cost-Benefits*

The concept to implement aerial enhanced enforcement of OGV fuel sulfur content compliance was modeled for a three-year period with 150 days of UAV based monitoring/yr. For modeling purposes, of the total 150 UAV based monitoring days, approximately 108 were assigned to the San Pedro Bay area and 42 were assigned outside San Francisco Bay. These numbers are roughly proportional to the number of ports of call in the Ports of Los Angeles and Long Beach vs. the number of ports of call in or near San Francisco Bay.

Only a scenario of 150 days/yr. of monitoring was considered as it was expected that, on average, four OGV's plumes could be reliably "sniffed" per day – which when multiplied yields 600 inspections/yr. (150 OGV monitoring days x 4 OGV's monitored/day). This level of inspection is close to the current number of at pier inspections conducted by CARB each year, and thus the CARB at pier inspection workload remains unchanged.

A standard 8-hour monitoring day was defined as one chase boat leaving the dock to position itself out at sea, upon which a minimum of two UAV pilots (one to operate the UAV, the other to provide line of sight data) launch one UAV into the plumes of four to five OGVs entering or exiting the port for a total "on station" monitoring time of approximately five hours per day. The assumption is made that it takes one and a half hours to position the chase boat- and another hour and a half to return to base. The results of at sea emission monitoring are expected to allow for judicious selection of which OGVs the CARB inspector(s) will board to investigate potential fuel sulfur rule violations. It is further expected that these at pier CARB inspections will yield a greater number of "hits" (determinations of fuel sulfur content violations) vs. the current near random vessel-to-be inspected selection process. The use of marine exchange software to track incoming and outgoing ships allows for the strategic positioning of the chase boat in target rich OGV port traffic on any given day.

The current CARB fuel sulfur content enforcement process was taken as the baseline scenario, in which no UAV emission monitoring occurred. The purpose of cost-benefit modeling was not to evaluate the totality of costs associated with fuel sulfur rule enforcement with and without proposed UAV implementation, but rather, to evaluate strictly the additional costs incurred with implementation of UAV emission monitoring in the enforcement process compared to the baseline scenario. Benefits were defined as the additional benefits accrued upon incurrence of the direct costs associated with implementation of UAV emission monitoring.

The direct costs incurred each year by CARB for 150 standard 8-hour monitoring days over the course of the proposed three-year program were identified as: (1) purchase of two UAV systems, (2) contracting two UAV pilots, (3) contracting two AEROMON BH-12 systems (4) contracting one BH-12 system operator, (5) contracting one chase boat for the region monitored, and (6) purchase of one Maritime Exchange software license for the Southern California region and one Maritime Exchange software license for the San Francisco Bay region.

Two different options for drone implementation, and their associated costs, were considered: Option #1 was defined as CARB purchasing its own UAV systems and separately contracting UAV pilots, whereas Option #2 was defined as CARB purchasing no UAV systems, instead contracting UAV pilots who supply their own UAV systems.

The benefits associated with incurrence of these direct costs include- and are not limited to : (1) additional penalties assessed from more identified fuel sulfur content violations, and (2) the economic valuation of improved health outcomes from reduced fuel sulfur content violations associated with UAV emission monitoring. The annual benefit and cost estimates used in cost-benefit modeling, and their related assumptions, are presented in Table B-1 (for Option #1) and B-2 (for Option #2) of Appendix B.

***Determination of Annual Non-Compliance Rates***

The baseline scenario, which represented current CARB enforcement practices, assumed two different % non-compliance values for the fuel sulfur rule: the average 2.0% non-compliance identified by CARB at baseline ($x_{b,0}$), and the 10.0% true non-compliance expected at baseline ($x_{b,T}$). The need for two separate values represented the limitation that the current enforcement process may not be able to capture the true rate of non-compliance in the absence of effective forms of monitoring.

The average 2.0% non-compliance identified by CARB at baseline, which can be understood as year zero of UAV implementation, was determined by averaging and rounding the fuel sulfur content non-compliance rates from 2015 to 2018; each year's non-compliance rate was determined by dividing the number of Fuel Sulfur Content violation Case Settlements available online on CARB's Enforcement Case Settlements website for that year by the number of OGV fuel sulfur content inspections conducted for that year as identified in the respective annual CARB Enforcement Report (CARB, n.d.; CARB, 2016; CARB, 2017; CARB, 2018; CARB, 2019). This period of time was chosen because the 2018 CARB Enforcement Report provided the most recent available enforcement data, and fuel sulfur content requirements in the North American Emission Control Area were reduced to a more stringent 0.1% allowable fuel sulfur content as of January 1, 2015 (EPA & OTAQ, 2010).

The 10.0% estimated non-compliance was selected per the 5.0-15.0% range of fuel sulfur content non-compliance at sea suggested by the Compliance Monitoring Pilot Study for MARPOL Annex VI, a.k.a. CompMon 2018 (CompMon, 2018). The 2019 study "What Explains SECA compliance: rational calculation of moral judgement" provided further support for this assumption through its references to the 8% non-compliance shown in the North Sea in 2016 upon implementation of the Belgian Sniffer Campaign and preliminary results showing the SECA compliance rate to be above 90% in Danish waters and close to Gothenburg (Lähteenmäki-Uutela et al., 2019; Van Roy and Schedleman, 2016; Mellqvist et al., 2017a, b, c). Studies from 2015 to 2016 indicated an average 4.5% non-compliance in the Baltic and North Seas when measurements were taken with remote fixed sensing and at pier data collection (Alda, 2016). Once aerial monitoring came into play, the infraction detection rate jumped by 35% to 7.3%, despite the additional two year time frame to comply (as of 2017) since introduction of the more stringent SECA rule in 2015 (Ministry of Environment and Food of Denmark, 2019). Recent literature supports the assumption that aerial monitoring is a more effective method to detect non-compliance, compared to sole reliance on stationary remote emissions monitoring or at pier inspections. OGVs flagged in North and Baltic Sea countries may also be more likely to comply than vessels flagged elsewhere. Further, OGV operators are generally aware that in Nordic waters there are three concomitant non-compliance detection methods (e.g. stationary remote, aerial and in port at pier) and that in California there is only one (e.g. in port at pier).

The cost-benefit analysis assumed that the non-compliance rate identified by CARB at the end of Year 1 of UAV emission monitoring ($x_1$) equaled the true non-compliance rate at baseline (i.e. 10%), and the non-compliance rate identified by CARB in successive years was assumed to decrease at a constant rate until it reached 1.5% non-compliance by Year 3 ($x_3$). Fewer violations over time were thus assumed to occur in response to improved OGV monitoring. Recent literature suggested that once OGV operators understand that enhanced enforcement has been introduced, they are likely to comply fairly quickly. Lähteenmäki-Uutela et al. (2019) referenced the Harrington paradox, in which compliance to environmental regulations is generally greater than would be expected under the typical assumptions of rational economic behavior (Harrington, 1988; Nyborg and Telle, 2006). In addition, Lähteenmäki-Uutela et al. (2019) discussed the relationship between perceptions of monitoring activity and associated OGV behavioral responses in the EU: the more frequent violations in the Baltic Sea were typically attributed to OGVs that rarely entered this area and were perhaps less familiar with local emission monitoring; the Great Belt Bridge, which is known to be monitored, experienced greater compliance than the Baltic Sea, which is likely perceived to be less monitored and suggested that the fear of being caught played a role in compliance behavior. However, the sanctions incurred by OGVs from being caught in violation of fuel sulfur content rules can vary between port states and may not always be stringent enough to deter non-compliance (Lähteenmäki-Uutela et al., 2019). With these considerations, the non-compliance rate identified by CARB at the end of Year 3 of UAV monitoring was assumed to be 1.5%.

From CARB's Enforcement Division it was learned that daily workloads can vary from 2 to 7 OGVs. For the purposes of Cost-Benefit modeling, 4 OGV inspections were assumed per 150 emission monitoring days each year. The resulting 600 OGV inspections projected for each year were similar to the 523 fuel sulfur inspections conducted in 2018 and below the 897 and 987 fuel sulfur inspections conducted in 2016 and 2015, respectively (CARB, 2016; CARB, 2017; CARB, 2019). The 600 OGV inspections per year value was held constant for each year as aerial monitoring is reasonably expected to increase the efficiency of the enforcement process, defined as identifying more fuel sulfur content violations with the same number of inspections. As fewer violations over time were assumed to occur in response to improved OGV monitoring, the resulting health benefits were expected to increase over time. At the end of Year 1, where the identified % non-compliance was assumed to equal the expected true % non-compliance at baseline, no health benefits were expected to be incurred; however, at the end of Year 2, where the identified % non-compliance rate was assumed to decrease, health benefits were attributed to the %-point change in non-compliance compared to the previous year's identified % non-compliance, and so forth for Year 3 (discussed later in this section's "Valuation of Health Benefits").

### *Determination of Assessed Penalties*

Estimates for average penalties assessed to non-compliant OGVs were determined by identifying all case settlements for fuel sulfur content violations from 2015 to 2019 available on the Enforcement Case Settlement section of CARB's website; the resulting total penalties per violation ranged from a minimum of $1,000 to a maximum of $129,500 (CARB, n.d.). Similar to determination of the baseline non-compliance rate identified by CARB ($x_{b,0}$), this period of time was chosen because 2019 represented the most recent completed year of available enforcement data, and fuel sulfur content requirements in the North American Emission Control Area were reduced to a more stringent 0.1% allowable fuel sulfur content as of January 1, 2015 (EPA & OTAQ, 2010). Given the wide range of total penalties per violation, an optimistic and a conservative estimate were calculated. The optimistic estimate of $14,740 per violation was determined by averaging the total penalties per fuel sulfur content violation from 2015 to 2019. The conservative estimate of $8,250 was determined by removing outliers in total penalties per violation from 2015 to 2019, identified as values outside the range of $3,750 to $13,750 (where the lower limit was taken as 1.5 times the interquartile range below the first quartile and the upper limit was taken as 1.5 times the interquartile range above the third quartile) and averaging the results. For each year, the range of benefits for additional penalties assessed (relative to the baseline scenario) over the three years of UAV emission monitoring was determined through the following equation:

$$p(t) = (600\ inspections)(\ x_t - x_{b,0}\ )(v) \tag{1}$$

where: $p(t)$ = Benefit of additional penalties assessed in Year $t$ relative to the baseline
$x_t$ = Non-compliance rate identified by CARB in Year $t$
$x_{b,0}$ = Non-compliance rate identified by CARB at baseline
$v$ = Average penalty assessed per identified fuel sulfur violation
(Note: $v$ = \$8,250/violation for conservative estimate; $v$ = \$14,740/violation for optimistic estimate)

Variables for non-compliance in Equation (1) were expressed as rates rather than percentages. The non-compliance rate identified by CARB at baseline ($x_{b,0}$) was subtracted from $x_t$ in Equation (1) such that only additional penalties due to UAV-related changes in non-compliance would be captured by the benefits, rather than the total penalties assessed for that year. The assumption was thus made that, in the absence of improved monitoring technologies, the current baseline % non-compliance identified by CARB would be maintained in future years at around 2.0% non-compliance on average.

### *Valuation of Health Benefits*

Improvements in health outcomes between scenarios of 0% fuel sulfur content non-compliance and 10% fuel sulfur non-compliance were economically valuated by BenMAP-CE at $210,597,090 (as discussed in Section 2.2.2). For the purposes of cost-benefit modeling, a linear relationship was assumed between the non-compliance rate and the economic valuation of improved health outcomes, and health benefits were assumed to be incurred within three years of the start of UAV emission monitoring. A regression line was fitted between a $210,597,090 valuation at 10% non-compliance and a $0 valuation at 0% non-compliance, resulting in a rate of $21,059,709 gained in health benefits per 1.0%-point decrease from the % non-compliance identified by CARB in the previous year. Through linear interpolation, the resulting slope of the regression line was incorporated into the following equation to estimate monetized health benefits incurred under different non-compliance rates in the first, second, and third years of UAV emission monitoring:

$$h(t) = (\ \$210{,}597{,}090\ /\ 0.10)(\ x_{b,T} - x_t\ ) \tag{2}$$

where: $h(t)$ = Benefit of Adjusted Economic Valuation for Avoided Health Burden in Year $t$
$x_{b,T}$ = True Non-Compliance Rate Expected at Baseline
$x_t$ = Non-Compliance Rate identified by CARB in Year $t$

Variables for non-compliance in Equation (2) were expressed as rates rather than percentages.

Of note is that the health benefits in Year 1 were modeled to be $0, regardless of the non-compliance rate identified by CARB in Year 1, due to health benefits being calculated from the decreases in non-compliance from Year 1 to Year 2 and again from Year 2 to Year 3. The non-compliance rate identified by CARB in Year 1 was thus assumed to equal the true non-compliance rate expected at baseline.

### *Discounting Future Net Benefits*

The Net Present Value (NPV) approach was taken by separately estimating the present value of direct costs incurred within the UAV monitoring program's three year period, the present value of monetized benefits incurred within the UAV monitoring program's three year period, and a comparison of both to determine the net present value. In accordance with EPA Guidelines for Preparing Economic Analyses, discounting to the present to estimate an NPV is likely to be most informative when an immediate investment is required and offers highly variable future benefits (EPA, 2014). Costs were expected to accrue at the start of each year such that discounting began in the second year of the UAV program, whereas benefits were expected to accrue at the end of each year such that discounting began in the first year of the UAV program. The following two equations derived from the EPA Guidelines for Preparing Economic Analyses were used to calculate the net present value:

$$NPV = ( B_0 - C_0 ) + d_1( B_1 - C_1 ) + d_2( B_2 - C_2 ) + d_3( B_3 - C_3 ) \tag{3}$$

$$d_t = 1/(1+r)^t \tag{4}$$

where: $B_t$ = Benefits at the end of year $t$

$C_t$ = Costs at the end of year $t$

$d_t$ = Discounting weight at the end of year $t$

$r$ = Discount rate

Note that not all variables presented in equation (3) were non-zero, such as the benefits at time $t = 0$. The same discount rate was used for both benefits and costs for any given estimation of NPV. The use of a 3% discount rate and a 7% discount rate were evaluated separately and chosen following the recommendations of the EPA Guidelines for Preparing Economic Analyses and the Office of Management and Budget (OMB) Circular A-4 (EPA, 2014; OMB, 2003). Benefit Cost Ratios were calculated by dividing the present value of Benefits by the present value of Costs. Table 2-1 in Section 2.3 summarizes the results of the present values calculated for Benefits, Costs, Net Benefits (i.e. Net Present Values), and Benefit Cost Ratios for Option #1 and Option #2 under discount rates of 3% and 7%.

### *2.2.4 Methods for Sensitivity Analysis*

A parametric sensitivity analysis, or "one-at-a-time (OAT)" sensitivity analysis, approach was taken to investigate the individual influence of key model assumptions on model output. In accordance with EPA Guidance on the Development, Evaluation, and Application of Environmental Models, a function of sensitivity analysis is the systematic apportionment of uncertainty in model output to different sources of uncertainty in model input, which is a special case of uncertainty analysis (EPA, 2009). Due to their reliance on assumed OGV behavior, the two main model parameters of interest were: (1) the non-compliance rate identified for OGV fuel sulfur content after the Year 1 of UAV implementation (henceforth "Parameter #1"), and (2) the non-compliance rate identified for OGV fuel sulfur content after Year 3 of UAV implementation (henceforth "Parameter #2"). The base cost-benefit model assumed 10.0% identified non-compliance for Parameter #1 and 1.5% identified non-compliance for Parameter #2.

For Parameter #1, a range of +/- 5.0%-points was chosen in accordance with the 5.0-15.0% range of fuel sulfur content non-compliance at sea discussed in Section 2.2.3 ("Determination of Annual Non-Compliance Rates"). Holding all other variables constant, Parameter #1 was iteratively increased or decreased within the +/- 5.0%-point range, and the observed percent changes in both net benefits and benefit cost ratios for Option #1 with a 3% discount rate, Option #1 with a 7% discount rate, Option #2 with a 3% discount rate, and Option #2 with a 7% discount rate were plotted separately. Each plot was fitted with a linear regression to identify the relative change in model output per unit absolute change in model input (i.e. in Parameter #1). For Parameter #2, since deterrence of fuel sulfur violations over time was expected from UAV implementation, a range of -1.5%-points to +8.0%-points was investigated through the same iterative process as Parameter #1 to evaluate the effect of the base model's first year 10.0% non-compliance rate decreasing to a value within the range of 0.0% to 9.0% by the third year.

The relationship between Parameter #1 and Parameter #2, wherein the value of Parameter #1 in year one was assumed to decrease at a constant rate until it arrived at the value of Parameter #2 in year three, was considered through a joint sensitivity analysis. Through an iterative process similar to the individual parametric sensitivity analysis, the joint sensitivity analysis differed in that iterations of both Parameter #1 and Parameter #2 were evaluated simultaneously to identify the influence of their interaction on model output. Rather than present the relative changes in model output, the results of each iteration were included as a reference in Tables B-3 through B-6 of Appendix B to present alternative Net Benefit and Benefit Cost Ratio outcomes under various scenarios of Parameter #1 and Parameter #2 assumptions when all other variables were kept constant.

## *2.3 Results & Discussion*

The results of cost-benefit modeling over the proposed three year period of CARB UAV emission monitoring are summarized in Table 2-5.

**Table 2-5:** Summary of Benefits and Costs Incurred with UAV Implementation over Three Year Period (2021-2023) during CARB Fuel Sulfur Rule Enforcement (in 2020 dollars)

| Description | Year 2023: Option #1[a] | Year 2023: Option #2[b] |
|---|---|---|
| Total Estimated Costs | | |
| 3 percent discount rate | $3,141,864 | $3,338,856 |
| 7 percent discount rate | $3,027,339 | $3,216,838 |
| Total Estimated Benefits | | |
| 3 percent discount rate | $248,719,912 to $249,142,183 | $248,719,912 to $249,142,183 |
| 7 percent discount rate | $224,811,539 to $225,214,330 | $224,811,539 to $225,214,330 |
| Net Benefits (Total Benefits - Total Costs) | | |
| 3 percent discount rate | $245,578,048 to $246,000,319 | $245,381,055 to $245,803,326 |
| 7 percent discount rate | $221,784,200 to $222,186,991 | $221,594,701 to $221,997,492 |
| Benefit Cost Ratio (Total Benefits / Total Costs) | | |
| 3 percent discount rate | 79.2 to 79.3 | 74.5 to 74.6 |
| 7 percent discount rate | 74.3 to 74.4 | 69.9 to 70.0 |

Notes:
[a] CARB purchases UAV systems and separately contracts UAV pilots
[b] CARB does not purchase UAV systems, instead contracting UAV pilots who supply their own UAV systems

The benefit and cost estimates used in each year of cost-benefit modeling, and their related assumptions, are included as references in Table B-1 (for Option #1) and B-2 (for Option #2) of

Appendix B. Figure 2-1 summarizes the net benefits over time expected for each year of the UAV program. Note that these net benefits are undiscounted and provided for reference (refer to Table 2-5 for the discounted estimates at their net present value). The primary takeaway from Figure 2-1 was that differences in assessed penalties due to changes in non-compliance were inconsequential relative to the magnitude of health benefits projected to be incurred as non-compliance decreased.

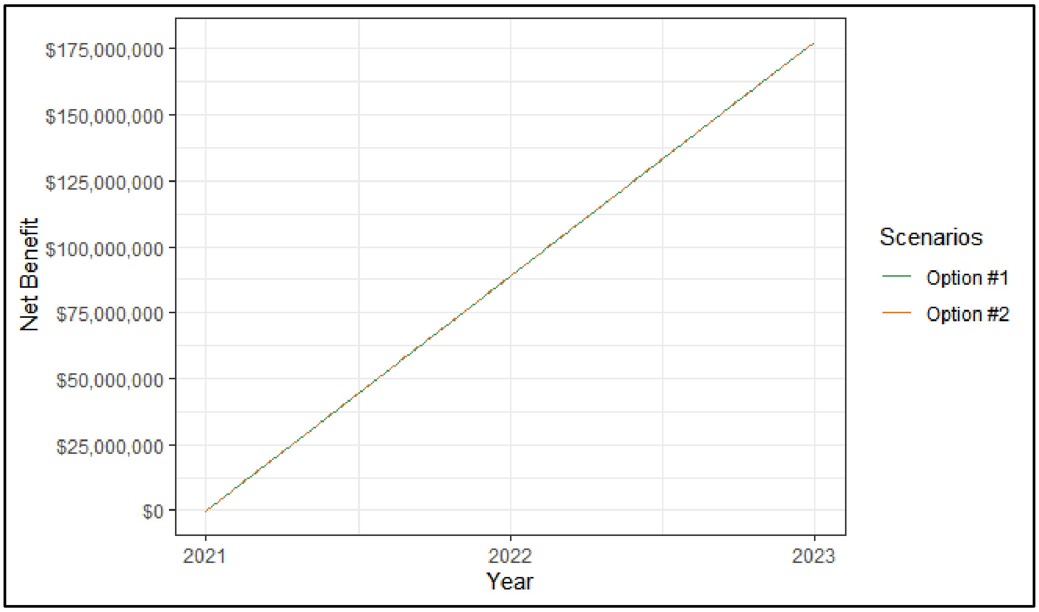



**Figure 2-1:** Summary of undiscounted net benefits for each year of UAV-based fuel sulfur enforcement program. Note that Option #1 and Option #2 have similar but unequal net benefits, and net benefits are negative in Year 1.

A comparison of Option #1 and Option #2, as depicted in Table 2-5, indicates that it may be more cost effective for the enforcement agency to pursue Option #1, wherein CARB purchased its own UAV system and separately contracted UAV pilots, for the 150 days per year conducting OGV emission monitoring.

Although the actual cost of running the proposed program was spread throughout California between the Southern California region and San Francisco Bay region, this comparison of costs and benefits was conservative in that health benefits were quantified only for the Southern California region in the ports of Long Beach and Los Angeles. Additionally, only the monetary value of three measures of avoided health burden were considered: (1) reduced incidence of acute bronchitis, (2) exacerbated asthma, and (3) premature mortality related to non-compliant OGV $SO_x$ emissions, butit excluded other unexplored outcome improvements like expected productivity gains (e.g. economic value of less lost work days).

Although historical enforcement data was evaluated to determine realistic conservative and optimistic average estimates of penalties assessed per non-compliant OGV identified, both estimates likely undervalued potential gains from increased OGV monitoring and systematic UAV-based OGV targeting. This undervaluing reflected the difference between identifying an inadvertent violator compared to identifying deliberate, and/or repeat violators who were out of compliance for a period of days far exceeding the average 1-2 days out of compliance for the majority of violators between 2015 and 2019. Collateral penalties would not have been collected were it not for the detected fuel infraction, which further demonstrated the value of UAV emission monitoring.

Currently, the combination of underwhelming penalties and the low risk of being caught in fall short of motivating greater OGV compliance- given that the fuel cost savings far outweigh the expected value of penalties. Investment in UAV emission monitoring presents the opportunity to not only identify and inspect OGVs more systematically and efficiently per the same number of inspections conducted, but also to better identify repeat violators who can no longer safely assume that they have a grace period before their next inspection from having successfully passed an inspection, potentially deterring future non-compliance through positive behavior modification.

As discussed in Section 1, "Assessment of Associated Health Burdens," pollution mapping through BenMAP-CE conferred the advantage of isolating health incidence outputs that were directly attributed to PM 2.5 emissions associated with $SO_X$ emissions from OGVs. As a result, the monetary valuation of avoided health burden from the difference between 0% non-compliance and 10% non-compliance was associated solely with OGV fuel sulfur content violations without interference from background $SO_X$ emissions resulting from other activities. While the relationship between OGV-attributed health burden and fuel sulfur content non-compliance was assumed to be linear for the purposes of proportionally interpolating monetary valuations of health burden at different non-compliance rates, this 1:1 relationship is likely an oversimplification of their true relationship. The lungs may instead possess a degree of tolerance to increases in ambient $SO_X$ emissions such that they are able to cope with a certain level of additional pollution burden until a threshold is exceeded, after which increases in morbidity and mortality occur suddenly at a substantial rate compared to before threshold exceedance.

The results of parametric sensitivity analysis for Parameter #1 (% non-compliance identified by CARB in Year 1) are summarized in Figure 2-2. For every +1.0%-point increase in the base model's reference value of 10.0%, both Net Benefits and Benefit Cost Ratios increased by approximately 12%; conversely, for every -1.0%-point decrease, model output decreased by approximately 12%. The choice of discount rate or whether Option #1 or Option #2 was evaluated did not change these outcomes for Parameter #1.

The results of parametric sensitivity analysis for Parameter #2 (% non-compliance identified by CARB in Year 3) are summarized in Figure 2-3. For every +1.0%-point increase in the base model's reference value of 1.5%, both Net Benefits and Benefit Cost Ratios decreased by approximately 12%; conversely, for every -1.0%-point decrease, model output increased by approximately 12%. Similar to Parameter #1, the choice of discount rate or whether Option #1 or Option #2 was evaluated did not change these outcomes for Parameter #2.

The results of joint sensitivity analysis to identify the net benefits and benefit cost ratios under different iterations of Parameter #1 and Parameter #2 performed simultaneously are included for reference in Tables B-3 and B-4 (for Option #1) and Tables B-5 and B-6 (for Option #2) in Appendix B. This allows for a variety of net benefits and benefit cost ratios to be evaluated under different assumptions of Parameter #1 and Parameter #2 and is advantageous for also considering the effect of the interaction between the two on model output. For Option #1, net benefits ranged from $12,192,919 to $435,619,139 and benefit cost ratios ranged from 4.9 to 139.6. For Option #2, net benefits ranged from $11,995,926 to $435,422,146 and benefit cost ratios ranged from 4.6 to 131.4. Results demonstrated that, despite the uncertainties and choice of assumptions between these two parameters, the combination of additional penalties assessed and monetized social benefits through avoided health burden exceeded the direct costs of the three year program such that in all cases the estimated net benefits were positive and benefit cost ratios were greater than 1.0 under the premise of decreased OGV non-compliance over time.

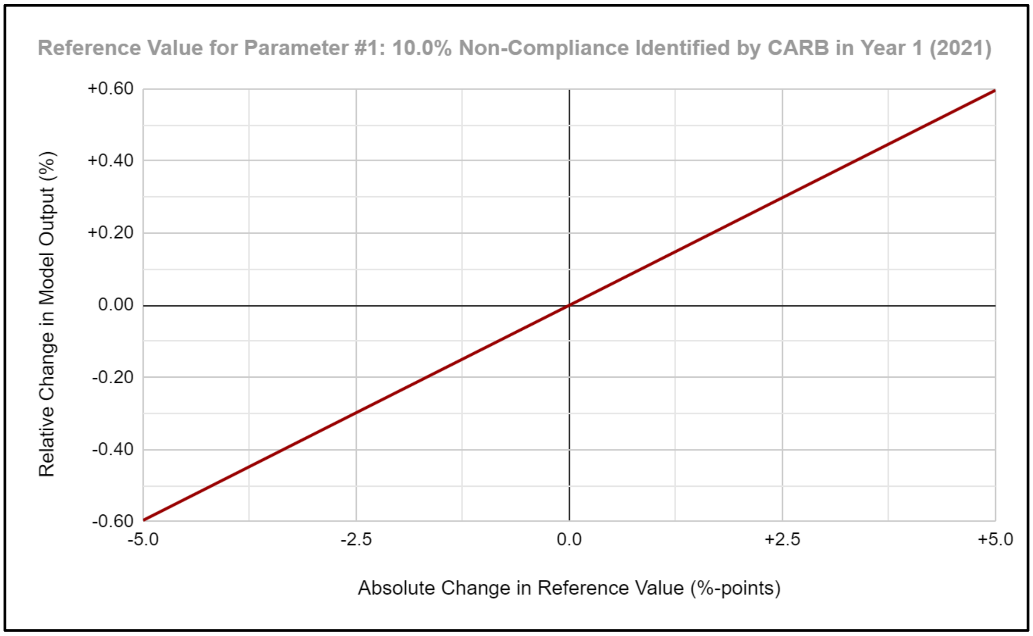



**Figure 2-2:** Summary of Parametric Sensitivity Analysis for Parameter #1. Model Output refers both to Net Benefits and Benefit Cost Ratios, which experienced the relative change displayed here for each absolute change in the reference value regardless of the discount rate (3% or 7%) or option (#1 or #2) considered.

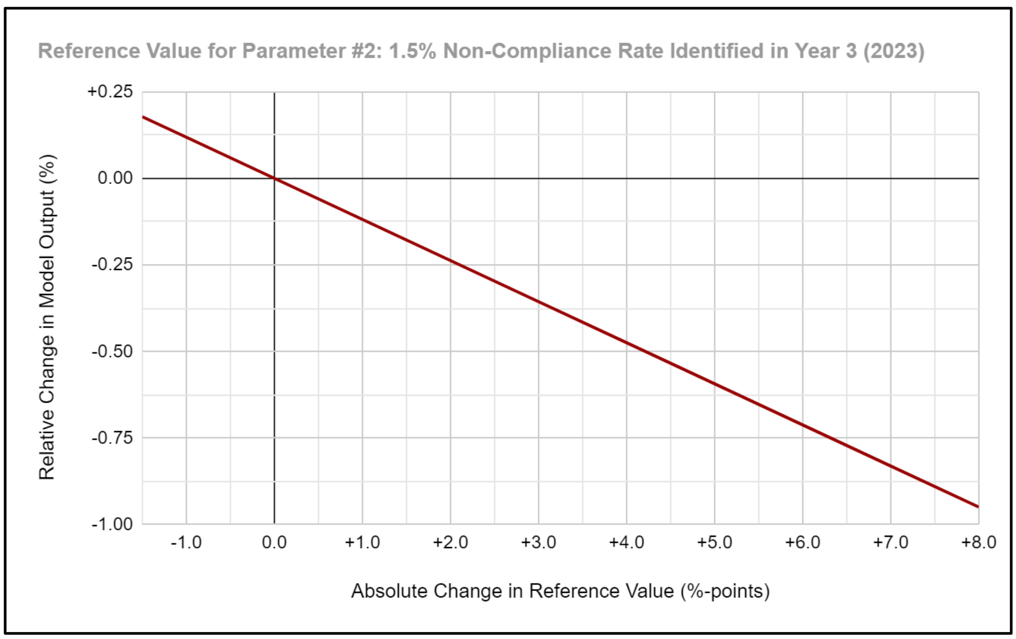



**Figure 2-3:** Summary of Parametric Sensitivity Analysis for Parameter #2. Model Output refers both to Net Benefits and Benefit Cost Ratios, which experienced the relative change displayed here for each absolute change in the reference value regardless of the discount rate (3% or 7%) or option (#1 or #2) considered.

## *2.4 Conclusions*

One of the primary requirements for novel technologies to be incorporated into the enforcement processes of regulatory bodies is to demonstrate financial feasibility. Across all base case scenarios, benefits are expected to outweigh costs by up to 69.9 to 79.3 times.

After the end of the three-year enhanced monitoring program, it is advisable to keep consistent monitoring in place at a lesser level to promote continued positive compliance behavior. Although interpolation of monetary health benefits and uncertainties related to future OGV behavior limited the Cost-Benefit Analysis' ability to definitively yield a narrow range of expected regulatory and social benefits, it nonetheless identified and provided reasonable estimates for the expected additional costs incurred through UAV enforcement monitoring. Key uncertainties in model output were addressed through sensitivity analysis, including reference tables that allowed a variety of outcomes for two key assumptions in ship behavior over time to be explored.

The above work undertaken by the IoES Practicum team serves to justify further support from CARB to continue to investigate the implementation of UAV + sensor suite based OGV monitoring at sea in California waters. This analysis has addressed cogent economic viability concerns as well as quantified medium and long-term benefits.

Future avenues of research include – and are not limited to: (i) refine the relationship between fuel sulfur rule compliance and expected health benefits; (ii) keep track of compliance rates over time in areas with established aerial monitoring; (iii) take into account additional benefits (e.g. productivity gains from avoided health outcomes/undesirable birth outcomes); and (iv) include emissions from OGVs travelling through California waters without stopping at California ports (a.k.a. "innocent passage"). It is suggested that aerial monitoring allows for all OGVs to be monitored, including those which do not stop at a California port.

# 3 . Fundraising & Support Campaign

## *3.1 Introduction*

The main focus for this year's Practicum team was to seek and obtain funds and/or letters of support from both private and public entities. It was determined that it is important to separate the targets as either private or public entities, since the previous Practicum team focused solely on larger, public, environmental regulatory entities such as SCAQMD, CARB, and EPA. Winter Quarter discussions led to the conclusion that advancing our project required continuing to pursue the previously mentioned public entities as well as newly added private entities as the combination of the two would demonstrate that this project appeals to a broader, more complete audience.

## *3.2 Methods*

First, research was conducted on American and European companies that have ties to the maritime industry- specifically those who demonstrate a shared mission for cleaner and more regulated ports. To isolate target entities from the larger pool, the mission statements, and past and/or present projects of the companies were reviewed. The team sought to forge a unique connection with the entities from whom funds are requested as this kept them responsive and interested in the project.

To make that connection, a list of possible companies to look into and contact information for each company were compiled and submitted to the client. Such data was not always readily available and so extensive research was required to compile this list of entities. Once the list was completed, the team reviewed all factors and confirmed which companies and organizations would be most valuable when it came to obtaining a letter of support and/or funding. With this list in hand, several email templates were drafted to help standardize outreach, while considering variation amongst companies in terms of interests and projects they were already engaged in.

While the team received responses from most of those that were reached out to, some correspondence was not reciprocated, possibly due to challenges that many companies and organizations faced due to COVID-19 issues. This was most apparent with some of the 501(c)(3) which, even to begin with, have smaller budgets. Thus, the lack of response from them was, while disappointing, understandable. Although follow up emails were sent and phone calls were made, their unresponsiveness may be overcome by next year's Practicum Team.

Table 3-1 consists of the final list of private and public entities that constituted the fundraising and outreach campaign. A more detailed description, along with the efforts made by the team members in charge of funding, can be seen in Appendix C. As a note for Table 3-1, three private companies [American RoRo, Eagle Bulk, and Sea Trade Holdings] are included in the table, but not in Appendix C because the Practicum team did not have enough time to open discussions; future directions for the Practicum includes outreach to these plausible sources of funding.

***Table 3-1**: Private and Public Companies*

| Practicum Team 19'-20' Co-funding List | | |
|---|---|---|
| *Private* | Trident Alliance | American RoRo |
| | MAERSK | Eagle Bulk |
| | Harbor Community Benefit Foundation Grant | Sea Trade Holdings |
| *Public* | Bay Area Air Quality Management District | Clean Air Action Plan |
| | California Air Resource Board | Santa Barbara County Air Pollution Control District |
| | EPA Region IX | South Coast Air Quality Management District |
| | U.S. Maritime Administration | Supplemental Environmental Program |
| | UCLA School of Engineering | U.S. Coast Guard |
| | UCR Bourns College of Engineering | Ventura County Air Pollution Control District |
| | American Maritime Partnership | California Climate Investments |

## *3.3 Results*

Table 3-2 (below) contains a more detailed list of companies and agencies pursued during the 2019 through 2020 school year (each labeled with progress status and results). Notably, positive highlights are the confirmed sources of funding from EPA Region IX, UCLA and UCR collaboration with Aeromon, and the Letter of Support from both the Port of Los Angeles and Port of Long Beach under the Clean Air Action Plan (CAAP) (see Appendix C).

Roughly 13 new potential funding sources were identified and contacted; however, five have no measurable progress. Of those five, however, three American entities [American RoRo, Eagle Bulk, and Sea Trade Holdings] -- as mentioned in the methodology section -- are only listed as "No Progress" as a result of the time constraints since the Practicum team pivoted to focus on larger public entities (e.g. Santa Barbara and Ventura County Air Pollution Control Districts).

The Practicum team contacted Mr. Roger Strevens (Chair, Trident Alliance) and formally presenting the project via Zoom on May 27, 2020. A letter of support for is anticipated.

For MAERSK Line, Alex contacted Dr. Lee Kindberg, Head of Sustainability and Environment at MAERSK, with -so far- limited feedback.

For grants, the Practicum team drafted and submitted a co-funding application for a Harbor Community Benefit Foundation Grant on May 15, 2020. An awards date has not been announced.

***Table 3-2:*** *Results of Co-funding*

| Company | Progress Status | Results |
|---|---|---|
| Bay Area Air Quality Management District | Confirmed | $100,000 |
| California Air Resource Board | Confirmed | $48,000 In-Kind Support |
| EPA Region IX | Confirmed | $200,000 |
| U.S. Maritime Administration | Confirmed | $138,000 to CE-CERT |
| UCLA School of Engineering | Confirmed | $50,000 In-Kind Support |
| UCR Bourns College of Engineering | Confirmed | $60,000 In-Kind Support |
| Clean Air Action Plan | In Progress | Letter of Support |
| Harbor Community Benefit Foundation Grant | In Progress | Submitted May 15th |
| Santa Barbara County Air Pollution Control District | In Progress | N/A |
| South Coast Air Quality Management District | In Progress | N/A |
| Trident Alliance | In Progress | Awaiting Letter of Support |
| U.S. Coast Guard | In Progress | N/A |
| Ventura County Air Pollution Control District | In Progress | N/A |
| California Climate Investments | No Progress | None |
| Eagle Bulk | No Progress | None |
| MAERSK Line | No Progress | None |

## *3.4 Conclusions*

Tables 3-1 and 3-2 are to provide the next Practicum team a general list of potential funding alternatives to continue to pursue, as well as to highlight which entities are to be avoided. A complete database encapsulates those attempts that did not progress past initial discussions or that did not engage the target entities. Tables may also help to determine new entities to pursue, particularly those who share similar objectives within the shipping industry.

The representation of private and public companies who lent their support for this project, either financially, in-kind, or by letter, is diverse, and hopefully, the list will continue to grow. Increasing the representation of nonprofit companies involved in this project is to be explored in the future. There are several 501(c)(3) organizations representing port communities that should continue to be informed and updated about the project.

Appended to this report, Appendix C, provided detailed memos with a timeline of outreach efforts for all companies with “In Progress” status, for convenience of next year’s Practicum Team.

# 4 . Activities to Support Field Experiments

## 4.1 Overview of Experimental Needs

A remaining research gap is the determination of the optimal technology to measure the horizontal distance between the UAV and OGV smokestack. Distance from the stack is important for three primary reasons:

A. Producing a scientific paper means a wealth of highly accurate data must be known on the precise location each air sample was taken. This information will serve as adequate evidence to prove that UAV monitoring can accurately predict the sulfur content of fuels at feasible sampling distances. This is particularly of interest to stringent governmental enforcement agencies: EPA, CARD, AQMD, etc.
B. UAV monitoring systems in the EU may become restricted from coming within 150 feet of an OGV. The two leading EU UAV sensor package providers seem to prefer to take plume samples in the 25 to 50 m range – which translates to 82 to 164 ft. As such, it is important to measure several in-plume air samples -- and test accuracy of fuel predictions – in a range that covers at least 50 to 180 ft. – and look for variations.
C. There is no certainty as to whether the theoretical hypothesis that the ratio of NO : $NO_2$ is a constant as emissions are measured farther from the OGV's stack. Thus, the upcoming in-field trials will yield critical data on the validity of the IMO formula used to calculate the fuel sulfur content (FSC) in the fuel burned by an OGV.

This choice of technology will have to be completed before the sea trials in October- so the next Practicum team is not likely to be charged to address this issue- but the work already completed by the year's Practicum team has prepared a solid foundation for an upcoming selection. Many technology options have been, and will continue to be, reviewed -- as summarized in Section 4.2 of this report. Critical considerations in determining best technology include:

I. range of measurement: 200 feet and associated uncertainty
II. ability of UAV to continually target OGV smokestack with sound, light, laser, etc.
III. cost that fits within the project budget
IV. durability through a wide range of environmental conditions: wind (moving altitude of drone), rain or shine, dust/smog, etc.
V. ability of UAV to interface with a pair of Arduinos/Raspberry Pi so as to wirelessly transmit real-time distance measurement regularly to the UAV operator.

An important note is that the review of technology options as performed by this Practicum team was based on the premise that it was merely to support field experiments, and feasibility of implementation during real-world monitoring and enforcement was not taken into account. For example, while it is possible to mount large retro reflective targets on the OGV smokestack during field experiments to take advantage of certain technology forms described in Table 4-1, that is not something expected of every ship passing through Californian waters.

## *4.2 Review of Technology Options*

Table 4-1 (below) summarizes the strengths and weaknesses of all reviewed technology categories, with respect to considerations I. to V. laid out in *Section 4.1*. Detailed accounts of specific companies and models targeted as "best" within that category were listed for ease of future reference. No technology was deemed perfect. This research question is still open-ended.

***Table 4-1:*** *Review of Technology Options*

| Technology Category | Specific Technology Models | Strengths | Weaknesses |
|---|---|---|---|
| **Ultrasound** | Arduino HC-SR04 Ultrasound sensor | - Easy interface with a pair of Arduino modules for wireless transmitting of real-time data<br>- Code for above scheme already written<br>- Unaffected by pollution, light, environmental conditions | - Unreliable over larger distances like 150 feet (50 m)<br>- Ultrasound will scatter off any object so it will be difficult to attribute measured scatter back is from the target* and not any other confounding objects |
| **Laser Altimetry** | Lightware LW20/c | - Long range: measurements cover our distance requirements (0-100m!)<br>- Limited programs available to interface with a pair of Arduinos<br>- GitHub code available to be customized for above scheme<br>- Real-time data points at 678 readings/second<br>- IP67 rated: highly resistant to environmental conditions like pollution, light, water, etc. | - Field of scope yet to determined (able to find the target*?)<br>- Medium tier expense<br>- Ideal in sunlit conditions (field testing in San Francisco means this is not a certainty) |
| **Light Detection and Ranging (Lidar)** | - LeddarTech (Vu8)<br>- LIDAR-Lite v3 | - Long range: measurements cover our distance requirements<br>- Could interface with a pair of Arduinos to wirelessly transmit distance measurements | - Expensive<br>- Issue with field of view (has 8 smaller fields) and can extend to 100m at 20° field, but is that large enough to find target?<br>- Need to adhere retroreflective tape covered target to smokestack |
| **Visual Calculations** | - Newark Raspberry Pi Camera<br>- Handheld Laser | - Cheap & simple using by hand geometry calculation<br>- Does not require complex equipment or trained professionals to operate. | - Hard to get real time distance measurement unless staff is doing math in the field<br>- Hard for tiny laser/light point to focus on target especially as distance increases and while considering environmental conditions: altitude, wind |
| **Time-of-Flight Calculations** | SICK mid/long range distance sensors | - Long range: measurements cover our distance requirements<br>- Highly precise measurements | - Heavy (> 200 g) considering needs to be mounted on drone<br>- Field of scope yet to determined (able to find the target*?)<br>- Requires a reflector target meaning one needs to be assembled and adhered to target*<br>- Multiple model options |
| **Drone with Built-In Ranging** | Matrice 300 with H20T rangefinder | - One single piece or equipment<br>- Comes with Smart Track which relieves stress of finding the target* since range finder can be calibrated to it<br>- No concerns about weight/durability of product considering environmental conditions | - Very expensive<br>- New technology without many experts to collaborate with<br>- H20T rangefinder is only compatible with this newest model of drone and cannot be combined with drones already approved for testing |

*target translates to the active smokestack of the OGV being tested during the field experiment

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# **Appendix A:** *Air Quality & Health Burdens Report*

**Preface**

The following report was submitted to our client and other third parties at the conclusion of this project. Its content is largely the same as that of ***Research***, *Section 1* above. However, for brevity, discussions of ozone $O_3$ were omitted, and for clarity, a highlights and abstract section were included before the introduction. We would like to acknowledge and thank both those who lended their intellectual expertise to provide model inputs along with the reviewers of this report:


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# Modeling air quality changes and quantifying $PM_{2.5}$-associated mortality increases in southern California communities as a result of non-compliance to the California Sulfur Rule

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**H I G H L I G H T S**

- $SO_X$ emissions from Ocean Going Vessels (OGVs) are the target of the California Sulfur Rule where 100% compliance is considered the baseline. In the case of $SO_2$, one of the species that contributes to $SO_X$, the increase in concentrations is 100 to 120% of the baseline concentrations along shipping lines and around 30% of the baseline along the coast. For $PM_{2.5}$, a similar spatial pattern is observed but the magnitude is on the order of 3% and 0.5% of the concentration over the ocean and along the coast respectively. The greatest increase in concentration across all species discussed is observed directly in and around the Port of Long Beach. Due to topographic features, pollutants tend to accumulate significantly inland and east of the ports as well.
- The air quality models currently used by California regulatory agencies assume 100% OGV compliance. There is reason to believe that this assumption might not be valid and that there are incidences of gross deliberate non-compliance wherein a percentage of ships burn fuels with high sulfur contents capable of producing discernible difference in SOx emissions.
- The increase in atmospheric $SO_X$ species positively correlates with an increase in $PM_{2.5}$ concentrations. BenMAP-CE estimates that this resultant increase in OGV $PM_{2.5}$ emissions in Los Angeles (LA) County as a result of 10% non-compliance to the California Sulfur Rule results in the annual addition of approximately 24 cases of mortality among 30 to 99 year olds, 618 cases of asthma exacerbation, cough among 6 to 18 year olds, and 40 cases of acute bronchitis among 8 to 12 year olds.

**A B S T R A C T**

Over 80% of global trade is enabled by marine transportation. According to the International Maritime Organization (IMO), the emissions contributions of OGVs are substantial: more than 13% of global $SO_X$ emissions, 15% of global $NO_X$ emissions, and 3% of global $CO_2$ emissions (IMO et al., 2014). As of January 1, 2020, new international regulations under International Maritime Organization (IMO) 2020 mandate that no OGV can burn fuels exceeding 0.5% in sulfur content by weight without using mitigative technologies (ie. scrubbers). As of 2014, California passed more stringent regulations, stating that sulfur content cannot exceed 0.1% by mass within 24 nautical miles off the state coast. However, there is reason to suspect that ships frequently flout these maximum sulfur content mandates. This paper estimates the unaccounted for $SO_X$ emissions from OGVs violating this rule and the resultant public health impacts particularly on economically disadvantaged port communities. Results show that health impacts include cases of lower respiratory symptoms, acute bronchitis, and mortality (all causes). The incidence rates of each of these health burdens seem to affect all age groups.

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## 1. Introduction

On January 1st, 2020, IMO's new global sulfur cap regulations came into effect, declaring 0.50% as the new global limit for sulfur content in marine fuel oil (IMO, 2020). In IMO designated Emission Control Areas (ECAs), this limit is further reduced to 0.10% sulfur content by mass. Prior to January 1, 2020, OGVs were allowed to burn high sulfur "bunker fuels" -- which were capped at 4.50% and then later at 3.50% per the global sulfur cap. These are the bottom of the barrel, sulfur-rich, noxious sludges that remain after petroleum processing. Since 2014, the 'California Sulfur Rule' has required the use of low sulfur marine fuels, currently at or below 0.10% sulfur by mass within 24 nautical miles of the California coastline (Fuel Sulfur and Other Operational Requirements for Ocean-going Vessels within California Waters and 24 Nautical Miles of the California Baseline, 2008). While past iterations of these regulations were implemented to reduce environmental and health burdens on portside communities worldwide, challenges to their full enforcement continue to exist.

The combustion of non-compliant marine fuel oil contributes to highly localized emissions of dangerous pollutants, most importantly the oxides sulfur ($SO_X$). More than 13% of global $SO_X$ emissions, 15% of global $NO_X$ emissions, and 3% of global $CO_2$ emissions are attributed to OGVs and these emissions are expected to reduce by up to 77% under the most recent mandates (IMO, 2020). $SO_X$ encompasses gaseous sulfur oxides such as sulfur monoxide (SO), sulfur dioxide ($SO_2$), sulfur trioxide ($SO_3$), or secondary particular sulfates ($SO_4^{2-}$), and sulfites ($SO_3^{2-}$).

Secondary particulate sulfites consist of a combination of sulfuric acids, ammonium bisulfate, and ammonium sulfate, and are formed through transformations of sulfur dioxide emissions either through gaseous or aqueous pathways. For the former, sulfur oxides react with hydroxyl radicals to form hydrogen sulfite, which then reacts with oxygen and water vapour to form gaseous sulfuric acid (Transportation Research Board, 2002; Lin *et al.*, 2011).

$$SO_{2(g)} + OH\bullet + M \Rightarrow HOSO_2\bullet + M \tag{1}$$

$$HOSO_2\bullet + O_{2(g)} \Rightarrow HO_2\bullet + SO_{3(g)} \tag{2}$$

$$SO_3 + H_2O_{(l)} + M \Rightarrow H_2SO_{4(g)} + M \tag{3}$$

This gas has two possible endpoints: condensation on existing particles as a sulfuric acid droplet or neutralization to ammonium sulfate or bisulfate in the presence of ammonia gas. Sulfur dioxides can also directly condense in foggy or cloudy conditions, and then oxidize with ozone or hydrogen peroxide to form sulfuric acid without intermediate products thereby resulting in acid rain (Transportation Research Board, 2002; Lin *et al.*, 2011).

$$HSO_3^-{}_{(aq)} + H_2O_{2(aq)} \Leftrightarrow SO_2OOH^-{}_{(aq)} + H_2O_{(l)} \quad (4)$$

$$O_{3(aq)} + SO_3^{2-}{}_{(aq)} \Rightarrow O_{2(g)} + SO_4^{2-}{}_{(aq)} \quad (5)$$

These secondary sulfates have been proven to represent up to 100% of atmospheric sulfate measured, and are a major contributor to mass fractions of fine particulate matter ($PM_{2,5}$, particles with aerodynamic diameters less than or equal to 2.5 μm). Atmospheric concentrations of secondary sulfates can increase up to 68% at sites of combustion- such as near OGV smokestacks- compared to pre-combustion levels, within 20 km of the combustion source (Buzcu *et al.*, 2006).

There are a myriad of health issues associated with inhalation of $SO_X$ emissions and associated exposure to $PM_{2.5}$, both of which result from the burning of high sulfur content fuels in OGVs (EPA & OTAQ, 2010). Clinical, epidemiological, and toxicological studies indicate that there exists a causal relationship between short-term exposure to atmospheric emissions and respiratory morbidity (WHO, 2013). Sulfur dioxide, or sulfur oxides in general, "irritate the mucous membranes of the eyes, nose, throat, and lungs" and can cause a host of symptoms including inflammation, difficulty in breathing, and reduced lung and heart function (NPS, 2018). Nitrogen oxides similarly irritate the respiratory and cardiovascular systems. They are also associated with abdominal pain, fertility issues, and genetic mutations in future generations (U.S. National Library of Medicine, n.d.).

It is important to reiterate the contribution that the transformation of sulfur oxides to secondary sulfate particles has on the rising concentrations of atmospheric $PM_{2.5}$. $SO_X$ and $PM_{2.5}$ concentrations are positively correlated. As such, the increase in $PM_{2.5}$ concentrations as a result of an increase in atmospheric $SO_X$ species can be quantified. These fine particulates are *most* closely associated with oxidative stress, airway hyper-responsiveness, respiratory distress, and decreases in lung function contributing to premature deaths, even more so than $NO_X$ and $SO_X$ (Guarnieri & Balmes, 2014).

Air pollution can affect human health in both the short and the long-term and is linked with premature mortality and reduced life expectancy from lung cancer, asthma attacks, respiratory infections, and long-term respiratory and heart disease (Kampa & Castanas, 2008).

The objective was to model the differences in atmospheric concentrations of $SO_X$ species and $PM_{2.5}$ as well as to quantify the associated health burdens measured in the number of cases of lower respiratory symptoms, acute bronchitis, mortality (all causes), cough and asthma exacerbation for two different scenarios. The first scenario assumes 100% compliance to the California Sulfur Rule while the second introduces a 10% non-compliance rate. This model was chosen as an approximation based on results from OGV emissions monitoring and enforcement by the European Union Sulfur Directive. These efforts in the EU show that there was a non-compliance rate of 5-15% at sea, but 5% at port. This latter figure was confirmed to also apply regionally during a private interview with Alex Barber at the California Air Resource Board (CARB), who reported an average

96.5% compliance based on inspections conducted at port since 2009. However, since a larger component of the research task at hand was to extend the effectiveness of inspection range from just port-side to actual at-sea assessments of OGV smokestack emissions, a non-compliance scenario of the average of the reported 5-15% range was used.

## 2. Method

### *2.1 WRF-Chem Model*

To understand air quality differences between the 100% compliance and the 10% non-compliance scenarios, the Weather Research and Forecasting (WRF) model coupled with Chemistry was used. This WRF-Chem modeling system simulates emissions, transport, mixing, and reacting of chemical constituents, particularly trace gases and aerosols, in various meteorological conditions. The simulation ran over a domain that covered the western U.S. in grids at a resolution of 4km x 4km. The vertical scale of the simulation, from surface level to 100 hPa, was divided into 24 layers. Over the ocean, the surface layer is approximately 37m thick and there are nine layers within 1km. Thus, the model adequately captures the mixing layer and has subsequently been used in multiple studies for similar assessments such as Wang, *et al.*, (2019).

Meteorological data over this 3D domain was gathered from the Final Operational Global Analysis data (ds083.2) of the National Center for Environmental Protection. Anthropogenic emissions are from the CARB emissions inventory with the Southern California domain replaced by emission from the South Coast Air Quality Management District (SCAQMD) where shipping lanes are explicitly resolved. Here, the data used was for the month of July 2012.

The model was run for an observation period, from 1st July to 1st August 2012 with 6 hour intervals such that four grid outputs were generated per day. In addition, a 6-day spin-up period was run from June 26th to July 1st. This was to minimize the effect of initial conditions or perturbations on the results of the simulation. To generate a grid of emissions it is important to understand how the chemicals are speciated and mapped over California, the simulation domain. A complete list of specifications is found in Wang, *et al.*, (2019).

Scaling of shipping emissions was achieved using data derived from CARB's Access Database. This database has two outputs which can be used to create a general snapshot of the net OGV emissions when OGVs are exclusively burning either high sulfur fuel oils or compliant low sulfur fuel oils. As this is a binary view of emissions, 10% non-compliance was calculated by using a weighted average of the two database emission factors. The first was multiplied by 0.10 and the second was multiplied by 0.90. The sum of these provided a 2.2 scaling factor to sulfur emissions from shipping which was needed to calculate air quality results for the 10% non-compliance case. For non-sulfur species, changes in emissions were estimated using the in-built WRF-Chem equations which summarize how other atmospheric chemical species concentrations change with respect to perturbations in sulfur species.

## *2.2 BenMAP*

Health Impact Functions (HIFs) were derived from epidemiological studies that associate air pollutant concentrations with targeted health effects. A HIF incorporates four key parameters: population data, air quality data, baseline mortality and morbidity rates, and a health risk estimate. Three health endpoints among different age groups are of particular interest.

The Environmental Benefits Mapping and Analysis Program-Community Edition (BenMAP-CE) is an open-source software developed by the Environmental Protection Agency (EPA). It calculates estimates for the number of air pollution-related morbidity and mortality cases over a specified spatial domain. The program provides a navigable graphical user interface (GUI) with pre-loaded databases that supplement the user-required data inputs in quantifying health impacts of air pollution.

There were six datasets required in the setup to calculate air pollution-related health impact estimates of interest. This included the grid definitions, pollutant attributes, monitoring data, incidence rates, population data, and the HIF. While some datasets were user-required inputs, others were provided by the BENMAP50.FDB and POPSIMDB.FDB databases of the software program.

Grid definitions identify geographic cells to which the air quality data, population data, incidence rates, and health impact functions will be assigned. The primary grid definition was provided by Wang *et al.,* (2019), and specified the region intended for analysis. The attribute table included two integer fields specified as Column and Row, with each polygon of the shapefile containing a non-repeating combination of values for the two fields. This allowed for a direct association between the shapefile grid definition, incidence/prevalence data, and the air quality modeling data. A crosswalk between the primary grid definition and all other pre-loaded grid definitions in the setup was then created. This step allowed BenMAP-CE to aggregate population data, incidence/prevalence rates, health impact functions, and other datasets at the geographic resolution of our analysis.

The pollutant of primary interest was $PM_{2.5}$, which is correlated with atmospheric $SO_X$ concentration. Its air quality metrics were subsequently defined. The main metric was D24HourMean, which describes a daily average of the hourly measurements taken to observe pollutant concentrations. The seasonal metric was defined as QuarterlyMean, which allowed aggregation of the daily pollutant concentration values over a specified period of time within the year. In this case, it was the observation period for which the WRF-Chem model was run: July 1st to August 1st.

The BENMAP50.FDB database provided baseline incidence and prevalence rates data required for the HIFs. BenMAP-CE provided census block population data that included over 200 age, gender, and race-specific variables. Population data was required to estimate exposure to specified health endpoints and adverse health impacts due to the change in air quality and pollutant concentrations.

BenMAP provided a database with a library of HIFs derived from multiple peer-reviewed epidemiological studies. The HIFs and corresponding health endpoints chosen for this analysis were sourced from the EPA Standard Health Functions dataset.

Following the setup modifications, the second stage involved creating the air quality surfaces, which have a grid structure that allows uniform grid cells to be populated with average pollutant concentration values in order to estimate population exposure. BenMAP-CE is dependent on air quality inputs from external modeling software or monitoring data. Our project employed the Model Direct approach to create the baseline and control air quality grids, which represented 90% and 100% compliance to the California Sulfur Rule scenarios respectively. The air quality input files were formatted to include the following variables: column, row, metric, seasonal metric, annual metric, and values.

The $PM_{2.5}$ concentration data from the WRF-Chem model was interpolated onto the primary grid definition to align the air pollution values with the unique column and row values assigned. Prior to importing the baseline and control air quality grids, the previously loaded shapefile grid definition was specified as the grid type. After the files passed the validation tests, an air quality delta air quality grid (baseline - control) was generated.

Aa BenMAP configuration file was built to estimate the incidence of adverse health effects due to the change in $PM_{2.5}$ concentration values. This file contained the parameters required for analysis, including the air quality grids, health impact functions, and population data, among others.

The chosen population dataset and year was the United States Census from 2012, which corresponded to the WRF-Chem modeled data. Incidence in BenMAP is defined as the "total number of adverse health effects avoided due to a change in air pollution levels," (U.S. EPA, 2015). Three representative health endpoints from the EPA Standard Health Functions Dataset were chosen. The first health endpoint was Mortality, All Cause among 30 to 99 year olds with the HIF derived from an epidemiological study by Krewski *et al*., (2009). The second health endpoint was Asthma Exacerbation, Cough among 6 to 18 year olds with the HIF derived from an epidemiological study by Ostro *et al*., (2001). The third health endpoint was Acute Bronchitis among 8 to 12 year olds with the HIF derived from an epidemiological study by Dockery *et al*., (1996). Incidence outputs are directly attributed to $PM_{2.5}$ emissions associated with $SO_X$ emissions from OGVs as modelled in this paper, and are thus free from confounding environmental factors or background industrial activities.

**Table 1 -** Health Burdens Due to 10% Non-Compliance to the California Sulfur Rule; Generated by BenMAP

| Incidence* Categories | Affected Age Groups | Health Impact Function (HIF) | Incidence* |
|---|---|---|---|
| Acute Bronchitis | 8 to 12 years old | $\left(1 - \frac{1}{(1-I)\, e^{(\beta * \Delta Q) + I)}}\right) * I * \text{P}$ | 40 |
| Asthma Exacerbation | 6 to 18 years old | $\left(1 - \frac{1}{(1-\text{A})\, e^{(\beta * \Delta Q) + A)}}\right) * \text{A} * \text{P} * \text{R}$ | 618 |
| Mortality (All Causes) | 30 to 99 years old | $\left(1 - \frac{1}{e^{(\beta * \Delta Q)}}\right) * I * \text{P}$ | 24 |

*Incidence defined as the total number of adverse health effects (cases) avoided due to compliance with the California Sulfur Rule

$\beta$ : coefficient for the health impact function; typically represents the percent change in a given adverse health impact per unit of pollution

$\Delta Q$ : absolute air quality change in $PM_{2.5}$ concentrations between the baseline scenario (90% compliance) and control scenario (100% compliance)

$I$ : health baseline incidence rate; estimate of the average number of people who die (or suffer from an adverse health effect) in a given population over a given period of time

$P$ : exposed population; number of people affected by the reduction in air pollution
$R$ : prevalence rate; percentage of individuals in a given population who already have a given adverse health condition
$A$ : parameter from epidemiological study by Ostro et al.; weighted average of the daily prevalence of cough among 8 to 13 year olds

## 3. Results and Discussion

The WRF-Chem model was run with the specifications described in the previous section to estimate the concentrations of various chemical species as a result of a 100% compliance (baseline scenario) and 10% non-compliance to the California Sulfur Rule during the month of July 2012. The results in this section include plots showing the absolute difference in chemical species concentrations between the 100% compliance and 10% non-compliance scenarios. In addition to these are maps of the ratio of this difference to the baseline 100% compliance scenario. This latter map delineates the effect that non-compliance can have with respect to the ambient air quality that can be expected when inland businesses and industries continue their activities as per their norm but with the California Sulfur Rule in place. For example, if a point on this map takes the value of *x*, then this means that the difference in species concentration at that point is *x*% of the baseline concentration. As observed, *x* is greater than 100 for many of the chemical species in question. Together, these two interpretations of the results provide a picture of the degree and spatial extent of air quality changes that can be expected as a result of a 10% non-compliance to the California Sulfur Rule.

**Table 2 -** Emission Changes at Hotpots$^{\Psi}$ Due to 10% Non-Compliance to the California Sulfur Rule, as Generated by WRF-Chem

| Species | Difference from Baseline* | Increase as a Percent of Baseline* |
|---|---|---|
| | μg m$^{-3}$ | % |
| Sulfur Dioxide ($SO_2$) | 0 - 4 | 80 - 120 |
| Sulfate ($SO_4^{2-}$) | 0.3 - 0.5 | 20 - 35 |
| Ammonium ($NH_4^+$) | 0.05 - 0.1 | 8 - 12 |
| Particulate Matter ($PM_{2.5}$) | 0.3 - 0.5 | 1 - 3 |

$^{\Psi}$ Hotpots spatially correlated with shipping lane and Ports of LA & Long Beach
* Baseline being ambient chemical species concentration during July 2012 as a result of 100% compliance with the California Sulfur Rule

### *3.1 $SO_X$ emissions*

The most direct improvement in ambient air quality that the California Sulfur Rule aims to achieve is a reduction in $SO_X$ emissions, particularly in and around ports and coastal communities. To understand the extent of such improvements, the following species were analyzed: $SO_2$, $SO_4^{2-}$, and $NH_4^+$. The objective here is to show how $SO_2$ concentrations change when non-compliant OGVs burn fuels that contain more sulfur than is permitted by the directive in addition to how atmospheric chemistry then encourages the formation of ammonium sulfate as described in Equation (5). In Figure 1, on the left, it is noted that the absolute difference in $SO_2$ concentrations is dampened over land by a spike of 14 μgm$^{-3}$ that is observed immediately off the coast of the Port of Long Beach. This suggests that the impact of $SO_2$ emissions as a result of OGV non-compliance is highly concentrated on communities in and near ports and along a narrow strip along the coast. However, it is important to note the difference itself can reach 14 μgm$^{-3}$ and that the spatial extent of this peak is dependent on meteorological conditions which have only been modeled for a single month. Conclusions from over a longer period of observation and in varying environmental conditions have yet to be drawn.

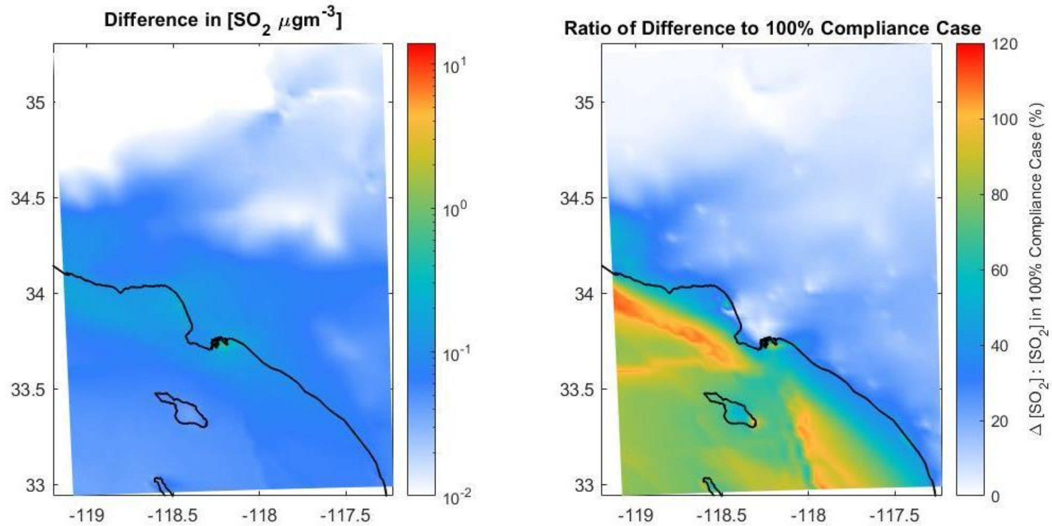



**Figure 1:** *Plot of: the difference in concentration of $SO_2$ between the two compliance scenarios (left); ratio of the difference in concentration of $SO_2$ to the concentration of $SO_2$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

Interestingly, the plot on the right of Figure 1 shows that the impact of the change in $SO_2$ concentrations as a result of non-compliance is substantial over the ocean when it is viewed as relative to concentrations of $SO_2$ in the baseline case. During the month-long simulation, it is clear that the change in $SO_2$ concentrations is between 100% to 120% of the baseline concentrations along the shipping lanes, which are markedly red-yellow in the plot. This can lead to a number of localized repercussions. A study of $SO_2$ emissions and their impact on marine ecosystems may be worth investigating to grasp a complete picture of some of these implications, particularly those which bring into question the sensitivity of marine species and ecosystems to perturbations of this magnitude. Additionally, it is important to note that, as a result of the shipping lines running close to the coast and extending both north and south of the ports, $SO_2$ concentrations directly along the coast can potentially increase by an average of 30% of the baseline concentrations if 10% of OGVs are non-compliant, a non-linear relationship further discussed after Figure 4.

The contribution of non-compliance in increasing $SO_2$ concentrations decreases further inland but is highest at the Port of Long Beach, where the increase in $SO_2$ concentration is around 80% the baseline concentration. As such, it is clear that the change in $SO_2$ concentrations as a result of non-compliance is dramatic when compared to the baseline, even if the absolute increase in concentrations is relatively small.

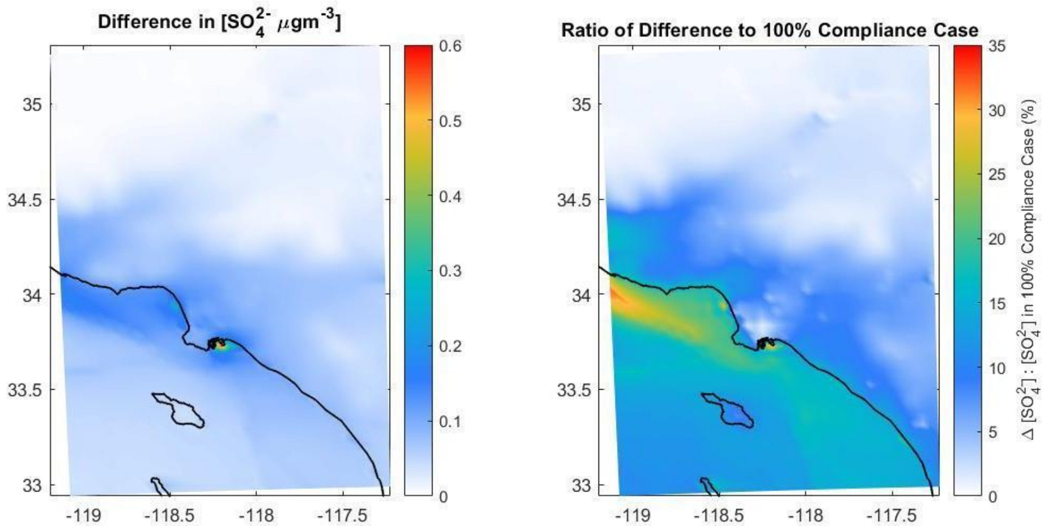



**Figure 2:** *Plot of: the difference in concentration of $SO_4^{2-}$ between the two compliance scenarios (left); ratio of the difference in concentration of $SO_4^{2-}$ to the concentration of $SO_4^{2-}$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

When analyzed in the context of $SO_4^{2-}$ concentrations, a very different view of $SO_X$ emissions is gained. Figure 2 shows that $SO_4^{2-}$ concentrations increase by a much smaller amount but that the increase is reflected across a wide spatial extent. Concentrations are expected to increase by around 0.5 $\mu gm^{-3}$ over the ocean, particularly along the shipping lines to the north and to the west of the Bay of San Pedro. This is consistent with the plot on the right, where, along the same shipping lines, the increase in $SO_4^{2-}$ concentrations is around 30% of the baseline concentrations. On the other hand, concentrations of $SO_4^{2-}$ along the coast and even a few miles inland are expected to increase by only around 0.1 $\mu gm^{-3}$. The most concentrated increase, however, is once again right over the Port of Long Beach, where an increase in $SO_4^{2-}$ concentrations of almost 0.6 $\mu gm^{-3}$ can be observed.

The increase in $SO_4^{2-}$ concentration relative to the baseline concentrations that can be expected is substantial, even many miles inland. As is shown on the right of Figure 2, much of the land along the coast can experience an increase in $SO_4^{2-}$ concentrations up to 10% of the baseline concentration. However, the closer one gets to the ports, the further inland this increase can be experienced. Further north and south of the port, the increase in $SO_4^{2-}$ concentration is only localized to a thin stretch along the coast. This means that, as was the case in Figure 1, the baseline concentrations of $SO_4^{2-}$ are low; however, the change that can occur as a result of just 10% non-compliance is a sizable fraction of ambient level and particularly exacerbated around the ports. This observation is useful when assessing the sensitivity of the populations and ecosystems to changes in such factors.

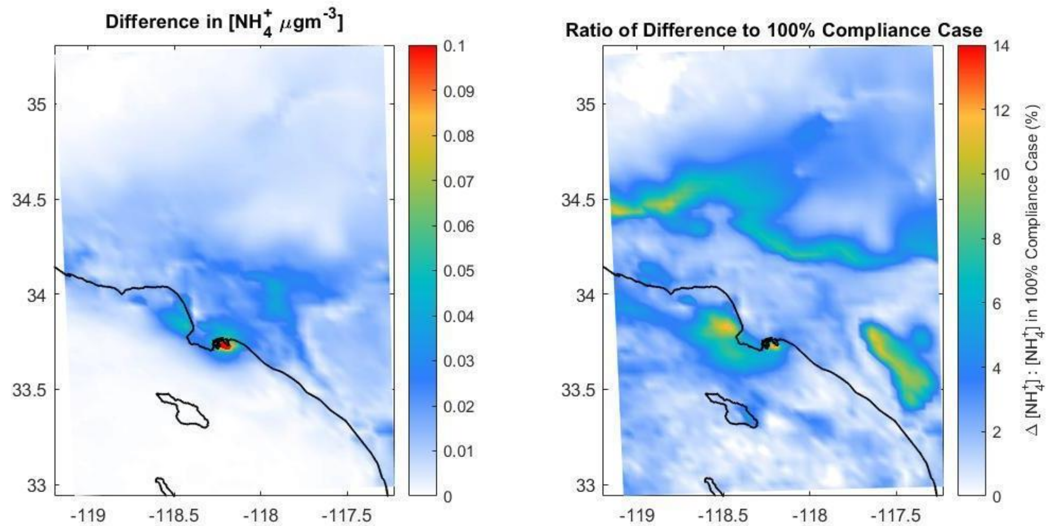



**Figure 3:** *Plot of: the difference in concentration of $NH_4^+$ between the two compliance scenarios (left); ratio of the difference in concentration of $NH_4^+$ to the concentration of $NH_4^+$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

It is important to note that atmospheric $SO_4^{2-}$ is often in the form of ammonium sulfate. For this reason, it is necessary to look at the spatial distribution of $NH_4^+$ concentrations under the same simulation. Atmospheric $NH_4^+$ has both natural and anthropogenic sources, including ammonia based fertilizers, animal by-products, and some industrial processes (Behera *et al*., 2013). This explains why the absolute difference in $NH_4^+$ between the two cases is minimal and on the order of 0.05 $\mu gm^{-3}$ except just off the coast of the Port of Long Beach where it is 0.1 $\mu gm^{-3}$. Looking at the plot of the ratio of the difference to the baseline, a "plume" is observed in and around the ports but which extends mainly off the coast rather than inland. Here, the difference in $NH_4^+$ concentrations is between 8 to 12% the baseline concentrations. However, there are also two additional "plumes" that are noted much further inland. One is located southeast of the ports while the other forms a band that is directly north of the ports. These "plumes" are hypothesized to visualize how the mountain ranges surrounding the LA basin trap pollutants and can result in the accumulation of pollutants and chemical species in areas far away from their sources. Here, a longer period of observation is required to better analyze such movements and trapping that can occur under different environmental conditions.

$NO_3^-$ is another chemical species that is associated with fuel emissions and often competes with $SO_4^{2-}$ to chemically bind with atmospheric $NH_4^+$. Thus, a spatial understanding of $NO_3^-$ concentrations illuminates which of the two species is limited and how they contribute to $PM_{2.5}$ concentrations over land or over the ocean. In Figure 4, there is an overall decrease in $NO_3^-$ concentrations over the ocean as a result of non-compliance. This is particularly true along the shipping lanes where there is a decrease of between 0.1 and 0.2 $\mu gm^{-3}$. Here, $NO_3^-$ decreases where $SO_4^{2-}$ concentrations increase. This shows that over the ocean, where $NH_4^+$ concentrations are limited, $NO_3^-$ is displaced by $SO_4^{2-}$, thereby resulting in a minimal change in $PM_{2.5}$ concentrations (Figure 5). Over land and particularly along the coast, $NH_4^+$ is no longer limiting, as seen in Figure 3. Here, $PM_{2.5}$ concentrations increase as both $NO_3^-$ and $SO_4^{2-}$ are able to chemically bind with the ambient $NH_4^+$

contributing to particulate matter. A map of $PM_{2.5}$ concentrations is used to understand the effect of atmospheric composition on portside communities.

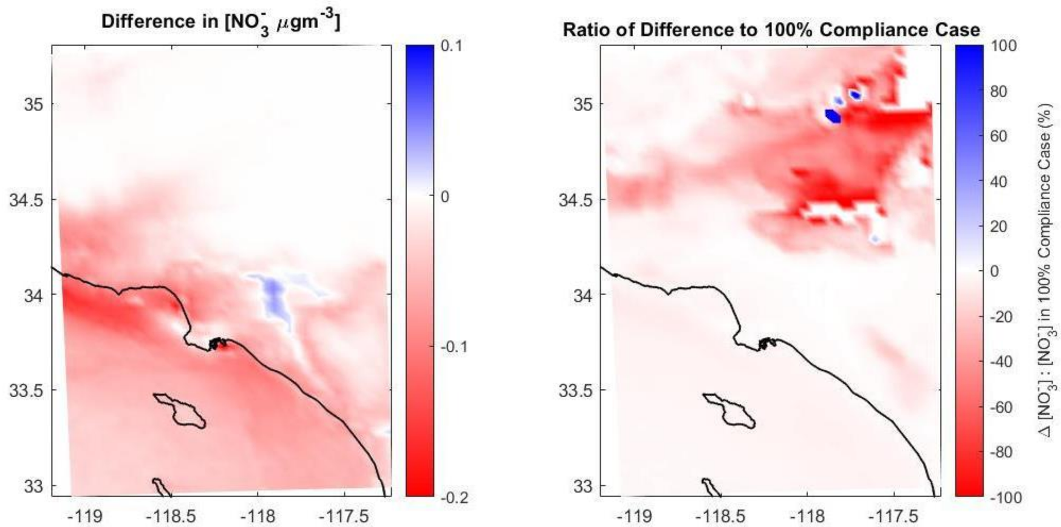



**Figure 4:** *Plot of: the difference in concentration of $NO_3^-$ between the two compliance scenarios (left); ratio of the difference in concentration of $NO_3^-$ to the concentration of $NO_3^-$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

## *3.2 $PM_{2.5}$-associated mortality*

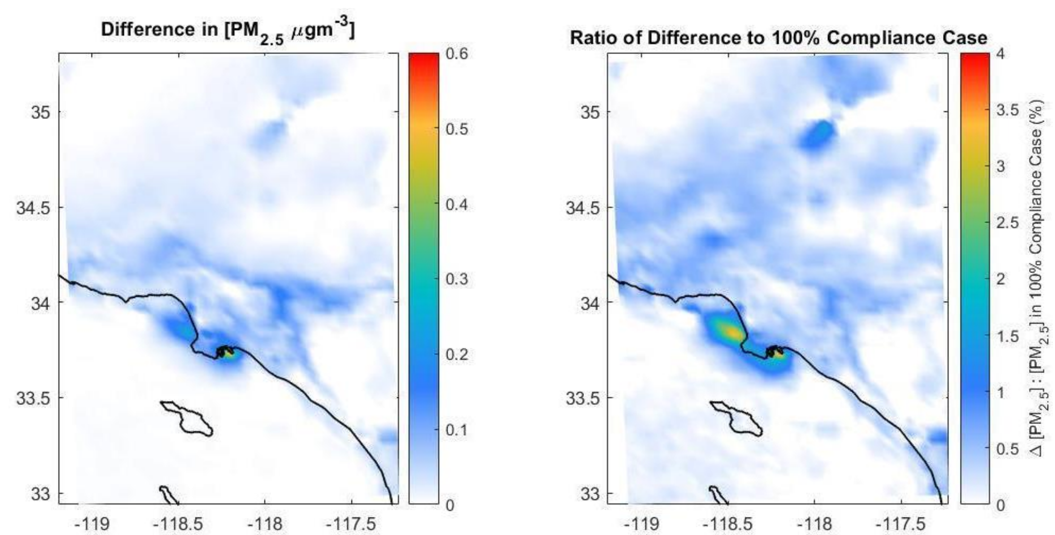
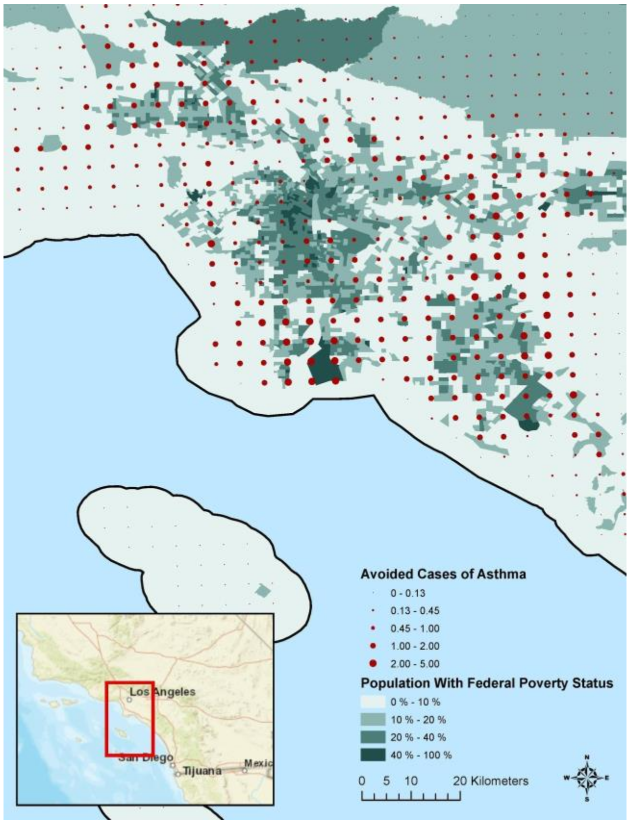


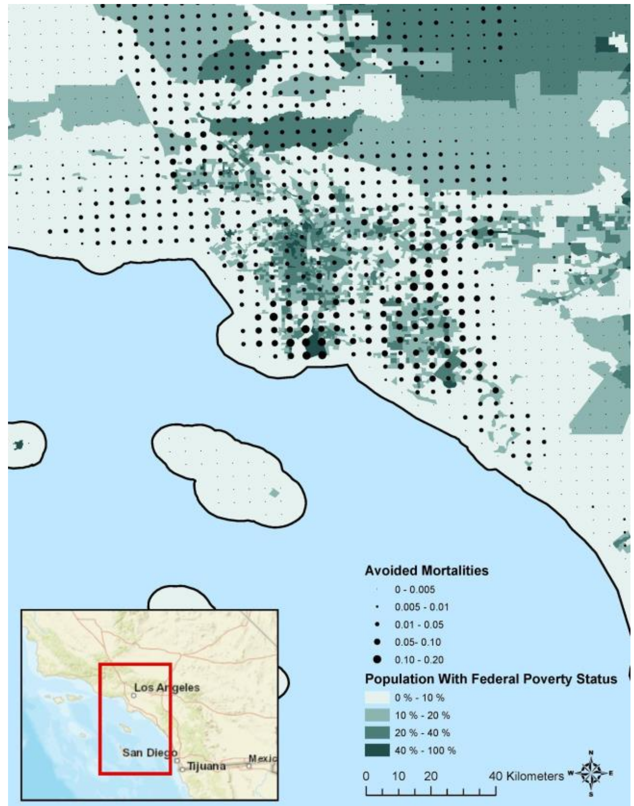

**Figure 5:** *Plot of: the difference in concentration of $PM_{2.5}$ between the two compliance scenarios (left); ratio of the difference in concentration of $PM_{2.5}$ to the concentration of $PM_{2.5}$ in the 100% compliance case (right). Both are averaged over the month of July 2012.*

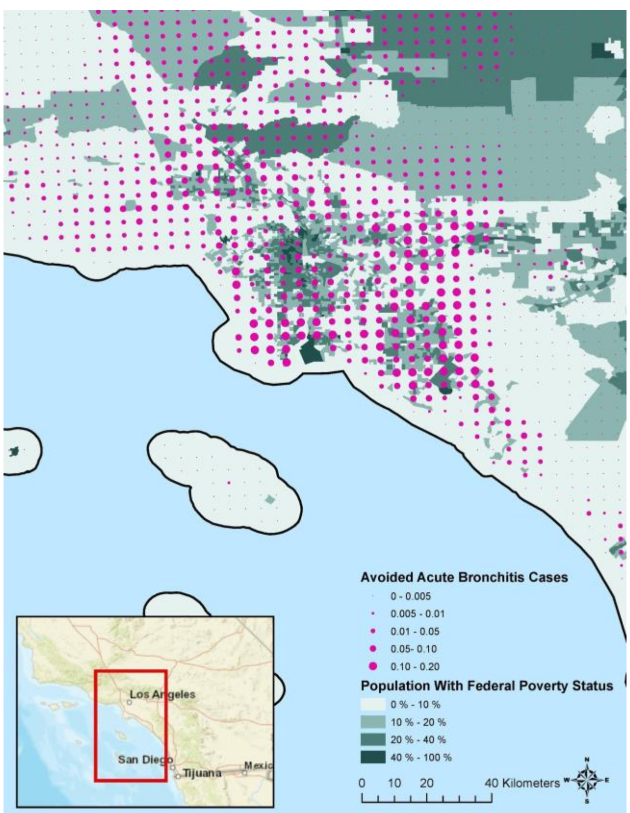
The WRF-Chem results for $PM_{2.5}$ concentrations were used as inputs in the health impact analysis that was completed on BenMAP. Spatially, concentrations of $PM_{2.5}$ are greatest in and around the Ports of LA and Long Beach. The peak in absolute difference is well correlated with the location of peaks in $SO_X$ concentrations: they are all observed just off the coast of the Port of Long Beach. In addition, it was noted that the change in concentration around the port is at most 3.5% of the baseline concentration of $PM_{2.5}$. From Figure 2, it can be seen that the change in $SO_4^{2-}$ concentration was increased by 10% of the baseline concentration of $SO_4^{2-}$ in the same region. In Figure 1, increases in $SO_2$ concentrations directly along the coast was 30% of the baseline concentration. This shows that $SO_2$ and $SO_4^{2-}$ contribute significantly to the increase in $PM_{2.5}$.

Visualizations for Figure 6 were modeled in ArcGIS: shapefiles with incidence values were sourced directly from BenMAP-CE; poverty data per census tract, and TIGER/Lines shapefiles were downloaded from the U.S Census Bureau. These maps visualize the spatial distribution of the total 24 deaths among 30 to 99 year olds and multiple hospitalizations: 618 cases of asthma exacerbation among 6 to 18 year olds, and 40 cases of acute bronchitis among 8 to 12 year olds caused by $PM_{2.5}$ exacerbation due 10% noncompliance. High incidence rates for all three categories: asthma exacerbation, acute bronchitis, and all cause mortality, are concentrated in hotspots where $PM_{2.5}$ concentrations are greatest -- near the coast closest to the Port of LA and Long Beach and also at the eastern end of the basin around Riverside and San Bernardino where secondary pollutants accumulate. As seen in the maps, when overlayed on poverty, there is a spatial correlation where higher incidence rates for asthma exacerbation, acute bronchitis, and all cause mortality are highly correlated with census tracts where populations have extremely high percentages of poverty. This has important environmental justice implications, since the burden of health risks is laid on those in poverty who are often disenfranchised and without health care.

**A.** **B.**




**C.**

**Figures 6A-C:** *Maps visualizing geographical distributions of the change in morbidity and mortality incidence/prevalence rates due to $PM_{2.5}$ emissions (***A***: Asthma Exacerbation,* **B***: All Cause Mortality,* **C***: Acute Bronchitis) overlayed on top of populations with poverty status. Incidence rate magnitudes are represented by the size of dots (larger meaning more incidence) visualizing the number of annual avoided cases when compliance with California Sulfur Rule regulations increases from 90% to 100%; or in reverse, the cases caused by OGV $PM_{2.5}$ emissions due to 10% non-compliance. Poverty was determined by federal determination for poverty status in 2018, where darker hues represent higher percentages of the census tract population with poverty status.*

## 4. Conclusions

While it is well documented that OGVs burning high-sulfur fuel have a drastic effect on public health, especially in Southern California where intense port-related activities create both occupational and public risks, air quality regulatory entities lack the resources and tools to enforce full OGV compliance with the California Sulfur Rule. There is strong economic motivation to flout this rule due to: a difference over $200 per ton of clean fuel versus low sulfur fuel, a relatively low, non-targeted inspection rate of approximately 4 - 12 %, and the fact that these inspections can only be conducted at pier with a limited number of trained staff. Coupled with the fact that there is no checking for compliance while leaving the ports and that there is a known inspection pattern, it is clear that the levied penalties are minimal in comparison to the potential gain from non-compliance.

A 10% non-compliance rate -- and its associated sulfur emissions -- has been modelled to account for an additional 24 deaths among 30 to 99 year olds and multiple hospitalizations each year, 618 cases of asthma exacerbation/coughs among 6 to 18 year olds, and 40 cases of acute bronchitis among 8 to 12 year olds, ceteris paribus. As evident in our model, there do exist emission hotspots associated with ports and shipping lanes; however, the degree of emission exacerbation in these hotspots cannot be proven to perfectly reflect real-world conditions, as exact conditions of compliance are unknown. As with any model, unassailable conclusions on emission differences, nor their associated health burdens, can be drawn. However, results from past studies show that an 80% reduction in sulfur content of OGV fuels from 2.7% to 0.5% sulfur by weight results in a 50% reduction in premature mortalities while a further 80% reduction from 0.5% to 0.1% sulfur by weight results in a 30% reduction in premature mortalities (Winebrake, *et al.*, 2009). Thus, the relationship between sulfur content of OGV fuels and the resultant health burdens is non-linear. As such, it is important to first understand the degree of non-compliance of OGVs in and around the Ports of LA and Long Beach so that the underlying assumptions in this study can be tuned to better capture the real-world conditions. This, in turn, will more clearly illuminate how the reduction in fuel sulfur content truly correlates with mitigating health burdens.

Approximately 40% of Americans live within coastal counties. This number grows to 60%, or 26.5 million people, in California (NOAA, 2016). Populations in many of the coastal counties are either heavily employed in or rely on the shipping industry, thus making research on the health impacts contributed by marine commercial activity highly relevant (Coker & Sok, n.d). Looking at the case of Southern California, it is known that OGV activity at large ports, such as the Ports of LA and Long Beach, endangers the health of nearby communities in Long Beach, Belmont Shore, the Westside, San Pedro, Harbor, Wilmington, West Carson, and Lomita as seen during spatial visualization of aforementioned health burdens. Based on proximity to loading and unloading docks, it is acknowledged that these regions are vulnerable to public health harms caused by emissions from the combustion of sulfur-rich fossil fuels. What has not been acknowledged to date are the additional “hidden” ill health effects from unreported sulfur emissions from yet to be recognized non-compliant OGVs. If these suspected health effects continue to be ignored, the necessary mitigating measures are unlikely to be taken to protect human health and lives.

Quantifying the incidence and progression of mortality and human health endpoints is a critical component of regional health risk assessments and the policy decision-making process of air pollution-based regulatory agencies such as the California Air Resources Board (CARB) and the South Coast Air Quality Management District (SCAQMD). Despite legislation that mandates a reduction in sulfur content of fuels, OGVs and their emissions will still account for approximately 250,000 deaths and 6.4 million childhood asthma cases each year globally (Sofiev, *et al.,* 2018). Thus, it is hoped that this research will galvanize interest in enhancing the existing inspection practices -- specifically frequency and range -- by implementing aerial monitoring and active targeting systems at a level similar to that of Unmanned Aerial Vehicles (UAVs) being used in the EU to fly in the smokestacks of sailing OGVs. It is hoped that non-compliance can thus be better monitored and that the collection of significant penalties from sulfur rule violators can be facilitated. One such system in Norway has reportedly paid for itself in one year from the collected fines.

Based on this research, it is suggested that a fleet of a small number of UAVs, suitably equipped with sensor package payloads, can be deployed to help facilitate California's enforcement agencies to catch non-compliant OGVs on a real time basis, and thus discourage non-compliance. This will eliminate the health effects from suspected OGV non-compliance highlighted in this study, resulting in a significant air quality improvement, a decrease in air pollution related morbidity and mortality, and an overall rise in the quality of life for communities in and around the ports.

**Future Recommendations**

While the spatial analysis examined general regions where the incidence of health effects were localized, a more substantial manipulation of data with ArcGIS could assess aforementioned health impacts for individual communities and cities, galvanizing local interest in UAV program funding. AB 617 clearly mandates the allocation of financial gains from emissions fines towards lowering air pollution in California's disadvantaged communities, attributing mortalities and hospitalizations (asthma, acute bronchitis, lower respiratory symptoms) to these communities. Putting forth incidences of morbidity and mortality due to the lack of tools to fully document the level of non-compliance could help promote and enact projects leading to aerial monitoring solutions for both medium and long-range compliance assessments.

Furthermore, this significant quantification of statistics on health impacts -- which so far are limited only to $PM_{2.5}$-associated health burdens -- should be extended to $NO_X$, $SO_X$, and ozone species and for longer than a one month snapshot. Of note is that this extension in the scope of research would require more initial WRF-Chem models to be run-specifically with more current emission data than July 2012 (2014 onward). As of 2014, California passed more stringent regulations, stating that sulfur content cannot exceed 0.1% by mass within 24 nautical miles off the state coast, which is likely to affect ambient OGV emissions and thus model conclusions.

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# **Appendix B:** *Cost-Benefit Analysis Database*

**Table B-1:** Annual Benefits and Costs Incurred with UAV Implementation over Three Year Period during CARB Fuel Sulfur Rule Enforcement (Option #1[a])

| Description | Year 2021 | 2022 | 2023 |
|---|---|---|---|
| **Estimated Direct Costs** | | | |
| Purchase Two UAV Systems[b] | $128,000 | $0 | $128,000 |
| Contract Two UAV Pilots[c] | $480,000 | $489,600 | $499,392 |
| Contract Sensor Suites + Operator Services | $175,500 | $175,005 | $183,038 |
| Contract Chase Boat(s)[d] | $315,000 | $315,000 | $315,000 |
| Purchase Two Maritime Exchange Software Licenses[e] | $10,800 | $10,800 | $10,800 |
| **Estimated Benefits[f]** | | | |
| Additional Penalties Assessed (Conservative) | $396,000 | $185,625 | -$24,750 |
| Additional Penalties Assessed (Optimistic) | $707,520 | $331,650 | -$44,220 |
| Economic Valuation of Improved Health Outcomes | $0 | $89,503,763 | $179,007,527 |
| **Summary[g]** | | | |
| Total Direct Costs | $1,109,300 | $990,405 | $1,136,230 |
| Total Benefits (Conservative) | $396,000 | $89,689,388 | $178,982,777 |
| Total Benefits (Optimistic) | $707,520 | $89,835,413 | $178,963,307 |
| **Assumptions** | | | |
| Baseline True Non-Compliance Rate: 10.0% | | | |
| Baseline Non-Compliance Rate Identified by CARB: 2.0% | | | |
| Non-Compliance Rate Identified by CARB in Year 1: 10.0% | | | |
| Non-Compliance Rate Identified by CARB in Year 3: 1.5% | | | |
| Non-Compliance Rate decreases each year at a constant rate. | | | |
| Average Penalties Assessed Per Identified Non-Compliant OGV (Conservative): $8,250 | | | |
| Average Penalties Assessed Per Identified Non-Compliant OGV (Optimistic): $14,740 | | | |
| Number of CARB OGV Inspections Performed: 600 Inspections per Year (4 Inspections per Day for 150 Days) | | | |

Notes:

[a] CARB purchases UAV systems and separately contracts UAV pilots.

[b] Includes: UAV Units (2-Year Lifecycle), Cameras (Video + Infrared), Spare Parts (Motors, Propellor Blades, etc.), Extra Batteries.

[c] 2% Inflation rate applied to UAV pilot and to sensor operator costs each year.

[d] Chase boats are not contracted simultaneously. One chase boat is contracted in San Pedro Bay for approximately 108 days and in San Francisco Bay for approximately 42 days.

[e] Separate software licenses required for San Pedro Bay and San Francisco Bay. Lower costs can be incurred by paying for each on a monthly basis, as needed.

[f] Conservative versus optimistic benefits reflect the choice of average penalty assessed per identified non-compliant OGV. Note that benefits related to assessed penalties are negative in the third year because the CARB-identified non-compliance rate in year three was expected to be lower than the baseline CARB-identified non-compliance rate, resulting in fewer penalties collected due to overall increased compliance.

[g] Total Costs and Benefits are undiscounted and shown here for reference. Refer to Table 2-1 for the discounted, net present value of estimated costs and benefits.

**Table B-2:** Annual Benefits and Costs Incurred with UAV Implementation over Three Year Period during CARB Fuel Sulfur Rule Enforcement (Option #2[a])

| Description | Year 2021 | Year 2022 | Year 2023 |
|---|---|---|---|
| **Estimated Direct Costs** | | | |
| Contract Two UAV Pilots with UAV Systems[b] | $630,000 | $642,600 | $655,452 |
| Contract Sensor Suites + Operator Services | $175,500 | $175,005 | $183,038 |
| Contract Chase Boat(s)[c] | $315,000 | $315,000 | $315,000 |
| Purchase Two Maritime Exchange Software Licenses[d] | $10,800 | $10,800 | $10,800 |
| **Estimated Benefits[e]** | | | |
| Additional Penalties Assessed (Conservative) | $396,000 | $185,625 | -$24,750 |
| Additional Penalties Assessed (Optimistic) | $707,520 | $331,650 | -$44,220 |
| Economic Valuation of Improved Health Outcomes | $0 | $89,503,763 | $179,007,527 |
| **Summary[f]** | | | |
| Total Direct Costs | $1,131,300 | $1,143,405 | $1,164,290 |
| Total Benefits (Conservative) | $396,000 | $89,689,388 | $178,982,777 |
| Total Benefits (Optimistic) | $707,520 | $89,835,413 | $178,963,307 |
| **Assumptions** | | | |
| Baseline True Non-Compliance Rate: 10.0% | | | |
| Baseline Non-Compliance Rate Identified by CARB: 2.0% | | | |
| Non-Compliance Rate Identified by CARB in Year 1: 10.0% | | | |
| Non-Compliance Rate Identified by CARB in Year 3: 1.5% | | | |
| Non-Compliance Rate decreases each year at a constant rate. | | | |
| Average Penalties Assessed Per Identified Non-Compliant OGV (Conservative): $8,250 | | | |
| Average Penalties Assessed Per Identified Non-Compliant OGV (Optimistic): $14,740 | | | |
| Number of CARB OGV Inspections Performed: 600 Inspections per Year (4 Inspections per Day for 150 Days) | | | |

Notes:

[a] CARB does not purchase UAV systems, instead contracting UAV pilots who supply their own UAV systems.

[b] 2% Inflation rate applied to UAV pilot and to sensor operator costs each year.

[c] Chase boats are not contracted simultaneously. One chase boat is contracted in San Pedro Bay for approximately 108 days and in San Francisco Bay for approximately 42 days.

[d] Separate software licenses required for San Pedro Bay and San Francisco Bay. Lower costs can be incurred by paying for each on a monthly basis, as needed.

[e] Conservative versus optimistic benefits reflect the choice of average penalty assessed per identified non-compliant OGV. Note that benefits related to assessed penalties are negative in the third year because the CARB-identified non-compliance rate in year three was expected to be lower than the baseline CARB-identified non-compliance rate, resulting in fewer penalties collected due to overall increased compliance.

[f] Total Costs and Benefits are undiscounted and shown here for reference. Refer to Table 2-1 for the discounted, net present value of estimated costs and benefits.

**Table B-3:** Joint Sensitivity Analysis of Net Benefits[a] (3% Discount Rate[b]) for Option #1[c]

| | | Parameter #1: Non-Compliance Rate Identified by CARB in Year 1 | | | | |
|---|---|---|---|---|---|---|
| | | 5.0% | 7.5% | 10.0% | 12.5% | 15.0% |
| Parameter #2: Non-Compliance Rate Identified by CARB in Year 3 | 0.0% | $142,925,116 | $216,098,621 | $289,272,127 | $362,445,633 | $435,619,139 |
| | 1.0% | $113,795,729 | $186,969,235 | $260,142,741 | $333,316,247 | $406,489,753 |
| | 2.0% | $84,666,343 | $157,839,849 | $231,013,355 | $304,186,861 | $377,360,367 |
| | 3.0% | $55,536,957 | $128,710,463 | $201,883,969 | $275,057,475 | $348,230,981 |
| | 4.0% | $26,407,571 | $99,581,077 | $172,754,583 | $245,928,089 | $319,101,594 |
| | 5.0% | -- | $70,451,691 | $143,625,197 | $216,798,703 | $289,972,208 |
| | 6.0% | -- | $41,322,305 | $114,495,811 | $187,669,317 | $260,842,822 |
| | 7.0% | -- | $12,192,919 | $85,366,425 | $158,539,931 | $231,713,436 |
| | 8.0% | -- | -- | $56,237,039 | $129,410,544 | $202,584,050 |
| | 9.0% | -- | -- | $27,107,653 | $100,281,158 | $173,454,664 |
| | 10.0% | -- | -- | -- | $71,151,772 | $144,325,278 |
| | 11.0% | -- | -- | -- | $42,022,386 | $115,195,892 |
| | 12.0% | -- | -- | -- | $12,893,000 | $86,066,506 |
| | 13.0% | -- | -- | -- | -- | $56,937,120 |
| | 14.0% | -- | -- | -- | -- | $27,807,734 |

Notes:

[a] Net benefits shown are for the conservative lower limit estimate. The optimistic upper limit estimate increases net benefits by approximately 0 to 9%

[b] Use of a 7% discount rate decreases net benefits by approximately 10%

[c] CARB does not purchase UAV systems, instead contracting UAV pilots who supply their own UAV systems. Only decreases in the non-compliance rate over time were of interest.

**Table B-4:** Joint Sensitivity Analysis of Benefit Cost Ratios[a] (3% Discount Rate[b]) for Option #1[c]

| | | Parameter #1: Non-Compliance Rate Identified by CARB in Year 1 | | | | |
|---|---|---|---|---|---|---|
| | | 5.0% | 7.5% | 10.0% | 12.5% | 15.0% |
| Parameter #2: Non-Compliance Rate Identified by CARB in Year 3 | 0.0% | 46.5 | 69.8 | 93.1 | 116.4 | 139.6 |
| | 1.0% | 37.2 | 60.5 | 83.8 | 107.1 | 130.4 |
| | 2.0% | 27.9 | 51.2 | 74.5 | 97.8 | 121.1 |
| | 3.0% | 18.7 | 42.0 | 65.3 | 88.5 | 111.8 |
| | 4.0% | 9.4 | 32.7 | 56.0 | 79.3 | 102.6 |
| | 5.0% | -- | 23.4 | 46.7 | 70.0 | 93.3 |
| | 6.0% | -- | 14.2 | 37.4 | 60.7 | 84.0 |
| | 7.0% | -- | 4.9 | 28.2 | 51.5 | 74.8 |
| | 8.0% | -- | -- | 18.9 | 42.2 | 65.5 |
| | 9.0% | -- | -- | 9.6 | 32.9 | 56.2 |
| | 10.0% | -- | -- | -- | 23.6 | 46.9 |
| | 11.0% | -- | -- | -- | 14.4 | 37.7 |
| | 12.0% | -- | -- | -- | 5.1 | 28.4 |
| | 13.0% | -- | -- | -- | -- | 19.1 |
| | 14.0% | -- | -- | -- | -- | 9.9 |

Notes:

[a] Benefit cost ratios shown are for the lower limit estimate. Upper limit estimate increases benefit cost ratios by approximately 0 to 8%

[b] Use of a 7% discount rate decreases benefit cost ratios by approximately 6%.

[c] CARB does not purchase UAV systems, instead contracting UAV pilots who supply their own UAV systems. Only decreases in the non-compliance rate over time were of interest.

**Table B-5:** Joint Sensitivity Analysis of Net Benefits[a] (3% Discount Rate[b]) for Option #2[c]

| | | Parameter #1: Non-Compliance Rate Identified by CARB in Year 1 | | | | |
|---|---|---|---|---|---|---|
| | | 5.0% | 7.5% | 10.0% | 12.5% | 15.0% |
| Parameter #2: Non-Compliance Rate Identified by CARB in Year 3 | 0.0% | $142,728,123 | $215,901,628 | $289,075,134 | $362,248,640 | $435,422,146 |
| | 1.0% | $113,598,737 | $186,772,242 | $259,945,748 | $333,119,254 | $406,292,760 |
| | 2.0% | $84,469,350 | $157,642,856 | $230,816,362 | $303,989,868 | $377,163,374 |
| | 3.0% | $55,339,964 | $128,513,470 | $201,686,976 | $274,860,482 | $348,033,988 |
| | 4.0% | $26,210,578 | $99,384,084 | $172,557,590 | $245,731,096 | $318,904,602 |
| | 5.0% | -- | $70,254,698 | $143,428,204 | $216,601,710 | $289,775,215 |
| | 6.0% | -- | $41,125,312 | $114,298,818 | $187,472,324 | $260,645,829 |
| | 7.0% | -- | $11,995,926 | $85,169,432 | $158,342,938 | $231,516,443 |
| | 8.0% | -- | -- | $56,040,046 | $129,213,552 | $202,387,057 |
| | 9.0% | -- | -- | $26,910,660 | $100,084,165 | $173,257,671 |
| | 10.0% | -- | -- | -- | $70,954,779 | $144,128,285 |
| | 11.0% | -- | -- | -- | $41,825,393 | $114,998,899 |
| | 12.0% | -- | -- | -- | $12,696,007 | $85,869,513 |
| | 13.0% | -- | -- | -- | -- | $56,740,127 |
| | 14.0% | -- | -- | -- | -- | $27,610,741 |

Notes:

[a] Net benefits shown are for the conservative lower limit estimate. The optimistic upper limit estimate increases net benefits by approximately 0 to 9%

[b] Use of a 7% discount rate decreases net benefits by approximately 10%

[c] CARB does not purchase UAV systems, instead contracting UAV pilots who supply their own UAV systems. Only decreases in the non-compliance rate over time were of interest.

**Table B-6:** Joint Sensitivity Analysis of Benefit Cost Ratios[a] (3% Discount Rate[b]) for Option #2[c]

| | | Parameter #1: Non-Compliance Rate Identified by CARB in Year 1 | | | | |
|---|---|---|---|---|---|---|
| | | 5.0% | 7.5% | 10.0% | 12.5% | 15.0% |
| Parameter #2: Non-Compliance Rate Identified by CARB in Year 3 | 0.0% | 43.7 | 65.7 | 87.6 | 109.5 | 131.4 |
| | 1.0% | 35.0 | 56.9 | 78.9 | 100.8 | 122.7 |
| | 2.0% | 26.3 | 48.2 | 70.1 | 92.0 | 114.0 |
| | 3.0% | 17.6 | 39.5 | 61.4 | 83.3 | 105.2 |
| | 4.0% | 8.9 | 30.8 | 52.7 | 74.6 | 96.5 |
| | 5.0% | -- | 22.0 | 44.0 | 65.9 | 87.8 |
| | 6.0% | -- | 13.3 | 35.2 | 57.1 | 79.1 |
| | 7.0% | -- | 4.6 | 26.5 | 48.4 | 70.3 |
| | 8.0% | -- | -- | 17.8 | 39.7 | 61.6 |
| | 9.0% | -- | -- | 9.1 | 31.0 | 52.9 |
| | 10.0% | -- | -- | -- | 22.3 | 44.2 |
| | 11.0% | -- | -- | -- | 13.5 | 35.4 |
| | 12.0% | -- | -- | -- | 4.8 | 26.7 |
| | 13.0% | -- | -- | -- | -- | 18.0 |
| | 14.0% | -- | -- | -- | -- | 9.3 |

Notes:

[a] Benefit cost ratios shown are for the lower limit estimate. Upper limit estimate increases benefit cost ratios by approximately 0 to 8%

[b] Use of a 7% discount rate decreases benefit cost ratios by approximately 6%.

[c] CARB does not purchase UAV systems, instead contracting UAV pilots who supply their own UAV systems. Only decreases in the non-compliance rate over time were of interest.

## **Appendix C:** *Database of Partners: Financial & In-Kind Support*

**Table of Contents**


| | |
|---|---|
| Summary of Funds | 69 |
| **Private Companies** | **70-72** |
| Trident Alliance | 70 |
| MAERSK | 71 |
| HCBF | 72 |
| **Public Companies** | **73-85** |
| CARB | 73 |
| SCAQMD | 74 |
| BAAQMD | 75 |
| US EPA REGION IX | 76 |
| MARAD | 77 |
| CCI | 78 |
| CBE | 79 |
| CAAP | 80 |
| UCLA School of Engineering | 81 |
| UCR Bourns College of Engineering | 82 |
| SBCAPCD | 83 |
| VCAPCD | 84 |
| SEP | 85 |
| **Charts & Visuals** | **86-88** |


Summary of Funds

| Company | Progress Status | Results |
|---|---|---|
| Bay Area Air Quality Management District | Confirmed | $100,000 |
| California Air Resource Board | Confirmed | $48,000 In-Kind Support |
| EPA Region IX | Confirmed | $200,000 |
| U.S. Maritime Administration | Confirmed | $138,000 to CE-CERT |
| UCLA School of Engineering | Confirmed | $50,000 In-Kind Support |
| UCR Bourns College of Engineering | Confirmed | $60,000 In-Kind Support |
| Clean Air Action Plan | In Progress | Letter of Support |
| Harbor Community Benefit Foundation Grant | In Progress | Submitted May 15th |
| Santa Barbara County Air Pollution Control District | In Progress | N/A |
| South Coast Air Quality Management District | In Progress | N/A |
| Trident Alliance | In Progress | Awaiting Letter of Support |
| U.S. Coast Guard | In Progress | N/A |
| Ventura County Air Pollution Control District | In Progress | N/A |
| California Climate Investments | No Progress | None |
| Eagle Bulk | No Progress | None |
| MAERSK Line | No Progress | None |

Company Name:

Trident Alliance
http://www.tridentalliance.org/

Description:
The Trident Alliance was formed in 2014 with a goal to enforce more stringent enforcement of OGV Sulphur regulations. Under the leadership of Roger Strevens, VP for Sustainability at Wallenius Wilhelmsen, the alliance aids in enforcing Sulphur regulations to provide less deterioration towards the environment and human health.

Funds Obtained:

In Progress

Efforts Made:

01/23/20: Entered scope as a potential co-funding option.

01/26/20: [Fong] Found contact information for Roger Strevens [Trident Alliance Chair]

02/08/20: [Fong] Sent out an email to Roger Strevens.

02/10/20: Received an email asking for clarification of what we want with Trident Alliance.

03/26/20: Alex sent an email inquiring if Roger was interested in reading through the project scope.

03/26/20: Roger Strevens acknowledges Project Scope and begins to work on commenting & editing the document.

03/27/20: Alex sends Project Scope document.

04/15/20: Roger returns Project Scope with comments & edit suggestions.

05/22/20: [Fong] Sent a follow-up email asking if they would like to receive a project presentation in the next few weeks.

05/25/20: Roger Strevens responded with available times for presentation (7am). Email also mentions that he would gladly consider writing a letter of support.

05/27/20: Presented to Roger Strevens. Got good feedback for our project. Mentioned that he may write us a letter of support.

Company Name:

MAERSK
https://www.maersk.com/

Description:
MAERSK was formed in 1904 and has become one of the largest shipping cargo supply chain. In terms of sustainability, they focus on "working systematically to reduce negative and enhance positive impacts on people, society and environment" (MAERSK, 2019). Dr. Lee Kindberg is the current Head of Environment and Sustainability at MAERSK.

Funds Obtained:

In Progress

Efforts Made:

02/07/20: Entered scope as a potential co-funding option.

02/21/20: [Fong] Located Dr. Lee Kindberg's contact information.

02/25/20: [Fong] Sent Dr. Lee Kindberg's contact information to Alex and William.

03/08/20: [Fong] Drafted an email directed to Dr. Lee Kindberg; sent to Alex for comments & edits.

03/11/20: Received feedback. Told to look for her phone contact info.

03/12/20: [Fong] Found phone contact. Alex left a message in her voice mailbox.

03/14/20: Alex started an email conversation with Dr. Lee Kindberg.

03/24/20: Dr. Lee Kindberg has received Project Scope #1 and is commenting & editing Project Scope # 1.

04/15/20: Coronavirus cancelled all meeting plans between [Fong & Alex] in discussions for this company.

05/5/20: Alex mentioned sending Dr. Lee Kindberg another follow-up email.

05/11/20: [Fong] Sent Alex a reminder about sending Dr. Lee Kindberg an email

05/19/20: Alex sent another email to Dr. Lee Kindberg

05/26/20: Alex announced that there is no progress with MAERSK.

Company Name:

HCBF
https://hcbf.org/

Description:
The Harbor Community "was created as a result of the settlement known as the 'TraPac MOU,' an agreement where the Port of Los Angeles in collaboration with the City of Los Angeles addressed the negative cumulative environment and public health impacts of its local port communities" (HCBF, 2019).

Funds Obtained:

In Progress

Efforts Made:

02/28/20: Alex mentions that HCBF would be a potential source of funding.

03/4/20: [Katie] Background research on board members sent to Alex.

03/11/20: Alex reached out to HCBF Executive Director about Community Benefit Grant LOI

04/21/20: [Katie] Sent emails to Alex to clarify different portions of the HCBF application.

04/28/20: [Katie] Received edits for HCBF LOI version #3.

05/11/20: Alex suggested partnering with HCBF for SEP proposal

05/15/20: HCBF LOI submitted.

Company Name:

CARB
https://ww2.arb.ca.gov/homepage

Description:
The California Air Resource Board (CARB) was founded in 1967 with the goal of collaborating with different air districts to reduce air pollutant exposure in high impact communities.

Funds Obtained:

$48,000 (est.) in-kind

Efforts Made:

Pursued by Alex and William

[Information given]:

Began in summer of 2018.
Committed in-kind assistance and to facilitate transfer of EPA money through the “105” mechanism.

Company Name:

SCAQMD
http://www.aqmd.gov/

Description:
The South Coast Air Quality Management District (SCAQMD) was founded in 1994 with the goal of regulating harmful air quality levels in the Southern Coast of California. They are required to "demonstrate attainment of the federal national ambient air quality standards (NAAQS)" and are also required to meet the more stringent California Ambient Air Quality Standards (CAAQS) under the Clean Air Act (CAA).

Funds Obtained:

$15,000 (est.) In-kind Support

Efforts Made:

Pursued by Alex and William

[Information given]:

One of the first project in-kind supporters in fall 2018 and spring 2019. Helped set up project protocol. No further support. Currently pursuing renewal efforts to bring them on this project.

Company Name:

BAAQMD
https://www.baaqmd.gov/

Description:
The Bay Area Air Quality Management District (BAAQMD) was founded in 1955 to manage the air quality levels within the Bay Area. "The Air District aims to create a healthy breathing environment for every Bay Area resident while protecting and improving public health, air quality, and the global climate" (BAAQMD, 2019).

Funds Obtained:

$100,000

Efforts Made:

Pursued by Alex and William

[Information given]:

Began in early 2019.

Company Name:

US EPA REGION IX
https://www.epa.gov

Description:
EPA Region IX is an EPA district which spans across Hawaii, California, Nevada, and Arizona. This EPA district assures that the listed states are upholding the National Ambient Air Quality Standard regulations for each state.

Funds Obtained:

$200,000

Efforts Made:

Pursued by Alex and William

[Information given]:

Began in April of 2019.

Company Name:

MARAD
https://www.maritime.dot.gov/

Description:
The Maritime Administration (MARAD) was founded in 1950. Their mission is to promote maritime transportation, ensure infrastructure safety, and provide fleets to the U.S. during national emergencies.

Funds Obtained:

$138,000*
*Funds allocated directly to CE-CERT for on-board in-stack emission testing
$870,000 (est.) in-kind

Efforts Made:

Pursued by Alex and William

[Information given]:

Had a plan that originally provided a package consisting of $500,000; MARAD vessel for 2-3 days, two fuel supplies, etc.- estimated net cost of ~$1,000,000.

Company Name:

CCI

http://www.caclimateinvestments.ca.gov/

Description:

Clean Climate Investments (CCI) is a subgroup of the California Air Resource Board (CARB) this initiative focuses on innovative environmentally friendly projects that provide ships with the best available technologies (BAT) to deal with air pollutant emissions.

Funds Obtained:

None

Efforts Made:

01/15/20: Alex wants us to research various co-funding opportunities to approach.

01/26/20: Alex wants research done on CCI.

01/26/20: [Fong] Sent an email to Alex with information about CCI.

01/31/20: [Fong] More research done for Alex

02/02/20: [Fong} Sent email to Alex with the context of CCI.

Reasoning: Research was performed to determine whether the IoES-ADEPT Group Inc. project would qualify for this initiative grant. However, through that process, the IoES Group discovered that project funding is only given to projects that focus on BAT (best available technologies) upgrades on ships rather than off-ships technologies such as UAV + sensor packages.

Company Name:

Communities for a Better Environment
http://www.cbecal.org/

Description:
Communities for a Better Environment (CBE) is a distinguished environmental justice organization that works to ensure the environmental health and safety for communities of color and low income communities, which are disproportionately affected by the pollution levels in the ports of California.

Funds Obtained:

None

Efforts Made:

Email sent to Alicia Rivera asking if CBE would be interested in partnering together to submit a SEP proposal for funding

Repeated follow-ups, no-reply.

Company Name:

CAAP
https://cleanairactionplan.org/

Description:
The Clean Air Action Plan (CAAP) is a collaboration between the Port of Los Angeles and the Port of Long Beach with the focus of reducing port-related air and health risks, while producing jobs and stimulating the U.S. economy.
.
Funds Obtained:

Letter of Support

Efforts Made:

Pursued by Alex and William

[Information given]:

04/29/20: Letter of Support Received

Company Name:

UCLA School of Engineering
https://samueli.ucla.edu/

Description:
The UCLA Samueli School of Engineering and the UCR Bourns School of Engineering are currently collaborating with Aeromon to introduce the UAV-based sensor package technology to the Los Angeles Ports.

Funds Obtained:

$50,000 (est.) in-kind

Efforts Made:

Pursued by Alex and William

[No information given]

Company Name:

UCR Bourns College of Engineering
https://www.engr.ucr.edu/

Description:
The UCR Bourns School of Engineering and the UCLA Samueli School of Engineering are currently collaborating with Aeromon to introduce the UAV-based sensor package technology to the Los Angeles Ports.

Funds Obtained:

$60,000 (est.) in-kind

Efforts Made:

Pursued by Alex and William

[No information given]

Company Name:

Santa Barbara County Air Pollution Controls District
https://www.ourair.org/

Description:
The Santa Barbara County Air Pollution Control District was founded in 1975 under the California Air Pollution Control Officers Association (CAPCOA). It is a local government agency that ensures safe air quality exposure in Santa Barbara County.

Funds Obtained:

In Progress

Efforts Made:

04/14/20: Alex suggested that we look into other air districts besides BAAQMD and SCAQMD to collaborate in the project.

04/22/20: [Fong] Sent out an email to Ms. Arlin Aeron Genet (SBCAPCD) inquiring if she would be interested in commenting & editing our Project Scope #1.

04/30/20: [Fong] Sent out a follow up email asking if she received the email.

04/30/20: Ms. Genet responded saying that she was interested in providing feedback to our Project Scope #1.

04/30/20: [Fong] Sent Project Scope #1 document.

05/22/20: [Fong] Sent another email asking if she would like to receive a presentation from the Practicum 19'-20' team before we graduate.

05/23/20: In Progress

Company Name:

Ventura County Air Pollution Controls District
http://www.vcapcd.org/

Description:
The Ventura County Air Pollution Control District was founded in 1975 under the California Air Pollution Control Officers Association (CAPCOA). It is a local government agency that ensures safe air quality exposure in Ventura County.

Funds Obtained:

In Progress

Efforts Made:

04/14/20: Alex suggested that we look into other air districts besides BAAQMD and SCAQMD to collaborate in the project.

04/22/20: [Fong] Sent out an email to Dr. Laki Tisopulos, (VCAPCD) inquiring if she would be interested in commenting & editing our Project Scope #1.

04/30/20: [Fong] Sent out a follow up email asking if he received the email.

05/22/20: [Fong] Sent another follow up email asking if he would like to receive a presentation from the Practicum 19'-20' team before we graduate.

05/28/20: Response from Dr. Laki Tisopulos. Interested in hearing about our project.

06/06/20: Alex sent Dr. Laki Tisopulos the end-of-practicum student video.

Application Name:

SEP (California Air Resources Board)
https://calepa.ca.gov/

Description:
Supplemental Environmental Projects (SEP) are environmentally beneficial projects that receive funding from third parties who violate environmental regulations. The funding comes from a portion of their fines, and all projects are screened by the EPA in order to be considered by the third party violator.

Funds Obtained:

No Progress

Efforts Made:

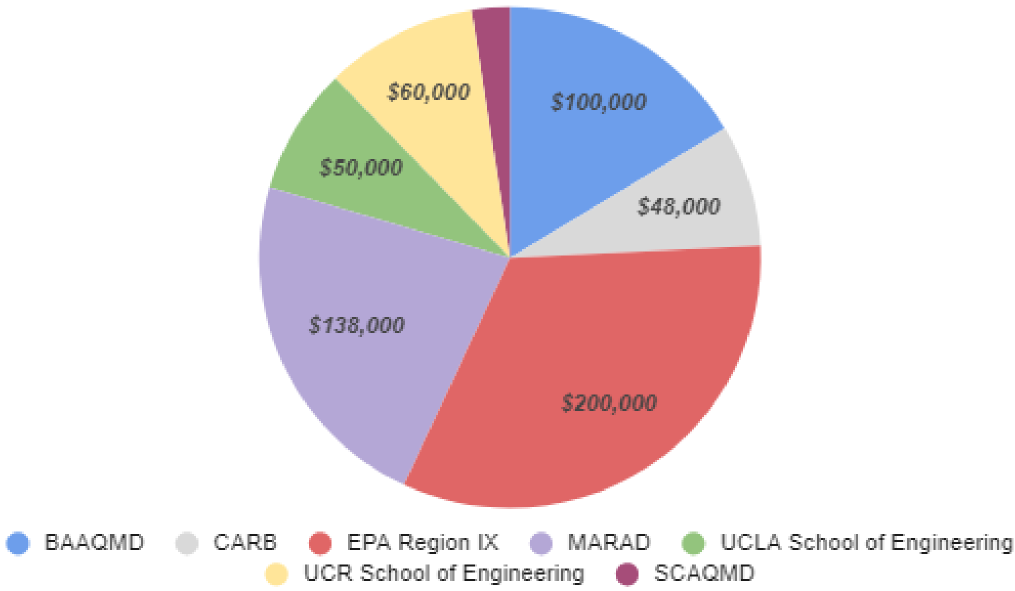
01/27/20: [Katie] began work on filling out the SEP application on behalf of The ADEPT Group Inc.

02/03/20: Suggestion to turn in SEP through a 501(c)(3) because it would better meet the requirements for turning in a SEP

02/15/20: Alex sent an email to Joe Lyou, President and CEO of Coalition for Clean Air (CCA), inquiring about partnering with CCA to submit a SEP

02/25/20: Alex exchanged emails with Chris Chavez, Deputy Policy Director at CCA, and he suggested other community organizations that might be a better fit for our SEP partnership, one being the Harbor Community Benefit Foundation

Funds and In-Kind Participation Contributed



SAN PEDRO BAY PORTS
# CLEAN AIR ACTION PLAN

April 24, 2020

Alex Spataru, PE
Chief Executive Officer
The ADEPT Group, Inc.
10866 Wilshire Blvd., Suite 400
Los Angeles, CA 90024

Dear Mr. Spataru:

**SUBJECT: LETTER OF SUPPORT FOR THE EVALUATION OF ADVANCED REMOTE AERIAL MONITORING OF OGV EMISSIONS PROJECT SERIES**

The Port of Los Angeles and Port of Long Beach (San Pedro Bay Ports, Ports) are pleased to support the series of projects developed by The Adept Group, Inc. in collaboration with engineering teams from UCLA and UC Riverside. Our understanding is that your team is implementing a series of four projects that work toward the validation and calibration of technology for advanced remote aerial monitoring of Ocean Going Vessel (OGV) emissions, with the goal to enhance compliance with Sulfur Emission Control Areas (SECAs) and California Air Resources Board's (CARB) OGV sulfur fuel regulation. We look forward to viewing the results of the projects.

The Ports' Clean Air Action Plan (CAAP), most recently updated in 2017, guides the Ports in collaborating with regulatory agencies in developing and implementing appropriate regulations to supplement the CAAP strategies to further reduce emissions from the large sources that move cargo in and out of the Ports. Compliance with current regulations and CAAP strategies assist the Ports in continuing to reduce air pollution as shown in our annual emission inventories.

OGV emission reductions are particularly challenging as the turnover of older, more polluting engines is slow, since most are designed to remain in service for 25 years or more. The goal of your project series to evaluate technology that has the potential to enhance compliance with these regulations aligns with our CAAP goals to reduce OGV emissions at the ports. These reductions will benefit our port and terminal operators and the local community at large.

If successful, the project will result in technology that could be used by CARB or the US Coast Guard to enhance their capabilities to enforce the use of low sulfur fuel in coastal waters. This facilitates an even playing field for maritime commerce within the San Pedro Bay Ports as well as all commercial North American ports. The Ports had instituted a voluntary incentive for shipping lines to switch to cleaner fuels well prior to CARB's adoption of the sulfur rule requirements and recognize the value in ensuring compliance with the current regulation.

We appreciate your project team's efforts to enhance compliance with sulfur fuel regulations. Please feel free to contact our staff, Jacob Goldberg or Rose Szoke, via email with any questions at jgoldberg@portla.org or rose.szoke@polb.org.

Sincerely,

CHRISTOPHER CANNON
Director of Environmental Management
Port of Los Angeles

MATTHEW ARMS
Acting Director of Environmental Planning
Port of Long Beach

CC:LW:TJD:TP:JG:yo