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Air Quality, GHG, and Human Health Impacts Associated with Fuel Cell Electric Technologies in Port Applications

THESIS

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By

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List of Acronyms

SPBPC	San Pedro Bay Port Complex
POLA	Port of Los Angeles
POLB	Port of Long Beach
TEU	Twenty-foot Equivalent Units
SoCAB	South Coast Air Basin of California
NOx	Oxides of Nitrogen
PM2.5	Fine Particulate Matter smaller than 2.5 microns
SOx	Oxides of Sulfur
VOC	Volatile Organic Compounds
NAAQS	National Ambient Air Quality Standards
AQM	Air Quality Model
CARB	California Air Resources Board
SCAQMD	South Coast Air Quality Management District
CEC	California Energy Commission
FCET	Fuel Cell Electric Truck
CMAQ	Community Multiscale Air Quality model
BAU	Business-As-Usual
SIP	State Implementation Plan
BenMAP	Benefits Mapping and Analysis Program
GHG	Greenhouse Gasses
PM	Particulate Matter of any size
HDFCT	Heavy Duty Fuel Cell Truck
CTE	Center for Transportation and the Environment
HDDT	Heavy Duty Diesel Trucks
VMT	Vehicle Miles Traveled
BET	Battery Electric Trucks
CHE	Cargo Handling Equipment
RTG	Rubber-tire Gantry cranes
OGV	Ocean-Going Vessels
HC	Harbor Craft

HFO	Heavy Fuel Oil
SOFC	Solid Oxide Fuel Cell
SMOKE	Sparse Matrix Operator Kernel Emission tool (emission processing tool)
EIC	Emission Inventory Code
FIPS	Federal Information Processing Standard
WRF	Weather Research and Forecasting model
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
CEPAM	California Emissions Projection, Analysis and Modeling tool
EMFAC	CARB Emissions Factor tool
MHE	Material Handling Equipment
YT	Yard Tractors
EICSUM	Summary Level Emission Inventory Code (portion of EIC)
ROG	Reactive Organic Gases
MEGAN	Model of Emissions of Gases and Aerosols from Nature
SMR	Steam Methane Reformation
AEC	Alkaline Electrolysis Cell
SOEC	Solid Oxide Electrolysis Cell
CO2e/MJ	Carbon Dioxide Equivalent per Megajoule
CI	Carbon Intensity
AQMP	Air Quality Management Plan
FCEL	Fuel Cell Electric Locomotives
FCES	Fuel Cell Electric Ships

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Abstract

The San Pedro Bay Port Complex is a critical piece of the world economy as a hub of good movement and its activities generate significant pollutant emissions in an air basin that frequently struggles with degraded air quality. This research explores fuel cell deployment in place of diesel combustion engines for port activities and the air quality, GHG emissions, and human health impacts as a mitigation strategy for the degraded air quality induced by the ports. Fuel cell deployments are modeled as emission reductions in the year 2035 for port activities and ambient concentrations of air pollutants are obtained by simulating atmospheric chemistry (CMAQ). Ambient pollutant concentrations are compared against national standards and human health response functions from literature to assess impacts on morbidity and mortality as well as socioeconomics. Finally, Greenhouse Gas equivalency is determined for the emissions reductions modeled for the atmospheric simulation including upstream impacts associated with displaced diesel production and new hydrogen production. Results show potential for widespread reduction in ozone and fine particulate concentrations with titration-related increases in ozone at the immediate vicinity of the port. The maximum change in ozone was calculated to be a reduction of 5.09 ppb with a corresponding reduction in $PM_{2.5}$ of 2.56 $\mu g/m^3$ for the same case. Human health and socioeconomic modeling predict large net health and economic benefits. The valuation of health benefits is estimated to range $3,209,700 to $7,108,100 per day using modeling strategies demonstrated by the U.S. Environmental Protection Agency and California Air Resources Board.

1 Introduction

The San Pedro Bay Port Complex (SPBPC) is comprised of the two most actives ports in the United States including the Port of Los Angeles (POLA, #1 in the United States) and the Port of Long Beach (POLB, #2 in the United States). The POLA handles more containerized cargo than any other port in the United States processing over 4.6 million Twenty-Equivalent Units (TEUs) in 2017 with an estimated total cargo value of $250 billion. The Port of Long Beach handles more than 3.8 million TEUs valued at $66 billion making it the second most active container port [1]. Globally both ports rank highly in TEUs, 17th for POLA and 21st for POLB. Combined they would rank 9th. Shanghai and Singapore, the world's largest and second largest port respectively, each handle more than twice the volume of the combined volume of POLA and POLB [2]. While it is clear that SPBPC is an important element in the world economy, these two ports contribute directly to degraded air quality and have adverse health impacts on the residents of the South Coast Air Basin of California (SoCAB). Activities of the ports are significant contributors of emissions of nitrogen oxides (NO_x), fine particulate matter ($PM_{2.5}$), sulfur oxides (SO_x), carbon monoxide (CO), and volatile organic compounds (VOC). Most of these emissions come from combustion engines that power drayage trucks, freight rail, hoteling and anchored ships, and cargo handling equipment such as yard tractors, top loaders, and gantry cranes [3]–[5].

SoCAB frequently experiences high concentrations of ozone, often in excess of National Ambient Air Quality Standards (NAAQS). While ozone is not directly omitted from the aforementioned engines, it is formed in the atmosphere and governed by a system of reactions involving NO_x and VOC [6]. The relationship between ozone, NO_x, and VOC is rather complex and non-linear, therefore it is necessary to use a comprehensive Air Quality Model (AQM) to determine the impact changes in emissions have on ambient ozone concentrations. Due to difficulties meeting NAAQs throughout the state of California and SoCAB in particular, NO_x emissions have regularly been the target of state agencies such as the California

Air Resources Board (CARB), the South Coast Air Quality Management District (SCAQMD), and the California Energy Commission (CEC). These agencies continue to explore zero or low emission alternatives to high polluting technologies including electrified versions of the aforementioned machines powered by fuel cells and/or batteries. These efforts are also supported by private interests such as the Toyota Portal Project has deployed a Fuel Cell Electric Drayage Truck (FCET) and currently operates at the POLA.

The potential emission reduction from deployment of electrified technologies is apparent. However, the impacts on overall air quality is not as straightforward as the relationship between emissions and concentration of air pollutants is non-linear. The air quality impacts of such deployments are lacking in the literature and so it is the goal of the research to assess the ambient air quality and human health impacts associated with electrification of port machinery. To achieve this goal several scenarios are developed to assess the span of potential deployments in the year 2035 of heavy-duty drayage trucks, freight rail, auxiliary ship power, and port operations equipment (cargo/material handling, yard tractors, gantry cranes, etc.…). For each type of equipment emissions impacts are determined individually and collectively. The emissions impacts are used as input to a comprehensive three-dimensional AQM, the Community Multiscale Air Quality model (CMAQ). The model outputs ambient pollutant concentrations including ozone and both primary and secondary $PM_{2.5}$.

The ambient concentrations of these pollutants are compared to a Business-As-Usual (BAU) scenario derived from projected emissions based on the CARB emission inventory associated with the 2016 State Implementation Plan (2016 SIP). The difference in pollutant concentration between the developed scenarios and the BAU scenario represent the contributions of the port technologies to degraded ambient air quality. Finally, the difference in pollutant concentrations allow the usage of the Benefits Mapping and Analysis Program (BenMAP), a health impact assessment tool, to quantify the benefits to society from improvements in air quality. BenMAP uses air pollutant concentrations and health impact functions to estimate reductions in the risk of premature death, heart attacks, and other adverse health effects. After estimating the reductions in the incidence of health effects, BenMAP calculates the monetary benefits associated with those reductions. Such estimations provide a metric of the changes in air pollutant concentration that is easy to understand for those who do not study atmospheric chemistry and epidemiology.

1.1 Goal

With these facts in mind, **it is the goal of this research to determine the air quality, greenhouse gasses (GHG), and human health impacts associated with the deployment of fuel cell electric technologies for port activities**. Achievement of this goal will assess a potential mitigation strategy for concerns raised in literature regarding relationship between goods movement and air quality and human health.

1.2 Objectives

Six objectives have been identified that, when reached will amount to the successful completion of the goal of this research. These objectives are as follows, (1) identify candidate port activities, (2) develop emissions fields for the AQM, (3) simulate atmospheric chemistry to determine concentrations of primary and secondary pollutants, (4) compare simulated concentrations with NAAQS and baseline projections, (5) compute GHG emissions changes, and (6) compute human health and economic impacts using BenMAP. Successful completion of these six objectives will reach the goal to determine the air quality, GHG, and human health impacts associated with the deployment of FCET for port activities.

2 Background

Since Arie Haagen-Smit published his findings on Los Angeles smog in 1952, ozone has been a major target of air pollution control efforts [7], [8]. These efforts have led to improvement in air quality in the SoCAB resulting in fewer days in exceedance of NAAQs and Health Advisory standards. However, these same trends show a recent spike in exceedance days in the SoCAB [9]. Therefore, to continue to strive towards attainment of the NAAQS it is necessary to continue push more aggressive efforts to reduce emissions of ozone precursors.

The SPBPC has been a part of the historical efforts to improve local air quality. The POLB calls itself "The Green Port" to draw attention to these efforts, which have been successful. The POLA publishes annual "Air Quality Report Cards" that report changes in emissions relative to emissions from a decade previous. The 2016 version shows vast improvements in emissions across the board, particularly with respect to Particulate Matter (PM) and SO_x [3]. However, these trends also show that NO_x emissions improvements consistently lag PM and SO_x. Indeed, the POLA inventory reports high NO_x emissions for many technologies [4]. It is therefore prudent to explore possibilities for further reduction in NO_x emissions at the SPBPC and it is the primary focus of this work to determine the air quality impacts associated with implementation of technologies to achieve reduction in NO_x emissions.

Emissions at SPBPC have been long studied and the potential benefits to air quality are no secret. It should be no surprise therefore that efforts to reduce NO_x emissions are ongoing and the introduction of zero-emissions technologies at the SPBPC has begun. One example of zero-emission technology operating at the SPBPC is Toyota's Project Portal – a project demonstrating the capability of a Heavy Duty Fuel Cell Truck (HDFCT) to handle drayage operations [10]. This demonstration was met with much anticipation and it did not take long for Toyota to announce a plan to construct a megawatt scale trigeneration hydrogen production plant at the POLB to provide hydrogen from HDFCT and other equipment [11].

Heavy-duty trucks are not the only target of fuel cell demonstration projects. CARB reports a multitude of funded projects at the SPBPC to bring fuel cell electric technologies to the other sectors including yard tractors and forklifts for Cargo Handling [12], a top loader demonstration by the Center for Transportation and the Environment (CTE) [13], a fuel cell yard truck by LOOP Energy [14] among many others. There are many technologies in use at the ports and many have fuel cell electric configurations that could be demonstrated in the near future if they aren't being demonstrated now. Figure 1 shows a comparison of the various sectors with significant emissions of NO_x, $PM_{2.5}$ and CO_2e.

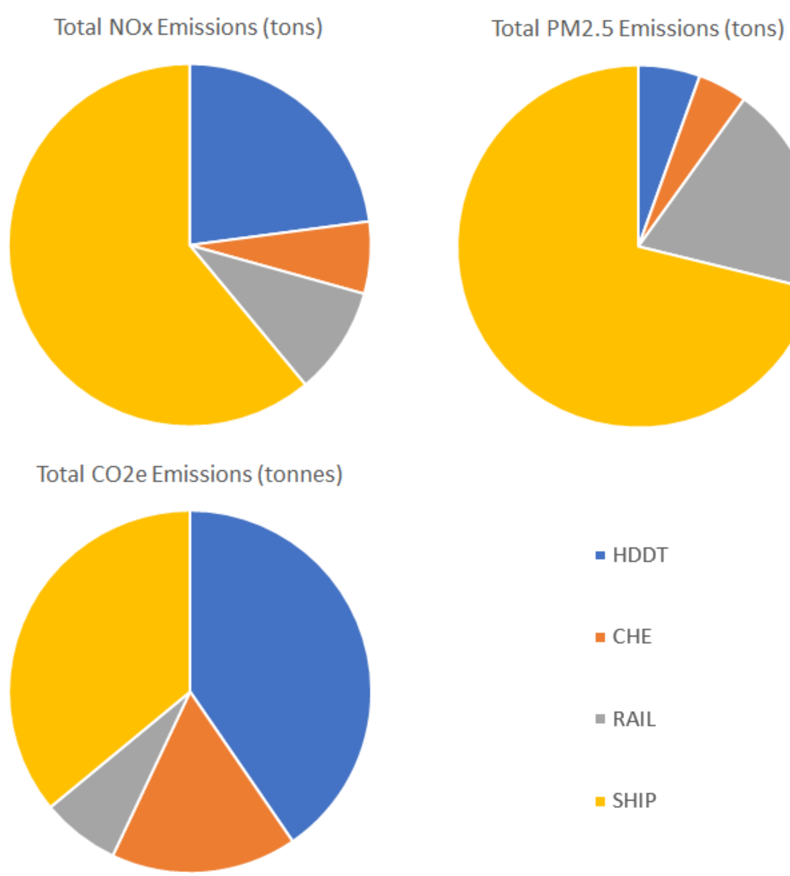

Figure 1: Total Emissions of NO_x, $PM_{2.5}$, and CO_2e divided by sources used for scenario development.

2.1 HDFCT for Drayage Services

Much of the work done in transporting goods out of the port is done by Class 8 Heavy Duty Diesel Trucks (HDDT) called Drayage trucks. Drayage trucks generally remain within the same urban region transporting goods between many goods distribution centers including seaports, border points, intermodal terminal, etc. Drayage activities require Class 8 HDDT with maximum gross capacities up to 80,000 pounds. It is common for drayage trucks to enter fleets with high mileage of 500,000 to 750,000 miles after they are no longer viable for long-haul and sold following use in long-haul activities [15]. Drayage truck have a different drive cycle from typical HDDT, e.g., drayage trucks have low daily Vehicle Miles Traveled (VMT), many stops and starts, and long idling periods.

SPBPC is located adjacent to population dense urban regions with high throughput thoroughfares serving the ports. Traffic conditions on Los Angeles highways are often congested worsening the impacts of high levels of drayage truck activity especially those of older, higher emitting HDDT. Emissions from drayage HDDT associated with the SPBPC have been shown to have prominent air quality impacts in adjacent communities [16]. Emissions from SPBPC can also impact air quality at the regional level due to transport events [17], [18]. Furthermore, health impacts from drayage trucks at the SPBPC can have substantial societal benefits [19]. CARB has implemented regulations to reduce emissions from drayage trucks at ports including SPBPC which require elimination of usage of old engine model years, requires retrofit of diesel particle filters, and incentivizes adoption of cleaner models [20]. However, regulation is not the only pressure on drayage environmental impacts. Indeed, projects indicate steep increases in demand for goods that will require additional drayage activity. For example, CARB estimates that SPBPC drayage trucks will emit approximately 21% of on-road NOx emissions in the SoCAB in 2035. CARB's estimate includes the fleet meeting all requirements and only comprising 1% of VMT [21].

Several features of HDFCT and attributes of drayage activity support the use of HDFCT, particularly in the near- to mid-term. The minimal hydrogen infrastructure available in that time frame will pose little issue for drayage cycles that would require only a home-base refueling station and perhaps a few strategically placed stations. Truck operators identified essential performance parameters in a survey. The vehicle must (1) have sufficient power for operation (400 horsepower, 1,200-1,800 foot pounds of torque), (2) achieve the necessary range between fueling of 200+ miles, and (3) have the capability to be used on all delivery routes [22]. HDFCT have been demonstrated to achieve these benchmarks and offer the additional benefits of refueling times similar to those for conventional HDDT (relative to Battery Electric Trucks (BET) which require long periods of charging). Toyota's Class 8 HDFCT demonstration developed for drayage activity weighs 80,000 lbs. and generates 670 horsepower and 1325 pound-feet (lb-ft) of torque with an estimated fueling range of 200 miles under average drayage drive cycles [10].

2.2 FCET for Cargo and Material Handling Applications (Port Operations)

FCET have been established in use for Cargo and Material Applications, particularly in warehouses and distribution centers that lack ventilation to safely handle combustion exhaust. In fact, forklifts are one of the few fuel cell applications that is already commercialized [23]. At the SPBPC, forklift activity is similar to activity at warehouses, but without the immediate danger created by the confined space of the warehouse and without the same necessity to deploy fuel cells. As such, diesel powered forklifts are the primary makeup of the fleet with propane powered forklifts in the mix as well [4]. However, as the literature shows, the SPBPC contributes significantly to degraded air quality and dose pose a danger to the public at large [4], [17], [24], [25]. It is for these reasons that fuel cell forklifts have been identified as a good candidate for SPBPC Cargo Handling Equipment (CHE) emission mitigation strategies [26].

Forklifts are not the only Cargo and Material Handling equipment that make good candidates for fuel cell deployment. Fuel cell-electric container handling equipment are also under development [26].

Container handling equipment includes top loaders, side loaders, rubber-tired gantry cranes (RTG) as well as many others [12], [13], [26], [27]. As was the case with HDDT, diesel powered CHE make good candidates for early demonstration of mobile fuel cells as their duty cycles keep them near refueling infrastructure which is a key element holding back FCET.

2.3 FCET for Locomotive Applications

Literature supports the use of FCET in locomotive power systems, including for freight applications [28]–[30]. Many of the studies of FCET in locomotive power systems analyze hybrid systems including gas turbines and diesel engines [28], [31]. Even in the case of hybrid systems, the literature demonstrates a potential for improvement of environmental impacts including reduction of GHGs and criteria pollutants [32]. In addition to the literature support, there also exist some demonstration projects of FCET in locomotive power systems [33]–[35].

FCET in locomotive power systems is being investigated by the CARB as an emission reduction strategy [36]. This is especially prudent for the ports whose railyards experience significant locomotive emissions, especially from switching and shunting applications which require operation at low speeds which is inefficient from an emissions perspective [4], [28]. However, linehaul emissions are the bulk of locomotive emissions and as such FCET are needed to reduce emissions in all locomotive applications [4], [32]. Moreover, unlike on-road vehicles, locomotive refueling strategies do not rely on a robust refueling network, particularly in railyard switching applications. Therefore, early locomotive FCET will not suffer much from lack of refueling infrastructure.

2.4 FCET for Maritime Applications

The POLA distinguishes between two types of maritime equipment, Ocean-Going Vessels (OGV) and Commercial Harbor Craft (HC), or often simply Harbor Craft. OGV refers to those vessels that carry goods in and out of the ports to/from other ports around the world. HC refers to vessels that stay near the port. OGV are generally very large vessels carrying containers or bulk goods whereas HC are smaller vessels and either serve their own business purposes e.g. fishing vessels or assist with port operations e.g. tugboats.

OGV generally have three types of energy conversion devices on board. First is the main propulsion engine that are generally high power output and run on a variety of fuels of depending on the stage of the voyage, e.g. bunker fuel or Heavy Fuel Oil (HFO) when traveling the ocean far away from any land and diesel fuel when within the port's fuel-switching zone [37]. The fuel switching-zone exists to reduce emissions that cause local air quality impacts [4]. OGV also employ Auxiliary engines for providing non-motive power for applications such as electricity generation and or crew accommodations [37]. OGV also utilize a boiler primarily for steam generation. The steam can be used for a variety of applications including driving steam turbines for power, pre-heating heavy fuels, cleaning, crew accommodations, and, in the case of tankers, pumping [38], [39]. Steam-powered pumping is a significant source of emissions at ports because of the heavy fuel oil burned in the boilers [38]. Many of these applications can be covered by a variety of electric technologies including FCET, particularly high temperature fuel cells e.g. Solid Oxide Fuel Cells (SOFC), for the applications that require heat [40]. Indeed, demonstration of SOFC combined heat and power systems is a potential candidate for OGV applications as on-board or shore-assist heat and power [37].

While it is noted that the literature is rich with assessments of various environmental impacts associated with port activities this literature review found a lack of air quality impact assessments for several port sectors [17]–[19], [25], [41]. Furthermore, the literature is also lacking in a comprehensive air quality assessment for the port that includes both GHG emissions impacts and impacts on human health. This research serves to begin to fill that void in literature.

3 Approach

Based on the known high emissions from port activities, ongoing efforts to reduce those emissions, and lack of study of air quality and human health impacts of these efforts, it is the goal of this research to assess the ambient air quality impacts, the GHG emission impacts, and the human health and economic impacts associated with deployment of fuel cell electric technologies for port activities**.** To accomplish these objectives, several tasks must be accomplished.

Task 1 – Identify candidate port activities.

This research aims to identify port activities that have significant impacts on local air quality. In general, emissions do serve as a good first pass estimate of air quality impacts, therefore candidacy for this research will be based heavily on emissions. The POLA and POLB produce their own emission inventories on an annual basis that will be used to identify the highest emitting port activities. This research uses the emission inventories produced in 2016 to identify technologies that produce relatively high emissions. These technologies could have significant benefits to air quality and human health via electrification as their emissions are highest per unit activity. The POLA Emission Inventory is divided into five sections: Ocean Going Vessels, Harbor Craft, Cargo Handling Equipment, Locomotives, and Heavy Duty Vehicles. For this research top emitting technologies are identified from each category independently.

Because this research is focused on SoCAB where ozone is a significant air quality issue, top emitters are identified by their NO_x emissions which drives the formation and fate of ozone. Examples include Top Loaders and Yard Tractors of the CHE and HDDT. Propulsion (main engine) for OGV and HC is the largest emitter of NO_x for this category, however it is unlikely for significant FCET deployment for main engine propulsion as these systems rely on HFO to keep operating costs low. Auxiliary engines and boilers on OGV and HC are considered as candidates for this study. Lastly all locomotive activities are considered for candidacy in this research.

Task 2 – Develop properly formatted Emission Fields for use in the AQM

The emission processing tool (SMOKE) projects the emission to a future year, 2035 for this research, based on control factors that represents emission reductions based on policy control measures. This differs from growth factors that represent changes in population and activity. These growth and control factors are used by SMOKE to grow emissions based on population and activity projections and control those emissions based on policy measures. The factors are applied directly to specific technologies according to their Emission Inventory Code (EIC) and Federal Information Processing Standard (FIPS) code for location. The emission inventory used for this research allows for control on a county-to-county basis.

Another important part of this task is aligning the emissions in the POLA and POLLB emission inventories with the EIC in the CARB emission inventory. The CARB inventory does not use the same technological resolution of the emissions inventory and does not group all port operations technologies in the same way as the POLA and POLLB emission inventory reports. The correct EIC is identified by comparing relative contributions to NO_x emissions in both inventories.

CMAQ simulations require that emissions be spatially resolved according to the same gridding used by the meteorological data, previously simulated using the Weather Research and Forecasting Model (WRF). Moreover, the emissions must be resolved temporally on an hourly basis. To simplify this process the SMOKE tool is used to apply the growth and control factors and spatially and temporally resolved the emissions for use by the AQM.

Task 3 – Use CMAQ to simulate the atmospheric reactions pertaining to the emissions resulting in concentrations of primary and secondary air pollutants

With the emissions spatially and temporally resolved it is possible to simulate the atmospheric reactions that control the ambient concentrations of criteria air pollutants. This task will result in the concentrations needed to determine the impact of port emissions on ambient air quality throughout the state of California.

The most significant impacts on ambient air quality are expected to occur in SoCAB because of the nature of the application of control factors. That is, emissions are reduced at the port locations as well as surrounding areas. That is not to say that all impacts on ambient air quality will occur at the port, meteorological conditions as well as changes to emissions of longer-lived air pollutants can have impacts throughout the state.

Task 4 – Compare the concentrations of air pollutants with and without the control factors applied in Task 2

Ambient concentrations of air pollutants do not tell the complete story of the effectiveness of control measures. It is necessary to compare these concentrations to ambient concentrations obtained by simulating with the same emission inventory and growth factors but with no control factors. These concentrations represent the ambient air quality without any control measures, otherwise known as BAU air quality. The differences between controlled ambient concentrations and BAU concentrations allow for changes in NAAQS to be computed e.g. maximum 8-hour ambient ozone concentration and maximum 24-hour ambient $PM_{2.5}$ concentration.

Task 5 – Calculate GHG Emission Impacts

The emission control factors determined in Task 2 are associated with FCET deployment that also have an impact on GHG emissions. The same emission control factors in Task 2 are applied to the tank-to-wheel GHG emissions associated with the diesel combustion engines displaced by FCET. Well-to-tank GHG emissions must also be calculated by associating tank-to-wheel GHG emissions reductions with diesel fuel consumption via carbon intensity determined from Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model version 3.0 (GREET) [42]. Diesel fuel consumption is used to compute diesel well-to-tank GHG emissions reduced as well as hydrogen fuel required. Hydrogen fuel required is used to compute hydrogen well-to-tank emissions. It is assumed that all FCET produce zero emissions at end use and therefore hydrogen well-to-tank emissions and well-to-wheel emissions are equivalent. The net GHG emission impact is the difference between well-to-wheel hydrogen GHG emissions and well-to-wheel diesel GHG emissions.

Task 6 – Use BenMAP to apply human health impact functions to the differences in air pollutant concentrations to determine the human health benefits of the control measures.

Changes in ambient air pollutant concentration and their impacts on NAAQS are great metrics for academics in the field. However, they are not excellent for many who have the opportunity to influence policy but do not have the expertise to understand the meaning a 3 ppb decrease in maximum 8-hour ambient ozone concentration. To this end, much effort has been put into the assessment of these changes and their impacts on human health and society. BenMAP is a tool that can couple changes in ambient air pollutant and health impact functions to provide metrics that are more resounding to all, especially those with influence on policy. BenMAP can produce metrics that show prevention of premature deaths, hospitalization, lost working hours. Moreover, the economic impacts of these preventions are accessible by computing the cost to society for paying for the hospital visits and the lost working hours.

4 Methods

A set of cases are analyzed, developing spatially and temporally resolved emissions, simulating the resulting air quality, and quantifying the human health benefits for the deployment of FCET at the SPBPC in 2035. Due to the uncertainty of projecting technology commercialization and adoption rates, cases are designed to span possible FCET deployment levels relative to both baseline diesel equipment and vehicles. Air quality impacts of FCET cases are then quantified, including changes in primary and secondary pollutant atmospheric concentrations.

The modeling domain selected for study is the SoCAB due to factors including pre-existing air quality concerns and areas of greatest freight activity. The SoCAB encompasses the greater Los Angeles metropolitan region, covering approximately 17,000 km^2 and supporting a population greater than 17 million people. SoCAB experiences degraded air quality characterized by very high levels of ground-level ozone and $PM_{2.5}$ that often exceed Federal health-based standards. Indeed, the American Heart and Lung Association ranks Los Angeles as the most ozone polluted city in the U.S. [43]. Given the importance of goods movement at the SPBPC to air quality in the SOCAB and the expected deployment of FCET, a set of cases is analyzed specific to the SoCAB. While the results are specific to the SoCAB, it should be noted that major ports also exist in other regions of California including the Port of Oakland, the various S.F. Bay Area ports, San Diego, Hueneme, Stockton, and others. The impacts assessed here can be considered within the framework that similar impacts may be attained at these, and other ports in the U.S.

4.1 Scenario Development

Several scenarios are developed based on the categories listed in the POLA and POLB emission inventories [4]. For each of these categories, three spanning cases are simulated, one with a low estimate of control impact, one with a middle estimate of control impact, and one with an upper estimate of control impacts. In all categories except drayage the lower estimate assumes 25% reduction in emissions relative to growth, middle assumes 50% reduction in emissions relative to growth, and upper assumes 75% reduction in emissions relative to growth.

4.1.1 Business-As-Usual Case

Necessary for comparison, first a case must be computed with growth factors but no control factors. The growth factors are obtained from data in the California Emissions Projection, Analysis and Modeling (CEPAM) tool for the 2016 SIP [44]. CEPAM provides projection estimates of annual average emissions for the year 2035 for all EICs in tons per day.

4.1.2 HDFCT Cases

Drayage trucks represent a key target for zero emission technology as on-road measurement studies have reported a skewed emissions distribution with a disproportionate contribution of emissions occurring from a small fraction of trucks, i.e., a smaller amount of older, higher emitting trucks are responsible for a majority of the emissions [45], [46]. The drayage cases are the only cases that apply control factors to on-road emission sources. These cases represent replacement of HDDT with HDFCT. The on-road emission inventory projections are calculated by the CARB Emission Factors (EMFAC) tool [47]. EMFAC2017 calculates statewide and regional emissions inventories for both historical and future years using vehicle activity data and emission rates from all on-road vehicle types in California. Forecasting within EMFAC2017 includes expected changes in vehicle age distributions, vehicle miles traveled, and the impact of current and future policies such as the Federal Phase 2 GHG Standards. EMFAC estimates drayage truck activity growth rates based upon 2013 Federal Highway Administration Freight Analysis Framework which projects freight tonnage for various port regions in California to 2040. Emission rates are derived from current test data. EMFAC2017 is used to quantify emissions during all processes including running exhaust, idling exhaust, start exhaust, various evaporative losses, and PM from tire and brake wear. As HDFCT have no tail pipe emissions, reductions are applied to all exhaust categories. PM from tire and brake wear is not reduced and it is assumed emission rates are equivalent between HDDT and HDFCT due to similar vehicle weight. Furthermore, diesel fuel vehicles are not associated with evaporative emissions due to fuel properties and therefore no change is expected between HDDT and HDFCT. The data provided in EMFAC2017 can be used to show that in 2035 the drayage truck fleet in SoCAB will be responsible for less than 1% of total VMT from on-road vehicles but will be responsible for emissions of over 17% of NO_x. Three cases are developed for drayage trucks spanning conservative and aggressive estimates of fleet electrification HDFCT.

- Lower estimate – HDFCT are 56% of fleet in 2035
- Middle estimate – HDFCT are 62% of fleet in 2035
- Upper estimate – HDFCT trucks are 79% of fleet in 2035

4.1.3 Port Operations Equipment

CHE cases include those technologies found in the CHE section of the POLA and POLB emission inventories. These cases are named as such because of discrepancies in the naming conventions used for these technologies in the POLA and POLB inventories and the CARB inventory. CEPAM provides six EICs for port operations shown in

Table 1. Comparing to the POLA inventory in

Table 2, the CARB inventory has highest emissions for Material Handling Equipment, but the POLA inventory has Material Handlers as the sixth highest contributor to NO_x emissions. The reasonable conclusion here is that the CARB uses Material Handling Equipment as a generalized category to include major contributors that are distinctly higher emitters than the equipment belonging to the Other CHE categories. Moreover, the ARB does not include separate EICs for propane fueled equipment such as the high emitting propane-fueled Yard Tractor and Forklift.

Table 1. EICs and NO_x Emissions for Port Operations from ARB Inventory

EIC	Technology	NO_x (tons/day)
860-896-1210-1900	Crane	0.4092
860-896-1210-2780	Forklift	0.1626
860-896-1210-4390	Material Handling Equipment	1.1785
860-896-1210-5230	Other Cargo Handling Equipment	0.1815
860-896-1210-9210	Tractor/Loader/Backhoe	0.4781
860-896-1210-9900	Yard Tractor	0.4898

Table 2. NO_x Emissions for Select Cargo Handling Equipment for POLA Inventory

Equipment	Engine	NO_x (tons/year)
Top-handler	Diesel	154.3
Yard-tractor	Diesel	79.6
RTG-crane	Diesel	69.3
Yard-tractor	Propane	57.8
Forklift	Propane	16.2
Material-handler	Diesel	11.6
Forklift	Diesel	9.9

To simplify the alignment of the inconsistencies between the dataset the spanning cases are applied equally to the four highest emitting EICs and to all six EICs together. That is there are a total of 15 Port Operations cases, three each for five groups; All Port Operations, Material Handling Equipment (MHE) (as labeled by CARB), Yard Tractors (YT), Tractor/Loader/Backhoe, and Crane. The three spanning cases for each of the five groups include a lower estimate of 25% reduction for all emitted species, a middle estimate of 50% reduction for all emitted species, and an upper estimate of 75% reduction for all emitted species. As before, these emissions reduction are relative to CEPAM projections of growth. These cases are summarized in

Table 3.

Table 3. Summary of Case Naming for Port Operations Cases

Category	Reduction Size (Name)		
	25% Reduction	**50% Reduction**	**75% Reduction**
All Port Operations	All-High	All-Mid	All-Low
Material Handling Equipment	MHE-High	MHE-Mid	MHE-Low
Yard Tractor	YT-High	YT-Mid	YT-Low
Crane	Crane-High	Crane-Mid	Crane-Low

4.1.4 Locomotive Cases

The literature supports electrification of rail propulsion including shunt locomotives for rail yards such as those found at SPBPC. The CARB Emission Inventory provides four EICs for trains, two of which apply to the ports (820-Trains, 822-Locomotive-Road Hauling and 820-Trains, 824-Locomotive-Switching). Locomotive-Road Hauling is the single largest contributor to daily NO_x emissions at 69.6772 tons/day. As SPBPC is among the largest rail yards in SoCAB it is expected that this category contributes greatly to the degraded air quality throughout the basin. Three cases are simulated for these two EICs, a conservative estimate of 25% reduction of all emitted species, a middle estimate of 50% reduction of all emitted species, and an aggressive estimate of 75% reduction of all emitted species.

4.1.5 Maritime Cases

OGV and HC generally carry auxiliary engines for supplying the ship with electricity during voyages. Literature does support fuel cells for auxiliary power for OGV and HC. Moreover, literature supports fuel cell and other zero emission technologies for providing power for anchorage and hoteling. The CARB Emission Inventory provides several categories that correspond to emissions from ships at SPBPC. There are four EICSUM (Summary level codes) 830 – Ships and Commercial Boats, 833 – Ocean Going Vessels, 835 – Commercial Harbor Craft, and 840 – Recreational Boats. For the Ship Scenarios the entire 830 and 840 blocks are treated as equal as they are potential candidates for electrified propulsion. The EIC convention provides several Sub-categories for the 833 and 835 Summary categories of which two are excluded: 9983 – Maneuvering Main and 9985 – Transit Main. The result is 83 unique EICs for OGV and HC whose emissions can be reduced by electrification. A total of 260 EICs are considered for the ship cases when the 83 unique OGV and HC EICs are added to the 177 codes represented by the 830 and 840 blocks. Same as the previous scenario groups these 260 EICs are reduced by spanning estimates of 25%, 50%, and 75%.

4.1.6 Combined Cases

Finally, a set of cases to encompass all previous cases. The combined cases, labeled ALL, include all of the EICs from all of the scenarios described in this section. As with the previous scenarios cases of lower, middle, and upper estimates of deployment are considered. The cases are described as follows:

- Lower estimate – HDFCT are 56% of the drayage fleet and FCET are 25% of other fleets
- Middle estimate – HDFCT are 62% of the drayage fleet and FCET are 50% of other fleets
- Upper estimate – HDFCT are 79% of the drayage fleet and FCET are 75% of other fleets

4.1.7 Summary of Scenarios and Naming Conventions

In summary, there are a total of five technology control groups each of which have at least one scenario assessed at three different levels of technology penetration. The Port Operations control group includes four scenarios; three that address Cranes, Material Handling Equipment, and Yard Tractors individually and one that encompasses all Off-road/Port Operations EICs. The cases and names are summarized in

Table 4. Summary of Case Names

Case Name	Tech Group	Level	Description
DRAYDN	Heavy Duty Trucks	DN	Low Deployment (56% of HDFCT)
DRAYMD	Heavy Duty Trucks	MD	Medium Deployment (62% of HDFCT)
DRAYUP	Heavy Duty Trucks	UP	High Penetration (79%) of HDFCT
SHIPDN	Maritime	DN	Low Deployment (25% of FCET)
SHIPMD	Maritime	MD	Medium Deployment (50% of FCET)
SHIPUP	Maritime	UP	High Deployment (75% of FCET)
RAILDN	Locomotive	DN	Low Deployment (25% of FCET)
RAILMD	Locomotive	MD	Medium Deployment (50% of FCET)
RAILUP	Locomotive	UP	High Deployment (75% of FCET)
OPSDN	Port Operations	DN	Low Deployment (25% of FCET)
OPSMD	Port Operations	MD	Medium Deployment (50% of FCET)
OPSUP	Port Operations	UP	High Deployment (75% of FCET)
CRNDN	Cranes	DN	Low Deployment (25% of FCET)
CRNMD	Cranes	MD	Medium Deployment (50% of FCET)
CRNUP	Cranes	UP	High Deployment (75% of FCET)
MHEDN	Material Handling	DN	Low Deployment (25% of FCET)
MHEMD	Material Handling	MD	Medium Deployment (50% of FCET)
MHEUP	Material Handling	UP	High Deployment (75% of FCET)
YTDN	Yard Trucks	DN	Low Deployment (25% of FCET)
YTMD	Yard Trucks	MD	Medium Deployment (50% of FCET)
YTUP	Yard Trucks	UP	High Deployment (75% of FCET)
ALLDN	Combined	DN	Low Deployment (25% of FCET, 56% of HDFCT)
ALLMD	Combined	MD	Medium Deployment (50% of FCET, 62% of HDFCT)
ALLUP	Combined	UP	High Deployment (75% of FCET, 79% of HDFCT)

4.2 Emissions and Air Quality Modeling

Electrification of port activities will impact direct pollutant emissions including NO_x, Reactive Organic Gases (ROG), PM, CO and SO_x. Such shifts occur quantitatively (in total), spatially (where), temporally (when), and in composition (what); all of which subsequently influence ambient concentrations of primary secondary air pollutant species. To evaluate regional air quality impacts in 2035, emissions must first be justifiably projected from current levels and spatially and temporally resolved. Further, the formation and fate of secondary air pollutants is governed by complex, non-linear atmospheric processes, e.g., shifts to FCET will achieve air quality benefits via reductions in ozone and $PM_{2.5}$ as a result of NO_x emission reductions. However, without atmospheric modeling quantification of ozone concentration reductions is not possible as ozone formation in the atmosphere does not linearly correlate to pre-cursor emission reductions. Nor can the spatial locations and temporal periods of ground-level ozone concentration changes be determined. Finally, how these impacts might be different in the future given the significant change in emissions and emission sources expected to the year 2035 is unclear. Therefore, an in-depth understanding must be obtained regarding emissions from all relevant stages followed by simulations of atmospheric chemistry and transport to properly evaluate air quality and GHG impacts of FCET.

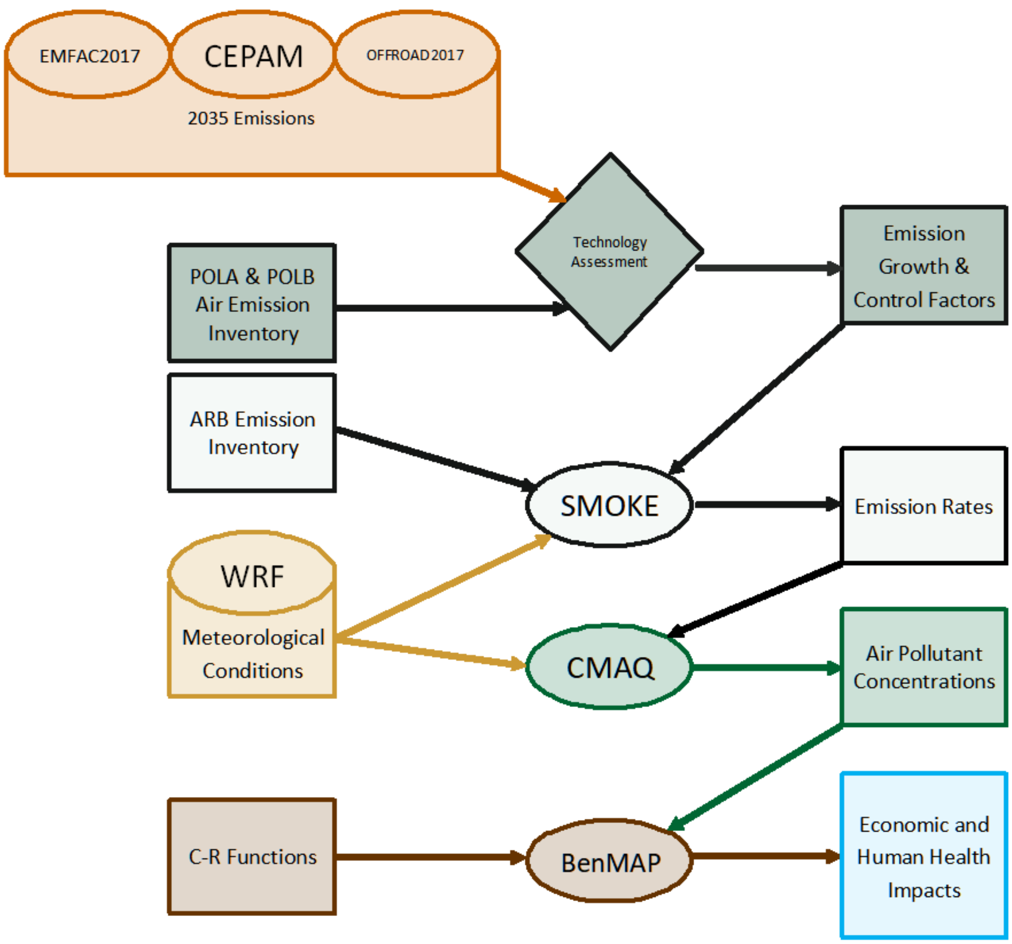

Figure 2: Flow Chart of Complete Emissions, Air Quality, and Human Health Impact Modeling

4.2.1 Preparation of Emissions Fields for Air Quality Modeling

The atmospheric model requires emissions rates of criteria pollutants throughout the modeling domain and period. Providing these emissions to the model requires two steps: 1 - project emissions from current levels to the simulation period and 2 - spatially and temporally allocate emissions throughout the modeling domain and period. The first step is achieved using the CEPAM SIP 2016 - Standard Emission Tool [44]. CEPAM provides future year estimates of emissions of criteria pollutants needed to run the atmospheric model including NO_x, PM, ROG, SO_x, and CO.

The second step is carried out using the Sparse Matrix Operator Kernel Emissions tool (SMOKE) [48]. SMOKE utilizes the CEPAM emissions projections, biogenic emissions from the Model of Emissions of Gases and Aerosols from Nature (MEGAN) [49], as well as spatial and temporal activity information. SMOKE divides pollutants into chemical species and allocates emissions throughout the modeling domain and period into a format readily accepted by an AQM.

4.2.2 Atmospheric Modeling

Valuation of ambient pollutant concentrations requires simulations of atmospheric chemistry and transport. The Community Modeling and Analysis System Center has developed software called the Community Multi-scale Air Quality model (CMAQ) for the purpose of performing such simulations [50]. CMAQ version 5.6 with SAPRC-07 chemical mechanism on a high-performance computing cluster were used to compute ambient concentrations of pollutants of interest, including ground-level ozone and $PM_{2.5}$. CMAQ has been used in the literature including research into ambient ozone concentration as well as many other atmospheric applications [51]–[53]. The model requires meteorological conditions, initial and boundary concentrations of atmospheric species, land use and land cover information, as well as emissions of species including both biogenic and anthropogenic sources. The model can utilize one of many chemical mechanisms, for this research SAPRC-07 is used as it accounts for photochemical formation of ozone, oxidation of organic gases as well as formation of organic aerosol precursors [54]. The simulation domain is defined by a 4 km × 4 km grid of 193 rows and 167 columns. Voxel heights are variable as the divisions between layers in the vertical dimension are all isobaric. Meteorological data were acquired using the WRF model [55].

Two episodes are simulated for each scenario; one episode for summer meteorology and another for winter meteorology. Each episode is two weeks long to allow the model to work out the effects of the initial conditions. The summer episode's dates are selected to capture high temperatures and sunlight, low scavenger species concentration, and inversion layers. These conditions are often associated with high concentrations of ozone and $PM_{2.5}$. The WRF meteorological output are analyzed and July 8-21, 2035 are the dates chosen for the summer episode. The winter episode's dates (January 1-14, 2035) are selected to explore periods of high $PM_{2.5}$ typically experienced in the modeling domain particularly the San Joaquin Valley. air quality impacts are measured by comparing the control cases' and BAU's averaged concentrations from the peak-day of each cell in the simulation domain. Maximum 8-hour average concentrations are compared for ozone while maximum 24-hour average concentrations are used for $PM_{2.5}$. These time windows are used to be consistent with the NAAQS metrics. Each metric is computed on a cell-by-cell basis and do not include overlap between calendar days. As such each day of simulation can be used to compute 16 ozone averages and one $PM_{2.5}$ averages. Due to model spin-up only the last week of simulation is considered for averaging. Therefore, each cell in each case has 112 ozone 8-hour averages that could be the largest and seven $PM_{2.5}$ 24-hour averages that could be the largest. The final metric used is the difference between the largest average for the control case and the largest average for the BAU case.

4.3 GHG Estimation

Emission reductions from FCET deployment are not only expected to impact air quality, but GHG emissions as well. Each of the electrification scenarios includes reduction of emissions of common GHGs including CO_2, CH_4, and N_2O. GHG impact in this study is comprised by three components: (1) well-to-tank GHG emissions associated with producing hydrogen and delivering it to the equipment at the ports, (2) displaced well-to-tank emissions associated with the production and delivery of fuel for combustion equipment used in the BAU scenario, ad (3) tank-to-wheels emissions associated with use of the combustion equipment in the BAU scenario. It should be noted that all FCET considered are zero-emissions at use so well-to-tank emissions are equivalent to well-to-wheels emissions for these technologies.

4.3.1 GHG Scenario Development

The previous cases are all designed to assess the impacts of FCET on air quality by assessing the changes of criteria pollutant emissions associated with deployment of FCET and simulating the atmospheric impacts. The deployment of FCET at SPBPC will also have an impact on emissions of GHGs. To assess these impacts several hydrogen production pathways are selected and evaluated with respect to GHG emissions. The GHG emissions associated with these pathways are then compared to the GHG emissions displaced by removing combustion-based technologies from the SPBPC, including emissions associated with diesel (and heavy fuel oil in the case of marine boilers) production and distribution. The GHG scenarios include three renewable pathways and three non-renewable pathways. The three renewable pathways are (1) electrolysis with 100% renewable electricity (e.g. solar photovoltaics), (2) reformation of renewably sourced biogas, and (3) gasification of renewably sourced biomass. In the biogas pathway it is assumed that four feedstocks are used in equal proportion: (1) landfill gas, (2) anaerobically digested animal waste, (3) anaerobically digested wastewater sludge, and (4) anaerobically digested municipal solid waste. The non-renewable paths are (1) Steam-Methane Reformation (SMR) of natural gas, (2) electrolysis using grid electricity and a conservative estimate of Alkaline Electrolysis Cell (AEC) efficiency, and (3) electrolysis using grid electricity and an optimistic estimate of Solid Oxide Electrolysis Cell (SOEC) efficiency. All GHG emission factors for feedstocks and production are derived from CA-GREET 3.0. [42]. It is assumed that all hydrogen is distributed through a pipeline network totaling 2000 miles. This choice was made based on literature assessment comparing hydrogen delivery methods using HDSAM [56]. It is also assumed that all dispensing occurs at 700 bar [57]. Well-to-tank GHG emission factors for diesel fuel and heavy fuel oil (assumed same as residual oil) are also derived from CA-GREET 3.0. Each pathway/scenario described herein is explored for each air quality scenario group, i.e. GHG impacts for all pathways are determined for each of the three drayage cases, the three aggregated cargo and material handling equipment cases, the three rail cases, the three ship cases, and the three combined cases. Note that the combined cases are merely the summation of the other cases at each level (down, middle, and up).

4.3.1.1 100% Renewable Electrolysis

The first case is the most optimistic and assumes all hydrogen is produced from electrolysis with renewable electricity. This results in a 0-gram CO_2 equivalent per megajoule (CO_2e/MJ) H_2 emission factor for Feedstock and Production and 13.06 g CO_2e/MJ H_2 for distribution and 8.89 g CO_2e/MJ H_2 for dispensing for a total GHG emission factor of 21.95 g CO_2e/MJ H_2.

4.3.1.2 100% Renewable Biogas Reformation

This case requires that all hydrogen be produced by reformation of biogas. The biogas feedstocks include landfill gas, animal waste, wastewater sludge, and municipal solid waste. Landfill gas has a Carbon Intensity (CI) of 31.11 g CO_2e/MJ H_2 according to CA-GREET 3.0 when used to produce natural gas as an intermediate fuel (i.e. natural gas used to produce another fuel). Animal waste, wastewater sludge, and municipal solid waste have Cis of -71.97, -102.32, and -46.30 g CO_2e/MJ H_2 respectively. Combined they account for a Feedstock CI of -47.37 g CO_2e/MJ H_2 for biogas reformation. This pathway also has a Production CI of 103.49 g CO_2e/MJ H_2, Distribution CI of 13.06 g CO_2e/MJ H_2 and 8.89 g CO_2e/MJ H_2 for Dispensing. The total biogas reformation CI is 78.07 g CO_2e/MJ H_2.

4.3.1.3 100% Renewable Biomass Gasification

The final 100% renewable case relies on hydrogen production from biomass. CA-GREET 3.0 has feedstock and production CIs of 5.77 and 25.61 g CO_2e/MJ H_2 respectively. Using the same distribution and dispensing CIs as the other cases yields a total CI of 53.33 g CO_2e/MJ H_2 for biomass gasification.

4.3.1.4 50% Natural Gas SMR & 50% Renewable Electrolysis

This case, and the subsequent cases assume that half of the hydrogen is derived from a conventional source, i.e. SMR of natural gas. This gas has the same production, distribution, and dispensing CIs as the biogas reformation case (103.49, 13.06, and 8.89 g CO_2e/MJ H_2 respectively) but has a feedstock CI of 14.76 instead of -47.37 g CO_2e/MJ H_2. This results in a total SMR CI of 140.2 g CO_2e/MJ H_2. SMR is only half of the pathway so the weighted sum of the two CIs makes the total CI for the scenario. That is the scenario CI is 50% of 100% Renewable Electrolysis (21.95 g CO_2e/MJ H_2) and 50% of SMR (140.2 g CO_2e/MJ H_2) which amounts to a CI of 81.08 g CO_2e/MJ H_2.

4.3.1.5 50% Natural Gas SMR & 50% Grid Electrolysis (Conservative)

The same SMR CI is used as in the scenario above (50% of 140.2 g CO_2e/MJ H_2) and 50% of a conservative estimate of AEC efficiency. This pathway uses a CI of 46.58 g CO_2e/MJ electricity for the grid component and an electrolyzer efficiency of 73%. The net result is a feedstock/production CI of 67.63 g CO_2e/MJ H_2 and an electrolysis pathway CI of 89.58 g CO_2e/MJ H_2. The total CI for the scenario is 50% of SMR (140.2 g CO_2e/MJ H_2) and 50% of conservative grid electrolysis (89.58 g CO_2e/MJ H_2) or 114.89 g CO_2e/MJ H_2.

4.3.1.6 50% Natural Gas SMR & 50% Grid Electrolysis (Optimistic)

The final scenario is much like the previous but assumes a more efficient electrolyzer. That is, an 80% efficient SOEC is used with the same CI for grid electricity. The result is a feedstock/production CI of 61.71 g CO_2e/MJ H_2 and a pathway CI of 83.66 g CO_2e/MJ H_2. The net result is a scenario CI of 50% of SMR (140.2 g CO_2e/MJ H_2) and 50% of optimistic grid electrolysis (83.66 g CO_2e/MJ H_2) or 111.93 g CO_2e/MJ H_2.

4.3.2 GHG Assessment Methodology

Displaced well-to-tank emissions for combustion technologies are determined by the product of displaced fuel energy content and CI derived from CA-GREET 3.0. Displaced tank-to-wheel combustion emission are derived from EMFAC2017 and its off-road counterpart OFFROAD2017 (also hosted by CARB) which offer the capability to project GHG emissions and diesel fuel consumption to the study year 2035. Displaced well-to-wheel emissions are the sum of displaced well-to-tank and tank-to-wheel emissions for each displaced fuel.

Well-to-wheel hydrogen emissions are derived using the CIs in section 3.1.7 and the energy content of hydrogen required to do the work of the displaced diesel fuel. The work of the displaced diesel fuel is the product of displaced fuel energy content and technology efficiency derived from literature. The hydrogen required to do that work is the ratio of the amount of work required to hydrogen fuel cell efficiency. Where efficiencies are unavailable from literature a conservative estimate of 40% for diesel engines and 60% for hydrogen fuel cells. Displaced emissions and fuel consumption associated with combustion technologies are the percentage of projected emissions and fuel consumption from the CARB tools associated with the level of the scenario, i.e. 25, 50, 75% for non-drayage cases and 56, 62, and 79% from drayage cases.

Net GHG impacts are the difference between well-to-wheel emissions for hydrogen and displaced well-to-wheel emissions for combustion technologies.

4.3.2.1 Considerations for Drayage Cases

Drayage cases differ from the others in a couple of ways. First, drayage emissions are classified as on-road and are therefore handled by different tools and inventories. Projected drayage emissions and fuel consumption come from EMFAC2017. Well-to-tank emissions for diesel fuel are derived from CA-GREET 3.0 using Crude for CA Refineries as feedstock and CA Ultra Low Sulfur Diesel for production, distribution and dispensing.

4.3.2.2 Considerations for Port Operations Cases

Cargo and material handling equipment are considered as a single category for all GHG emission scenarios. The aggregated GHG emissions and fuel consumption projected to 2035 are derived from OFFROAD2017 [58]. All equipment are assumed to burn diesel fuel and diesel well-to-tank CI is derived in the same manner as drayage diesel using CA-GREET 3.0 [59].

4.3.2.3 Considerations for Locomotive Cases

OFFROAD2017 only provides emission projections for linehaul locomotives but switching locomotives are a source of non-negligible GHG emissions at SPBPC. To accommodate for the lack of projected switching emissions, it is assumed that switching account for the same portion of locomotive emissions in 2035 as in 2016. Therefore, to compute assumed 2035 switching emissions, the 2035 linehaul emissions from OFFROAD2017 are multiplied by the ratio of CO_2e switching emissions to CO_2e linehaul emission in the 2016 POLA Air Emission Inventory. The total emissions are the sum of the switching and linehaul emissions. The same approach is applied to the fuel consumption and the rest of the process is the same as the other cases.

4.3.2.4 Considerations for Maritime Cases

OFFROAD2017 aggregates the emissions from all engines burning the same fuel on OGV and HC. In this study transit and maneuvering engines are not considered. Therefore, to break-out the auxiliary emissions for 2035, it is assumed that auxiliary engines commit the same portion of OGV and HC diesel emissions in 2035 as in 2016. To compute the 2035 auxiliary engine emissions for OGV and HC the ratio of CO_2e emissions from auxiliary engines to total CO_2e emissions from 2016 POLA Air Emission Inventory is multiplied by the total CO_2e emissions from OFFROAD2017. The same approach is applied to the auxiliary fuel consumption for OGV and HC. Displaced auxiliary diesel fuel and tank-to-wheels emissions as well as hydrogen fuel requirement are computed independently for OGV and HC.

Moreover, OFFROAD2017 does not provide the emissions projection for the boilers used on OGV which are the largest source of GHG emissions on OGV. OGV boilers are assumed to burn Heavy Fuel Oil (HFO) which is a residual oil from the crude oil refining processing. It is possible to estimate the GHG emissions by assuming that the ratio of boiler emissions to diesel OGV emissions are constant from 2016 to 2035 and that the 2035 boiler emissions are the product of this ratio and the 2035 diesel CO_2e emissions from OFFROAD2017. However, there is insufficient data from the POLA inventory and the CARB models to project fuel consumption, which has been used to compute CI for specific technologies. A CI is necessary to estimate the 2035 CO_2e emission change associated with the SOFC heat displacing boiler emission. It is possible to derive the CI for marine boilers working on residual oil from literature. (AP-42 VOL I 1.3 Fuel Oil Combustion).

Finally, the tank-to-wheel CO_2e emission, fuel consumption, and hydrogen requirement from the individual components are combined to compute net GHG impacts for ships using the same approach as the other sectors.

4.4 Health Impact Modeling

Epidemiology studies have proved that a diminution in air pollution concentration results in a health impact reduction. Concentration-Response functions allow the quantification of morbidity and mortality health effects that are a consequence of a change in air quality. And valuation functions from health economic studies are used to monetize these quantified public health effects.

The best available tool to perform this analysis is the environmental Benefits Mapping and Analysis Program—Community Edition (BenMAP) from the U.S. EPA [60]. BenMAP allows users to estimate the number and economic value of health impacts resulting from changes in air pollution concentrations, and adequately addressing uncertainty and variability. BenMAP relates air quality changes to human health benefits. It estimates benefits from improvements in human health, such as reductions in the risk of premature death, heart attacks, and other adverse health effects. After estimating the reductions in the incidence of health effects, BenMAP calculates the monetary benefits associated with those reductions.

BenMAP can be used to perform any simulation within California to evaluate the health and monetary benefits that are a consequence from a change in air quality in future years. First, BenMAP determines the change in ambient air pollution using the concentration changes provide in the output of CMAQ. Next, BenMAP applies the relationship between the pollution and certain health effects (also known as health endpoints). This relationship is often referred to as the health impact function or the concentration-response (C-R) function, which is derived from epidemiology studies. BenMAP applies that relationship to the exposed population to calculate health impacts, as shown in Figure 3. BenMAP also calculates the economic value of avoided health effects. After calculating the health changes, an estimate of the economic value is made by multiplying the reduction of the health effect by an estimate of the economic value per case, which is obtained from health economic studies.

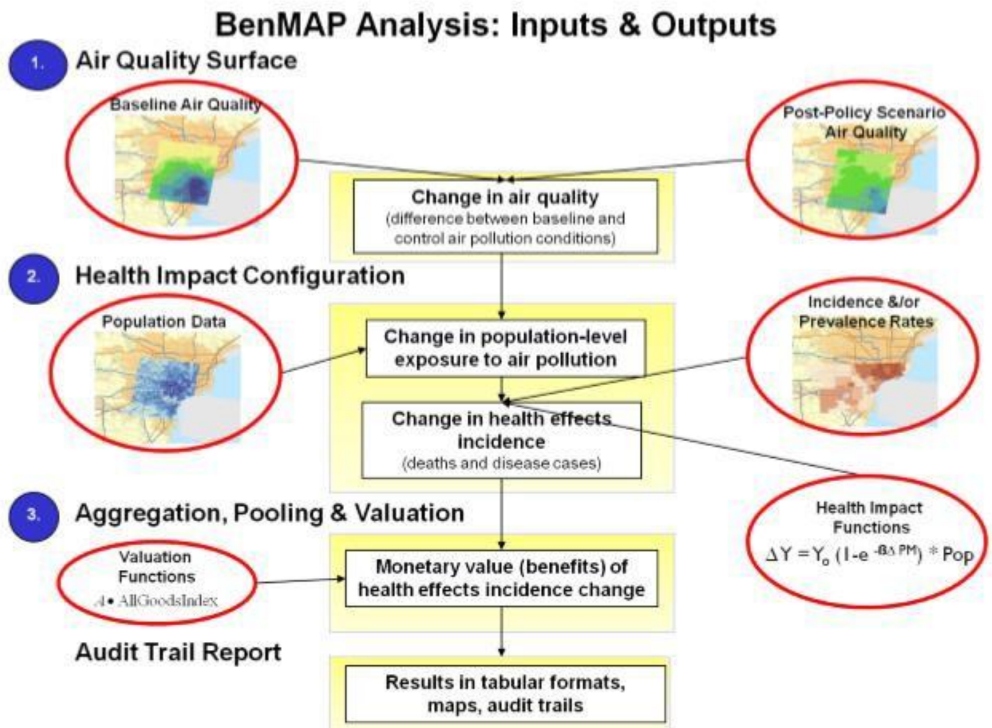

Figure 3. Overview of BenMAP

For this work, BenMAP-CE is used to quantify benefits from improvements in ozone and $PM_{2.5}$ attained through the FCET deployment within future drayage fleets. The methods used closely follow those in the SCAQMD Socioeconomic Report for the 2016 Air Quality Management Plan (AQMP) [61]. Population projections are based on suggested BenMAP practices using LandScan data [62] and grown to 2035 using projections from the California Department of Finance [63]. Baseline incidence rates for mortality and morbidity are selected at the county level by five-year age group based on recommendations from a comprehensive review of the literature [64]. The C-R functions are selected based on suggested criteria from a thorough review of the literature [65]. An overview of utilized C-R functions can be found in Table 3B-1 in Appendix B of Reference [61]. Valuation functions for both morbidity and mortality incidence are selected from a literature review with recommendations for the SoCAB [65], [66]. Though

BenMAP-CE can be used to estimate long-term health impacts such as those occurring from annual average $PM_{2.5}$ changes, impacts are reported here for short-term exposure to ozone and $PM_{2.5}$ as appropriate for the modeled episode. Therefore, the impacts are reported daily, i.e., avoided health incidence and dollars per day.

5 Results and Discussion

5.1 Air Quality Results

The following sections provide results from the air quality modeling for the cases considered. Baseline levels of atmospheric pollutant concentrations are predicted by CMAQ through the Base Case in 2035. Changes in concentration predicted for FCET cases occur as a result of emission changes driven by FCET deployment for port activities. Differences in ozone are reported as maximum 8-hour average and 24-hour average is used for $PM_{2.5}$. For each case, results are provided as difference plots for ozone and $PM_{2.5}$ in summer, and $PM_{2.5}$ in winter. Moreover, as shown in the Scenario Development section, sector will have three cases an upper estimate of deployment representing the largest reduction in emission (called UP or Upside), a conservative estimate of deployment representing the smallest reduction in emissions (called DN, Conservative, or Risk), and a mid-range estimate of deployment with emissions reduction between the upside and conservative cases (called MD or Mid).

5.1.1 HDFCT Cases

Drayage trucks represent a key target for zero emission technology as on-road measurement studies have reported a skewed emissions distribution with a disproportionate contribution of emissions occurring from a small fraction of trucks, i.e., a smaller amount of older, higher emitting trucks are responsible for a majority of the emissions [45], [46]. The drayage cases are the only cases that apply control factors to on-road emission sources. These cases represent replacement of HDDT with HDFCT. The on-road emission inventory projections are calculated by the CARB EMFAC tool [47]. EMFAC2017 calculates statewide and regional emissions inventories for both historical and future years using vehicle activity data and emission rates from all on-road vehicle types in California. Forecasting within EMFAC2017 includes expected changes in vehicle age distributions, vehicle miles traveled, and the impact of current and future policies such as the Federal Phase 2 GHG Standards. EMFAC estimates drayage truck activity growth rates based upon 2013 Federal Highway Administration Freight Analysis Framework which projects freight tonnage for various port regions in California to 2040. Emission rates are derived from current test data. EMFAC2017 is used to quantify emissions during all processes including running exhaust, idling exhaust, start exhaust, various evaporative losses, and PM from tire and brake wear. As HDFCT have no tail pipe emissions, reductions are applied to all exhaust categories. PM from tire and brake wear is not reduced and it is assumed emission rates are equivalent between HDDT and HDFCT due to similar vehicle weight. Furthermore, diesel fuel vehicles are not associated with evaporative emissions due to fuel properties and therefore no change is expected between HDDT and HDFCT. The data provided in EMFAC2017 can be used to show that in 2035 the drayage truck fleet in SoCAB will be responsible for less than 1% of total VMT from on-road vehicles but will be responsible for emissions of over 17% of NO_x. Three cases are developed for drayage trucks spanning conservative and aggressive estimates of fleet electrification HDFCT.

- Lower estimate – HDFCT are 56% of fleet in 2035
- Middle estimate – HDFCT are 62% of fleet in 2035
- Upper estimate – HDFCT trucks are 79% of fleet in 2035

5.1.1.1 DRAYDN – Low Estimate of HDFCT Deployment (Risk)

Significant benefits in ozone concentration are found for the Risk level deployment of HDFCT for drayage services. The peak benefits occur northeast of the ports in southwest San Bernardino County. The peak reduction of ozone is 1.98 ppb. Changes in peak 8-hour average ozone concentration are shown in Figure 4

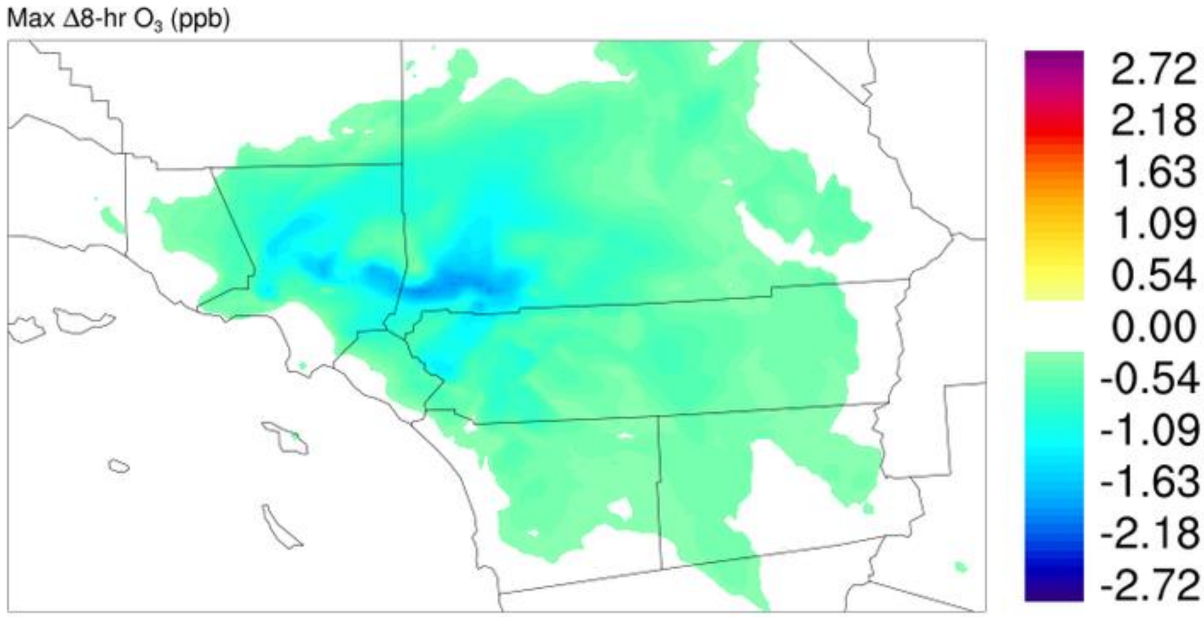

Figure 4. Difference between Maximum 8-hour Average Ozone Concentration of the DRAYDN case relative to the BAU case for the summer episode

HDFCT deployment for drayage services also results in a considerable benefit for $PM_{2.5}$ even at lower deployment levels. The largest reduction in peak 24-hour average $PM_{2.5}$ concentration is 0.21 µg/m^3. This largest reduction occurs around the same location as the largest reduction in peak 8-hour average ozone concentration in southwest San Bernardino County. Figure 5 summarizes the impacts of HDFCT deployment on $PM_{2.5}$ concentration in SoCAB at low deployment.

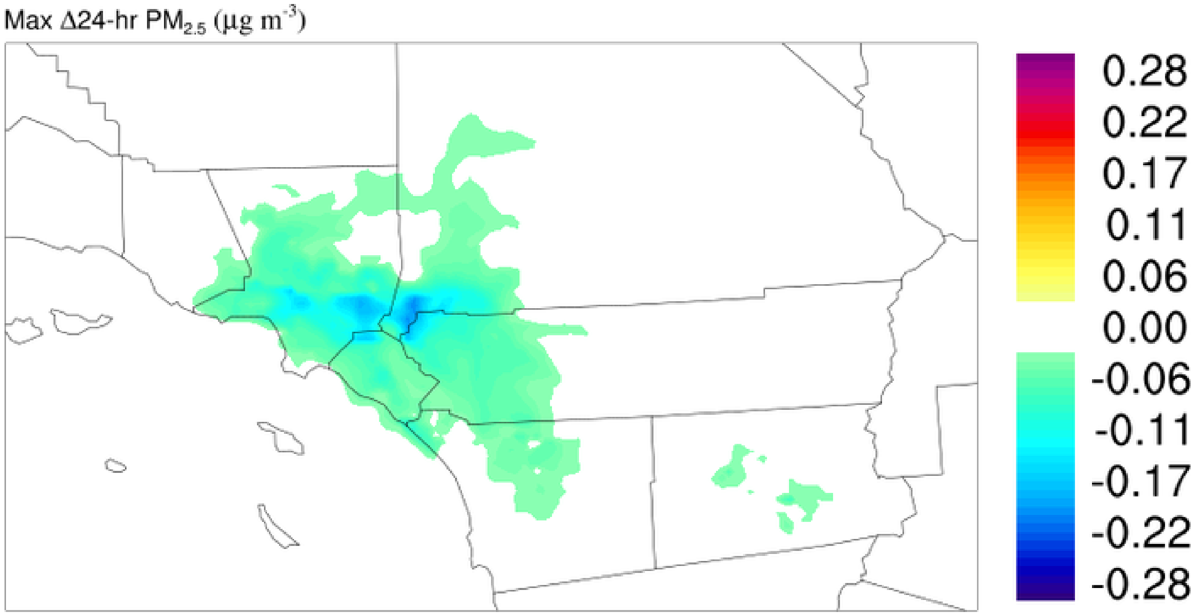

Figure 5. Difference between Maximum 24-hour Average PM2.5 Concentration of the DRAYMD case relative to the BAU case for the summer episode

Figure 6 displays the predicted difference in 24-hr $PM_{2.5}$ between the Base and the DRAYDN Case for the winter episode. While the magnitude of peak reduction is much higher than the summer episode, the location of the peak change occurs in the Central Valley where reductions reach 0.31 µg/m^3. This is notable as only a small portion of drayage activity from the SPBPC results in trip lengths that reach the Central Valley and S.F. Bay Area. This result highlights the sensitivity of PM formation in winter in the Central Valley. In the SoCAB, improvements are noted in and around the SPBPC including two areas of peak benefit associated with populations in L.A. with importance to the high populations located there. There are also impacts extending westward into the Pacific Ocean. This is a direct result of the meteorology assumed for the modeled episode with westward winds. It is likely that different meteorology, including eastward winds that are generally common for SoCAB, would demonstrate more impact on $PM_{2.5}$.

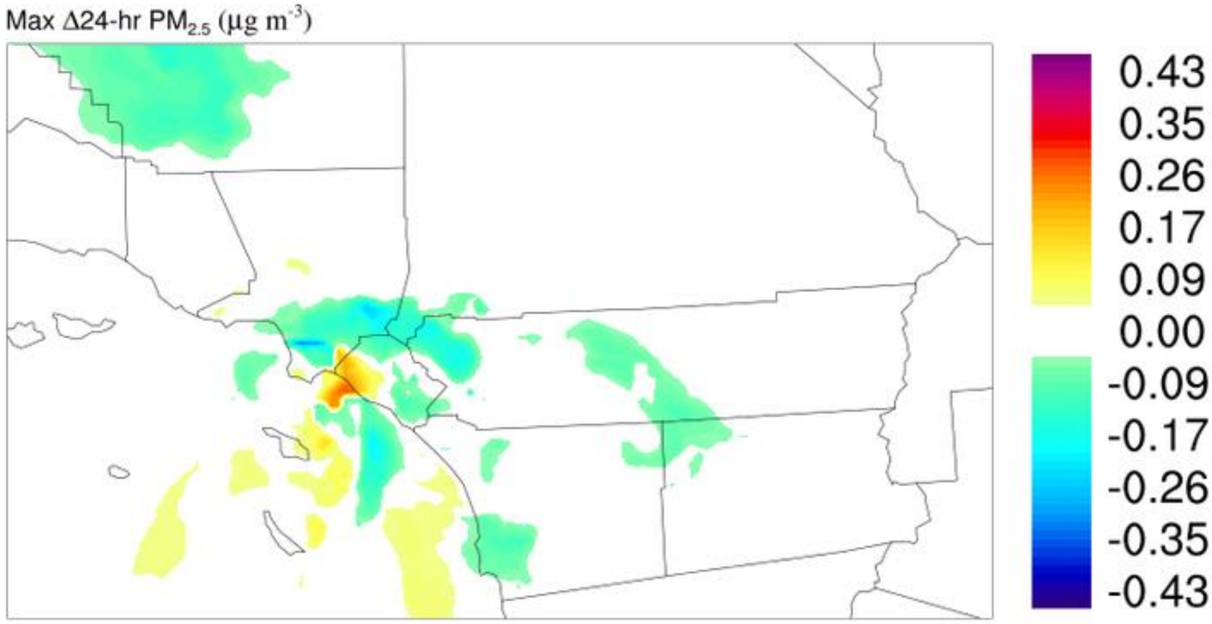

Figure 6. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the DRAYDN case relative to the BAU case for the winter episode

5.1.1.2 DRAYMD – Middle Estimate of HDFCT Deployment (Mid)

Figure 7 displays the predicted difference in maximum 8-hour ozone between the Base Case and the DRAYMD Case in the summer episode. Reductions in ozone reach 2.18 ppb in maximum 8-hr average while NO_x titration causes a maximum increase of 0.31 ppb. Spatially, impacts are pronounced in areas of the SoCAB that are downwind of port emission locations, i.e., emission reductions are highest at the port locations on the coast while peak ozone reductions occur in the eastern areas of the basin. This is a result of the dynamics of ozone formation that result in transport of precursor species NO_x and VOC during a temporal period between emission and formation of ozone.

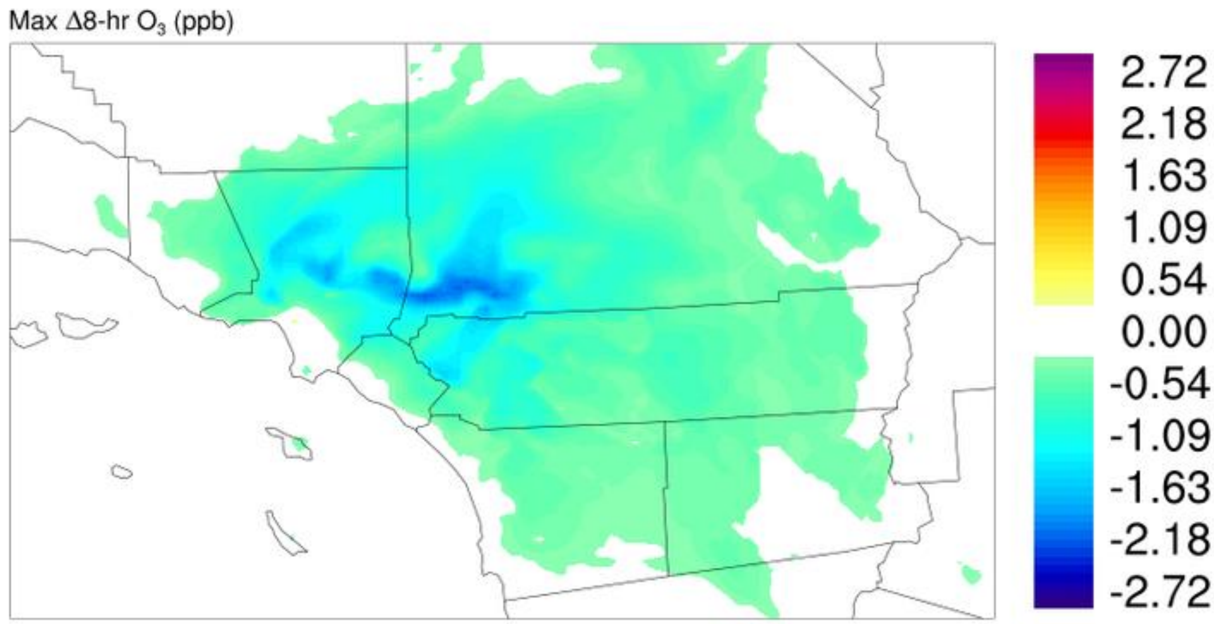

Figure 7. Difference between Maximum 8-hour Average Ozone Concentration of the DRAYMD case relative to the BAU case for the summer episode

Reductions in $PM_{2.5}$ reach 0.23 µg/m^3 in maximum 24-hr average. Similar to ozone, the largest predicted changes in concentration occur northeast of the ports around the border between Los Angeles and San Bernardino counties. In contrast to ozone, there are reductions in $PM_{2.5}$ concentration predicted at the SPBPC location demonstrating some key the differences in chemical dynamics associated with PM formation and the direct contribution of $PM_{2.5}$ from diesel engine tail pipe emissions. Therefore, benefits in PM occur in communities in and around the SPBPC. This is desirable due to the preexisting air quality challenges discussed for those areas. These results are shown in Figure 8

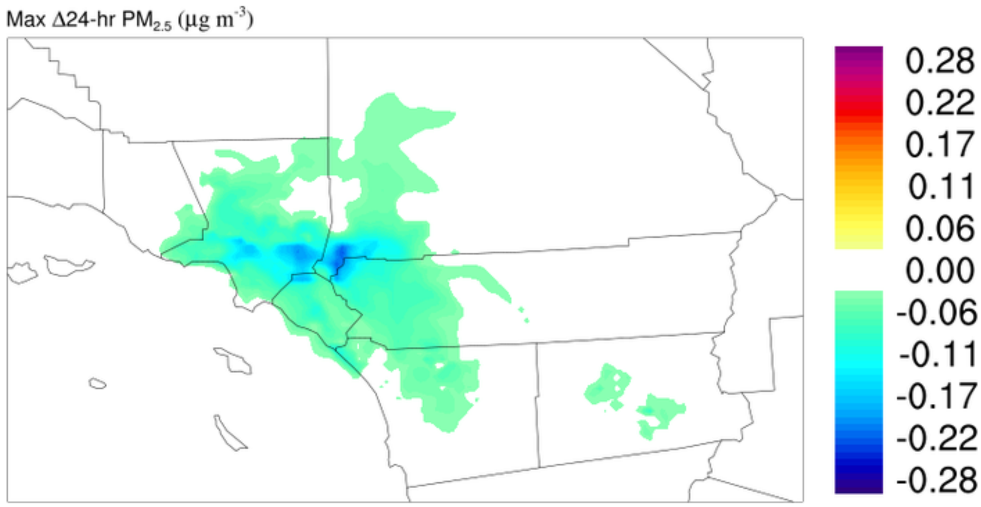

Figure 8. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the DRAYMD case relative to the BAU case for the summer episode

HDFCT deployment for drayage service causes some significant changes in peak 24-hour $PM_{2.5}$ in the winter episode in both directions. Most of the changes over populated areas are decreases in peak 24-hour average $PM_{2.5}$ concentration. The largest decreases occur just north of the ports in Torrance. There is also a significant increase at the border between Los Angeles County and Orange County that extends southward into Orange County along the coast. Figure 9 shows the complex changes in peak 24-hour average $PM_{2.5}$ concentration caused by HDFCT in the winter episode.

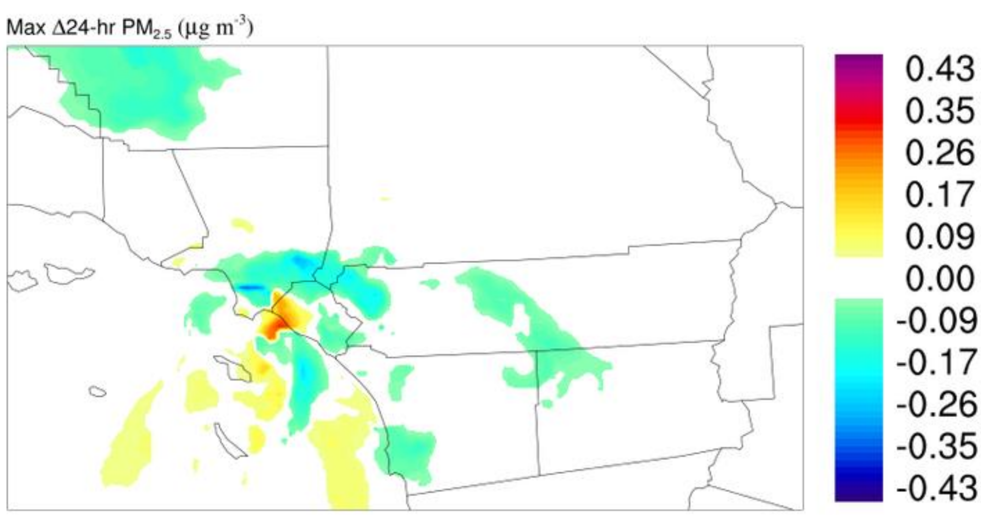

Figure 9. Difference between Maximum 24-hour Average PM2.5 Concentration of the DRAYMD case relative to the BAU case for the winter episode

5.1.1.3 DRAYUP – Upper Estimate of HDFCT Deployment (Upside)

Figure 10 displays the predicted difference in maximum 8-hour ozone between the Base Case and the DRAYUP Case in the summer episode. Reductions in ozone reach 2.81 ppb in maximum 8-hr average while NO_x titration causes a maximum increase of 0.40 ppb. Spatially, impacts are pronounced mostly in the same areas as the previous drayage cases. The impacts are at a maximum in the center of Los Angeles County and extend into San Bernardino County. Same as the previous cases, the largest ozone concentration changes are away from the largest changes in emissions because of the transport that is able to occur between the time of emission and ozone formation.

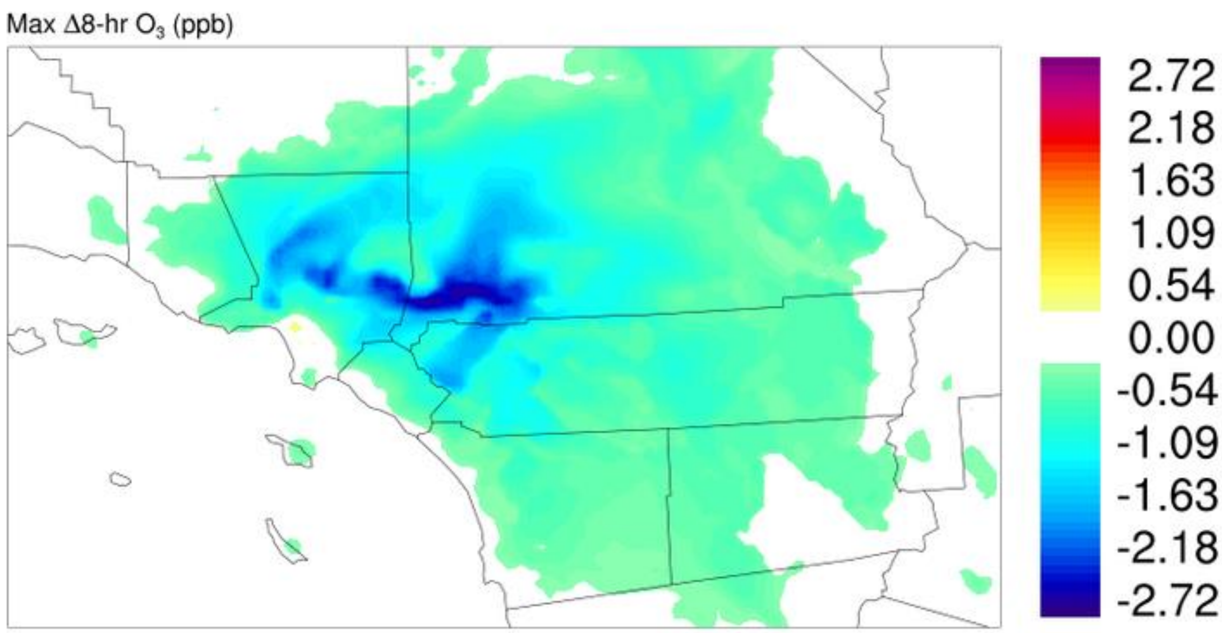

Figure 10. Difference between Maximum 8-hour Average Ozone Concentration of the DRAYUP case relative to the BAU case for the summer episode

Reductions in $PM_{2.5}$ reach 0.29 µg/m^3 in maximum 24-hr average. Similar to ozone, the largest predicted changes in concentration occur northeast of the ports around the border between Los Angeles and San Bernardino counties. In contrast to ozone, there are reductions in $PM_{2.5}$ concentration predicted at the SPBPC location demonstrating some key the differences in chemical dynamics associated with PM formation and the direct contribution of $PM_{2.5}$ from diesel engine tail pipe emissions. Therefore, benefits in PM occur in communities in and around the SPBPC. This is desirable due to the preexisting air quality challenges discussed for those areas. These results are shown in Figure 10.

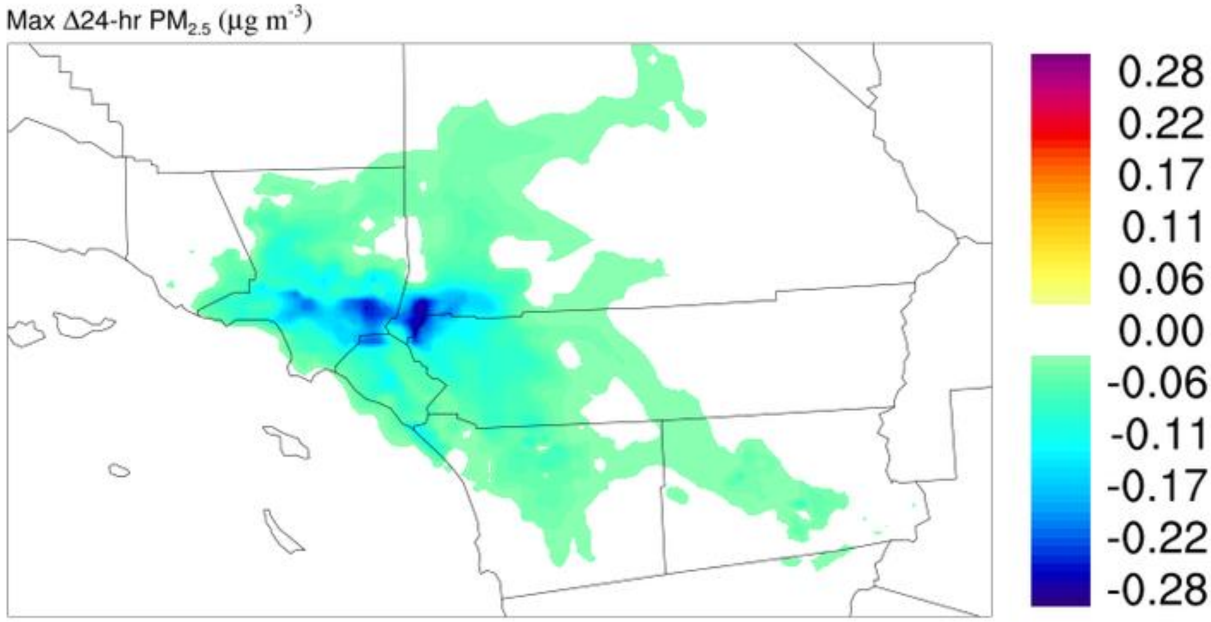

Figure 11. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the DRAYUP case relative to the BAU case for the summer episode

Figure 12 displays the predicted difference in 24-hr $PM_{2.5}$ between the Base and the DRAYDN Case for the winter episode. While the magnitude of peak reduction is much higher than the summer episode, the location of the peak change occurs in the Central Valley where reductions reach 0.44 μg/m^3. This is notable as only a small portion of drayage activity from the SPBPC results in trip lengths that reach the Central Valley and S.F. Bay Area. This result highlights the sensitivity of PM formation in winter in the Central Valley. Conversely, little impact is noted in the SoCAB other than slight worsening extending westward into the Pacific Ocean. This is a direct result of the meteorology assumed for the modeled episode with westward winds. It is likely that different meteorology, including eastward winds that are generally common for SoCAB, would demonstrate more impact on $PM_{2.5}$.

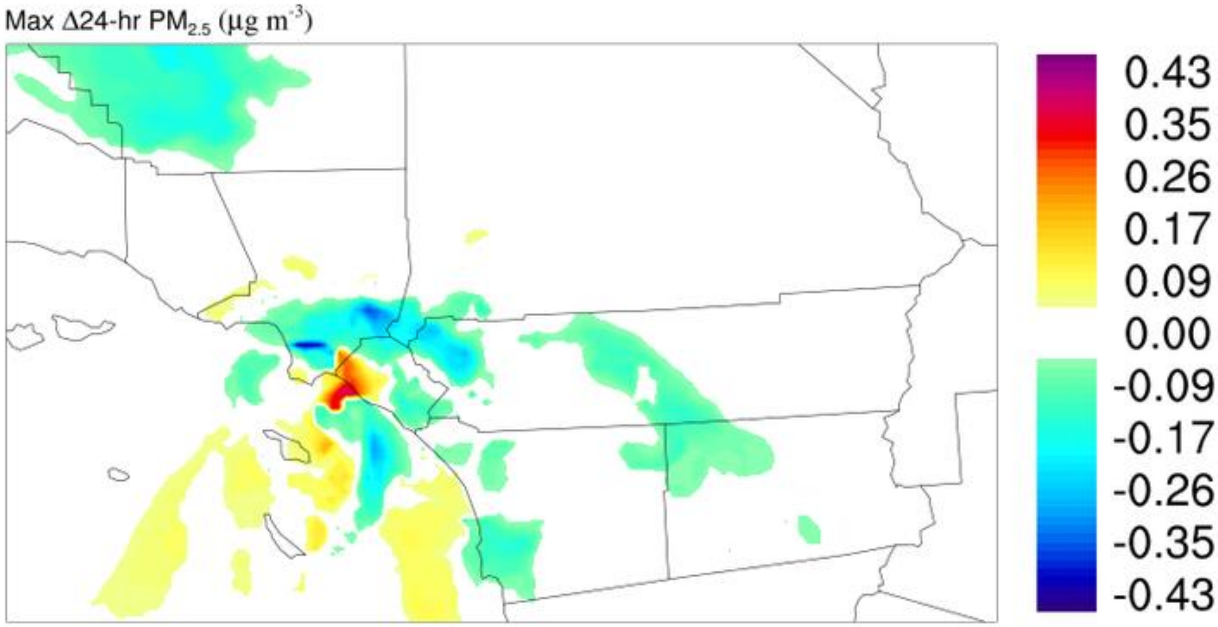

Figure 12. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the DRAYUP case relative to the BAU case for the winter episode

5.1.2 Port Operations Cases

The following cases assess air quality impacts from displacing diesel-powered top loaders, yard tractors, gantry cranes, forklifts, material handlers, etc. with fuel cell electric equivalent technologies. These cases are labeled CHE and include a range of penetration levels from 25% to 75%. The term used for these technologies in the POLA Air Emission Inventory is CHE and fuel cell powered CHE are referred to as FCCHE.

5.1.2.1 CHEDN – Low Estimate of FCCHE Deployment (Risk)

At a 25% rate of reduction of emissions from CHE at SPBPC, a maximum reduction of ozone concentration of 0.11 ppb with a maximum increase of 0.28 ppb due to NO_x titration. These results are shown in Figure 13 which shows that while the magnitudes of ozone increases are larger, the area covered (and possibly the exposed population) by the reductions in ozone is larger. Such results require tools like BenMAP to determine whether the negative effects of the large magnitude increase outweigh the benefits of the widespread low magnitude decreases (as shown in Section 0 it does achieve a net benefit in terms of health costs) . It is notable that the SPBPC itself experiences the highest impact of the ozone increases from NO_x titration while the largest improvements in ozone concentration are in San Bernardino County. The location of the improvements is due to the reduction of ozone precursors that are transported to San Bernardino County by wind before eventually forming ozone there.

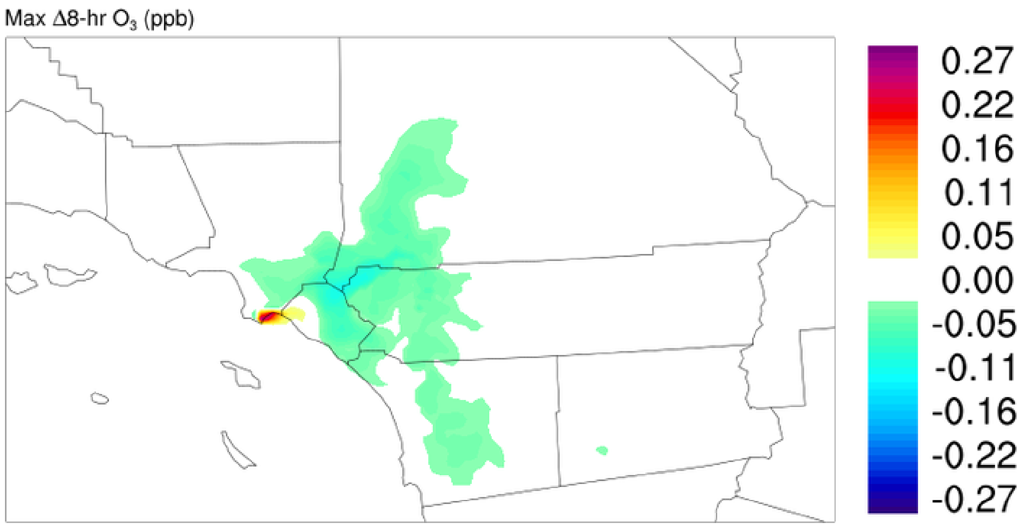

Figure 13. Difference between Maximum 8-hour Average Ozone Concentration of the CHEDN case relative to the BAU case for the summer episode

Figure 14 shows peak 24-hour $PM_{2.5}$ concentration reduction at the SPBPC of approximately 0.08 $\mu g/m^3$.

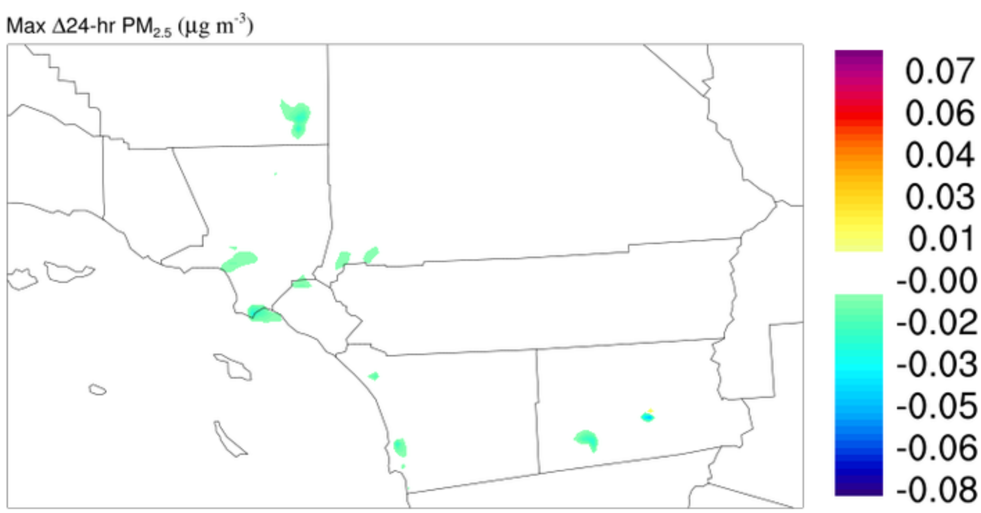

Figure 14. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the CHEDN case relative to the BAU case for the summer episode

In the winter episode CHE emission reduction results in peak 24-hour average $PM_{2.5}$ concentration reduction of 0.05 µg/m^3 at the SPBPC. There are also small reductions predicted in the neighboring areas to the north of the SPBPC.

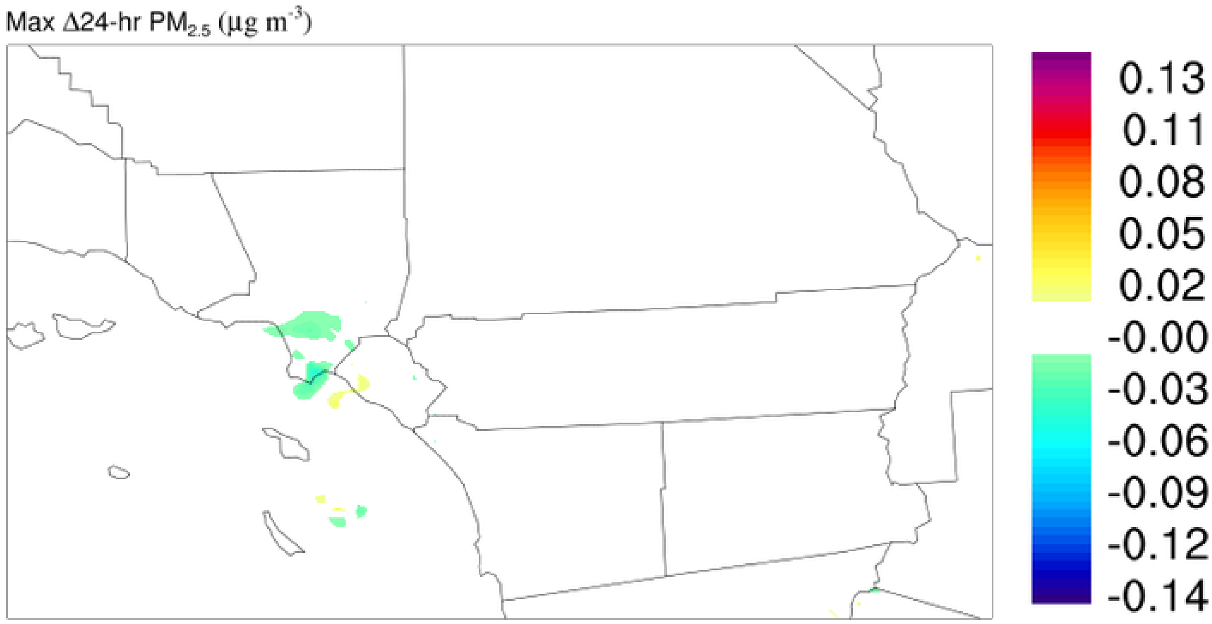

Figure 15. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the CHEDN case relative to the BAU case for the winter episode

5.1.2.2 CHEMD – Middle Estimate of FCCHE Deployment (Mid)

At a 50% rate of reduction of emissions by CHE at SPBPC, a maximum reduction of ozone concentration of 0.20 ppb with a maximum increase of 0.57 ppb due to NO_x titration. The peak reduction occurs around the intersection of San Bernardino, Riverside, and Orange Counties while the peak increase occurs at the SPBPC. These results are shown in Figure 16.

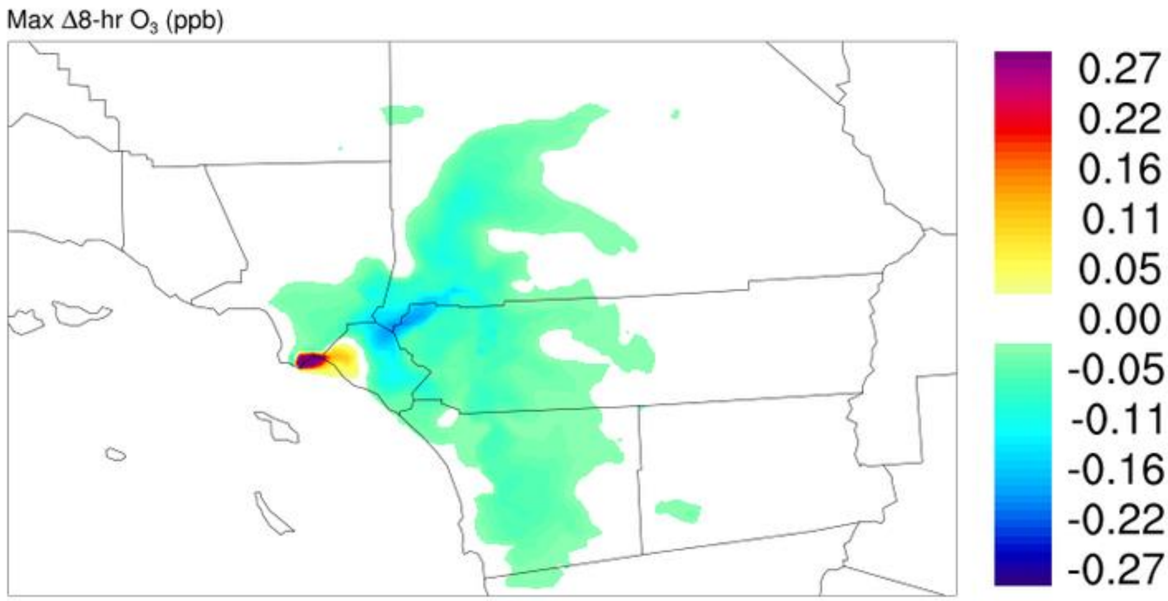

Figure 16. Difference between Maximum 8-hour Average Ozone Concentration of the CHEMD case relative to the BAU case for the summer episode

With the emission reduction rate at 50% the predicted change in $PM_{2.5}$ is large enough that the peak 24-hour average $PM_{2.5}$ concentration reduction occurs at the SPBPC. The predicted peak reduction is 0.05 $\mu g/m^3$. These results are shown in Figure 17.

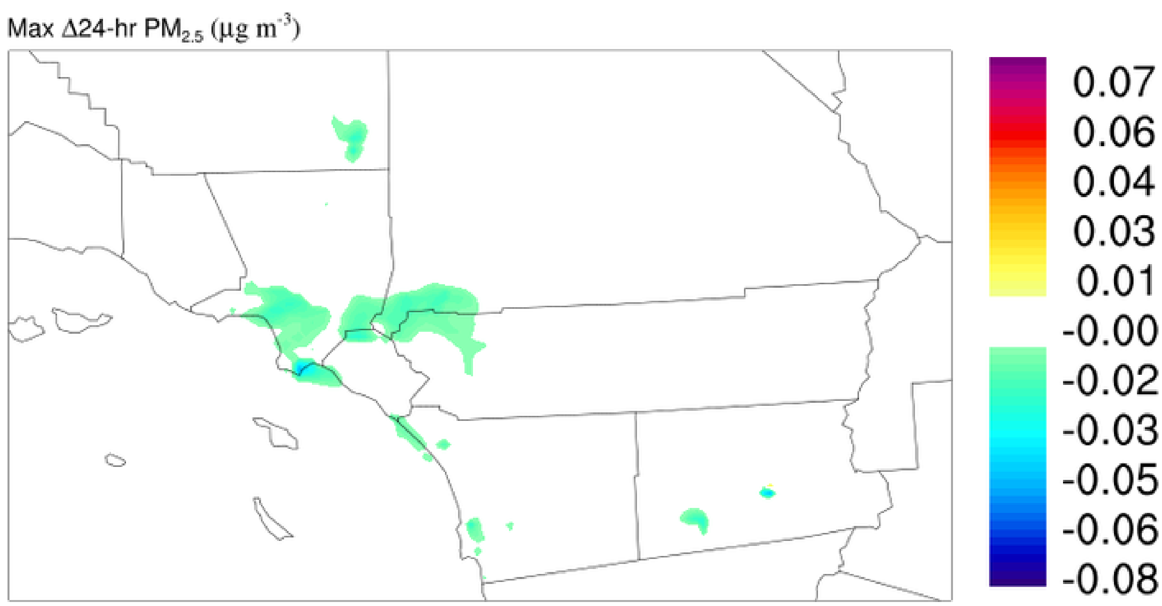

Figure 17. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the CHEMD case relative to the BAU case for the summer episode

The locations of changes in $PM_{2.5}$ are the same as the CHEMD case. The peak 24-hour average $PM_{2.5}$ concentration reduction in 0.09 μg/m^3 shown on the map in Figure 18.

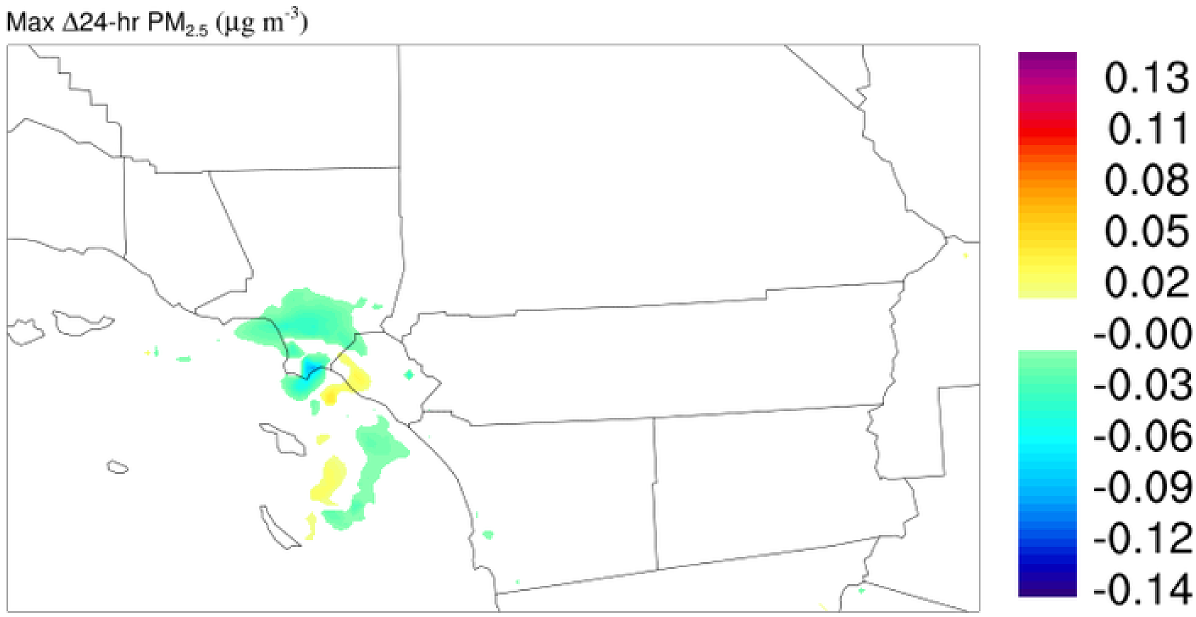

Figure 18. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the CHEMD case relative to the BAU case for the winter episode

5.1.2.3 CHEUP – Upper Estimate of FCCHE Deployment (Upside)

As the emission reduction rate increases to 75% it is clear that the locations of largest impacts are the same as with 25% and 50% reductions. The largest reduction of 0.28 ppb occurs in San Bernardino county and 0.86 ppb increase at the SPBPC.

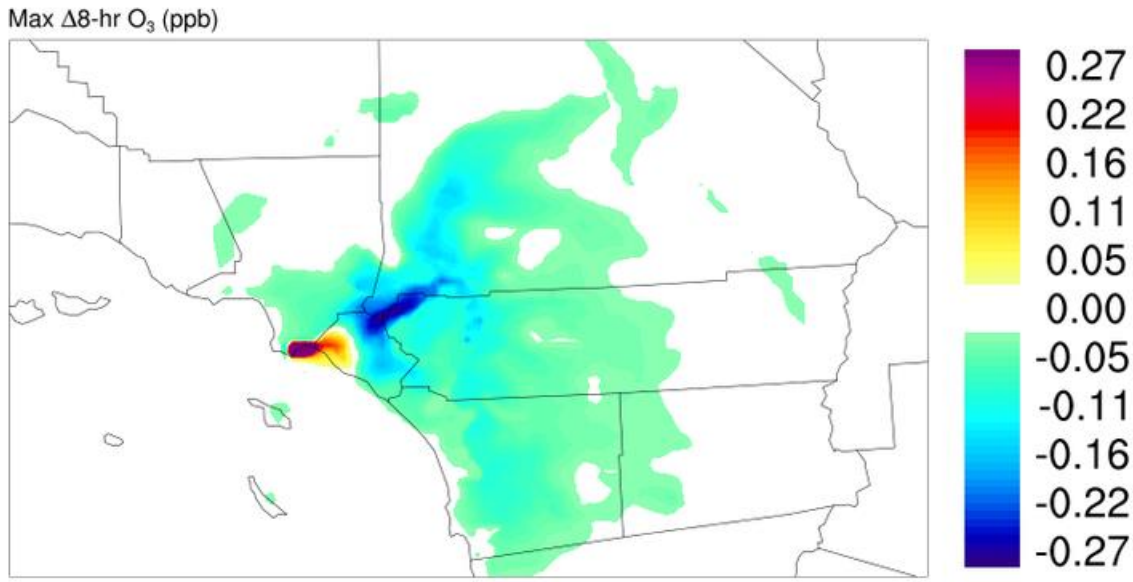

Figure 19. Difference between Maximum 8-hour Average Ozone Concentration of the CHEUP case relative to the BAU case for the summer episode

The 75% emission reduction rate results in a peak 24-hour average $PM_{2.5}$ concentration reduction of 0.08 µg/m^3. The peak reduction occurs at the SPBPC as the other CHE cases.

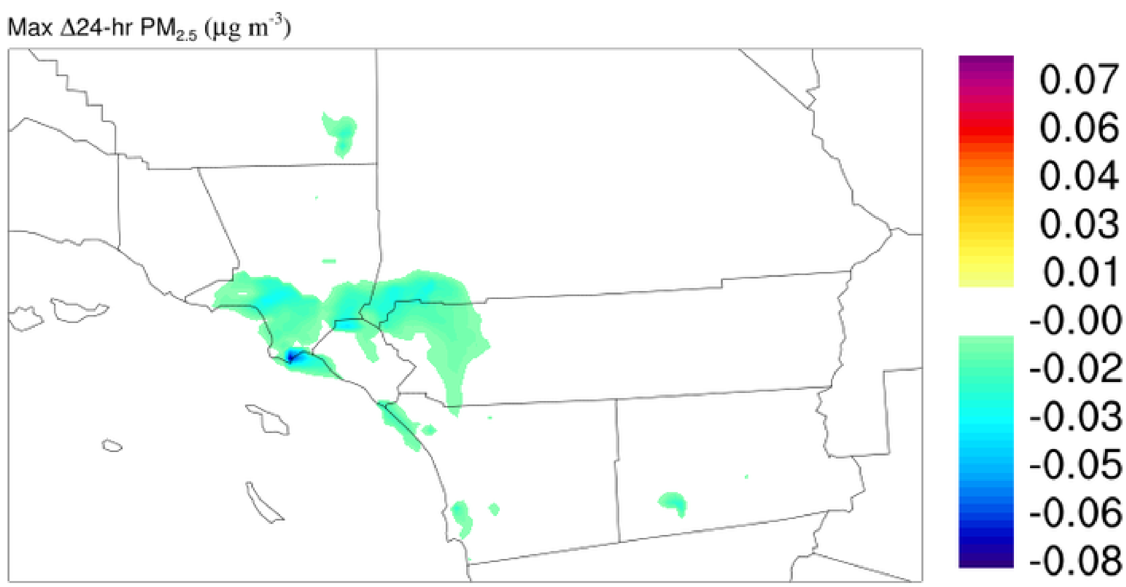

Figure 20. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the CHEUP case relative to the BAU case for the summer episode

At 75% emission reduction rate the peak 24-hour average $PM_{2.5}$ concentration reduction for the winter episode is 0.14 µg/m^3 at the SPBPC. Note that the peak predicted in Kern County in the Risk case is no longer observable on the map in Figure 21. That result is likely insignificant. The model predicts a 0.04 μg/m^3 increase in peak 24-hour average $PM_{2.5}$ concentration that is not shown in Figure 21.

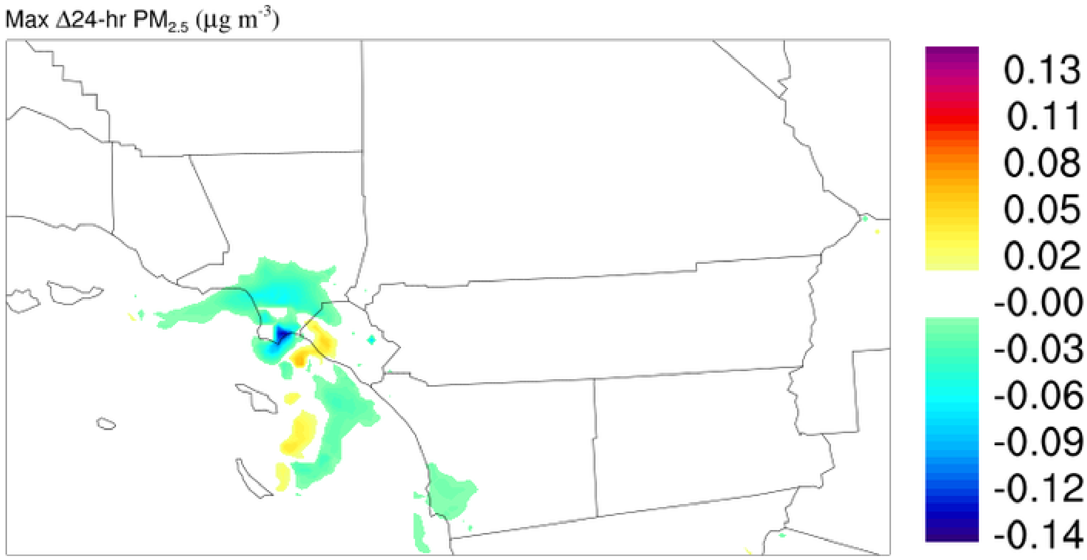

Figure 21. Difference between Maximum 24-hour Average PM2.5 Concentration of the CHEUP case relative to the BAU case for the winter episode

5.1.3 Port Operations Sub-Cases

The following sections present the results of the cases that look at the impacts of individual machine types operating at the ports. The types include Rubber Tired Gantry Cranes (CRN), Material Handling Equipment (MHE), and Yard Tractors (YT). These specific technologies have relatively high contributions of NO_x emissions relative to the CHE category, however the CHE category collectively had such small air quality impacts that the Down and Middle cases for these categories produce no discernible result. Therefore, only Upside results are presented.

5.1.3.1 CRNUP

The peak 8-hour average ozone concentration reduction is 0.07 ppb and occurs in San Bernardino. The peak 8-hour average ozone concentration increase is 0.18 ppb and occurs at the SPBPC.

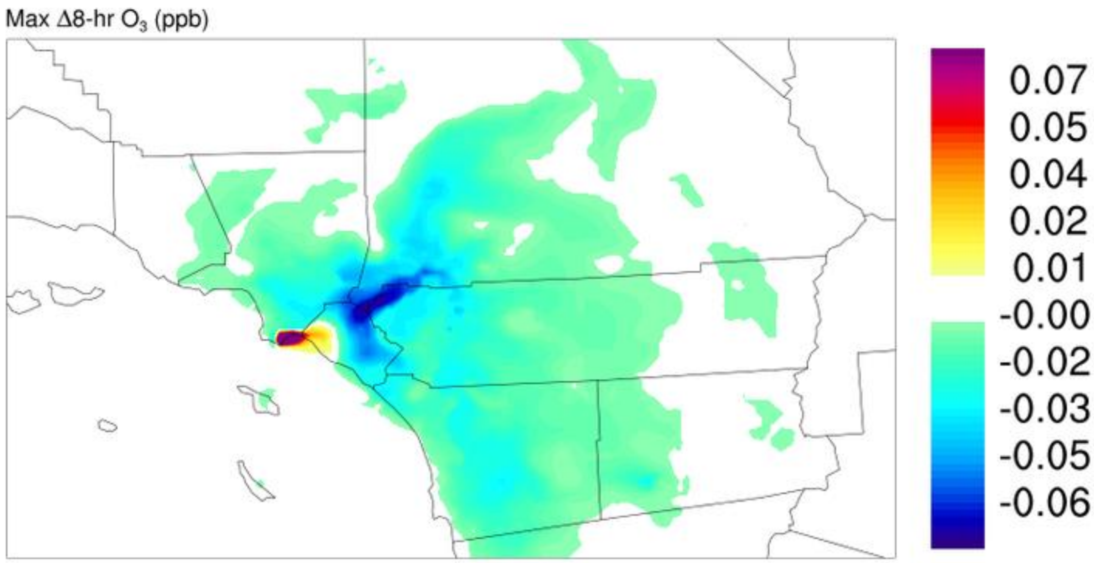

Figure 22. Difference between Maximum 8-hour Average Ozone Concentration of the CRNUP case relative to the BAU case for the summer episode

Peak 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 0.04 μg/m^3 at the SPBPC.

This result is shown in Figure 23.

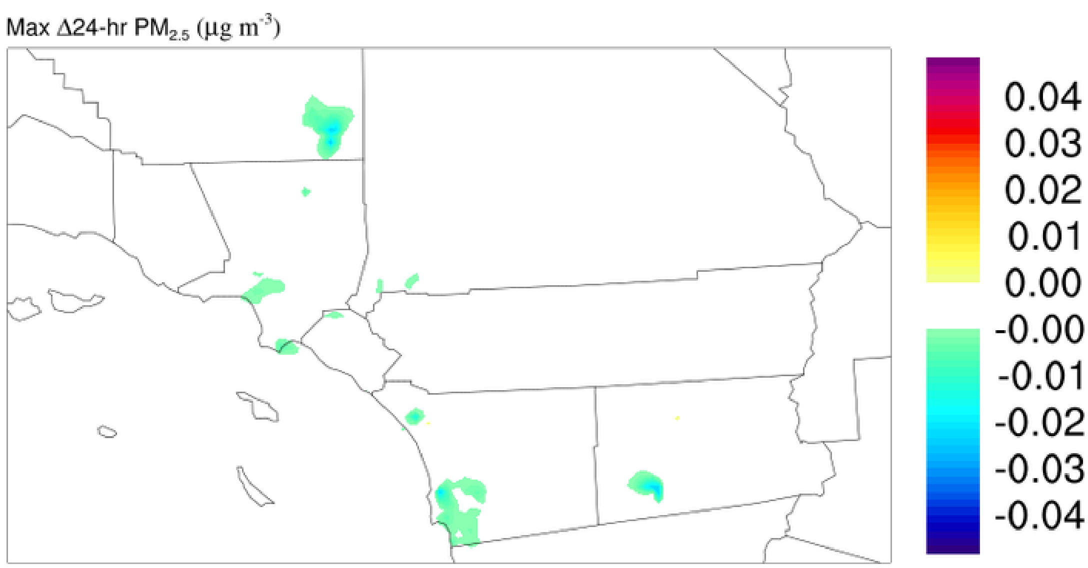

Figure 23. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the CRNUP case relative to the BAU case for the summer episode

5.1.3.2 MHEUP

The peak 8-hour average ozone concentration reduction is 0.10 ppb and occurs in San Bernardino. The peak 8-hour average ozone concentration increase is 0.22 ppb and occurs at the SPBPC.

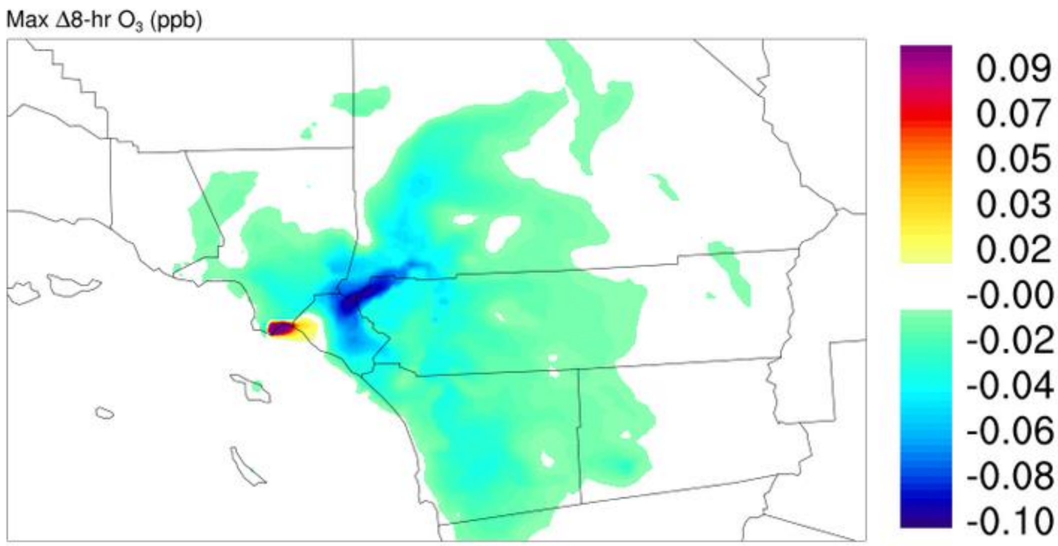

Figure 24. Difference between Maximum 8-hour Average Ozone Concentration of the MHEUP case relative to the BAU case for the summer episode

Peak 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 0.04 μg/m^3 at the SPBPC. This result is shown in Figure 25.

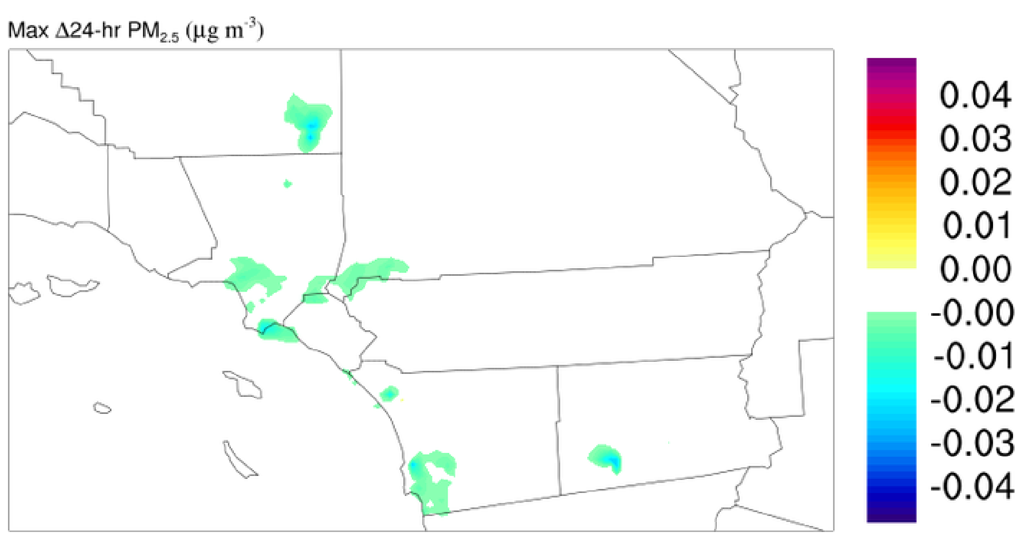

Figure 25. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the MHEUP case relative to the BAU case for the summer episode

Peak winter 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 0.04 μg/m^3 at the SPBPC. This result is shown in Figure 26.

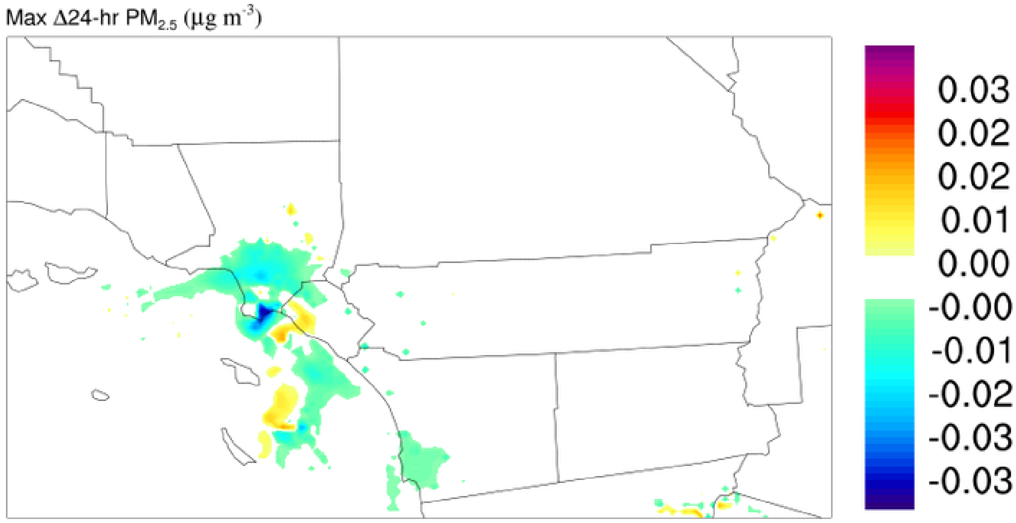

Figure 26. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the MHEUP case relative to the BAU case for the winter episode

5.1.3.3 YTUP

The peak 8-hour average ozone concentration reduction is 0.12 ppb and occurs in San Bernardino. The peak 8-hour average ozone concentration increase is 0.27 ppb and occurs at the SPBPC.

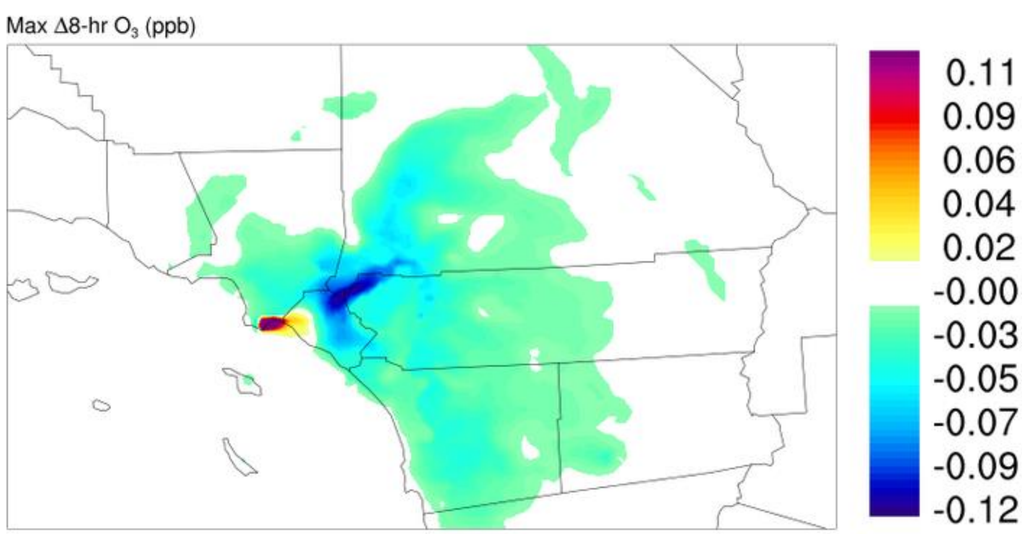

Figure 27. Difference between Maximum 8-hour Average Ozone Concentration of the YTUP case relative to the BAU case for the summer episode

Peak 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 0.04 μg/m^3 at the SPBPC.

This result is shown in Figure 28.

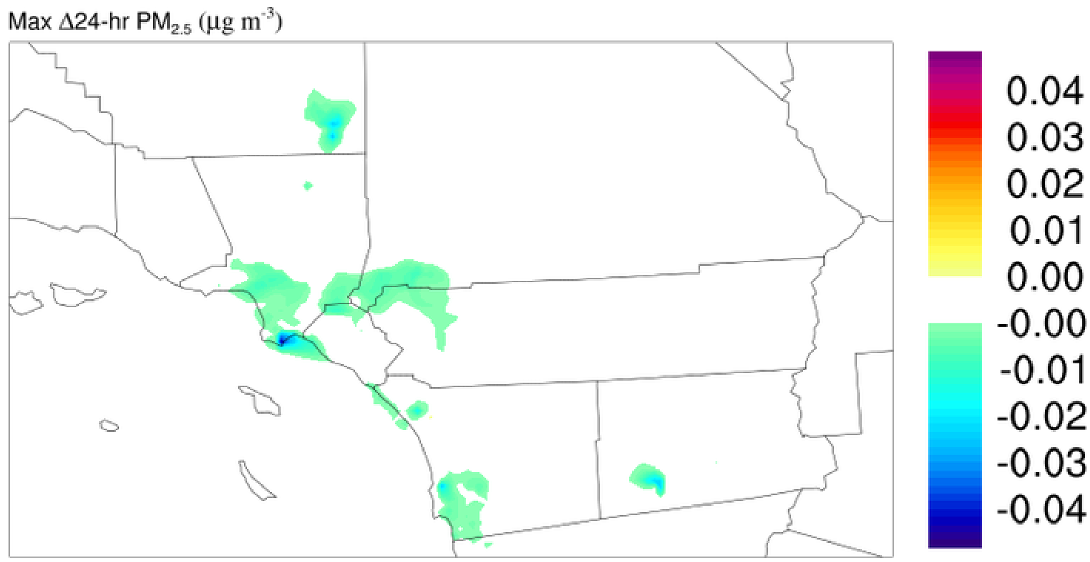

Figure 28. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the YTUP case relative to the BAU case for the summer episode

Peak winter 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 0.07 μg/m^3 at the SPBPC. This result is shown in Figure 29.

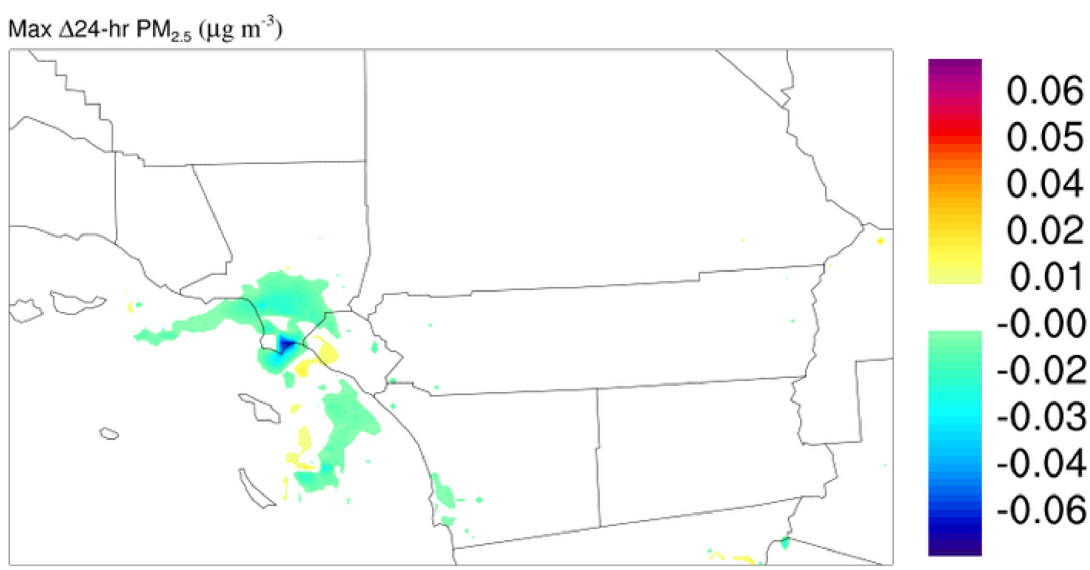

Figure 29. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the YTUP case relative to the BAU case for the winter episode

5.1.4 Locomotive Cases

The following cases demonstrate air quality impacts associated with displacement of diesel-powered locomotives with hydrogen powered fuel cell electric locomotives (FCEL). The cases are labeled RAIL and include penetration levels between 25% and 75% leading to equivalent reduction in operation emissions of criteria pollutants.

5.1.4.1 RAILDN – Low Estimate of FCEL Deployment (Risk)

Figure 30 shows an especially positive outlook for ozone impacts due to displacement of diesel locomotive emissions by FCET. The largest reduction, 0.30 ppb, occurs at the boundary between Los Angeles and San Bernardino counties providing benefits for communities in Pomona, Ontario, and surrounding cities. At the SPBPC some increase in ozone is predicted due to NO_x titration. However, it is noted that these results show much less titration than the other cases. This can be explained by the spatial distribution of locomotive NO_x emissions, 93% of which occur during linehaul, away from the port [4].

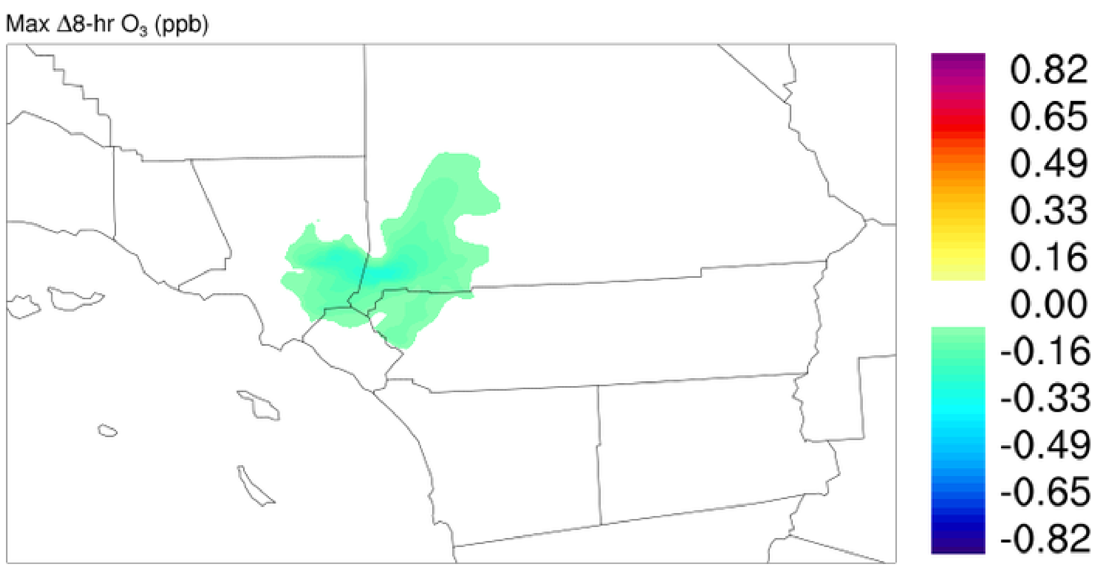

Figure 30. Difference between Maximum 8-hour Average Ozone Concentration of the RAILDN case relative to the BAU case for the summer episode

Benefits to $PM_{2.5}$ are also achieved for RAIL cases in the summer episode. Peak 24-hour average $PM_{2.5}$ concentration reduction is 0.07 μg/m^3 just north of the SPBPC in Los Angeles. Smaller reductions are spread throughout densely populated southern Los Angeles County.

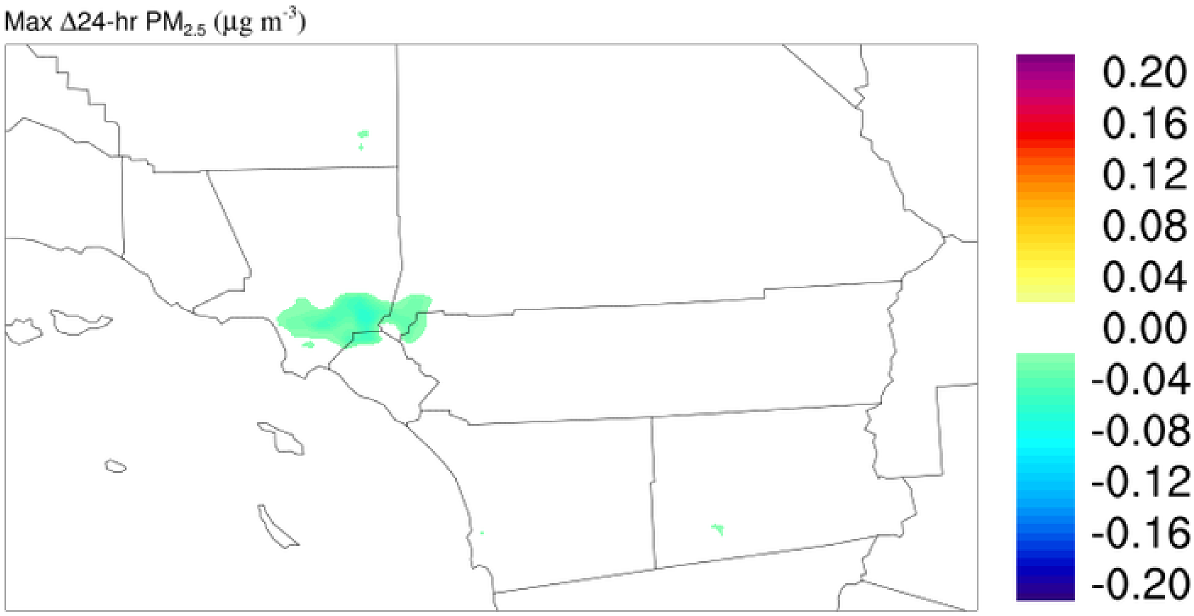

Figure 31. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the RAILDN case relative to the BAU case for the summer episode

The outlook for the winter cases is more complicated as there are several areas of both increase in $PM_{2.5}$ and reduction. The peak reduction occurs just north of the SPBPC in Inglewood. Peak 24-hour average $PM_{2.5}$ concentration reduction is 0.05 μg/m^3. Peak 24-hour average $PM_{2.5}$ concentration increase is 0.04 μg/m^3 south of the SPBPC over the Pacific Ocean southeast of Santa Catalina Island. The increase in $PM_{2.5}$ is of considerable magnitude it mostly occurs where there is no population to impact.

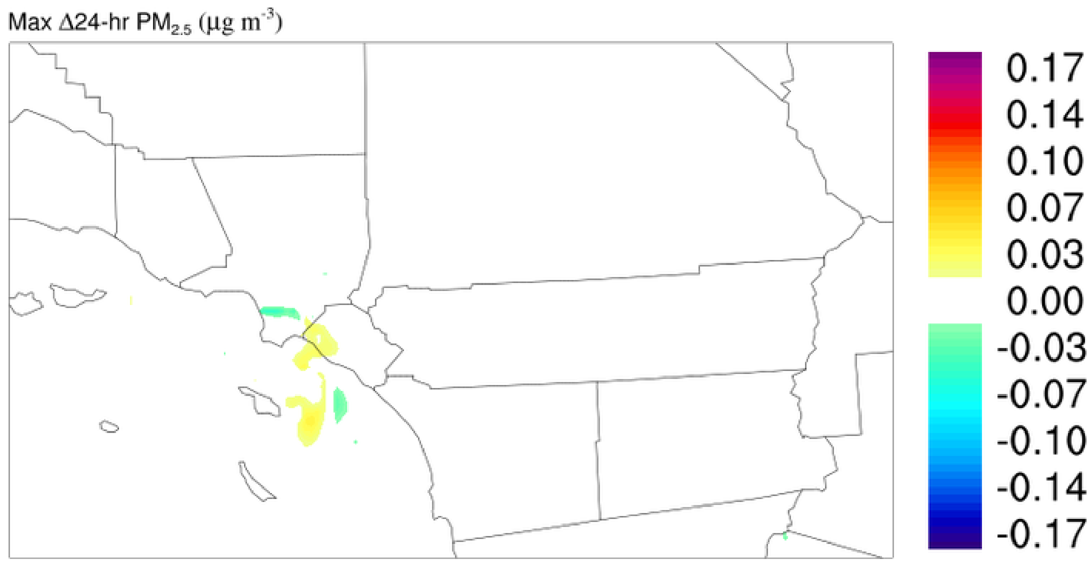

Figure 32. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the RAILDN case relative to the BAU case for the winter episode

5.1.4.2 RAILMD – Middle Estimate of FCEL Deployment (Mid)

With the 50% emission reduction rate the magnitudes of largest impact have changed but their locations have not. The largest reduction area is still around Pomona/Ontario at 0.57ppb and there is still increased ozone due titration at the SPBPC. The titration causes a maximum increase of 0.14 ppb.

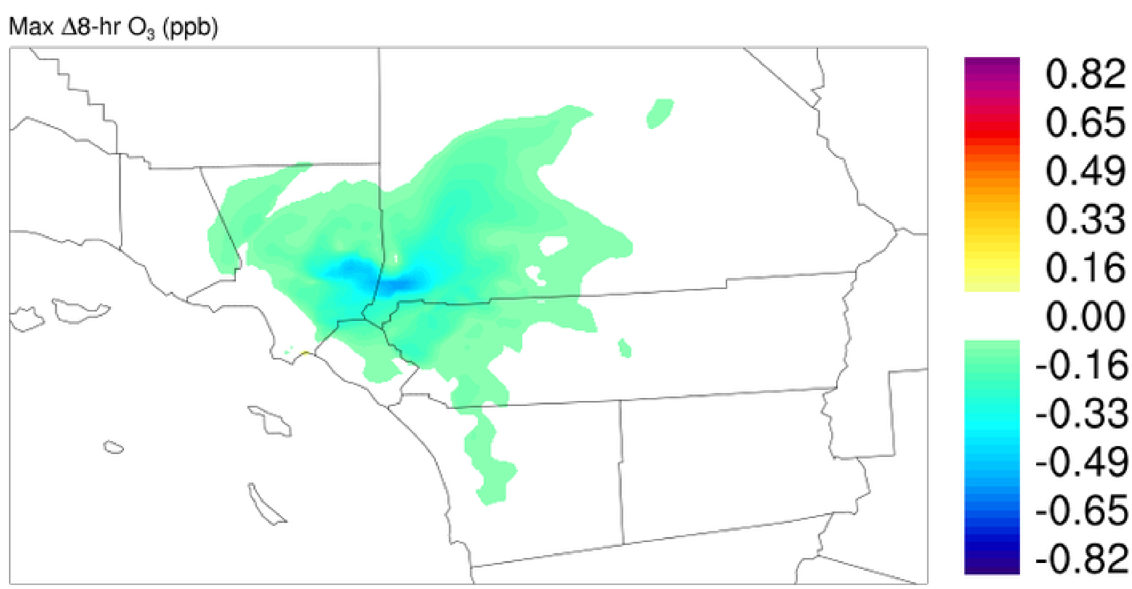

Figure 33. Difference between Maximum 8-hour Average Ozone Concentration of the RAILMD case relative to the BAU case for the summer episode

Peak 24-hour average $PM_{2.5}$ concentration reduction is 0.14 µg/m^3 for the Middle case. The geographic spread is very similar to the Risk case with magnitude increased.

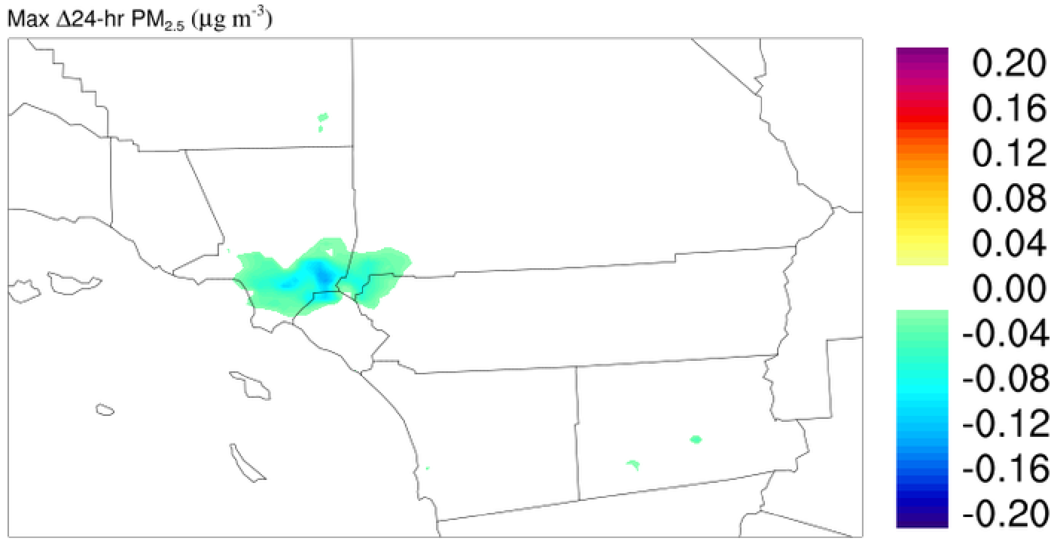

Figure 34. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the RAILMD case relative to the BAU case for the summer episode

Peak 24-hour average $PM_{2.5}$ concentration reduction is 0.11 µg/m^3 whereas maximum increase is 0.11 µg/m^3 for the winter episode. The geographic extent of the changes is similar to the low case and the peak increases in $PM_{2.5}$ are above the ocean and away from the population.

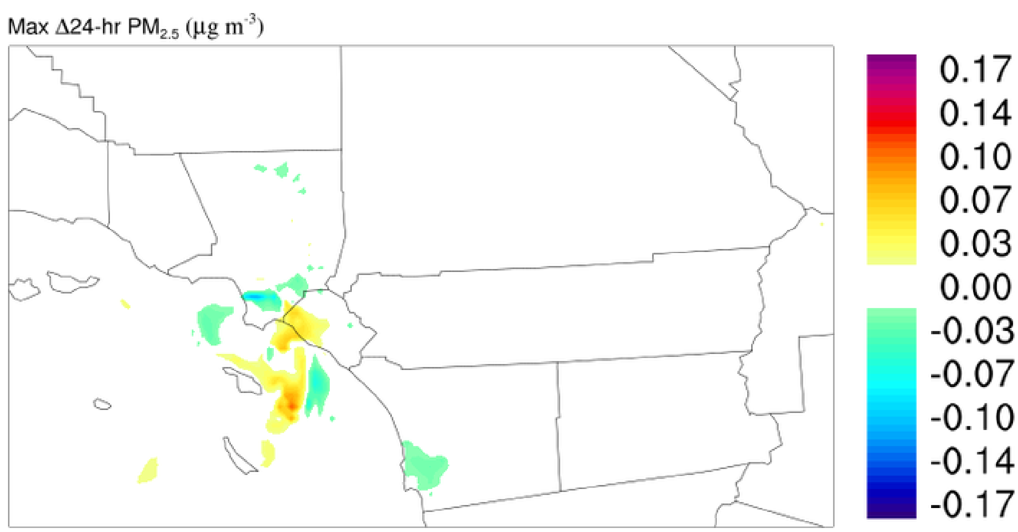

Figure 35. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the RAILMD case relative to the BAU case for the winter episode

5.1.4.3 RAILUP – Upper Estimate of FCEL Deployment (Upside)

75% reduction has roughly the same spatial impact as the downside and middle cases. However, the maximum reduction in ozone concentration is 0.84 ppb in this case and the largest increase in ozone is 0.18 ppb.

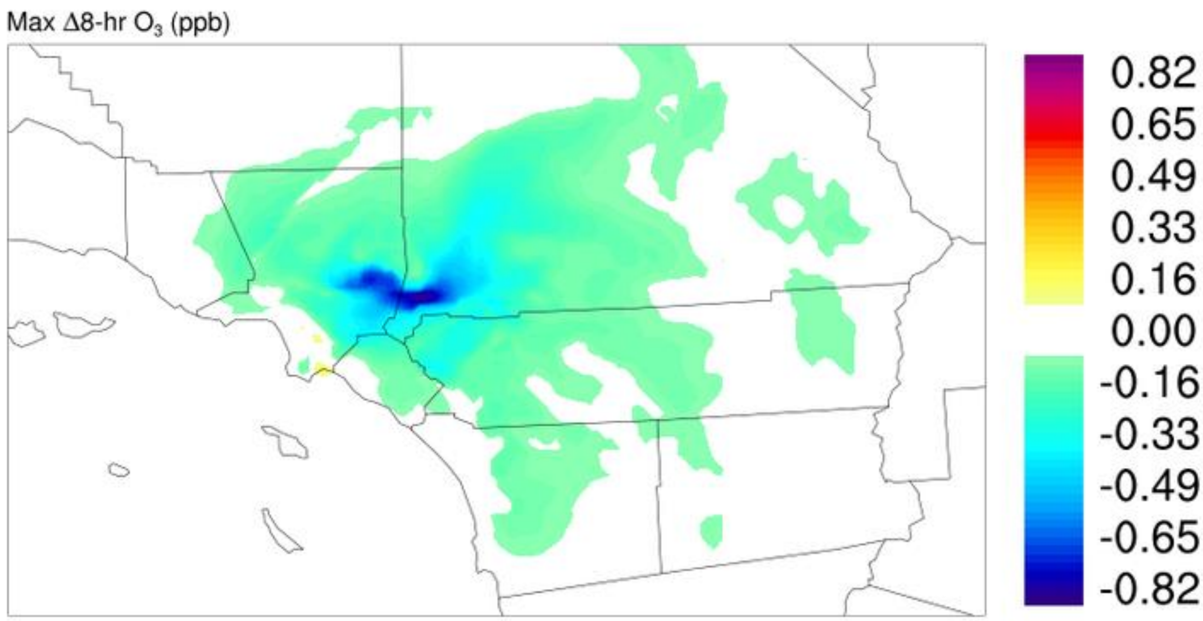

Figure 36. Difference between Maximum 8-hour Average Ozone Concentration of the RAILUP case relative to the BAU case for the summer episode

The outlook for summer $PM_{2.5}$ is best for the high case with 75% emission reduction. Peak 24-hour average $PM_{2.5}$ concentration reduction is 0.20 µg/m^3 in the same densely populated location in Los Angeles near the borders of Orange and San Bernardino Counties.

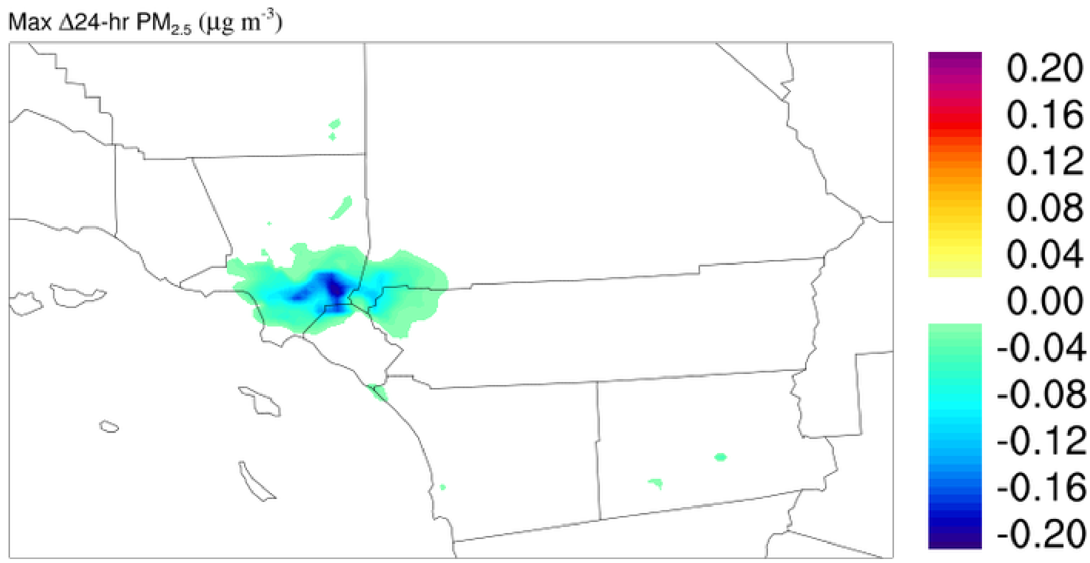

Figure 37. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the RAILUP case relative to the BAU case for the summer episode

In the winter episode of the Upside case peak 24-hour average $PM_{2.5}$ concentration reduction is 0.18 $\mu g/m^3$ in Inglewood. The oceanic $PM_{2.5}$ increase peaks at 0.14 $\mu g/m^3$ 24-hour average concentration.

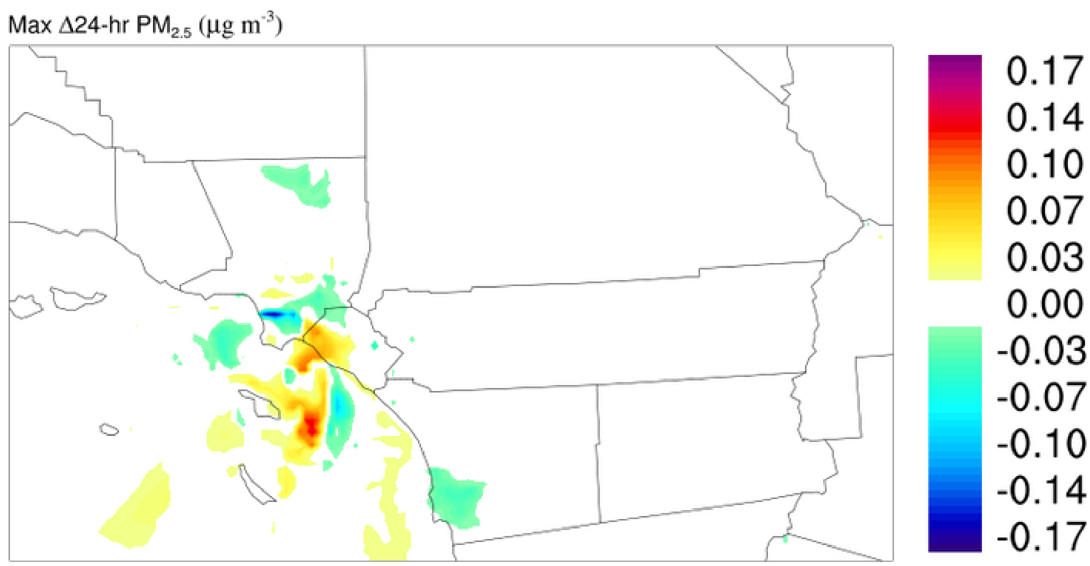

Figure 38. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the RAILUP case relative to the BAU case for the winter episode

5.1.5 Maritime Cases

The following cases assess air quality impacts from deployment of water-bound FCET. That is, these cases impact emissions from those technologies that maneuver on the water at the port including those categorized as Ocean Going Vessels (OGV) and Harbor Craft (HC) in the port emission inventories. These cases are labeled SHIP and include the same 25% to 75% penetration range as the other non-drayage cases. The fuel cell electric equivalent technologies are referred to as FCES for Fuel Cell Electric Ships.

5.1.5.1 SHIPDN – Low Estimate of FCES Deployment (Risk)

Displacement of emissions from auxiliary engines and boilers on OGV and HC produce the widest spatial ozone impacts of any of the technology groups. The largest reductions occur around San Bernardino and reach an 8-hour average peak of 0.90 ppb 8-hour average. Titration induced ozone increases occur at the location and extend northeast along the Orange County/Los Angeles County border. The 8-hour average peak ozone concentration increase is 2.03 ppb

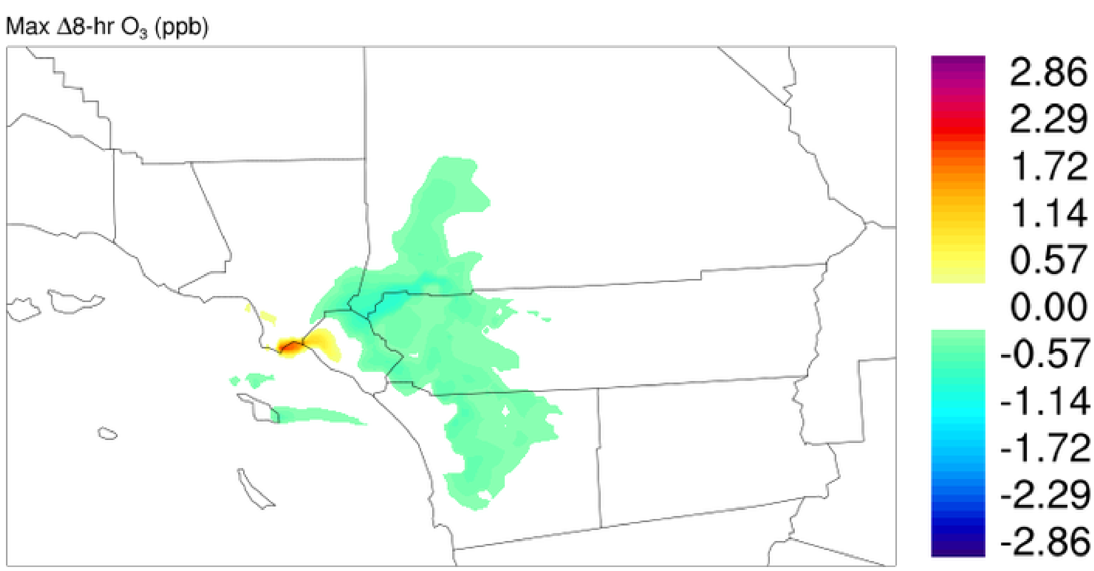

Figure 39. Difference between Maximum 8-hour Average Ozone Concentration of the SHIPDN case relative to the BAU case for the summer episode

Reduction of OGV and HC emissions results in $PM_{2.5}$ concentration reductions around the SPBPC. With 25% emissions reduction rate, the peak 24-hour average $PM_{2.5}$ concentration reduction is 0.56 μg/m^3.

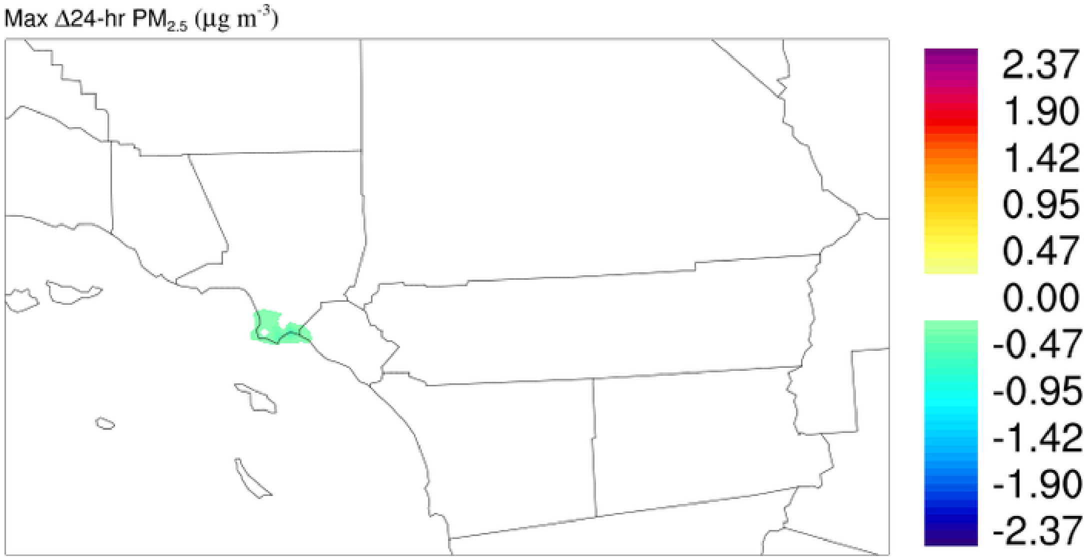

Figure 40. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the SHIPDN case relative to the BAU case for the summer episode

In the winter episode of the Risk case peak 24-hour average $PM_{2.5}$ concentration reduction is 0.91 $\mu g/m^3$ in Inglewood. The oceanic $PM_{2.5}$ increase peaks at 1.22 $\mu g/m^3$ 24-hour average concentration.

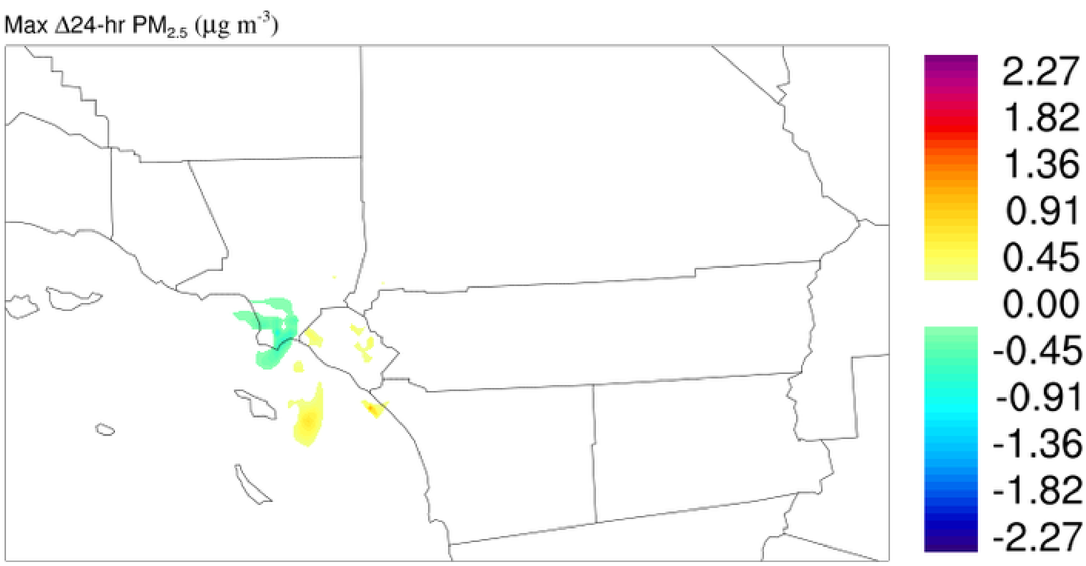

Figure 41. Difference between Maximum 24-hour Average PM2.5 Concentration of the SHIPDN case relative to the BAU case for the winter episode

5.1.5.2 SHIPMD – Middle Estimate of FCES Deployment (Mid)

The peak 8-hour average ozone concentration reduction is 1.88 ppb and occurs in San Bernardino. The peak 8-hour average ozone concentration increase is 4.21 ppb and occurs at the SPBPC.

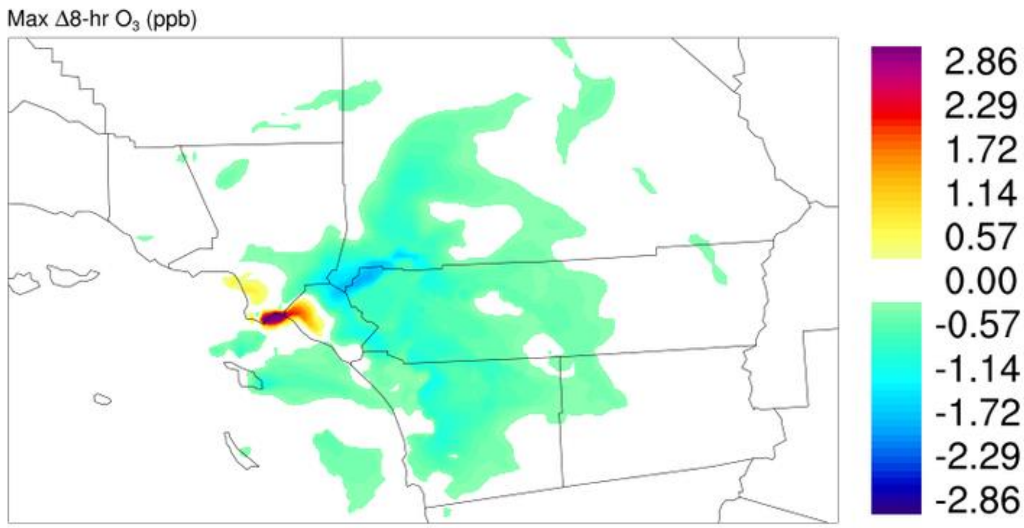

Figure 42. Difference between Maximum 8-hour Average Ozone Concentration of the SHIPMD case relative to the BAU case for the summer episode

With 50% emissions reduction rate, the peak 24-hour average $PM_{2.5}$ concentration reduction is 1.20 µg/m^3.

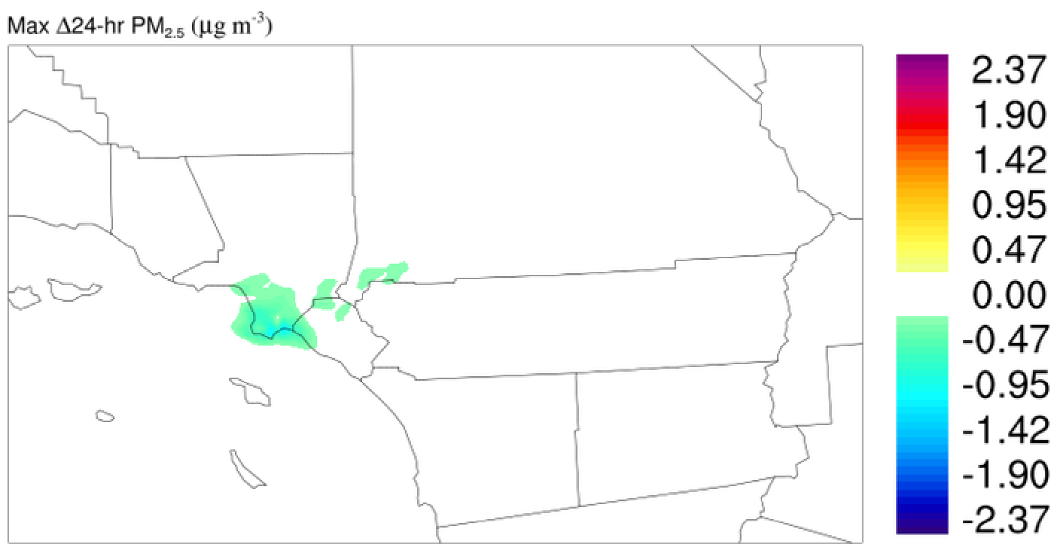

Figure 43. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the SHIPMD case relative to the BAU case for the summer episode

The winter episode includes a max benefit of 1.78 μg/m[3] $PM_{2.5}$ reduced with a max increase of 1.65 μg/m[3]. The benefits occur at the port and its surrounding areas whereas the max increases occur over the ocean where there is no population exposed to the increase in pollution.

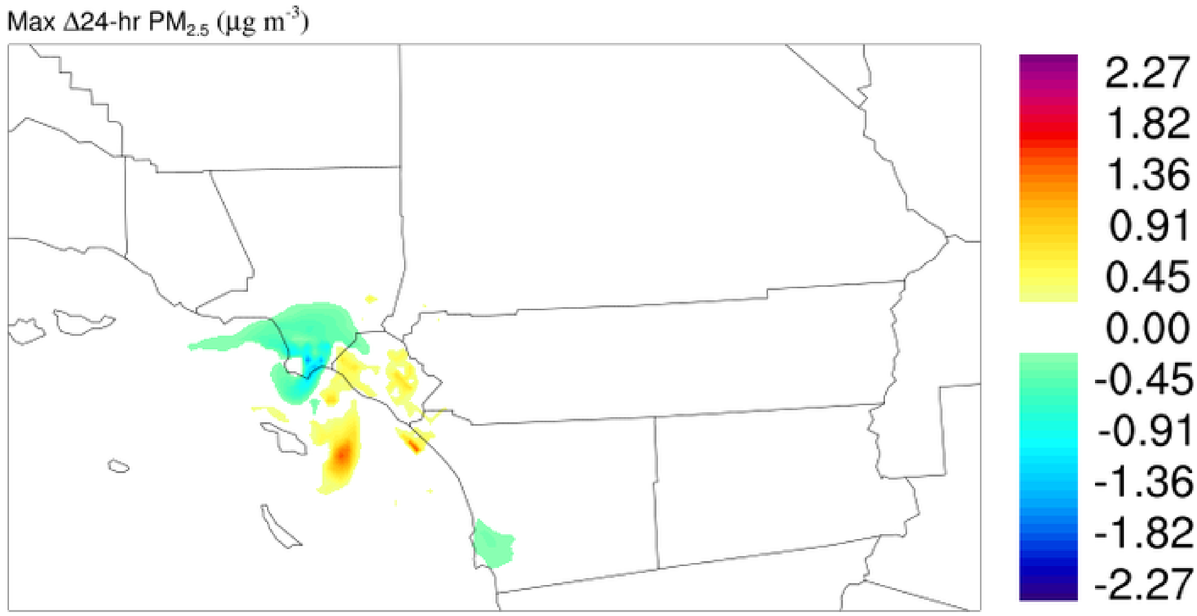

Figure 44. Difference between Maximum 24-hour Average PM2.5 Concentration of the SHIPMD case relative to the BAU case for the winter episode

5.1.5.3 SHIPUP – Upper Estimate of FCES Deployment (Upside)

The peak 8-hour average ozone concentration reduction is 2.96 ppb and occurs in San Bernardino. The peak 8-hour average ozone concentration increase is 6.41 ppb and occurs at the SPBPC.

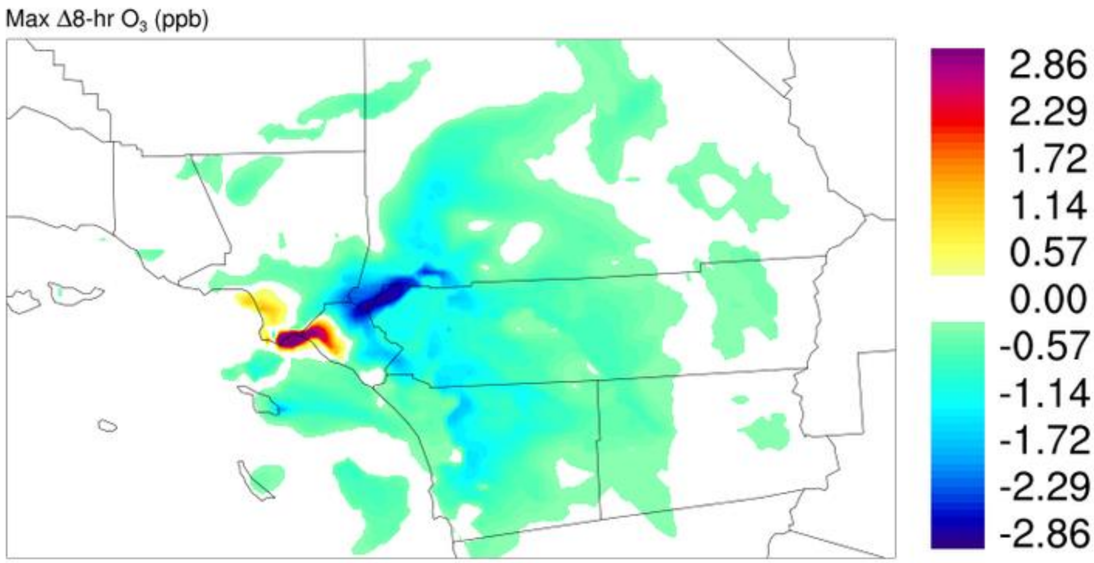

Figure 45. Difference between Maximum 8-hour Average Ozone Concentration of the SHIPUP case relative to the BAU case for the summer episode

With 75% emissions reduction rate, the peak 24-hour average $PM_{2.5}$ concentration reduction is 2.45 $\mu g/m^3$.

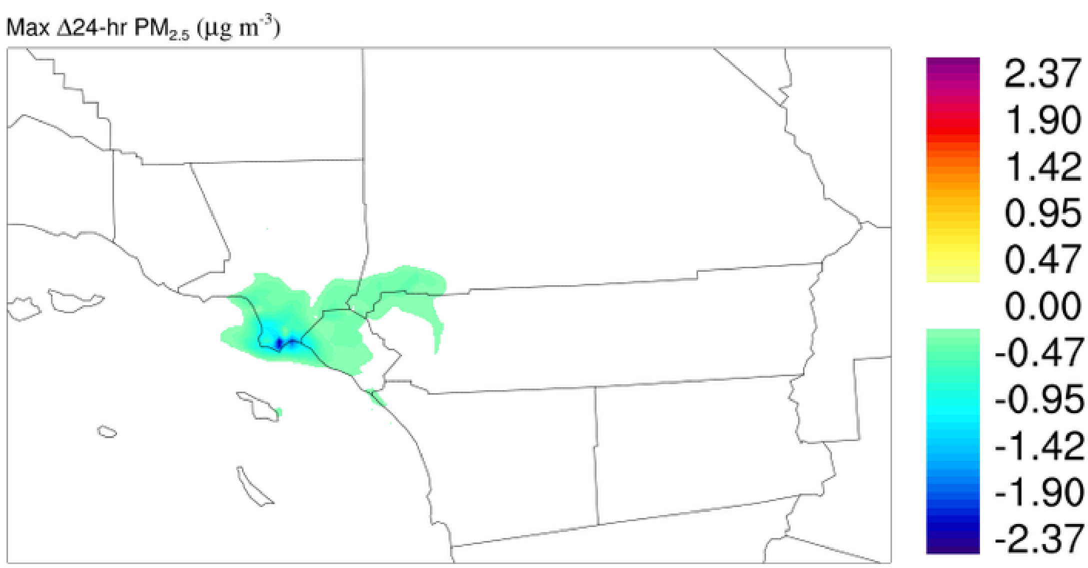

Figure 46. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the SHIPUP case relative to the BAU case for the summer episode

The winter episode with 75% emissions reduction rate, the peak 24-hour average $PM_{2.5}$ concentration reduction is 2.35 µg/m^3. An increase in peak 24-hour average $PM_{2.5}$ concentration of 2.12 µg/m^3 is predicted over the ocean east of Santa Catalina Island. These results are shown in Figure 47.

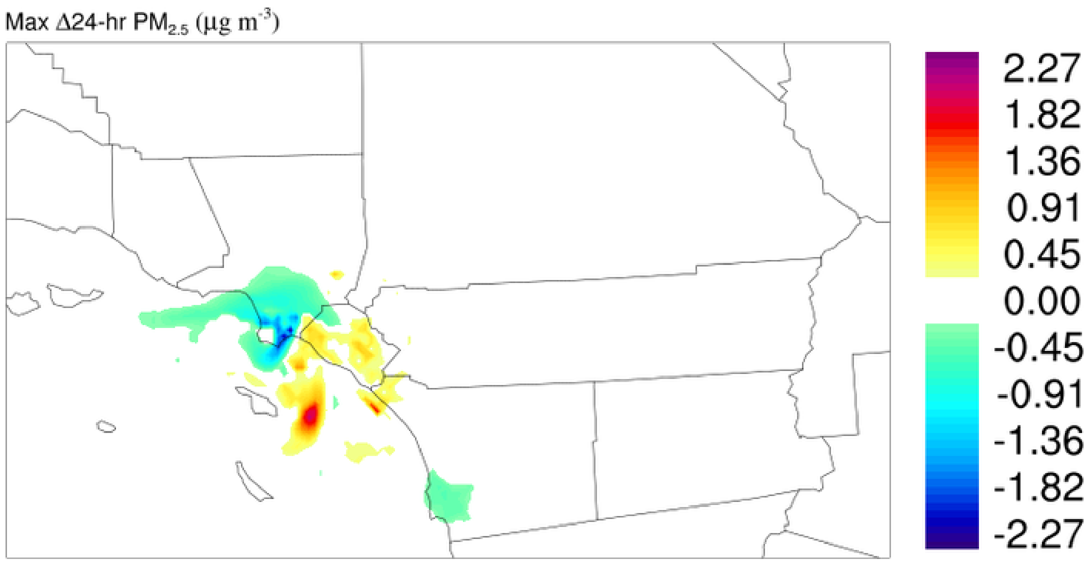

Figure 47. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the SHIPUP case relative to the BAU case for the winter episode

5.1.6 Combined Cases

The following cases assess air quality impacts associated with all of the aforementioned FCET deployed together. These cases are labeled, and the cases are designed to align the deployment levels of the previous cases. That is, all low cases are combined, and likewise for middle and high cases.

5.1.6.1 ALLDN – Low Estimate of FCET Deployment (Risk)

The cases that displace emissions in all technology sectors show large impacts even in the low case. In these cases, the peak reductions are larger than the peak increases and the areas of reduction are larger. For the risk case, the peak 8-hour ozone concentration reduction is 2.69 ppb. The peak 8-hour average ozone concentration increase is 2.19 ppb. The peak reductions effect most of San Bernardino County south of the San Bernardino Mountains and some areas of eastern Los Angeles County. Ozone increases are predicted at the SPBPC and at cities in Los Angeles County along the Orange County border.

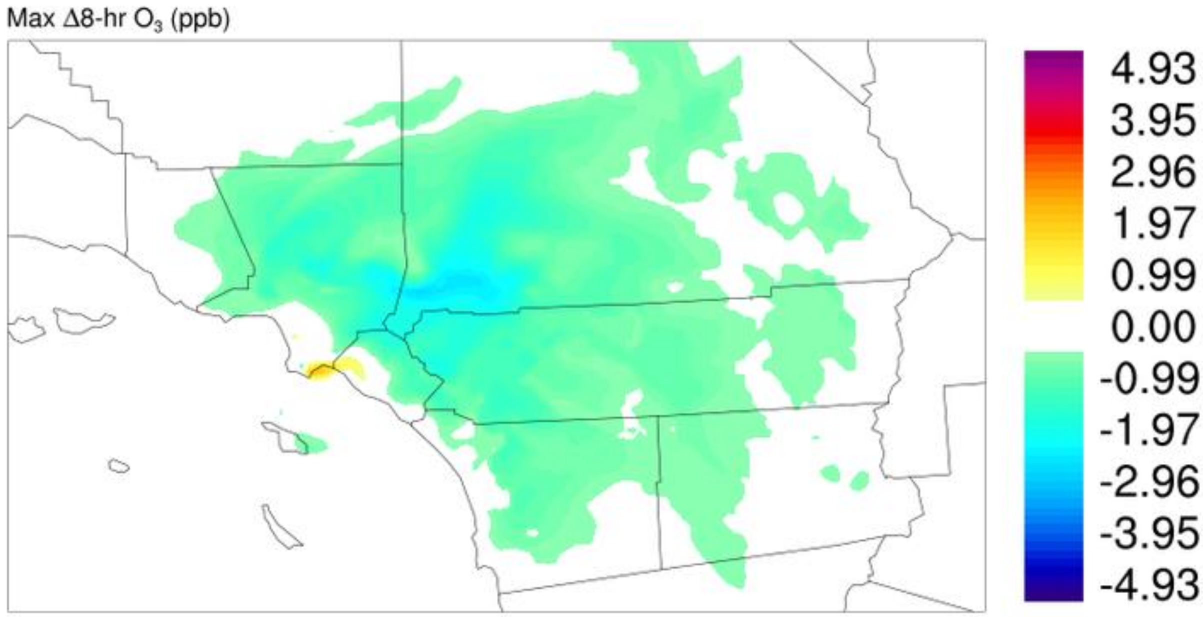

Figure 48. Difference between Maximum 8-hour Average Ozone Concentration of the ALLDN case relative to the BAU case for the summer episode

The low emission reduction rate for all technology yields a positive outlook for summer $PM_{2.5}$. Peak 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 0.60 μg/m^3 at the SPBPC. This result is shown in Figure 49.

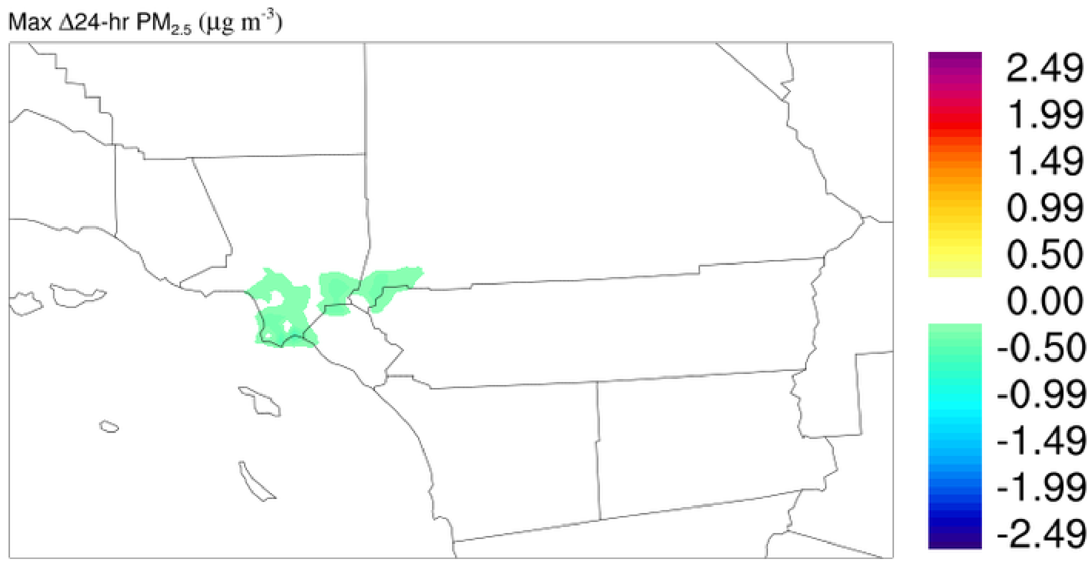

Figure 49. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the ALLDN case relative to the BAU case for the summer episode

Peak 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 0.99 µg/m^3 at the SPBPC. This result is shown in Figure 50. South of the SPBPC east of Santa Catalina is shown a predicted increase in peak 24-hour average $PM_{2.5}$ concentration of 1.20 µg/m^3.

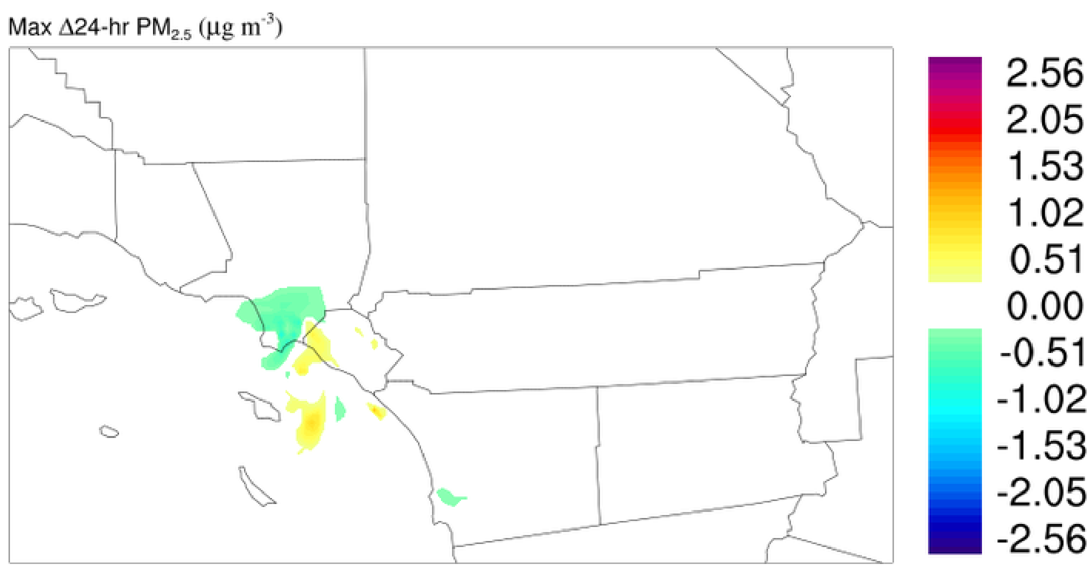

Figure 50. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the ALLDN case relative to the BAU case for the winter episode

5.1.6.2 ALLMD – Middle Estimate of FCET Deployment (Mid)

The peak 8-hour average ozone concentration reduction is 3.61 ppb and occurs in San Bernardino. The peak 8-hour average ozone concentration increase is 4.67 ppb and occurs at the SPBPC.

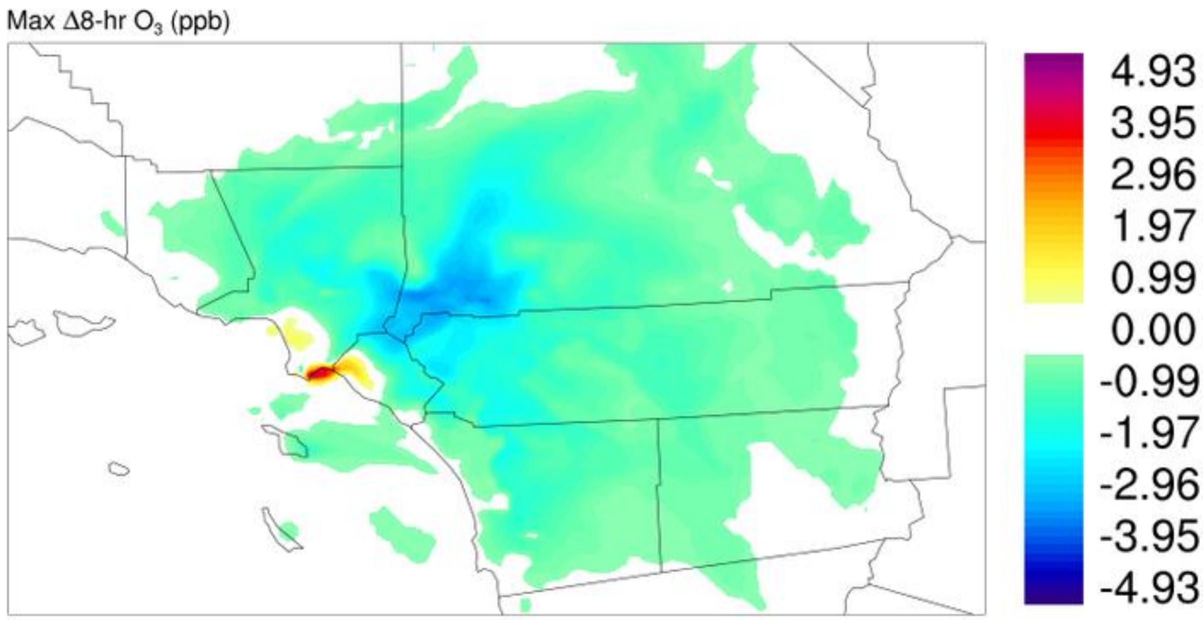

Figure 51. Difference between Maximum 8-hour Average Ozone Concentration of the ALLMD case relative to the BAU case for the summer episode

Peak 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 1.24 μg/m^3 at the SPBPC.

This result is shown in Figure 52.

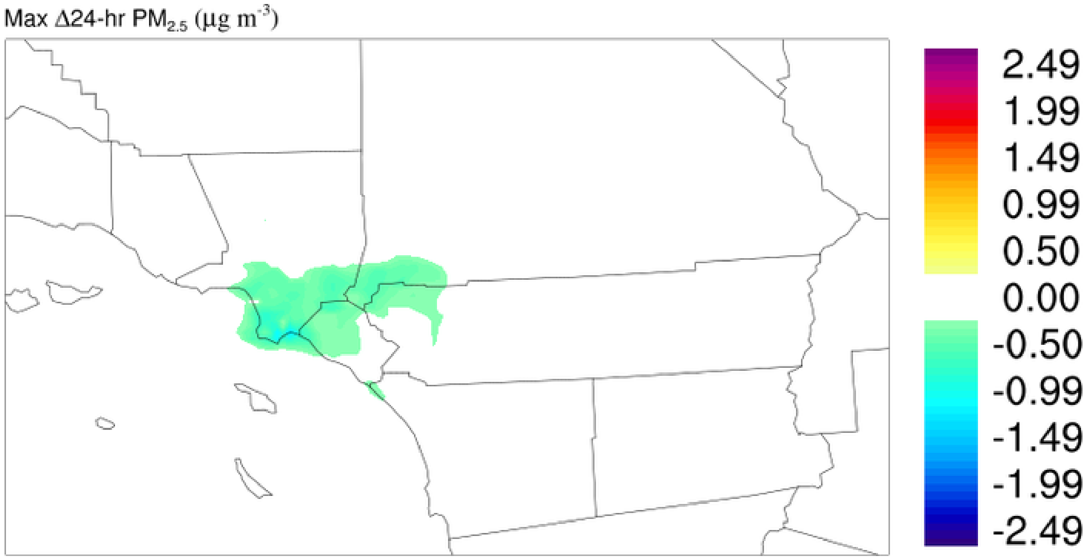

Figure 52. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the ALLMD case relative to the BAU case for the summer episode

Peak winter 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 1.80 μg/m^3 at the SPBPC. This result is shown in Figure 53. Over the ocean is predicted a 1.72 μg/m^3 increase in peak 24-hour average $PM_{2.5}$ concentration.

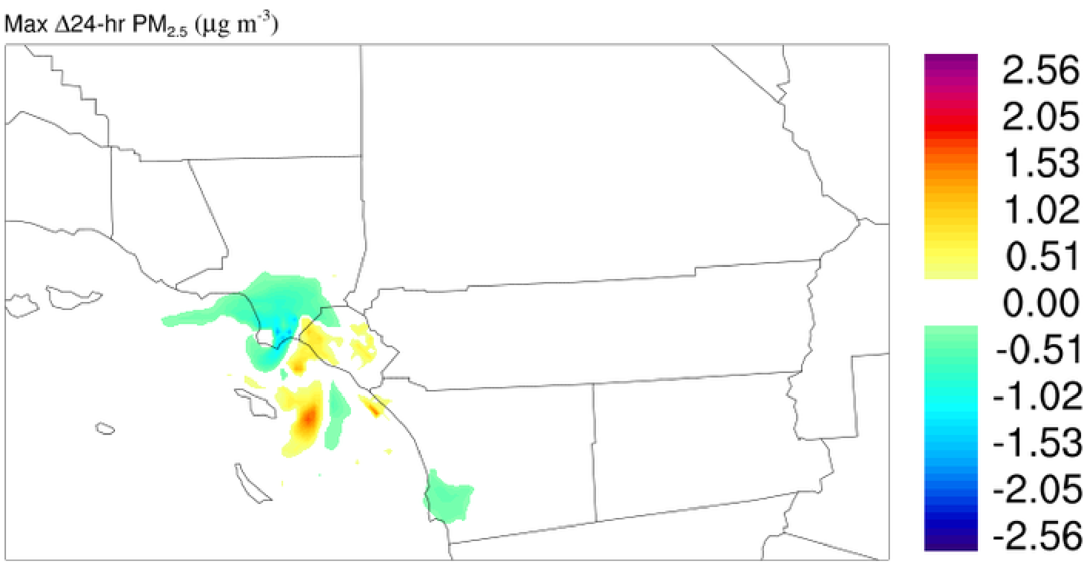

Figure 53. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the ALLMD case relative to the BAU case for the winter episode

5.1.6.3 ALLUP – Upper Estimate of FCET Deployment (Upside)

The peak 8-hour average ozone concentration reduction is 5.10 ppb and occurs in San Bernardino. The peak 8-hour average ozone concentration increase is 7.14 ppb and occurs at the SPBPC.

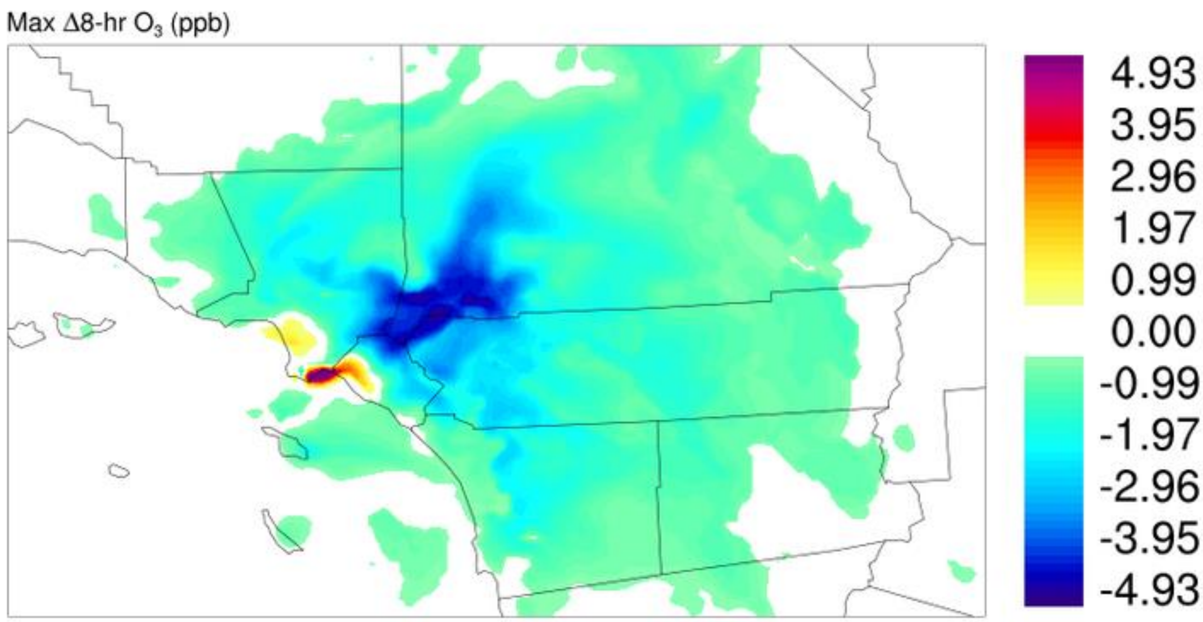

Figure 54. Difference between Maximum 8-hour Average Ozone Concentration of the ALLUP case relative to the BAU case for the summer episode

Peak 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 2.57 µg/m^3 at the SPBPC. This result is shown in Figure 55.

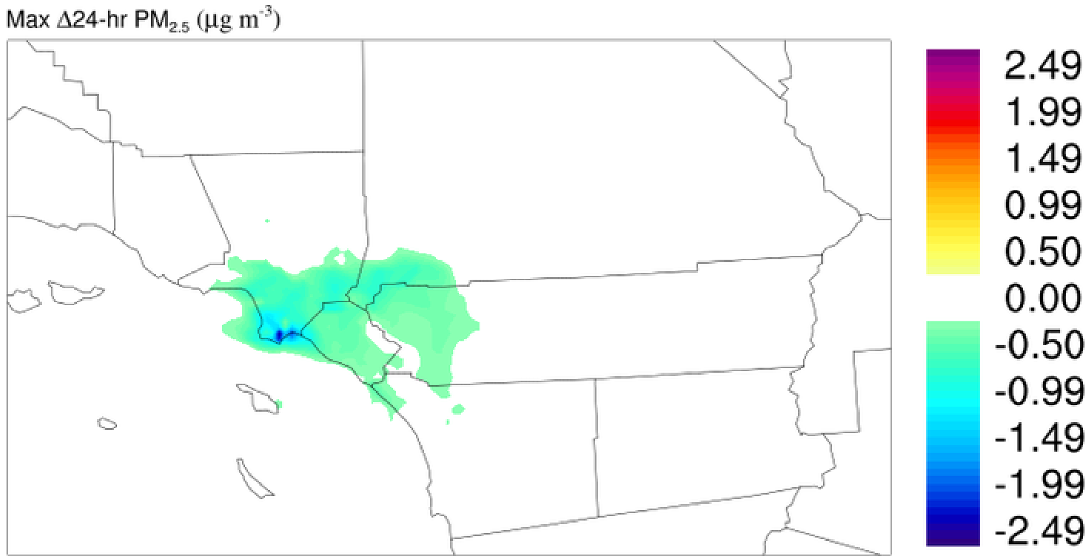

Figure 55. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the ALLUP case relative to the BAU case for the summer episode

Peak winter 24-hour average $PM_{2.5}$ concentration reductions reach a maximum of 2.64 μg/m^3 at the SPBPC. This result is shown in Figure 56. Over the ocean is predicted a 2.26 μg/m^3 increase in peak 24-hour average $PM_{2.5}$ concentration.

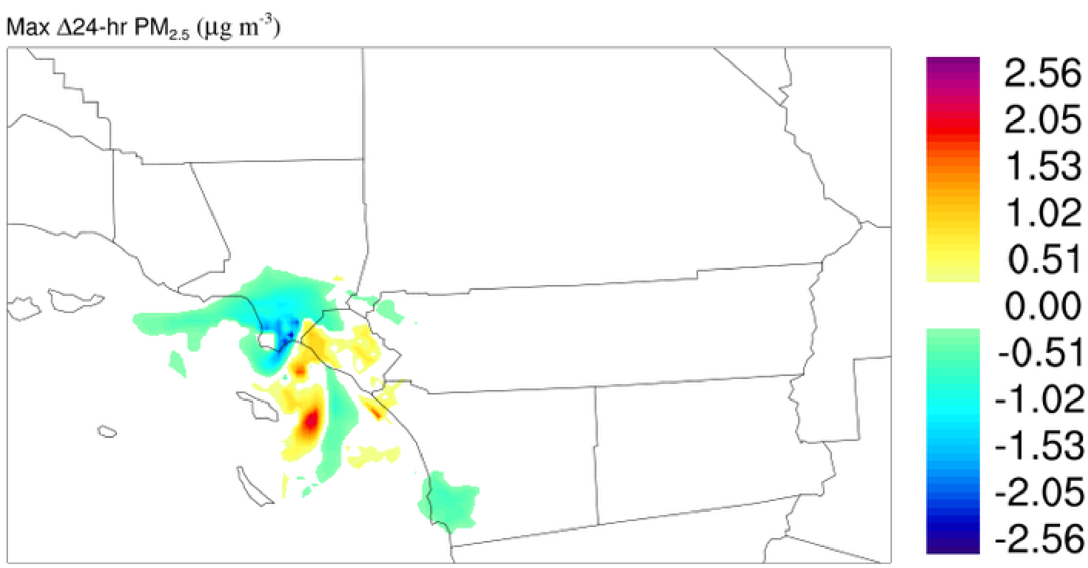

Figure 56. Difference between Maximum 24-hour Average $PM_{2.5}$ Concentration of the ALLUP case relative to the BAU case for the winter episode

5.1.7 Air Quality Results Summary

The peak impacts on ozone and $PM_{2.5}$ for all of the assessed cases are shown in

Table 5. As discussed earlier, ozone impacts are not reported for the winter period, primarily due to low baseline levels. Generally, summer ozone impacts are notable with reductions in the ALLUP Case exceeding 5 ppb, and the ALLDN Case nearly reaching 3 ppb. From a summer ozone perspective, the largest individual impact is predicted for the maritime cases, with the drayage truck scenario only marginally lower. This is notable given that drayage truck activity is only a small sub-set of on-road vehicle activity in the SoCAB, highlighting the disproportionate emissions associated with the baseline HDDT that HDFCT can replace. The locomotives case achieves a nearly 1 ppb reduction, which is reduced from ships and trucks but still notable. The Port Operations case has a comparably smaller impacts to other cases, reflecting the smaller amounts of pre-cursor emissions attributable to those sources. Furthermore, the peak improvements occur in areas that currently experience some of the poorest ozone air quality in the U.S., making the benefits from all sources particularly desirable.

Generally, impacts on $PM_{2.5}$ follow the same trends as ozone, with one major exception being a very large impacts from ships due to the use of heavy fuel oil. For example, while ships and drayage trucks have nearly comparable impacts on ozone, ships have a significantly higher impact on $PM_{2.5}$. This is due to two factors including (1) ship auxiliary engines and boilers consume heavy fuel oil which produces higher levels of PM than low sulfur diesel fuel used by trucks and (2) the drayage trucks comprising the baseline 2035 fleet are cleaner, newer HDDT vehicles with particulate filters and the replacement with HDFCT results in a moderate reduction in direct PM. The location of $PM_{2.5}$ benefits is again associated with communities that are heavily impacted by poor air quality surrounding the SPBPC. Therefore, the reductions in $PM_{2.5}$ estimated here still have an important impact on health which is demonstrated in the health impact assessment in the following section.

Table 5. Peak air quality impacts predicted for the high and low cases

	Summer		Winter
Case	Δ Ozone [ppb]	Δ $PM_{2.5}$ [μg/m³]	Δ $PM_{2.5}$ [μg/m³]
All High	-5.09	-2.56	-2.26
All Low	-2.69	-0.59	-0.99
Dray High	-2.81	-0.29	-0.44
Dray Low	-1.98	-0.21	-0.31
Ships High	-2.95	-2.44	-2.34
Ships Low	-0.90	-0.56	-0.90
Rail High	-0.84	-0.20	-0.17
Rail Low	-0.29	-0.06	-0.05
CHE High	-0.28	-0.07	-0.14
CHE Low	-0.11	-0.05	-0.04

5.2 Impacts on GHG Emissions

There are 15 FCET deployment scenarios and 8 hydrogen production pathways resulting in 120 different GHG impact results. The best case, with 79% deployment of HDFCT and 75% deployment of FCET in the other sectors and all hydrogen produced by electrolysis using renewable electricity, reduces GHG emissions by 9.44 million tonnes. The worst case, with the same technology deployment but with hydrogen derived half from NG SMR and half from electrolysis of grid power with a conservative AEC, increases GHG emissions by 636.9 thousand tonnes.

The results in the following sections use abbreviated names for the pathways. The descriptions for each scenario name are found in Table 6.

Table 6. Description of hydrogen supply pathway scenarios assumed for the GHG calculations

Scenario Name	Scenario Description
RE100	100% Renewable Electrolysis
RR100	100% Renewable Reformation
RG100	100% Renewable Gasification
NGE50/50	50/50 NG SMR Renewable Electrolysis
NGR50/50	50/50 NG SMR/Renewable Reformation
NGG50/50	50/50 NG SMR/Renewable Gasification
NGC50/50	50/50 NG SMR/Grid Electrolysis (Conservative)
NGO50/50	50/50 NG SMR/Grid Electrolysis (Optimistic)

5.2.1 HDFCT Cases

Of the 24 GHG impact estimates associated with the drayage only deployment scenarios the best reduces GHG emissions by 1.51 million tonnes CO_2e while the worst reduces emissions by 0.28 million tonnes CO_2e. The best case was upside deployment with hydrogen produced by electrolysis of 100% renewables and the worst case was downside deployment with hydrogen production split between NG SMR and conservative AEC electrolysis of grid electricity. The complete results are summarized in Table 7.

Table 7. Summary of the estimated GHG emission reductions for drayage cases

GHG Emission Change (thousand tonnes CO_2e)			
Pathway	**Down**	**Middle**	**Up**
RE100	-1071.24	-1186.01	-1511.21
RR100	-591.29	-654.64	-834.14
RG100	-802.89	-888.91	-1132.65
NGE50/50	-565.60	-626.20	-797.90
NGR50/50	-325.63	-360.52	-459.37
NGG50/50	-431.43	-477.65	-608.62
NGC50/50	-276.44	-306.06	-389.98
NGO50/50	-301.74	-334.07	-425.67

5.2.2 Port Operations Cases

As expected, the best case is associated with high deployment and renewable electrolysis for hydrogen production which reduces GHG emissions by 754.3 thousand tonnes CO_2e. Similarly the worst case is low deployment with NG SMR and conservative AEC electrolysis of grid electricity which reduces GHG emissions by 57.8 thousand tonnes CO_2e. The complete results for cargo and material handling equipment are summarized in Table 8.

Table 8. Summary of the estimated GHG emission reductions for CHE cases

GHG Emission Change (thousand tonnes CO_2e)

Pathway	Down	Middle	Up
RE100	-251.43	-502.86	-754.29
RR100	-134.49	-268.97	-403.46
RG100	-186.04	-372.09	-558.13
NGE50/50	-128.23	-256.45	-384.68
NGR50/50	-69.75	-139.51	-209.26
NGG50/50	-95.53	-191.07	-286.60
NGC50/50	-57.77	-115.54	-173.31
NGO50/50	-63.93	-127.87	-191.80

5.2.3 Locomotive Cases

The rail deployment scenarios have the min and max for the same pathways as the CHE scenarios. For rail the best case reduced GHG emissions by 2.60 million tonnes CO_2e and the worst case reduces GHG emissions by 199.2 thousand tonnes CO_2e. The complete results are summarized in

Table 9.

Table 9. Summary of the estimated GHG emission reductions for rail cases

GHG Emission Change (thousand tonnes CO_2e)			
Pathway	**Down**	**Middle**	**Up**
RE100	-865.98	-1731.97	-2597.95
RR100	-463.33	-926.66	-1389.99
RG100	-640.85	-1281.71	-1922.56
NGE50/50	-441.78	-883.56	-1325.35
NGR50/50	-240.46	-480.91	-721.37
NGG50/50	-329.22	-658.43	-987.65
NGC50/50	-199.19	-398.38	-597.57
NGO50/50	-220.42	-440.83	-661.25

5.2.4 Maritime Cases

Shown in Table 10, as is expected the highest reduction occurs for the upside deployment with renewable electrolysis at 7.81 million tonnes CO_2e reduced, however, the worst case is different for these scenarios. The worst case is upside deployment with NG SMR and conservative AEC electrolysis of grid electricity. This result draws attention to an interesting balance between efficiency and carbon intensity when comparing the NGC50/50 pathway with the NGO50/50 pathway which have similar carbon intensities, but one result is negative and one result is positive. This means that the effective carbon intensity on a unit work basis of the diesel auxiliary engine and HFO boiler combination is between the effective carbon intensities of the NGC50/50 and NGO50/50.

Table 10. Summary of the estimated GHG emission reductions for ship cases

GHG Emission Change (thousand tonnes CO_2e)			
Pathway	**Down**	**Middle**	**Up**
RE100	-982.70	-1,965.39	-2,948.09
RR100	-373.96	-747.93	-1,121.89
RG100	-642.34	-1,284.69	-1,927.03
NGE50/50	-341.39	-682.78	-1,024.16
NGR50/50	-37.02	-74.04	-111.06
NGG50/50	-171.21	-342.42	-513.64
NGC50/50	25.37	50.73	76.10
NGO50/50	-6.73	-13.45	-20.18

5.2.5 Combined Cases

Shown in

Table 11, the max and min scenarios are the same for the port-wide scenario as for the ship cases showing that the magnitude of the emissions from the ships boilers are considerable compared to the other sectors.

Table 11. Summary of the estimated GHG emission reductions for combined cases

GHG Emission Change (thousand tonnes CO2e)

Pathway	Down	Middle	Up
RE100	-3171.35	-5386.23	-7811.54
RR100	-1563.07	-2598.20	-3749.48
RG100	-2272.13	-3827.40	-5540.38
NGE50/50	-1477.00	-2449.00	-3532.10
NGR50/50	-672.86	-1054.98	-1501.06
NGG50/50	-1027.39	-1669.58	-2396.51
NGC50/50	-508.03	-769.24	-1084.76
NGO50/50	-592.82	-916.22	-1298.90

Table 12 displays a summary of the estimated GHG reductions for all of the technology scenarios considered.

Table 12. Summary of the estimated GHG emission reductions for all technology categories

Change in GHG Emissions (thousand tonnes CO2e)

	RE100	**RR100**	**RG100**	**NGE50/50**	**NGR50/50**	**NGG50/50**	**NGC50/50**	**NGO50/50**
ALLDN	-3171.35	-1563.07	-2272.13	-1477.00	-672.86	-1027.39	-508.03	-592.82
ALLMD	-5386.23	-2598.20	-3827.40	-2449.00	-1054.98	-1669.58	-769.24	-916.22
ALLUP	-7811.54	-3749.48	-5540.38	-3532.10	-1501.06	-2396.51	-1084.76	-1298.90
DRAYDN	-1071.24	-591.29	-802.89	-565.60	-325.63	-431.43	-276.44	-301.74
DRAYMD	-1186.01	-654.64	-888.91	-626.20	-360.52	-477.65	-306.06	-334.07
DRAYUP	-1511.21	-834.14	-1132.65	-797.90	-459.37	-608.62	-389.98	-425.67
OPSDN	-251.43	-134.49	-186.04	-128.23	-69.75	-95.53	-57.77	-63.93
OPSMD	-502.86	-268.97	-372.09	-256.45	-139.51	-191.07	-115.54	-127.87
OPSUP	-754.29	-403.46	-558.13	-384.68	-209.26	-286.60	-173.31	-191.80
RAILDN	-865.98	-463.33	-640.85	-441.78	-240.46	-329.22	-199.19	-220.42
RAILMD	-1731.97	-926.66	-1281.71	-883.56	-480.91	-658.43	-398.38	-440.83
RAILUP	-2597.95	-1389.99	-1922.56	-1325.35	-721.37	-987.65	-597.57	-661.25

SHIPDN	-982.70	-373.96	-642.34	-341.39	-37.02	-171.21	25.37	-6.73
SHIPMD	-1965.39	-747.93	-1284.69	-682.78	-74.04	-342.42	50.73	-13.45
SHIPUP	-2948.09	-1121.89	-1927.03	-1024.16	-111.06	-513.64	76.10	-20.18

Figure 57 shows the relative contribution of each sector to port-wide GHG emissions reductions for each hydrogen production pathways. In cases with increases in emissions, the net impact is the difference between increases and decreases. The handling of theses impacts was linear within a given case between the different levels. Therefore, their plots would be the same as these but with the scale reduced.

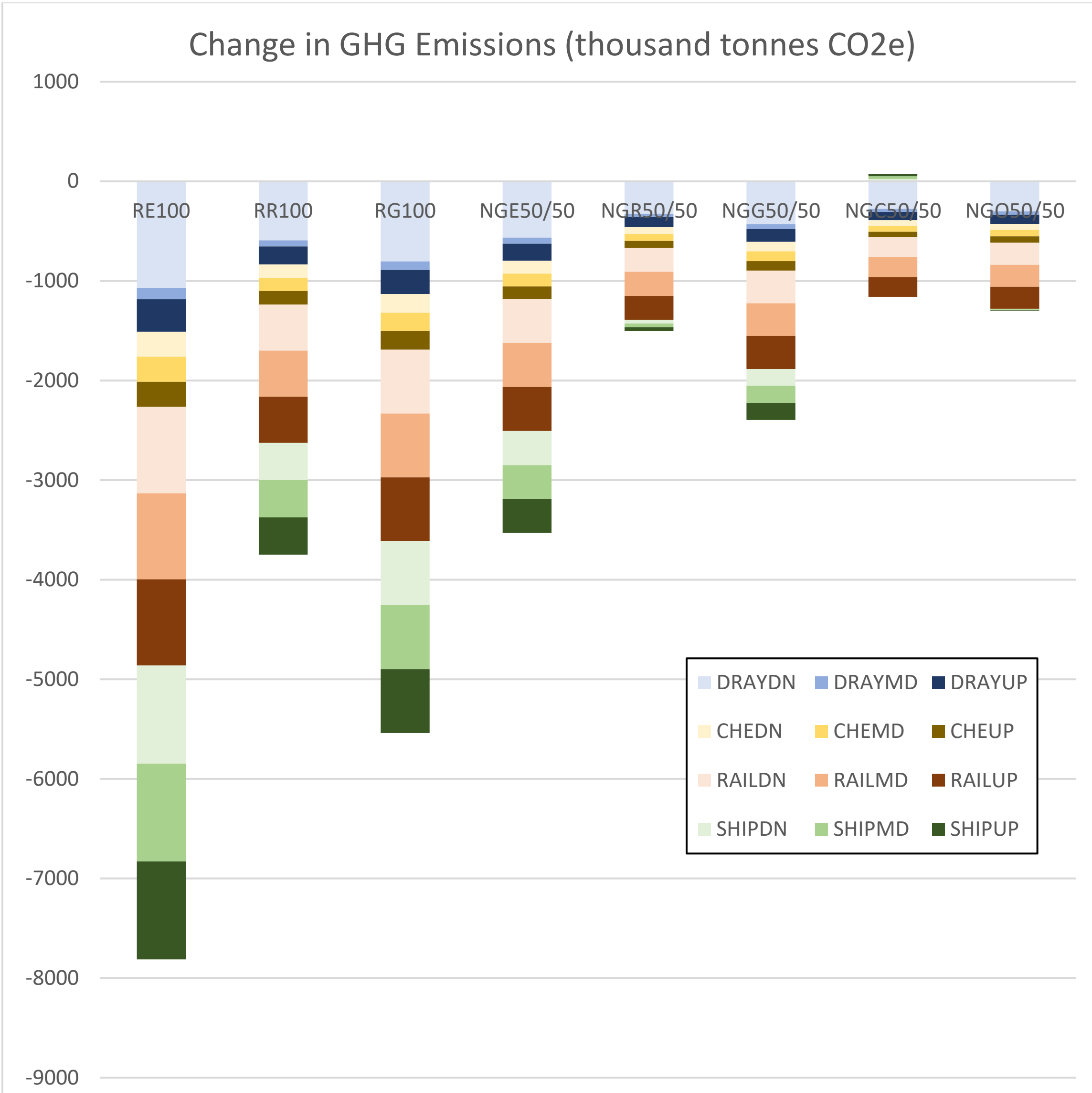

Figure 57: Bar Chart Showing Contribution of Each Sector to Total GHG Emission Reduction in Each Pathway for Upside Cases

5.3 Health Impact Assessment Results

The reductions in ground-level concentrations of ozone and $PM_{2.5}$ estimated in Section 5.1 have beneficial impacts on the health of people living in the areas around the ports. These benefits manifest, for example, by reducing occurrences of morbidity and disease caused by exposure to unhealthy air. Health benefits have economic impacts including benefits in the form of reductions in lost work days, hospital admissions, etc. For this work BenMAP was utilized to quantify the short-term health and monetary benefits occurring as a result of the pollutant concentration changes driven by port activity emission reductions. BenMAP results include an estimation of 1) avoided and induced health risks from air quality changes and 2) an economic assessment of these health effects.

The following section presents the BenMAP results for the ALLUP and ALLDN Cases for both the summer episode as this provides an upper and lower bound for the comprehensive benefits estimated within scenarios considered for this research. The winter episode is not considered here due to the inverse correlation with NO_x emissions and ozone concentrations and the low baseline concentrations.

5.3.1 Combined Health Impacts Valuation – Upper Estimate

Table 13 presents the estimated health impacts for the ALLUP case in the summer episode. Improvements in summer ozone and $PM_{2.5}$ concentrations result in estimated health benefits through reduced exposure including avoided incidence of premature deaths and reduced morbidity. The mean avoided incidence of premature mortality are estimated at nearly 0.2 incidence per day for short-term ozone, and 0.3 incidence per day for short-term $PM_{2.5}$ exposure per person per day. Additionally, a range of important impacts on morbidity incidences are reported for both ozone and $PM_{2.5}$ including reduced work loss, emergency room and hospital admissions, school and work loss days, and incidence of asthma, myocardial infarction (non-fatal), and other respiratory disease.

Table 13. Estimated avoided health impacts from air quality improvements in the summer episode for the ALLUP Case

Endpoint	**Health Effect Estimates (# incidences/people/day)**		
	Mean	**2.5 CI***	**97.5 CI***
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	0.2	0.02	0.4
Short-Term PM25 Exposure	0.3	0.3	0.4
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA Asthma	0.1	0.03	0.1
HA All Respiratory	0.2	-0.1	0.5

School Loss Days All Cause	213.9	-25.3	447.3
Emergency Room Visits Asthma	3.5	0.6	6.2
Minor Restricted Activity Days	726.2	300.7	1149.4
Short-Term PM_2.5 Exposure			
Lower Respiratory Symptoms	18.1	6.9	29.3
Upper Respiratory Symptoms	35.6	6.5	64.6
Asthma Exacerbation Wheeze Asthma Exacerbation Cough Asthma Exacerbation Shortness of Breath	32.7	-2.1	75.0
HA and ED Visits Asthma	0.2	-0.04	0.6
HA All Cardiovascular (less Myocardial Infarctions)	0.4	0.3	0.5
HA Ischemic Stroke	0.2	0.1	0.4
HA All Respiratory HA Chronic Lung Disease (less Asthma)	0.4	0.2	0.5
Minor Restricted Activity Days	858.2	699.4	1016.6
Work Loss Days	148.5	125.7	171.2
Asthma New Onset Wheeze	5.9	-2.7	14.3
Acute Myocardial Infarction Nonfatal	0.1	0.04	0.3

***These values represent a 95% confidence interval for the mean**

Table 14 summarizes the estimated monetary valuation of the avoided health impacts for the ALLUP case in the summer episode. The total mean is $7,108,100 for both avoided premature mortality and reduced morbidity incidence with a 95% CI of $2,239,600 to $12,844,800. Avoided premature death is the largest impact with a mean of $6,851,400 per day. Of that total, reduction in short-term $PM_{2.5}$ exposure is more beneficial than ozone. This is calculated based on the statistical cost of life, i.e., the monetary value that a group of people are willing to pay to slightly reduce the risk of premature death in the population. This work uses an initial value of $9 million which is projected to increase in 2035 as a function of per-capita income growth [61].

The estimated total valuation for reduced morbidity incidences is $256,700 per day with a 95% CI of $122,000 to $406,600 per day. For the 2.5% CI, it is estimated that ozone has a negative impact on morbidity, i.e. there are more incidences. However, the overall impacts are beneficial when summed with $PM_{2.5}$ even for the 2.5% CI as the higher $PM_{2.5}$ benefits offset the ozone negative valuation.

The monetary values reported here are for a single day of exposure, i.e., the air quality improvements from reducing emissions from port sources is estimated to provide a total value of $6.8 million from avoided mortality and $256,700 from avoided morbidity per day. Therefore, it should be noted that these benefits would accrue daily depending on season and would in actuality be higher in total from an annual perspective. These values demonstrate the important economic value to California that improvements in air quality attain in summer through FCET deployment at the SPBPC.

Table 14. Estimated valuation of avoided health impacts from air quality improvements in the summer episode for ALLUP Case

Endpoint	Valuation Estimates (thousands $/day)		
	Mean	**2.5 CI***	**97.5 CI***
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	2480.0	180.2	5516.7
Short-Term PM25 Exposure	4371.3	1937.5	6921.6
Total Premature Deaths	6851.4	2117.6	12438.3
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA, Asthma	0.6	0.3	0.8
HA, All Respiratory	5.2	-1.6	11.9
School Loss Days	46.9	-5.6	98.1
Emergency Room Visits, Asthma	1.8	0.3	3.6
Minor Restricted Activity Days	15.4	6.4	24.3
Total Short-Term Ozone	69.9	-0.2	138.8
Short-Term PM_2.5 Exposure			
Lower Respiratory Symptoms	0.4	0.1	0.6
Upper Respiratory Symptoms	0.8	0.1	1.4
Asthma Exacerbation, Wheeze Asthma Exacerbation, Cough Asthma Exacerbation, Shortness of Breath	0.7	-0.04	1.6
HA and ED Visits, Asthma	0.4	-0.1	1.0
HA, All Cardiovascular (less Myocardial Infarctions)	9.6	6.5	12.3
HA, Ischemic Stroke	13.1	4.4	26.4
HA, All Respiratory	8.1	5.0	10.7
Minor Restricted Activity Days	18.2	14.8	21.5
Work Loss Days	32.6	27.6	37.6
Acute Myocardial Infarction, Nonfatal	103.1	63.7	154.7
Total Short-Term PM2.5	186.8	122.2	267.8
Total Morbidity (PM2.5+Ozone)	256.7	122.0	406.6
Total Valuation (Mortality + Morbidity)	7108.1	2239.6	12844.8

***These values represent a 95% confidence interval for the mean**

5.3.2 Combined Health Impacts Valuation – Lower Estimate

Table 15 displays the estimated health impacts for the ALLDN Case in the summer episode. The mean avoided incidences of premature mortality are estimated at nearly 0.1 incidence per day for short-term ozone, and 0.1 incidence per day for short-term $PM_{2.5}$ exposure per person per day. Similar to the ALLUP case, a range of important impacts on morbidity incidences are reported for both ozone and $PM_{2.5}$.

Table 15. Estimated avoided health impacts from air quality improvements in the summer episode for the ALLDN Case

Endpoint	Health Effect Estimates (# incidences/people/day)		
	Mean	2.5 CI*	97.5 CI*
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	0.1	0.01	0.2
Short-Term PM25 Exposure	0.1	0.1	0.2
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA Asthma	0.03	0.02	0.04
HA All Respiratory	0.1	-0.04	0.3
School Loss Days All Cause	114.1	-13.4	240.1
Emergency Room Visits Asthma	1.9	0.3	3.4
Minor Restricted Activity Days	387.5	160.2	614.1
Short-Term PM_2.5 Exposure			
Lower Respiratory Symptoms	7.6	2.9	12.2
Upper Respiratory Symptoms	14.8	2.7	26.9
Asthma Exacerbation Wheeze Asthma Exacerbation Cough Asthma Exacerbation Shortness of Breath	13.6	-0.9	31.2
HA and ED Visits Asthma	0.1	-0.01	0.2
HA All Respiratory HA Chronic Lung Disease (less Asthma)	0.1	0.1	0.2
HA All Cardiovascular (less Myocardial Infarctions)	0.2	0.1	0.2
HA Ischemic Stroke	0.1	0.03	0.2
Minor Restricted Activity Days	355.6	289.7	421.4
Work Loss Days	61.5	52.1	70.9
Asthma New Onset Wheeze	2.5	-1.1	6.0
Acute Myocardial Infarction Nonfatal	0.04	0.02	0.1

***These values represent a 95% confidence interval for the mean**

Table 16 presents the estimated valuation of the avoided health impacts for the ALLDN Case in the summer episode. The total monetary value is $3,209,700 for both avoided premature mortality and reduced morbidity incidence with a 95% CI of $949,800 and $5,916,800. The largest impact is associated with avoided premature deaths with a mean of $3,124,500 per day. The total valuation for reduced morbidity incidences is estimated at $85,200 per day with a 95% confidence interval of $53,400 to $124,100 per day.

The estimated value of health impacts from air quality improvements is lesser for ALLDN than for ALLUP which follows the trends for emissions. However, the benefits are still notable and demonstrate that any increase in FCET deployment will secure important value to society in the form of environmental quality benefits.

Table 16. Estimated valuation of avoided health impacts from air quality improvements in the summer episode for ALLDN Case

Endpoint	Valuation Estimates (thousands $/day)		
	Mean	**2.5 CI***	**97.5 CI***
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	1318.1	95.7	2932.4
Short-Term PM25 Exposure	1806.4	800.6	2860.3
Total Premature Deaths	3124.5	896.3	5792.7
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA, Asthma	0.3	0.2	0.4
HA, All Respiratory	2.8	-0.8	6.4
School Loss Days	25.0	-2.9	52.7
Emergency Room Visits, Asthma	1.0	0.1	1.9
Minor Restricted Activity Days	8.2	3.4	13.0
Total Short-Term Ozone	37.3	-0.1	74.4
Short-Term PM_2.5 Exposure			
Lower Respiratory Symptoms	0.2	0.1	0.3
Upper Respiratory Symptoms	0.3	0.1	0.6
Asthma Exacerbation, Wheeze Asthma Exacerbation, Cough Asthma Exacerbation, Shortness of Breath	0.3	-0.02	0.7
HA and ED Visits, Asthma	0.2	-0.03	0.4
HA, All Respiratory	3.3	2.0	4.4
HA, All Cardiovascular (less Myocardial Infarctions)	4.0	2.6	5.1
HA, Ischemic Stroke	5.4	1.8	10.9
Minor Restricted Activity Days	7.5	6.1	8.9
Work Loss Days	13.5	11.4	15.6
Acute Myocardial Infarction, Nonfatal	42.4	25.9	64.3
Total Short-Term PM2.5	77.0	50.1	111.1
Total Morbidity (PM2.5+Ozone)	85.2	53.4	124.1
Total Valuation (Mortality + Morbidity)	3209.7	949.8	5916.8

***These values represent a 95% confidence interval for the mean**

5.3.3 Maritime Case Health Impacts Valuation

Table 17 presents the estimated health impacts for the replacement of ship auxiliary engines and boilers in the summer episode with optimistic deployment (SHIPUP). The mean avoided incidence of premature mortality are estimated at nearly 0.1 incidence per day for short-term ozone, and 0.2 incidence per day for short-term $PM_{2.5}$ exposure per person per day. These impacts are slightly higher than the ALLDN case, indicating the importance of air quality benefits achieved from the avoidance of auxiliary ship engine and boiler emissions.

Table 17. Estimated avoided health impacts from air quality improvements in the summer episode for the most optimistic ships case (SHIPUP)

Endpoint	**Health Effect Estimates (# incidences/people/day)**		
	Mean	2.5 CI*	**97.5 CI***
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	0.1	0.01	0.2
Short-Term PM25 Exposure	0.2	0.2	0.2
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA Asthma	0.02	0.01	0.04
HA All Respiratory	0.1	-0.02	0.3
School Loss Days All Cause	69.2	-8.2	240.1
Emergency Room Visits Asthma	1.1	0.2	3.4
Minor Restricted Activity Days	222.5	92.1	614.1
Short-Term PM_2.5 Exposure			
Lower Respiratory Symptoms	11.3	4.3	12.2
Upper Respiratory Symptoms	22.2	4.0	26.9
Asthma Exacerbation Wheeze Asthma Exacerbation Cough Asthma Exacerbation Shortness of Breath	20.4	-1.3	31.2
HA and ED Visits Asthma	0.1	0.0	0.2
HA All Cardiovascular (less Myocardial Infarctions)	0.2	0.2	0.2
HA Ischemic Stroke	0.1	0.0	0.2
HA All Respiratory HA Chronic Lung Disease (less Asthma)	0.2	0.1	0.2
Minor Restricted Activity Days	539.3	439.5	421.4
Work Loss Days	93.3	79.0	70.9
Asthma New Onset Wheeze	3.7	-1.7	6.0
Acute Myocardial Infarction Nonfatal	0.1	0.02	0.1

***These values represent a 95% confidence interval for the mean**

Table 18 displays the estimated valuation of the avoided health impacts for the SHIPUP Case in the summer episode. The total monetary value is $3,650,600 for both avoided premature mortality and reduced morbidity incidence with a 95% CI of $1,351,800 to $6,259,200.

Table 18. Estimated valuation of avoided health impacts from air quality improvements in the summer episode for the most optimistic ships case (SHIPUP)

Endpoint	Valuation Estimates (thousands $/day)		
	Mean	2.5 CI*	97.5% CI*
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	758.2	55.1	1686.7
Short-Term PM25 Exposure	2752.6	1220.0	4358.6
Total Premature Deaths	3510.9	1275.1	6045.3
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA, Asthma	0.2	0.1	0.3
HA, All Respiratory	1.6	-0.5	3.6
School Loss Days	15.2	-1.8	31.8
Emergency Room Visits, Asthma	0.6	0.1	1.2
Minor Restricted Activity Days	4.7	1.9	7.5
Total Short-Term Ozone	22.2	-0.1	44.3
Short-Term PM_2.5 Exposure			
Lower Respiratory Symptoms	0.2	0.1	0.4
Upper Respiratory Symptoms	0.5	0.1	0.9
Asthma Exacerbation, Wheeze Asthma Exacerbation, Cough Asthma Exacerbation, Shortness of Breath	0.4	-0.03	1.0
HA and ED Visits, Asthma	0.2	-0.04	0.6
HA, All Cardiovascular (less Myocardial Infarctions)	6.1	4.1	7.8
HA, Ischemic Stroke	8.3	2.8	16.7
HA, All Respiratory	5.1	3.1	6.8
Minor Restricted Activity Days	11.4	9.3	13.5
Work Loss Days	20.5	17.3	23.6
Acute Myocardial Infarction, Nonfatal	64.8	40.1	98.4
Total Short-Term PM2.5	117.5	76.8	169.6
Total Morbidity (PM2.5+Ozone)	139.7	76.7	213.9
Total Valuation (Mortality + Morbidity)	3650.6	1351.8	6259.2

***These values represent a 95% confidence interval for the mean**

5.3.4 Drayage Health Impacts Valuation

Drayage trucks represent a significant portion of air quality impacts with summer ozone changes nearly as large as the maritime case. Furthermore, on-road measurement studies have reported a disproportionate contribution of emissions occurring from a small fraction of trucks, i.e., a smaller amount of older, higher emitting trucks are responsible for a majority of the emissions [45], [46]. Indeed, the data used from EMFAC2017 show that in 2035 the drayage truck fleet in SoCAB will be responsible for less than 1% of total VMT from on-road vehicles but will be responsible for emissions of over 17% of NO_x [21]. This is a result of the significant time and emissions that occur during idling at the ports and includes regulations on idling emission mitigation technologies [47].

Table 19 summarizes the estimated health impacts for the DRAYUP Case (the most optimistic case for replacement of HDDT with HDFCT) in the summer episode. The mean avoided incidence of premature mortality are estimated at 0.11 incidence per day for short-term ozone, and 0.08 incidence per day for short-term $PM_{2.5}$ exposure per person per day in California. The impact estimated here are slightly lower than the SHIPUP Case, but higher than the other individual cases, indicating the importance of the air quality benefits achieved from the avoidance of HDDT in the drayage fleet.

Table 19. Estimated avoided health impacts from air quality improvements in the summer episode for the most optimistic drayage truck case (DRAYUP)

Endpoint	Health Effect Estimates (# incidences/people/day)		
	Mean	2.5 CI*	97.5% CI*
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	0.11	0.01	0.20
Short-Term PM25 Exposure	0.08	0.07	0.10
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA Asthma	0.03	0.02	0.05
HA All Respiratory	0.13	-0.04	0.29
School Loss Days All Cause	116.61	-13.65	245.59
Emergency Room Visits Asthma	1.90	0.34	3.45
Minor Restricted Activity Days	402.52	166.33	638.02
Short-Term PM_2.5 Exposure			
Lower Respiratory Symptoms	4.56	1.73	7.37
Upper Respiratory Symptoms	8.90	1.62	16.17
Asthma Exacerbation Wheeze Asthma Exacerbation Cough Asthma Exacerbation Shortness of Breath	8.17	-0.53	18.71
HA and ED Visits Asthma	0.05	-0.01	0.14
HA All Respiratory HA Chronic Lung Disease (less Asthma)	0.09	0.05	0.11
HA All Cardiovascular (less Myocardial Infarctions)	0.09	0.06	0.12
HA Ischemic Stroke	0.05	0.02	0.10
Minor Restricted Activity Days	212.11	172.81	251.35
Work Loss Days	36.67	31.04	42.30
Asthma New Onset Wheeze	1.47	-0.65	3.58
Acute Myocardial Infarction Nonfatal	0.02	0.01	0.06

***These values represent a 95% confidence interval for the mean**

Table 20 presents the estimated valuation of the avoided health impacts for the DRAYUP Case in the summer episode. The total monetary value is $2,525,700 for both avoided premature mortality and reduced morbidity incidence with a 95% CI of $604,200 to $4,886,800.

Table 20. Estimated valuation of avoided health impacts from air quality improvements in the summer episode for the most optimistic drayage truck case (DRAYUP)

Endpoint	Valuation Estimates (thousands $/day)		
	Mean	2.5 CI*	97.5% CI*
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	1369.4	99.4	3046.5
Short-Term PM25 Exposure	1072.3	475.3	1698.0
Total Premature Deaths	2441.7	574.7	4744.5
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA, Asthma	0.3	0.2	0.5
HA, All Respiratory	2.9	-0.9	6.6
School Loss Days	25.6	-3.0	53.9
Emergency Room Visits, Asthma	1.0	0.2	2.0
Minor Restricted Activity Days	8.5	3.5	13.5
Total Short-Term Ozone	38.3	0.0	76.4
Short-Term $PM_{2.5}$ Exposure			
Lower Respiratory Symptoms	0.1	0.04	0.2
Upper Respiratory Symptoms	0.2	0.03	0.3
Asthma Exacerbation, Wheeze Asthma Exacerbation, Cough Asthma Exacerbation, Shortness of Breath	0.2	-0.01	0.4
HA and ED Visits, Asthma	0.1	-0.02	0.2
HA, All Respiratory	2.0	1.2	2.6
HA, All Cardiovascular (less Myocardial Infarctions)	2.3	1.6	3.0
HA, Ischemic Stroke	3.2	1.1	6.4
Minor Restricted Activity Days	4.5	3.7	5.3
Work Loss Days	8.0	6.8	9.3
Acute Myocardial Infarction, Nonfatal	25.2	15.1	38.1
Total Short-Term PM2.5	45.7	29.5	65.9
Total Morbidity (PM2.5+Ozone)	84.0	29.5	142.3
Total Valuation (Mortality + Morbidity)	2525.7	604.2	4886.8

***These values represent a 95% confidence interval for the mean**

5.3.5 Locomotive Case Health Impacts Valuation

Table 21 displays the estimated health impacts for the RAILUP Case in the summer episode. The mean avoided incidence of premature mortality are estimated at 0.02 incidence per day for short-term ozone, and 0.03 incidence per day for short-term $PM_{2.5}$ exposure per person per day. The impact estimated here are significantly lower than both the ships and drayage truck cases, indicating the more moderate air quality benefits achieved from the avoidance of diesel locomotives in SoCAB.

Table 21. Estimated avoided health impacts from air quality improvements in the summer episode for the most optimistic locomotives case (RAILUP)

Endpoint	Health Effect Estimates (# incidences/people/day)		
	Mean	2.5 CI*	97.5% CI*
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	0.02	0.00	0.03
Short-Term PM25 Exposure	0.03	0.02	0.04
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA Asthma	0.005	0.002	0.01
HA All Respiratory	0.02	-0.01	0.04
School Loss Days All Cause	17.5	-2.0	36.9
Emergency Room Visits Asthma	0.3	0.1	0.5
Minor Restricted Activity Days	59.2	24.4	93.8
Short-Term $PM_{2.5}$ Exposure			
Lower Respiratory Symptoms	1.6	0.6	2.6
Upper Respiratory Symptoms	3.1	0.6	5.7
Asthma Exacerbation Wheeze Asthma Exacerbation Cough Asthma Exacerbation Shortness of Breath	2.9	-0.2	6.6
HA and ED Visits Asthma	0.02	0.00	0.1
HA All Respiratory HA Chronic Lung Disease (less Asthma)	0.03	0.02	0.04
HA All Cardiovascular (less Myocardial Infarctions)	0.03	0.02	0.04
HA Ischemic Stroke	0.02	0.01	0.04
Work Loss Days	13.3	11.2	15.3
Minor Restricted Activity Days	76.8	62.6	91.0
Asthma New Onset Wheeze	0.5	-0.2	1.3
Acute Myocardial Infarction Nonfatal	0.01	0.00	0.02

***These values represent a 95% confidence interval for the mean**

Table 22 summarizes the estimated valuation of the avoided health impacts for the RAILUP Case in the summer episode. The total monetary value is $602,900 for both avoided premature mortality and reduced morbidity incidence with a 95% CI of $192,400 to $1,085,200.

Table 22. Estimated valuation of avoided health impacts from air quality improvements in the summer episode for the most optimistic locomotive case (RAILUP)

Endpoint	Valuation Estimates (thousands $/day)		
	Mean	2.5 CI*	97.5% CI*
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	199.6	14.5	444.2
Short-Term PM25 Exposure	388.3	172.1	614.8
Total Premature Deaths	587.9	186.6	1058.9
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA, Asthma	0.05	0.02	0.1
HA, All Respiratory	0.4	-0.1	1.0
School Loss Days	3.8	-0.4	8.1
Emergency Room Visits, Asthma	0.1	0.02	0.3
Minor Restricted Activity Days	1.3	0.5	2.0
Total Short-Term Ozone	5.69	-0.01	11.40
Short-Term $PM_{2.5}$ Exposure			
Lower Respiratory Symptoms	0.03	0.01	0.1
Upper Respiratory Symptoms	0.1	0.01	0.1
Asthma Exacerbation, Wheeze Asthma Exacerbation, Cough Asthma Exacerbation, Shortness of Breath	0.1	0.00	0.1
HA and ED Visits, Asthma	0.0	-0.01	0.1
HA, All Respiratory	0.7	0.4	1.0
HA, All Cardiovascular (less Myocardial Infarctions)	0.9	0.6	1.1
HA, Ischemic Stroke	1.2	0.4	2.4
Work Loss Days	2.9	2.5	3.4
Minor Restricted Activity Days	1.6	1.3	1.9
Acute Myocardial Infarction, Nonfatal	1.8	0.6	4.7
Total Short-Term PM2.5	9.30	5.82	14.81
Total Morbidity (PM2.5+Ozone)	15.00	5.81	26.21
Total Valuation (Mortality + Morbidity)	602.9	192.4	1085.2

***These values represent a 95% confidence interval for the mean**

5.3.6 Port Operations Health Impacts Valuation

Table 23 displays the estimated health impacts for the OPSUP Case (the most optimistic case for replacement of diesel CHE with hydrogen fuel cell powered CHE) in the summer episode. The mean avoided incidence of premature mortality are estimated at 0.01 incidence per day for short-term ozone, and 0.01 incidence per day for short-term $PM_{2.5}$ exposure per person per day in California. The impact estimated here are significantly lower than both the ships and drayage truck cases, indicating the more moderate air quality benefits achieved from the avoidance of diesel CHE in SoCAB.

Table 23. Estimated avoided health impacts from air quality improvements in the summer episode for the most optimistic CHE case (OPSUP)

Endpoint	**Health Effect Estimates (# incidences/people/day)**		
	Mean	2.5 CI*	97.5% CI*
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	0.01	0.001	0.01
Short-Term PM25 Exposure	0.01	0.01	0.01
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA Asthma	0.002	0.001	0.003
HA All Respiratory	0.01	-0.002	0.02
School Loss Days All Cause	8.0	-0.9	16.9
Emergency Room Visits Asthma	0.1	0.0	0.2
Minor Restricted Activity Days	26.5	10.9	42.0
Short-Term $PM_{2.5}$ Exposure			
Lower Respiratory Symptoms	0.5	0.2	0.9
Upper Respiratory Symptoms	1.0	0.2	1.9
Asthma Exacerbation Wheeze Asthma Exacerbation Cough Asthma Exacerbation Shortness of Breath	1.0	-0.1	2.2
HA and ED Visits Asthma	0.01	0.00	0.02
HA All Respiratory HA Chronic Lung Disease (less Asthma)	0.01	0.01	0.01
HA All Cardiovascular (less Myocardial Infarctions)	0.01	0.01	0.01
HA Ischemic Stroke	0.01	0.00	0.01
Minor Restricted Activity Days	24.9	20.3	29.6
Work Loss Days	4.3	3.7	5.0
Asthma New Onset Wheeze	0.2	-0.1	0.4
Acute Myocardial Infarction Nonfatal	0.003	0.001	0.01

***These values represent a 95% confidence interval for the mean**

Table 24 shows the estimated valuation of the health benefits for the OPSUP Case in the summer episode. The total monetary value is $225,100 for both avoided premature mortality and reduced morbidity incidence with a 95% CI of $66,000 to $415,100.

Table 24. Estimated valuation of avoided health impacts from air quality improvements in the summer episode for the most optimistic CHE case (OPSUP)

Endpoint	Valuation Estimates (thousands $/day)		
	Mean	2.5 CI*	97.5% CI*
Premature Deaths Avoided, All Cause			
Short-Term Ozone Exposure	90.9	6.6	202.2
Short-Term PM25 Exposure	126.3	56.0	199.9
Total Premature Deaths	217.2	62.6	402.2
Reduced Morbidity Incidence			
Short-Term Ozone Exposure			
HA, Asthma	0.02	0.01	0.03
HA, All Respiratory	0.2	-0.1	0.4
School Loss Days	1.7	-0.2	3.7
Emergency Room Visits, Asthma	0.1	0.01	0.1
Minor Restricted Activity Days	0.6	0.2	0.9
Total Short-Term Ozone	2.59	-0.01	5.19
Short-Term $PM_{2.5}$ Exposure			
Lower Respiratory Symptoms	0.01	0.004	0.02
Upper Respiratory Symptoms	0.02	0.004	0.04
Asthma Exacerbation, Wheeze Asthma Exacerbation, Cough Asthma Exacerbation, Shortness of Breath	0.02	-0.001	0.05
HA and ED Visits, Asthma	0.01	-0.002	0.03
HA, All Respiratory	0.2	0.1	0.3
HA, All Cardiovascular (less Myocardial Infarctions)	0.3	0.2	0.4
HA, Ischemic Stroke	0.4	0.1	0.8
Minor Restricted Activity Days	0.5	0.4	0.6
Work Loss Days	0.9	0.8	1.1
Acute Myocardial Infarction, Nonfatal	3.0	1.8	4.5
Total Short-Term PM2.5	5.39	3.46	7.79
Total Morbidity (PM2.5+Ozone)	7.98	3.45	12.98
Total Valuation (Mortality + Morbidity)	225.1	66.0	415.1

***These values represent a 95% confidence interval for the mean**

6 Summary and Conclusions

The following section presents key conclusions from this work. Moving forward the use of advanced technologies, including FCET, that reduce emissions from current goods movement technologies can improve air quality and human health in California. This work demonstrates the benefits specifically from using fuel cells in replacement of marine auxiliary engines and boilers, even in a future where shore power is the dominant source of electricity for ships at dock. Additionally, FCET for drayage services within the goods movement industry is a key target as this vocation is highly suitable for the deployment of alternative vehicle technologies and achieves important benefits to air quality and human health.

6.1 Summary

The use of FCET in place of diesel vehicles and equipment provides reductions in criteria pollutant emissions that reduce ground-level concentrations of air pollutants in the atmosphere. The corresponding peak reductions for ozone and $PM_{2.5}$, which are the criteria air pollutants of greatest concern in California, are shown in Table 25. At the SPBPC the use of FCET provide reductions in precursor emissions that reduce ground-level concentrations of ozone in summer ranging from -2.69 ppb to -5.09 ppb maximum 8-hour average relative to a future where goods movement technology does not significantly advance (the Base Case). Similarly, reductions in summer $PM_{2.5}$ are predicted between -0.29 μg/m^3 to -0.59 μg/m^3 24-hour average and impacts on $PM_{2.5}$ in winter are predicted to range from -2.26 μg/m^3 to -0.99 μg/m^3. The largest single impact on air quality comes from the replacement of ship auxiliary engines and boilers, including the largest reductions in peak ozone and $PM_{2.5}$. Drayage trucks also have a significant impact on air quality with nearly identical impacts to ships on ozone. Therefore, the increasing the deployment of FCET above levels that are currently expected or targeted at the SPBPC can offer important air quality benefits by reducing atmospheric pollutant concentrations in currently affected areas of the State.

Table 25. Peak reduction in concentrations of ozone and Particulate Matter < 2.5 microns ($PM_{2.5}$) from the Base Case for the scenarios investigated.

	Summer		**Winter**
Case	**Δ Ozone [ppb]**	**Δ $PM_{2.5}$ [μg/m^3]**	**Δ $PM_{2.5}$ [μg/m^3]**
ALLUP	-5.09	-2.56	-2.26
ALLDN	-2.69	-0.59	-0.99
DRAYUP	-2.81	-0.29	-0.44
DRAYDN	-1.98	-0.21	-0.31
SHIPUP	-2.95	-2.44	-2.34
SHIPDN	-0.90	-0.56	-0.90
RAILUP	-0.84	-0.20	-0.17
RAILDN	-0.29	-0.06	-0.05
OPSUP	-0.28	-0.07	-0.14
OPSDN	-0.11	-0.05	-0.04

Improvements in summer ozone and $PM_{2.5}$ concentrations result in health benefits through reduced exposure including avoided incidence of premature deaths and reduced morbidity including work loss, emergency room and hospital admissions, school and work loss days, and incidence of asthma, myocardial infarction (non-fatal), and other respiratory disease. The health impacts have significant economic value to society. **Error! Reference source not found.** shows the estimated value of reductions in incidence of premature mortality and morbidity from air quality improvements in both the combined source cases assuming 75% and 25% FCET penetration (ALLUP and ALLDN) and the individual source cases (ships, drayage trucks, rail, and CHE). For the cases assuming FCET deployment in all sources, the mean value of air quality improvements range from $3,209,700 per day in the All Low Case to $7,108,100 per day in the All High Case. Individually, estimated improvements range from $225,100 per day in the CHE Case to $3,650,600 per day for the Ships Case. The impacts of emissions from auxiliary engines and boilers on ships (ocean going vessels, harbor craft) has the largest single impact, responsible for approximately 51% of the benefits predicted for the ALLUP Case. One key reason for this is the significant direct PM emissions from such sources, which are much higher than the other sources considered here. The magnitude of avoided costs also demonstrates the important benefits to California of attaining air quality improvements through HDFCT deployment in the drayage fleet, as approximately 35% of the monetary benefits associated with ALLUP Case. The attained monetary benefits also support the continued funding of zero-emission ship and drayage truck projects through incentives and other policy mechanisms at various government levels.

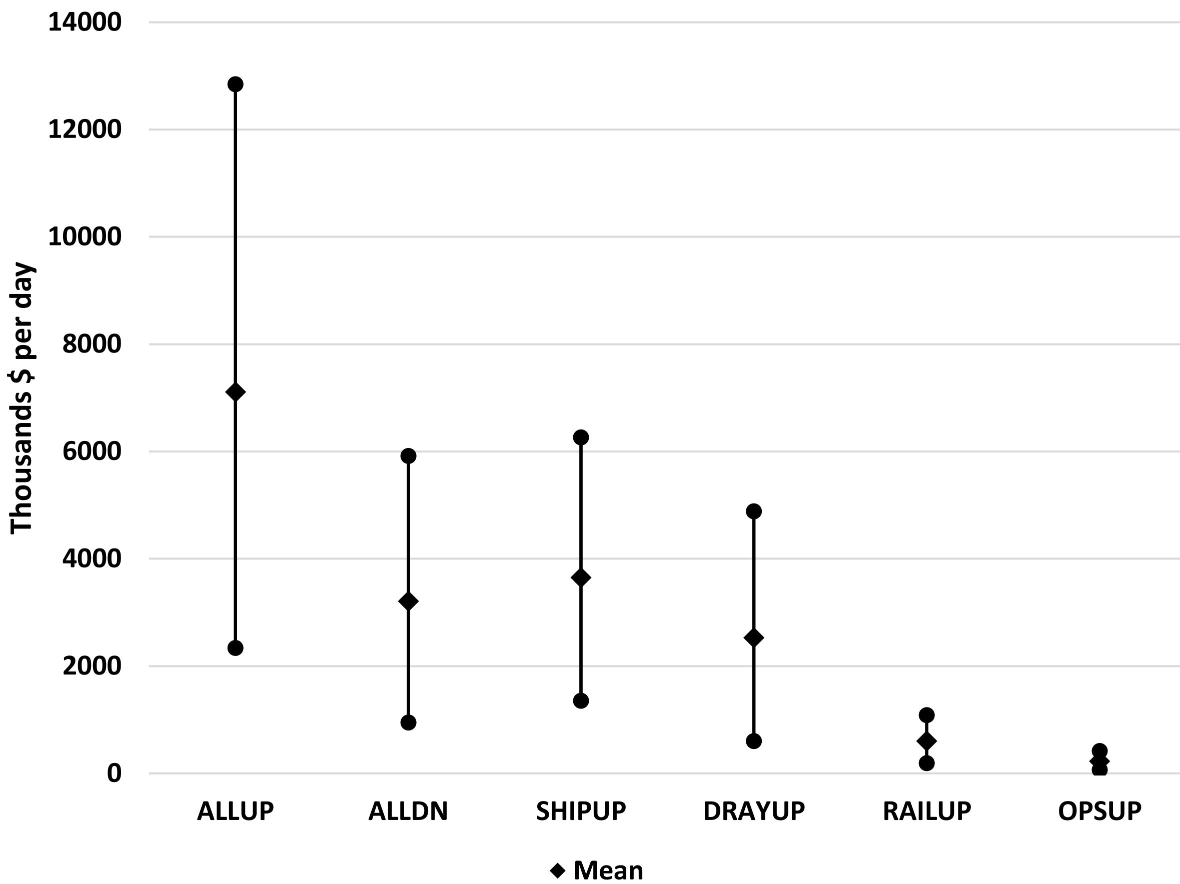

Figure 58. Estimated total value of air quality improvements modeled for the summer period in thousand $ per day for ocean going vessels and harbor craft (SHIP), locomotives (RAIL), cargo handling equipment (CHE), and Class 8 drayage trucks (DRAY). *Bars represent 95% confidence interval, mean shown as black diamond.

6.2 Conclusions

The following are key conclusions from this work:

- FCET deployment in Port Activities can bring the SoCAB significantly closer to achieving compliance with ozone related NAAQS

  The use of FCET can reduce ozone in summer from -2.69 ppb to -5.09 ppb peak 8-hour average with largest improvements occurring in SoCAB locations experiencing the highest baseline concentrations (the unhealthiest levels). These values are significant when it is considered that the margin for compliance with the 70 ppb standard is 12 ppb (the baseline level in that location is 82 ppb).

- FCET deployment in Port Activities can help the SoCAB get significantly closer to achieving compliance with $PM_{2.5}$ related NAAQS

  Reductions in summer $PM_{2.5}$ are predicted between -0.59 $\mu g/m^3$ to -02.57 $\mu g/m^3$ 24-hour average and impacts on $PM_{2.5}$ in winter are predicted to range from -0.99 $\mu g/m^3$ to -2.26 $\mu g/m^3$. The magnitude of these changes is significant given the baseline concentrations and the margin required for compliance.

- Utilizing hydrogen in place of conventional fuels achieves significant reductions in GHG emissions

  GHG emissions are reduced in every case and pathway with the sole exception of maritime scenarios with the most conservative hydrogen production pathway. When the hydrogen is generated from renewable sources the reductions are significant. In the best case, with 79% deployment of HDFCT and 75% deployment of FCET in the other sectors, reduction of GHG emissions by 7.81 to 1.08 million tonnes depending on whether the hydrogen pathway selected is renewable or a mix of renewable and non-renewable.

- The air quality improvements for the deployment of FCET have benefits to health including reductions in incidence of premature mortality and morbidity.

The valuation of health benefits is estimated to range \$3,209,700 to \$7,108,100 per day. These findings support the continued funding of zero-emission FCET projects through incentives and other policy mechanisms at various government levels.

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