OFFICE OF
BEN BARTLETT
CITY COUNCILMEMBER, DISTRICT 3

SUPPLEMENTAL AGENDA MATERIAL
BERKELEY CITY COUNCIL MEETING

For Supplemental Packet 3

Meeting Date: April 20, 2021

Item Number: 27

Item Description: Letter of Opposition to the Federal Aviation Administration's proposal to shift the WNDSR commercial airliner flight corridor directly over residential neighborhoods in Berkeley, Richmond, El Cerrito, and Albany

Submitted by: Councilmember Ben Bartlett

Amendment would make the following additions to the referral:

Attachments of

1. Fact Sheet: President Biden Takes Executive Actions... Biden-Harris Administration Commits on Climate Change – Creating Jobs, Building Infrastructure, and Delivering Environmental Justice
2. Overview of Office of Airports Engagement on Environmental Justice (EJ) Issues– Prepared for: FAA National Civil Rights Training Conference
3. Bay Area Air Quality Management District: Air Toxics Data Analysis and Regional Modeling in the SF Bay Area to Support AB617
4. Bendtsen, K.M., Bengtsen, E., Saber, A.T. *et al.* A review of health effects associated with exposure to jet engine emissions in and around airports. *Environ Health* **20,** 10 (2021). https://doi.org/10.1186/s12940-020-00690-y
5. Bay Area Air Quality Management - Sustainable Aviation Fuel: Greenhouse Gas Reductions from Bay Area Commercial Aircraft, Oct 2020

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BRIEFING ROOM

FACT SHEET: President Biden Takes Executive Actions to Tackle the Climate Crisis at Home and Abroad, Create Jobs, and Restore Scientific Integrity Across Federal Government

JANUARY 27, 2021 • STATEMENTS AND RELEASES

Biden-Harris Administration Commits on Climate Change – Creating Jobs, Building Infrastructure, and Delivering Environmental Justice

Today, President Biden will take executive action to tackle the climate crisis at home and abroad while creating good-paying union jobs and equitable clean energy future, building modern and sustainable infrastructure, restoring scientific integrity and evidence-based policymaking across the federal government, and re-establishing the President's Council of Advisors on Science and Technology.

These Executive Orders follow through on President Biden's promise to take aggressive action to tackle climate change and build on the executive actions that the President took on his first day in office, including rejoining the Paris Agreement and immediate review of harmful rollbacks of standards that protect our air, water, and communities.

President Biden set ambitious goals that will ensure America and the world can meet the urgent demands of the climate crisis, while empowering American workers and businesses to lead a clean energy revolution that achieves a carbon pollution-free power sector by 2035 and puts the United States on an irreversible path to a net-zero economy by 2050. Today's actions advance those goals and ensure that we are tapping into the talent, grit, and innovation of American workers, revitalizing the U.S. energy sector, conserving our natural resources and leveraging them to help drive our nation toward a clean energy future, creating well-paying jobs with the opportunity to join a union, and delivering justice for communities who have been subjected to environmental harm.

President Biden will also sign an important Presidential Memorandum on scientific integrity to send a clear message that the Biden-Harris Administration will protect scientists from

political interference and ensure they can think, research, and speak freely to provide valuable information and insights to the American people. Additionally, and in line with the scientific-integrity memorandum's charge to reestablish scientific advisory committees, President Biden will sign an Executive Order re-establishing the President's Council of Advisors on Science and Technology.

TACKLING THE CLIMATE CRISIS AT HOME AND ABROAD EXECUTIVE ORDER

Today's Executive Order takes bold steps to combat the climate crisis both at home and throughout the world. In signing this Executive Order, President Biden has directed his Administration to:

Center the Climate Crisis in U.S. Foreign Policy and National Security Considerations

- The order clearly establishes climate considerations as an essential element of U.S. foreign policy and national security.
- The order affirms that, in implementing – and building on – the Paris Agreement's objectives, the United States will exercise its leadership to promote a significant increase in global ambition. It makes clear that both significant short-term global emission reductions and net zero global emissions by mid-century – or before – are required to avoid setting the world on a dangerous, potentially catastrophic, climate trajectory.
- The order reaffirms that the President will host a Leaders' Climate Summit on Earth Day, April 22, 2021; that the United States will reconvene the Major Economies Forum; that, to underscore the administration's commitment to elevating climate in U.S. foreign policy, the President has created a new position, the Special Presidential Envoy for Climate, which will have a seat on the National Security Council, and that it will be a U.S. priority to press for enhanced climate ambition and integration of climate considerations across a wide range of international fora.
- The order also kicks off the process of developing the United States' "nationally determined contribution" – our emission reduction target – under the Paris Agreement, as well as a climate finance plan.
- Among numerous other steps aimed at prioritizing climate in U.S. foreign policy and national security, the order directs the Director of National Intelligence to prepare a National Intelligence Estimate on the security implications of climate change, the State Department to prepare a transmittal package to the Senate for the Kigali Amendment to the Montreal Protocol, and all agencies to develop strategies for integrating climate considerations into their international work.

Take a Whole-of-Government Approach to the Climate Crisis

- The order formally establishes the White House Office of Domestic Climate Policy – led by the first-ever National Climate Advisor and Deputy National Climate Advisor – creating a central office in the White House that is charged with coordinating and implementing the President's domestic climate agenda.
- The order establishes the National Climate Task Force, assembling leaders from across 21 federal agencies and departments to enable a whole-of-government approach to combatting the climate crisis.

Leverage the Federal Government's Footprint and Buying Power to Lead by Example

- Consistent with the goals of the President's Build Back Better jobs and economic recovery plan, of which his clean energy jobs plan is a central pillar, the order directs the federal agencies to procure carbon pollution-free electricity and clean, zero-emission vehicles to create good-paying, union jobs and stimulate clean energy industries.
- In addition, the order requires those purchases be Made in America, following President Biden's Buy American executive order. The order also directs agencies to apply and strictly enforce the prevailing wage and benefit guidelines of the Davis Bacon and other acts and encourage Project Labor Agreements. These actions reaffirm that agencies should work to ensure that any jobs created with funds to address the climate crisis are good jobs with a choice to join a union.
- The order directs each federal agency to develop a plan to increase the resilience of its facilities and operations to the impacts of climate change and directs relevant agencies to report on ways to expand and improve climate forecast capabilities – helping facilitate public access to climate related information and assisting governments, communities, and businesses in preparing for and adapting to the impacts of climate change.
- The order directs the Secretary of the Interior to pause on entering into new oil and natural gas leases on public lands or offshore waters to the extent possible, launch a rigorous review of all existing leasing and permitting practices related to fossil fuel development on public lands and waters, and identify steps that can be taken to double renewable energy production from offshore wind by 2030. The order does not restrict energy activities on lands that the United States holds in trust for Tribes. The Secretary of the Interior will continue to consult with Tribes regarding the development and management of renewable and conventional energy resources, in conformance with the U.S. government's trust responsibilities.

- The order directs federal agencies to eliminate fossil fuel subsidies as consistent with applicable law and identify new opportunities to spur innovation, commercialization, and deployment of clean energy technologies and infrastructure.

Rebuild Our Infrastructure for a Sustainable Economy

- The order catalyzes the creation of jobs in construction, manufacturing, engineering and the skilled-trades by directing steps to ensure that every federal infrastructure investment reduces climate pollution and that steps are taken to accelerate clean energy and transmission projects under federal siting and permitting processes in an environmentally sustainable manner.

Advance Conservation, Agriculture, and Reforestation

- The order commits to the goal of conserving at least 30 percent of our lands and oceans by 2030 and launches a process for stakeholder engagement from agricultural and forest landowners, fishermen, Tribes, States, Territories, local officials, and others to identify strategies that will result in broad participation.
- The order also calls for the establishment of a Civilian Climate Corps Initiative to put a new generation of Americans to work conserving and restoring public lands and waters, increasing reforestation, increasing carbon sequestration in the agricultural sector, protecting biodiversity, improving access to recreation, and addressing the changing climate.
- The order directs the Secretary of Agriculture to collect input from farmers, ranchers, and other stakeholders on how to use federal programs to encourage adoption of climate-smart agricultural practices that produce verifiable carbon reductions and sequestrations and create new sources of income and jobs for rural Americans.

Revitalize Energy Communities

- The order establishes an Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization, to be co-chaired by the National Climate Advisor and the Director of the National Economic Council, and directs federal agencies to coordinate investments and other efforts to assist coal, oil and natural gas, and power plant communities.
- The order tasks the new Interagency Working Group to advance projects that reduce emissions of toxic substances and greenhouse gases from existing and abandoned infrastructure and that prevent environmental damage that harms communities and poses

a risk to public health and safety – such as projects to reduce methane emissions, oil and brine leaks, and other environmental harms from tens of thousands of former mining and well sites.

- In addition, the new Interagency Working Group is also directed to explore efforts to turn properties idled in these communities, like brownfields, into new hubs for the growth of our economy.

Secure Environmental Justice and Spur Economic Opportunity

- The order formalizes President Biden's commitment to make environmental justice a part of the mission of every agency by directing federal agencies to develop programs, policies, and activities to address the disproportionate health, environmental, economic, and climate impacts on disadvantaged communities.

- The order establishes a White House Environmental Justice Interagency Council and a White House Environmental Justice Advisory Council to prioritize environmental justice and ensure a whole-of-government approach to addressing current and historical environmental injustices, including strengthening environmental justice monitoring and enforcement through new or strengthened offices at the Environmental Protection Agency, Department of Justice, and Department of Health and Human Services. The new bodies are also tasked with advising on ways to update Executive Order 12898 of February 11, 1994.

- The order creates a government-wide Justice40 Initiative with the goal of delivering 40 percent of the overall benefits of relevant federal investments to disadvantaged communities and tracks performance toward that goal through the establishment of an Environmental Justice Scorecard.

- The order initiates the development of a Climate and Environmental Justice Screening Tool, building off EPA's EJSCREEN, to identify disadvantaged communities, support the Justice40 Initiative, and inform equitable decision making across the federal government

SCIENTIFIC INTEGRITY PRESIDENTIAL MEMORANDUM

The Presidential Memorandum on Scientific Integrity and Evidence-Based Policymaking directs agencies to make evidence-based decisions guided by the best available science and data. Scientific and technological information, data, and evidence are central to the development and iterative improvement of sound policies, and to the delivery of effective and equitable programs. Improper political interference in the scientific process, with the work of scientists, and in the communication of scientific facts undermines the welfare of the nation, contributes to systemic inequities and injustices, and violates the public trust.

The memorandum charges the Director of the Office of Science and Technology Policy (OSTP) with the responsibility for ensuring scientific integrity across federal agencies. The OSTP Director is directed to review the effectiveness of agency scientific-integrity policies and assess agency scientific-integrity policies and practices going forward.

In addition, agencies that oversee, direct, or fund research are tasked with designating a senior agency employee as Chief Science Officer to ensure agency research programs are scientifically and technologically well founded and conducted with integrity. Because science, facts, and evidence are vital to addressing policy and programmatic issues across the Federal Government, all agencies – not just those that fund, conduct, or oversee scientific research – must designate a senior career employee as the agency's Scientific Integrity Official to oversee implementation and iterative improvement of scientific-integrity policies and processes.

EXECUTIVE ORDER ESTABLISHING THE PRESIDENT'S COUNCIL OF ADVISORS ON SCIENCE AND TECHNOLOGY

Leaders across the Biden-Harris Administration, including the President himself and his senior advisors in the Executive Office of the President, will seek input, advice, and the best-available science, data, and scientific and technological information from scientists, engineers, and other experts in science, technology, and innovation.

To that end, and in alignment with the scientific-integrity memorandum's charge to reestablish scientific and technological advisory committees, this order re-establishes the President's Council of Advisors on Science and Technology (PCAST). The PCAST– co-chaired by the President's Science Advisor – will advise the President on policy that affects science, technology, and innovation. The Council will also advise the President on scientific and technical information that is needed to inform public policy relating to the economy, worker empowerment, education, energy, environment, public health, national and homeland security, racial equity, and other topics.

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Overview of Office of Airports Engagement on Environmental Justice (EJ) Issues

Federal Aviation Administration

Prepared for: FAA National Civil Rights Training Conference

Presented by: Thomas Cuddy (APP-400)
FAA Office of Airports

Date: July 19, 2018

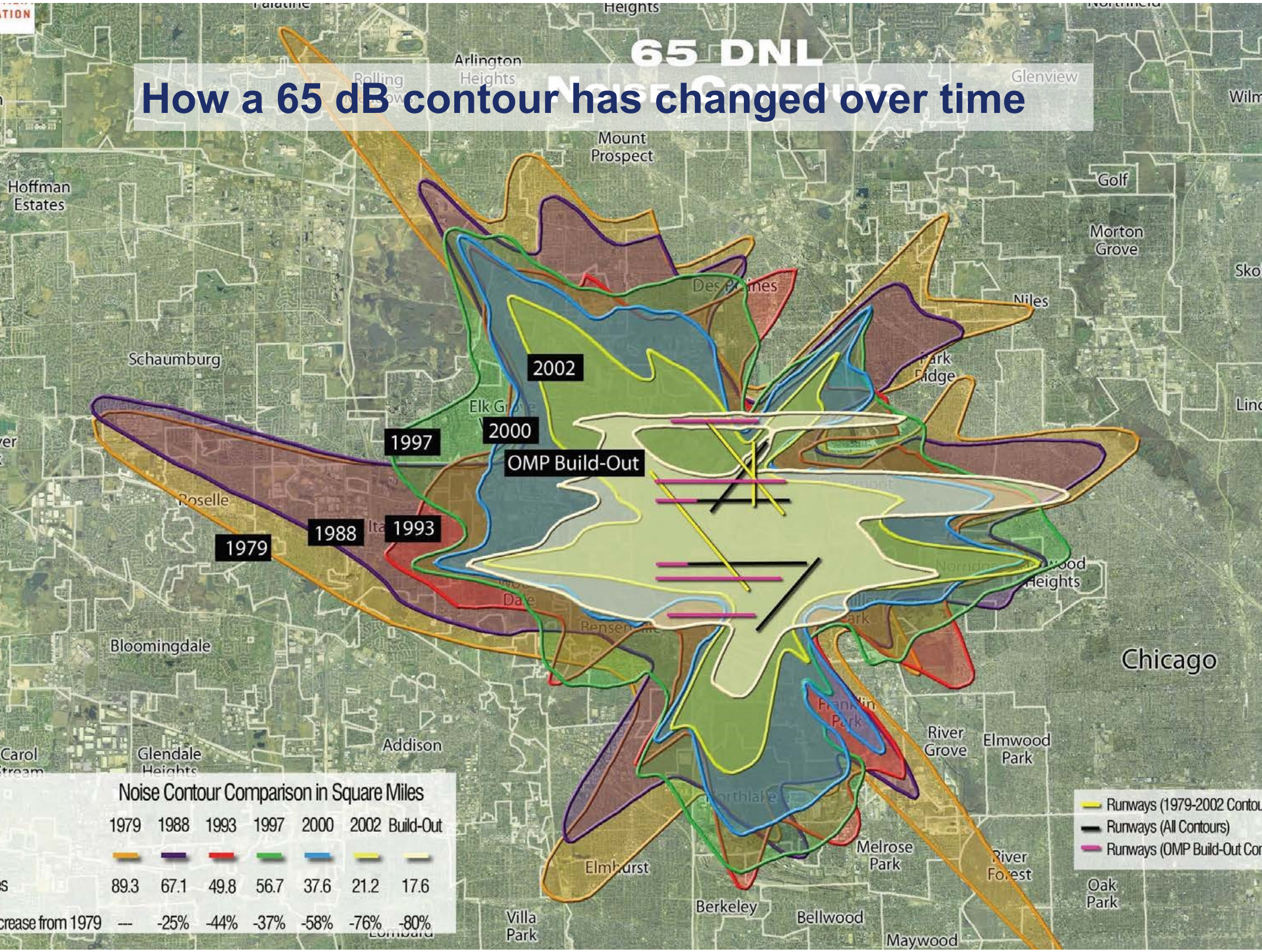
When does FAA Office of Airports get engaged on EJ?

- When there is a pending Federal action—most typically when there is a proposed airport construction project with potential environmental impacts that go beyond airport boundaries.

- Processes:
  - Airport Planning (e.g., Airport Master Plan)
  - Environmental Review (NEPA analysis)
- Impacts of concern:
  - Noise exposure
  - Land purchases

- ARP has had no big EJ issues in a number of years

How a 65 dB contour has changed over time



Noise Contour Comparison in Square Miles

	1979	1988	1993	1997	2000	2002	Build-Out
	89.3	67.1	49.8	56.7	37.6	21.2	17.6
crease from 1979	---	-25%	-44%	-37%	-58%	-76%	-80%

Federal Requirements

- Executive Order 12898 ("Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations") requires all Federal agencies to identify and address disproportionately high and adverse health or environmental effects of its programs, policies, and activities on minority and low-income populations.
- DOT Order 5610.2A requires Operating Administrations to fully consider environmental justice principles throughout planning and decision-making processes in the development of programs, policies, and activities that address or affect infrastructure planning and decision-making; social, economic, or environmental matters; public health; and public involvement.

(continued)

Federal Requirements (continued)

- FAA Order 1050.1F ("Environmental Impacts: Policies and Procedures") and FAA Order 5050.4B ("National Environmental Policy Act (NEPA) Implementing Instructions for Airport Actions") define how the FAA should address environmental justice issues for Airports actions.
- In addition, the Airports and the Order 1050.1F Desk References integrate compliance with NEPA and special purpose laws. Environmental Justice compliance procedures, including analysis and public outreach, are discussed in this document.
- The NEPA training course recently developed by the Office of Airports provides a detailed job-aid that gives background on legal authorities related to Environmental Justice as well as a framework of how to conduct an environmental justice evaluation.

MOU Between Office of Airports and Civil Rights

- In February 2012, the Office of Airports entered into a Memorandum of Understanding (MOU) with the FAA Office of Civil Rights to promote the sharing of environmental justice information and analyses for proposed AIP-funded airport projects.
- The MOU established a three-year pilot program (from January 2012 through January 2015).
- In September 2014, the MOU and the pilot program were extended for three more years, through December 2017.
- No projects have met the stated criteria for heightened coordination during this timeframe. However, the Environmental Impact Statement for development at Charlotte-Douglas International Airport, just beginning, will meet likely the criteria.

Types of issues that can Trigger EJ concerns

- EJ concerns are triggered by human health or environment effects, including interrelated social and economic effects:
  - — Displacement (e.g., of people and businesses) is the most likely significant Environmental Justice issue at and around airports.
  - — Noise and air quality are the most likely environmental issues.
  - — Other environmental issues may be raised during the EJ process (e.g., thresholds, subsistence resources, use of categorical exclusions).
- Although EJ is always an important part of NEPA review and analysis, it is relatively infrequent for significant EJ issues to materialize.
- Lower-cost housing is sometimes available near large, busy airports and as a result it is not unusual for low-income populations to live in these areas. These areas are often exposed to high noise levels from airport operations.

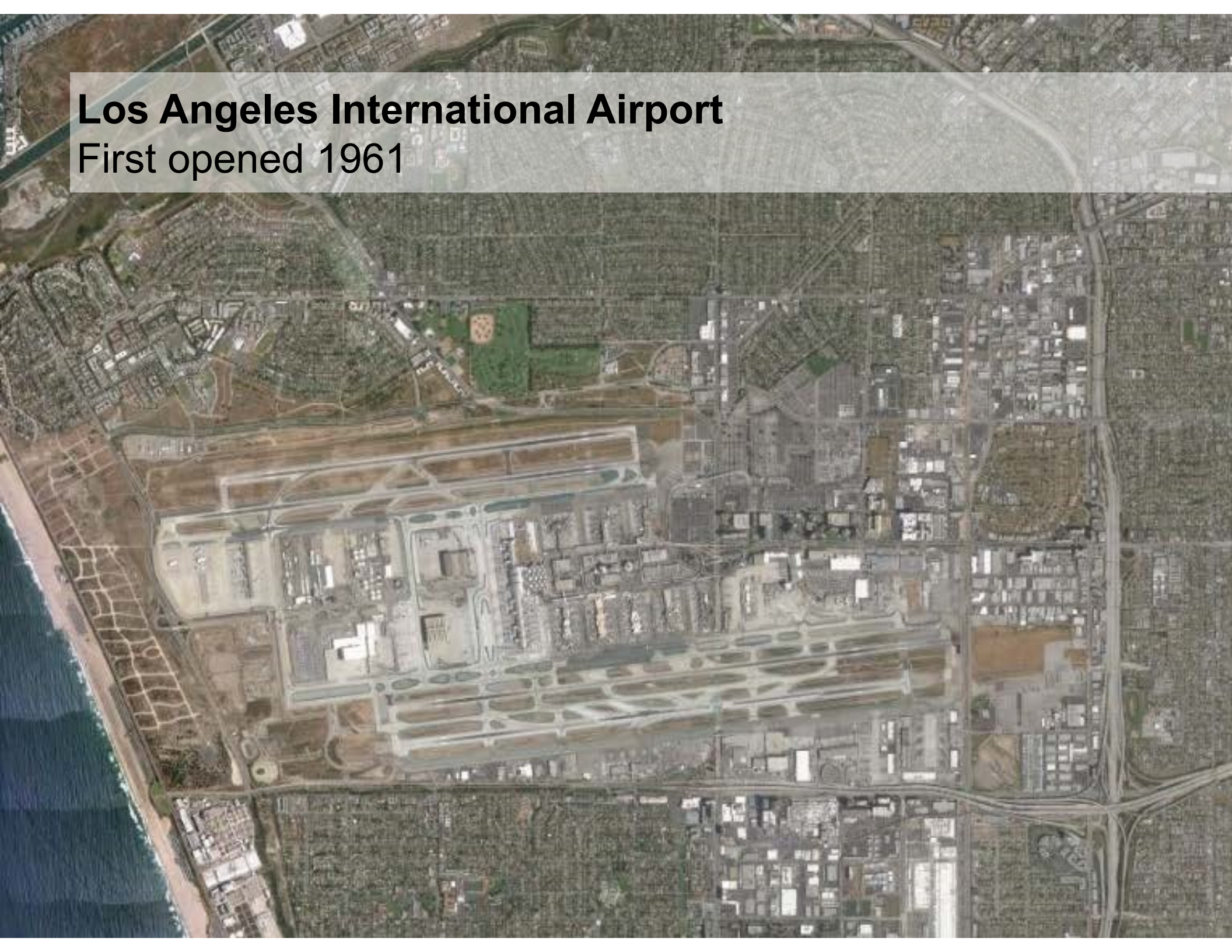
(continued)

Types of issues that can Trigger EJ concerns (cont'd)

- Noise-related EJ analysis may include reviewing potential alternatives to the proposed action, including different runway alignments, or other means of meeting the aviation need. As part of the EJ analysis, airport noise contour data and other data is compared with minority and low-income maps.
- EJ issues that have been studied in Environmental Impact Statements in Alaska have focused on impacts to subsistence resources used by Native Alaskans.

Potential Mitigation Measures

- Where possible, both airports and the FAA typically seek to avoid impacting populated areas at all—and particularly if they are disproportionately low-income areas.
- Mitigation measures may include property acquisition, sound insulation of homes and schools, or compensation through the purchase of avigation easements. The FAA is frequently able to support these measures through Airport Improvement Program (AIP) grants to the airport sponsor or the community.
- The FAA can also provide AIP funding to support airports that choose to work collaboratively with neighboring communities (through 14 CFR Part 150) to develop noise compatibility plans, which can include noise abatement measures such as preferred runway utilization plans, revised approach and departure paths for aircraft, voluntary nighttime restrictions, etc.


Los Angeles International Airport
First opened 1961

Example 1. Los Angeles International Airport

The EJ analysis was part of a highly detailed Final Environmental Impact Statement issued in 2005. The major projects included shifting of runways, a new Ground Transportation Center, and new passenger terminal buildings.

- The analysis found that three of four alternatives evaluated in the Final EIS could have disproportionately high and adverse effects on minority and low-income populations. However, the selected alternative did not have a disproportionate impact.
- The analysis also found that air quality impacts would disproportionately occur on minority and low-income populations due in part to construction related emissions. As a result, 16 specific mitigation measures to reduce these impacts were identified.
- The airport sponsor conducted 126 specific outreach efforts to low-income and minority populations over the course of four years during development of the Master Plan and EIS.

Philadelphia International Airport
First opened 1940

Example 2. Philadelphia International Airport

In 2010 an EIS was published for a capacity enhancement program for Philadelphia International Airport, including major runway and terminal expansion:

- Impacts to environmental justice populations were considered relative to (a) Land acquisition/community disruption and (b) areas significantly impacted by noise.
- The environmental justice analysis included a detailed assessment of minority, Hispanic, and low-income populations within the census blocks and census block groups where land would be acquired or impacts could occur.
- The EIS concluded that the proposed projects would not have a significant adverse impact to minority or low-income populations and would not result in disproportionate and high adverse impacts on these populations.
- FAA conducted an extensive public coordination process in minority communities. This outreach included public meetings, open houses, websites, and use of local newspapers. Meeting locations were selected to allow for easy access via public transportation.


Rezanof Dr W
Kodiak
Airport
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Example 3. Kodiak Airport

In 2013 the FAA published a Final EIS for Runway Safety areas at Kodiak Airport in AK.

- Impacts from a runway safety area project to environmental justice populations were considered relative to subsistence resources (fisheries) and practices tied to the cultural identity of three Alaska Tribes.
- The environmental justice analysis included a detailed assessment of minority and low-income populations within census tracts around the project area. About 45% of the population were identified as minority with about 13% of the population identified as Alaska Natives and the rest predominantly Asian.
- The EIS concluded that the proposed project would have a significant adverse impact to on customary and traditional practices and cultural identity of the Alaska Villages and the Tribe. Mitigation included funding subsistence management on an affected river and funding a tribe to monitor fisheries impacts of the project.
- FAA conducted an extensive coordination process in minority communities. This outreach included public meetings, open houses, websites, and use of local newspapers as well as extensive government to government coordination with the Native Alaska tribes.

Recent Efforts to address EJ analysis

FAA updated the agency-wide NEPA Order 1050.1 and created an accompanying Desk Reference (similar to the Airport Desk Reference), including more emphasis on environmental justice.

- The Order highlights public involvement for environmental justice populations in the planning chapter to be consistent with the DOT Order 5610.2A updates in May 2012.
- Order 1050.1F Desk Reference expands the guidance on FAA's EJ responsibilities from about 2 pages to 7 pages of content:

— FAA must consider impacts on the environment that would affect an environmental justice population in way that is unique and significant to that population.

— Some adverse impacts may not normally be considered significant under NEPA (i.e., normally cause an EIS to be prepared), yet may pose a significant impact when examined in the context of their effects on minority or low-income populations.

- ARP developed a job-aid as part of our Introduction to NEPA course that details how to conduct an EJ analysis

Recent Efforts to address EJ analysis (continued)

FAA updated agency-wide focus on Community Involvement

- **FAA Community Involvement Manual (CIM) online**
  - Office of Environment and Energy (AEE) updated the 1990 community involvement guidance document to reflect current practices for engaging communities.
  - Document is agency-wide guidance that applies policies to all agency actions (cover photo at left).
- **ATO Community Involvement Plan (CIP) online**
  - FAA Air Traffic Office has developed a Community Involvement Plan (CIP) in an effort to identify what types of community involvement can best help implement flight procedures effectively.
  - Plan involves several parts, including changes to the PBN Order, and checklists for implementation.
- **ATO Community Involvement PBN Desk Guide**
  - Developed by Airspace Services (AJV-1) with participation from FAA representatives from AGC, AEE, AJV-0, and the Service Center OSGs. The Guide is intended as a reference for those engaged in community involvement activities within ATO and other lines of business.

Recent Efforts to address EJ analysis (continued)

The Office of Airports updated Advisory Circular (AV) Community Involvement in Airport Actions.

Developed Strategic Direction:

- Encourage more robust interactions between sponsors and airport public
- Stay focused on the 'Citizen' part of public involvement
- Emphasize win-win benefits of good public involvement
- Emphasize continuity between public relations, planning, environmental, project development
- Highlight new tools for enhanced public involvement, e.g., social media

4 chapters with appendices:

- Need for Community Involvement
- Planning for Community Involvement
- Designing and Implementing a Community Involvement Program
- Documenting the Process, Assessing Effectiveness, and Closing Out a Program

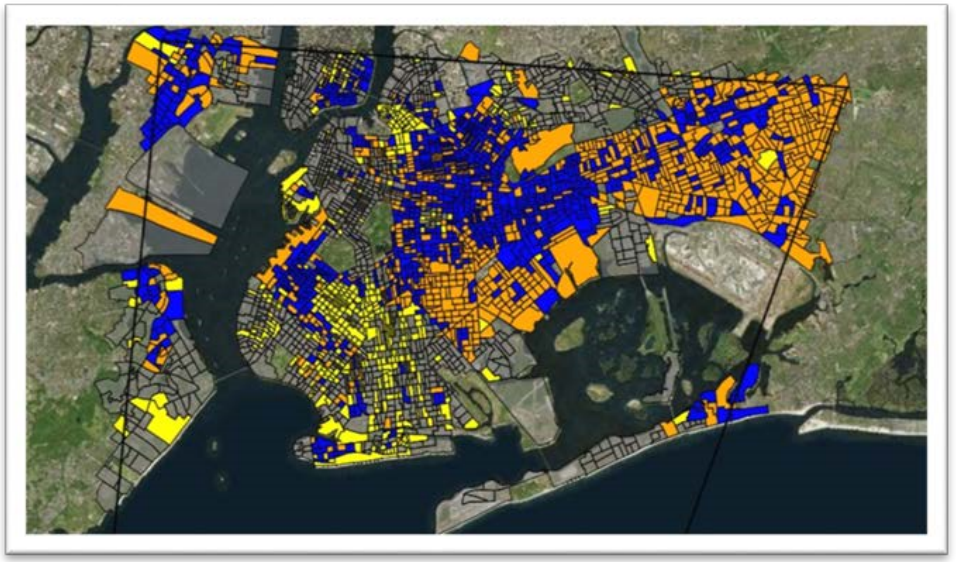
Environmental Visualization (EVT) Tool

Purpose:

- Provide a more easily-accessible and user-friendly web-based tool to visually evaluate potential environmental impacts.

Capabilities:

- Web mapping application accessible only on the FAA network.
- Ability to incorporate EJ data created in AEDT, and other data: flight paths and noise data.
- Integrate other sources of environmental and political data (e.g. congressional districts, air quality).
- The AEDT EJ functionality provides a "rough cut"; additional information and research may still be required.
- http://evt.faa.gov



Potential Future FAA EJ Activities

- To enhance engagement on EJ issues and best practices related to FAA actions, the FAA can improve communication and engagement across FAA, and with airports and EJ communities.
- Activities that could be further explored include:
  - Meetings and Outreach
  - Educational and Training materials
  - Web materials (e.g., comment boxes, a clearinghouse and/or repository).

BAY AREA AIR QUALITY MANAGEMENT DISTRICT
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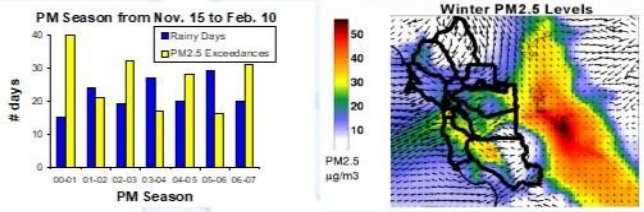
Air Quality Modeling and Analysis Section Publication No. 201903-019-Toxics

Air Toxics Data Analysis and Regional Modeling In the San Francisco Bay Area to Support AB617

April, 2019



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Air Toxics Data Analysis and Regional Modeling in the San Francisco Bay Area to Support AB617

1. Introduction

1.1 Background

The adoption of Assembly Bill 617 (AB617) established collaborative programs to reduce community exposure to air pollutants in neighborhoods most impacted by air pollution. Air District staff have been working closely with the California Air Resources Board (ARB), other local air districts, community groups, community members, environmental organizations, regulated industries, and other key stakeholders to reduce harmful air pollutants in Bay Area communities.

One purpose of this data analysis and regional modeling effort is to support the District's AB617 activities by assessing pollutant formation, quantifying the relative contribution of emission sources to ambient pollution levels, and assessing population exposures and the benefits of emission controls in impacted communities around the Bay Area. Another purpose is to support the AB617 activities by identifying geographic areas that are significantly overburdened relative to the Bay Area as a whole, prioritizing among the overburdened areas for AB617 community selection and characterizing relative ambient concentrations in rural, suburban and urban areas. Results of this effort are expected to help identify strategies for reducing regional concentrations of key species of air toxics. Analyses in this report focus on air toxics concentrations in the whole Bay Area with an emphasis on West Oakland. Follow-up analyses will include other Bay Area communities.

For the air toxics analyses, we evaluated ambient meteorological and air quality data, and applied the U.S. EPA's Community Multi-Scale Air Quality (CMAQ) model to simulate pollutant concentrations at a 1-km horizontal resolution over the entire Bay Area for 2016 (Figure 1.1). Then we repeated the simulation with West Oakland's anthropogenic emissions removed from the modeling inventory, leaving all other model input parameters unchanged. We calculated annual average air toxics concentrations using the output of each simulation. The first simulation provided the annual average air toxics concentrations for 2016 over the entire Bay Area, which will be used for air toxics cancer risk evaluation. The second simulation provided an estimate of background air toxics levels in West Oakland (i.e., the air toxics concentrations that would exist in the absence of local West Oakland sources).

Background air toxics concentrations will be combined with local-scale modeling of West Oakland sources using the AERMOD dispersion model to provide a complete picture of air toxics levels in the community and the relative contribution of different emission sources to those levels. Figure 1.2 shows the AERMOD modeling domain for West Oakland. The area outlined in blue represents the "source domain," and all significant emissions sources in that

area will be modeled in the AERMOD simulations. The red hatched area represents the "receptor domain," or the area for which pollutant concentrations will be calculated by AERMOD.

The application of the CMAQ model involves the preparation of meteorological and emissions inputs, model runs, analysis of simulated pollutant concentrations, and the evaluation of model performance via comparison between simulated and observed pollutant concentrations. A simulation year of 2016 was selected because (1) this is a recent year that is likely to be representative of current conditions in West Oakland and other communities; and (2) special measurement studies that took place in 2016 provide additional ambient data to support evaluations of model performance.

A total of 11 air toxics were simulated: diesel particulate matter (DPM), 5 toxic gases (acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde), and 5 trace metals (cadmium, chromium VI, lead, mercury, and nickel). Previous analyses have indicated that DPM and the 5 toxic gases cumulatively account for more than 90% of toxic air contaminant emissions in the Bay Area (Tanrikulu et al., 2011).

District staff have been applying and evaluating the CMAQ model in the Bay Area over the last several years, along with the Weather Research and Forecasting (WRF) model, which provides meteorological inputs for CMAQ. Findings from previous modeling work are documented in District reports on air toxics data analysis and modeling (Tanrikulu et al., 2009 and 2011) and $PM_{2.5}$ data analysis and modeling (Tanrikulu et al., 2019), as well as in the District's 2017 Clean Air Plan (BAAQMD, 2017). Both the CMAQ and WRF models were tested and evaluated for many cases in the Bay Area, and their performance has been iteratively improved. The 2016 simulations used the best-performing configuration of the model. The 2016 emissions inputs have been updated to reflect ARB's most recent estimates and have been evaluated to the extent possible.

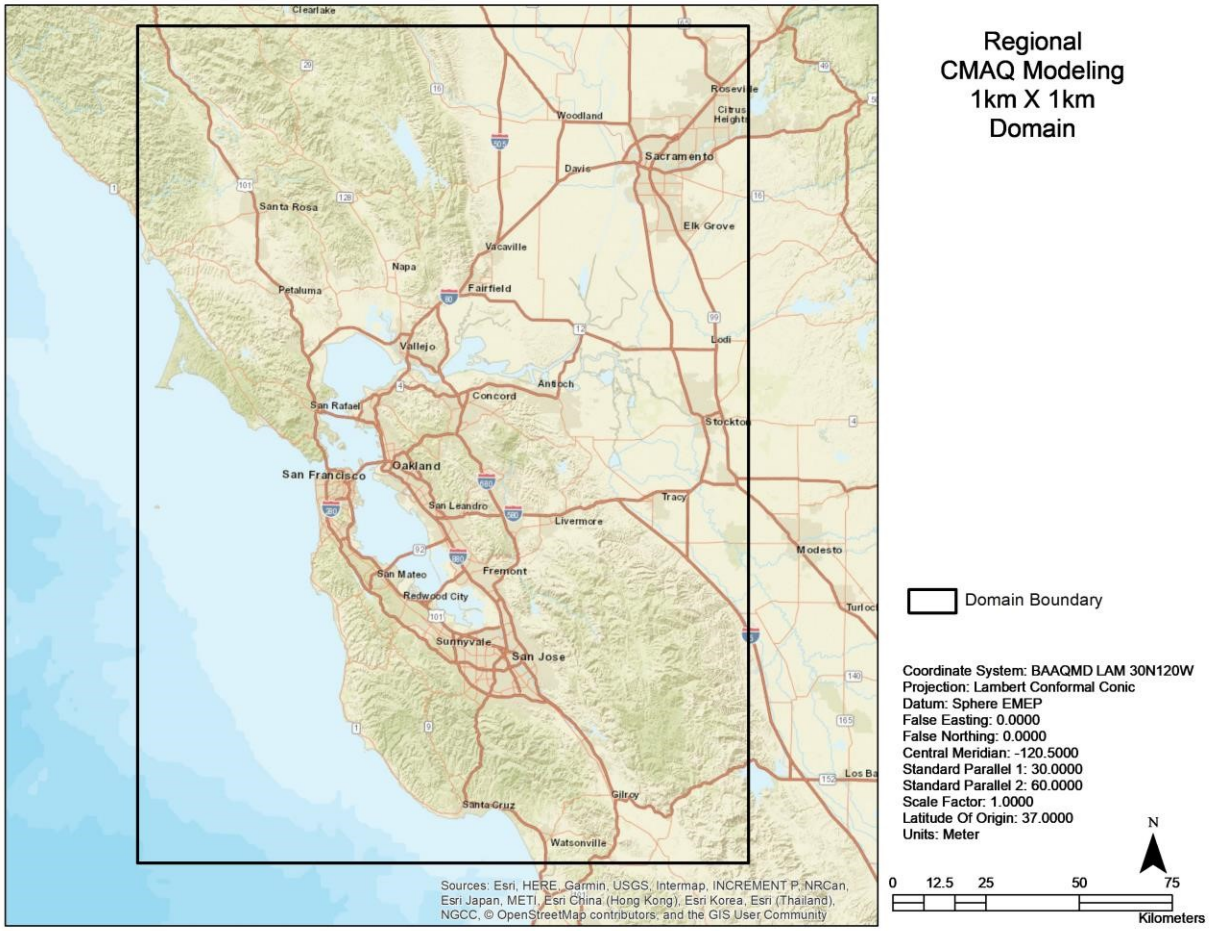


Figure 1.1: The regional 1-km modeling domain used for CMAQ simulations.

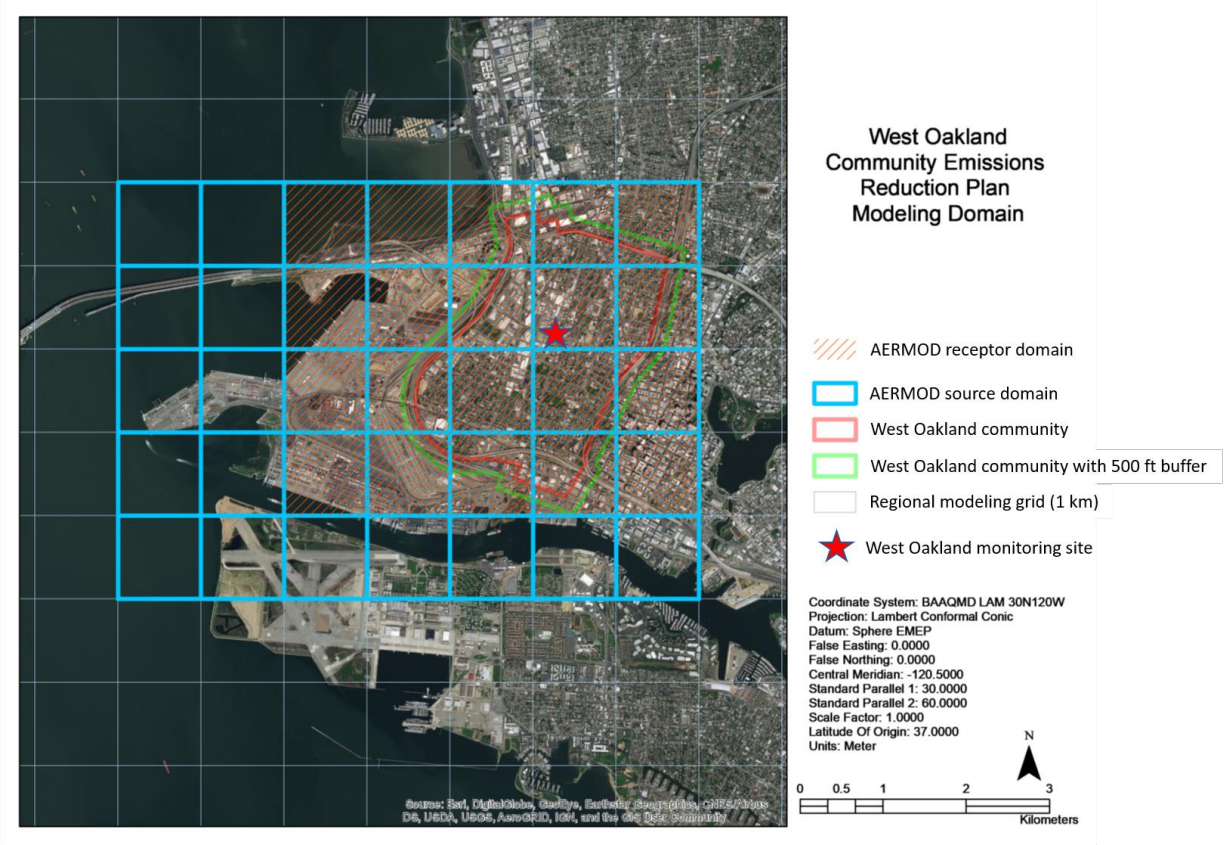


Figure 1.2: The West Oakland AERMOD modeling domain. The area outlined in blue represents the AERMOD source domain, and the red hatched area represents the AERMOD receptor domain.

1.2 Air Toxics and Their Health Impacts

Air toxics are a complex mixture of gases, suspended particles and liquid droplets in the atmosphere. Most air toxics originate from human-made sources, including mobile sources (e.g., cars, trucks, buses) and stationary sources (e.g., factories, refineries, power plants), as well as indoor sources (e.g., some building materials and cleaning solvents). Some air toxics are also released from natural sources such as forest fires.

One of the major human health outcomes resulting from air toxics exposure is cancer risk. The unit risk factor describes the excess cancer risk associated with an inhalation exposure to a concentration of 1 $\mu g/m^3$ of a given toxic air contaminant (assuming a 70-year lifetime exposure). Table 1.1 lists unit risk factors for the modeled air toxics that were recently updated based on CAPCOA recommendations. Unit risk factors for toxic metals tend to be higher than those of other air toxics; for example, the unit risk factor for hexavalent chromium is orders-of-magnitude higher than unit risk factors for other air toxics. However, typical atmospheric concentrations of toxic metals are much smaller than those of other toxics; thus, overall cancer risks due to the metals are relatively small.

Table 1.1: Inhalation unit cancer risk factors for the air toxic species included in this study.

Air Toxics[1]	**Unit Risk Factor (($\mu g/m^3)^{-1}$)**
Formaldehyde	0.000014
Acetaldehyde	0.0000068
Benzene	0.000068
1,3-Butadiene	0.00041
Diesel PM	0.00074
Hexavalent Chromium	0.38
Nickel	0.00062
Cadmium	0.010
Lead	0.00066

[1]Acrolein and mercury were also simulated in this study; however, they have no known cancer risk. Therefore, they are not included in this table.

Section 2 of this report presents a summary of air toxics observations in the Bay Area and results of analysis of observed data; Section 3 presents modeling methods, including emissions inventory preparation, preparation of meteorological inputs and application of the CMAQ model. Section 4 presents model evaluation. Section 5 presents the excess cancer risk associated with air toxics. Section 6 presents a summary and discussion of overall results.

There are several appendices that provide additional details on air toxics emissions estimates (Appendix A), primary vs. secondary air toxics formation (Appendix B), simulation of toxics metals (Appendix C), and West Oakland-specific cancer risk evaluation (Appendix D).

Simulation of toxics metals is discussed in Appendix C rather than the main body of this report because the emissions estimates for these species are preliminary and uncertain. In the absence of local data, emission estimates for metals were taken from the EPA's 2014 National Air Toxics Assessment (NATA) inventory and may be unrepresentative of 2016 emission levels in Bay Area communities. Simulated metal concentrations presented in Appendix C are preliminary and will be updated when improved emissions estimates are available. Note that, while these preliminary contributions of metals to Bay Area total cancer risk are included in the overall results, at their currently estimated levels, metals contribute only about 2% to the total Bay Area cancer risk.

2. Observations and Data Analysis

2.1 Ambient Measurements

Ambient air toxics data have been continuously collected in the Bay Area for many years. In 2016, there were 20 air toxics monitoring stations operating in the Bay Area. These stations, which are listed in Table 2.1 along with their sampling schedules, can be categorized into two types: (1) National Air Toxics Trend Stations (NATTS); and (2) Hazardous Air Pollutants Stations (HAPS). There is one NATTS station (San Jose – Jackson Street) and nineteen HAPS stations (all others) in the Bay Area.

Four air toxics species (formaldehyde, acetaldehyde, 1,3-butadiene and benzene) were measured at the San Jose NATTS every 6 days in 2016. Two air toxics species (1,3-butadiene and benzene) were measured at HAPS every 12 days. Chromium, cadmium, nickel, lead, and mercury were sampled as part of $PM_{2.5}$ speciation at Livermore, Oakland West and Vallejo every 6 days and at San Jose – Jackson Street every 3 days.

Acrolein was not measured in the Bay Area in 2016. The air quality monitoring network plan published by BAAQMD (Knoderer et al., 2017) provides additional details on the District's monitoring network.

All ambient data used in this study were subjected to quality assurance checks and validated prior to being used. These data were used for the establishment of relationships among emissions, meteorology and air quality, and the evaluation of models. Daily average data are used for most analyses and model evaluation, but annual averages are presented here for brevity.

Table 2.1: A list of air toxics monitoring stations in the Bay Area with their sampling schedule for 2016. Highlighted columns and rows show measurement schedule.

<table>
<tr><th>Station</th><th>Formaldehyde</th><th>Acetaldehyde</th><th>Benzene</th><th>1,3-butadiene</th><th>EC</th><th>Chromium</th><th>Cadmium</th><th>Lead</th><th>Nickel</th><th>Mercury</th></tr>
<tr><td>NATTS</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>San Jose -Jackson St.</td><td colspan="4">1 in 6 days</td><td colspan="6">1 in 3 days</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>HAPS and speciated $PM_{2.5}$</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Livermore</td><td></td><td></td><td colspan="2" rowspan="3">1 in 12 days</td><td colspan="6" rowspan="3">1 in 6 days</td></tr>
<tr><td>Oakland West</td><td></td><td></td></tr>
<tr><td>Vallejo</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

HAPS										
Berkeley			1 in 12 days							
Bethel Island										
Concord										
Crockett										
Fort Cronkhite										
Laney College										
Martinez										
Napa										
Oakland East										
Redwood City										
Richmond – 7th St.										
San Francisco										
San Jose – Knox Ave.										
San Pablo										
San Rafael										
Sebastopol										

2.2 Data Analysis

Table 2.2 shows the annual average observed air toxics concentrations for 2016. Concentrations below the minimum detection limit are not included in the annual averages. Stations with no annual average concentration value for a given pollutant either did not have measurements for that pollutant in 2016 or did not capture any samples above the minimum detection limit. Highlighted values in Table 2.2 represent averages calculated from less than 12 samples above the detection limit.

Formaldehyde and acetaldehyde were measured only at San Jose – Jackson Street. The annual average concentrations of these species were 2.18 µg/m^3 and 1.39 µg/m^3, respectively. Over 70% of atmospheric formaldehyde forms as an intermediate product of the oxidation (combustion) of methane and other carbon compounds (Zemba et al, 2019). The remaining atmospheric formaldehyde is directly emitted to the atmosphere, mainly from its use in industrial processes such as oil refining and the production of resins for particle board and coatings. Acetaldehyde forms as an intermediate product of the oxidation of ethylene and ethanol.

Benzene and 1,3-butadiene were monitored at all Bay Area toxics monitoring stations. The highest annual average benzene concentration in the Bay Area (0.39 ppb) was at San Jose – Knox Avenue. At seven other air monitoring stations (Berkeley, Napa, Vallejo, Oakland West, Oakland East, Redwood City and San Jose – Jackson Street), the annual average benzene concentrations exceeded 0.2 ppb. Benzene is used as a constituent in motor fuels; as a solvent for

fats, waxes, resins, oils, inks, paints, plastics, and rubber; in the extraction of oils from seeds and nuts; and in photogravure printing.

The highest Bay Area annual average 1,3-butadiene concentration (0.1 ppb) was measured at the San Jose – Knox Avenue air monitoring station. Concentrations at Sebastopol, Vallejo, San Jose – Jackson Street, Redwood City and Oakland West were above 0.07 ppb, higher than the remining Bay Area stations. Emission sources of 1,3-butadiene include: motor vehicle exhaust, manufacturing and processing facilities, forest fires or other combustion, and cigarette smoke. Higher levels of 1,3-butadiene may be found in highly industrialized cities or near oil refineries, chemical manufacturing plants, and plastic and rubber factories.

As mentioned, PM samples were speciated at four Bay Area air monitoring stations (San Jose – Jackson Street, Vallejo, Livermore and Oakland West), and concentrations of EC and five metals were extracted, among other species. As shown in Table 2.2, the annual average EC concentration at San Jose – Jackson Street is the lowest among the four stations. However, while samples were speciated at San Jose – Jackson Street throughout 2016 and averaged over the entire year, they were speciated only during winter, spring and fall months at the other three stations and averaged over those three seasons. Since PM concentrations are higher during winter months than summer months in the Bay Area, this mismatched averaging period led to lower annual average concentration at San Jose – Jackson Street compared to other three stations.

The annual average lead concentrations are significantly higher at Oakland West than at the other 3 stations (Livermore, San Jose – Jackson Street and Vallejo). At Oakland West, there were six samples during 2016 with concentrations around 100 ng/m^3 and above; as a result, the annual average concentration at this station stands out.

Table 2.2: Annual average observed air toxics concentrations for 2016. Highlighted values represent averages calculated from less than 12 valid samples.

Site	Formaldehyde	Acetaldehyde	Benzene	1,3-Butadiene	EC	Chromium	Cadmium	Lead	Nickel	Mercury
	[µg/m^3]	[µg/m^3]	[ppb]	[ppb]	[µg/m^3]	[ng/m^3]	[ng/m^3]	[ng/m^3]	[ng/m^3]	[ng/m^3]
Berkeley			0.2108							
Bethel Island			0.1263							
Concord			0.1356							
Crockett			0.1399	0.0540						
Fort Cronkhite			0.0796							
Laney College			0.1991	0.0635						
Livermore			0.1785	0.0638	0.5981		11.6242	3.8260	2.2144	2.6552
Martinez			0.1494	0.0670						
Napa			0.2192	0.0666						
Oakland East			0.2360	0.0606						
Oakland West			0.2239	0.0779	0.5580		9.0201	56.9884	4.4872	2.2439
Redwood City			0.2210	0.0703						
Richmond - 7th St			0.1424	0.0370						
San Francisco			0.1731	0.0485						
San Jose - Jackson St.	2.1871	1.3921	0.2609	0.0741	0.3608	8.4436		17.4300	4.1820	
San Jose - Knox Av			0.3971	0.1067						
San Pablo			0.1841							
San Rafael			0.1602	0.0625						
Sebastopol			0.1583	0.0850						
Vallejo			0.2027	0.0838	0.4915		8.8598	3.1431	1.3480	2.7547

Data for EC and metals are components of speciated $PM_{2.5}$.
Data for chromium include all oxidation states.

3. Modeling

3.1 Emissions Inventory Preparation

Emissions inputs for the CMAQ model were prepared using the Sparse Matrix Operator Kernel Emissions (SMOKE) processing system, version 4.5, which converts emissions inventory data to the spatial, temporal, and chemical resolution required by the air quality model. CMAQ-ready emissions inputs for 2016 included 11 air toxics: diesel particulate matter (DPM), 5 toxic gases (acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde), and 5 trace metals (cadmium, chromium VI, lead, mercury, and nickel).

The starting point for the emissions processing was the 2016 criteria pollutant inventories previously assembled for 1-km $PM_{2.5}$ modeling (Tanrikulu et al., 2019). These 2016 data, which include estimates for area sources,[1] point sources, onroad mobile sources, nonroad mobile sources, and biogenic sources, were assembled from a variety of data sources, including the District's in-house emissions estimates, emissions data from ARB, and outputs from ARB's EMFAC2017 model. Additional details on data sources and processing steps for air toxics emissions estimates are provided below.

3.1.1 Toxic Gases

SMOKE disaggregates total organic (TOG) and $PM_{2.5}$ emissions into a series of model species that CMAQ uses to represent atmospheric chemistry. For the 2016 $PM_{2.5}$ modeling, speciation profiles developed for the SAPRC07 chemical mechanism were applied to TOG emissions from all sources, and profiles developed for the AERO6 aerosol module (AE6) were applied to $PM_{2.5}$ emissions from all sources (Tanrikulu et al., 2019).

The SAPRC07 mechanism treats some toxic species explicitly, including acetaldehyde, benzene, and formaldehyde. However, other air toxics are lumped into model species that act as surrogates for multiple compounds with similar mass and reactivity. For the 2016 toxics modeling, existing SAPRC07 speciation profiles for TOG were modified to treat additional air toxics (acrolein and 1,3-butadiene) explicitly.[2] Once the revised speciation profiles were generated, the District used SMOKE to speciate existing 2016 TOG emissions estimates into the 5 toxic gases of interest, as well as other model species used by the SAPRC07 chemical mechanism.

3.1.2 Diesel Particulate Matter

To track DPM emissions separately from other PM emissions, speciation profiles related to diesel exhaust were edited to include DPM tracer species. For example, speciation profile

[1] Area sources are stationary sources such as dry cleaners that are too small or numerous to treat as individual point sources.

[2] The District contracted with Ramboll to perform this work.

91106 (for heavy duty diesel vehicle exhaust) was modified to include the DPM components shown in Table 1 below.

Table 3.1: DPM components for speciation profile 91106.

Component	Description	Weight fraction
DIESEL_PMEC	Elemental carbon	0.7712
DIESEL_PMOC	Organic carbon	0.1756
DIESEL_PMFINE	Unspeciated $PM_{2.5}$	0.049109
DIESEL_PMSO4	Sulfate	0.00295
DIESEL_PMNO3	Nitrate	0.001141

Running SMOKE with these revised diesel exhaust profiles produced separate DPM species that could be used to estimate DPM concentrations in CMAQ.

3.1.3 Trace Metals

The toxic metals of interest are not included in the AE6 mechanism; therefore, emission estimates for these species were taken from the EPA's 2014 NATA inventory. The 2014 NATA data includes air toxics emissions estimates for the entire U.S. at the county (for area, nonroad, and onroad sources) or facility (for point sources) level. Emissions records for cadmium, chromium VI, lead, mercury, and nickel were extracted from the NATA data for all counties in the 1-km modeling domain, processed through SMOKE, and merged with emissions data for the remaining toxic species being modeled.

Additional details on SMOKE processing steps, including ancillary data sets (e.g., spatial surrogates) used in SMOKE, are provided in a companion report on the 2016 $PM_{2.5}$ modeling for the Bay Area (Tanrikulu et al., 2019).

3.1.4 Emissions Summaries

This subsection provides emissions density plots and summary tables for DPM, the main driver of cancer risk in the Bay Area. Similar information for additional air toxics can be found in Appendix A. Figure 3.1 shows annual average DPM emissions for the 1-km modeling domain. Table 3.2 summarizes the annual average DPM emissions by county and source sector, as reported by the SMOKE emissions model. Within the District's jurisdiction, annual average DPM emissions total 4.2 tons per day (tpd). Nonroad and onroad mobile sources account for 57% and 41%, respectively, of total DPM emissions in the Bay Area.

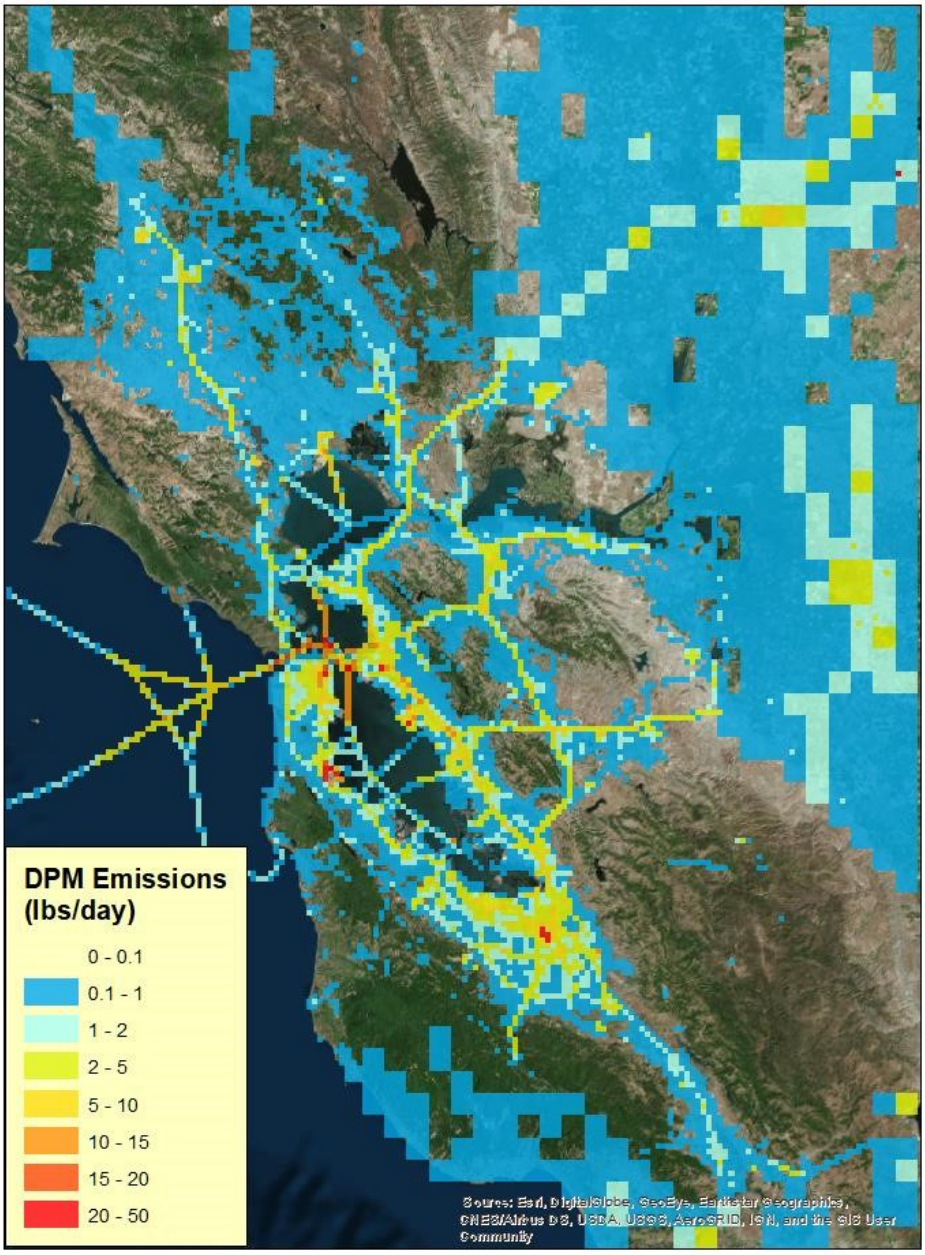


Figure 3.1: Spatial distribution of annual average DPM emissions for the 1-km modeling domain for 2016.

Table 3.2: Summary of 2016 DPM10 emissions (tpd) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.00	0.30	0.56	0.03	0.88
Contra Costa	0.00	0.23	0.23	0.00	0.47
Marin	0.00	0.09	0.05	0.00	0.14
Napa	0.00	0.10	0.06	0.00	0.16
San Francisco	0.00	0.65	0.11	0.01	0.76
San Mateo	0.00	0.38	0.10	0.01	0.49
Santa Clara	0.00	0.36	0.39	0.02	0.77

Solano[a]	0.00	0.06	0.10	0.00	0.17
Sonoma[a]	0.00	0.22	0.13	0.00	0.35
BAAQMD Subtotal	*0.00*	*2.38*	*1.74*	*0.08*	*4.19*
Non-BAAQMD Counties	0.02	1.44	1.11	0.03	2.60
Domain Total	**0.02**	**3.81**	**2.85**	**0.11**	**6.79**

[a]Emissions totals for Solano and Sonoma counties only include the portion of those counties in BAAQMD's jurisdiction.

For the West Oakland AERMOD modeling domain, annual average $DPM_{2.5}$ emissions total 0.1 tpd, or 2.4% of the BAAQMD total. Figure 3.2 shows that the distribution of emissions by source sector in West Oakland differs from the District as a whole. In West Oakland, onroad and nonroad mobile sources account for 85% of total $DPM_{2.5}$ emissions, while the same sources account for 98% of total $PM_{2.5}$ emissions districtwide. Figure 3.3 shows the spatial distribution of DPM emissions across the 1-km grid cells that coincide with the local-scale AERMOD modeling domain. Grid cells with high DPM emissions along the western edge of the domain are impacted by motor vehicle emissions from the Bay Bridge and marine vessel activity. Grid cells with high DPM emissions in the eastern portion of the modeling domain are impacted by motor vehicle emissions, especially from the I-880/I-980 and I-580/I-980 interchanges.

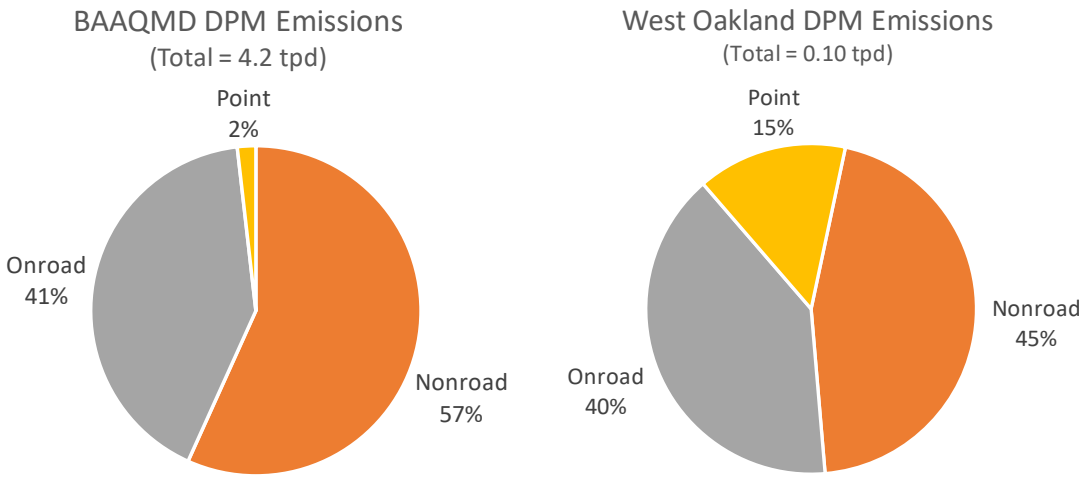


Figure 3.2: DPM emissions by source sector for the District (left) and West Oakland (right) for 2016.

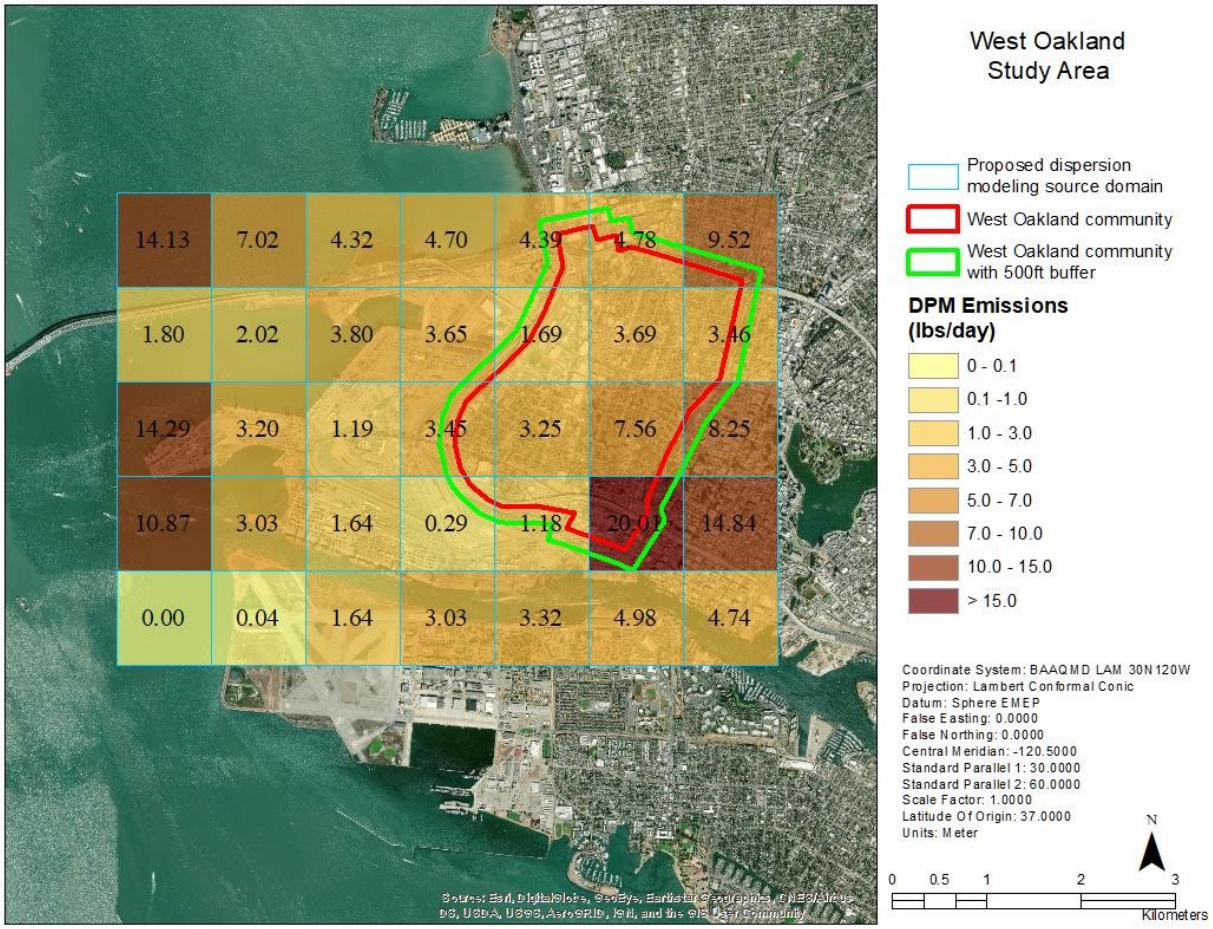


Figure 3.3: Spatial distribution of annual average DPM emissions in West Oakland for 2016.

3.2 Meteorological Modeling

The Weather Research and Forecasting (WRF) Model version 3.8 was used to prepare meteorological inputs to CMAQ. Four nested modeling domains were used (Figure 3.4). The outer domain covered the entire western United States at 36-km horizontal grid resolution to capture synoptic (large-scale) flow features and the impact of these features on local meteorology. The second domain covered California and portions of Nevada at 12-km horizontal resolution to capture mesoscale (sub-regional) flow features and their impacts on local meteorology. The third domain covered Central California at 4-km resolution to capture localized air flow features. The 4-km domain included the Bay Area, San Joaquin Valley, and Sacramento Valley, as well as portions of the Pacific Ocean and the Sierra Nevada mountains. The fourth domain covered the Bay Area and surrounding regions at 1-km resolution. All four domains employed 50 vertical layers with thickness increasing with height from the surface to the top of the modeling domain (about 18 km).

Meteorological variables are estimated at the layer midpoints in WRF. The thickness of the lowest layer to the surface was about 25 m. Thus, meteorological variables near the surface were estimated at about 12.5 m above ground level. The model configuration was tested using available physics options, including: (1) planetary boundary layer processes and time-based evaluation of mixing heights; (2) cumulus parameterization; (3) four-dimensional data assimilation (FDDA) strategy; (4) horizontal and vertical diffusion; (5) advection scheme; and (6) microphysics and radiation scheme. The final choice of options was the one that best characterized meteorology in the domain.

WRF was applied for 2016 to estimate parameters required by the air quality model, including hourly wind speed and direction, temperature, humidity, cloud cover, rain and solar radiation levels. Observations were assimilated into the model during the simulations to minimize the difference between simulations and real-world measurements. Two types of nudging methods were employed (analysis and observation). The National Centers for Environmental Prediction (NCEP) North America Mesoscale (NAM) 12-km analyzed meteorological fields were used for analysis nudging as well as for initializing the model. The NCEP ADP Global Surface and Upper Air Observational Weather Data were used for observational nudging. The analysis nudging was applied to the 36-km and 12-km domains. Frequency of surface analysis nudging was every three hours, while the frequency of 3D analysis nudging was every six hours. The 3D analysis nudging of winds was performed over all model layers, but the 3D analysis nudging of temperature and humidity was limited to layers above the planetary boundary layer. The observation nudging of wind was applied to all four domains every three hours.

The WRF model was rigorously evaluated for accuracy. Observations used to evaluate WRF were taken from the EPA's Air Quality System, the BAAQMD meteorological network, and the National Climate Data Center. Hourly and daily time series plots of observed and simulated wind, temperature and humidity were generated at each observation station and compared to each other hour by hour and day by day. Simulated hourly areal plots of wind, temperature,

humidity, planetary boundary layer height, pressure and other fields were generated and quantitatively compared against observations where observations were available.

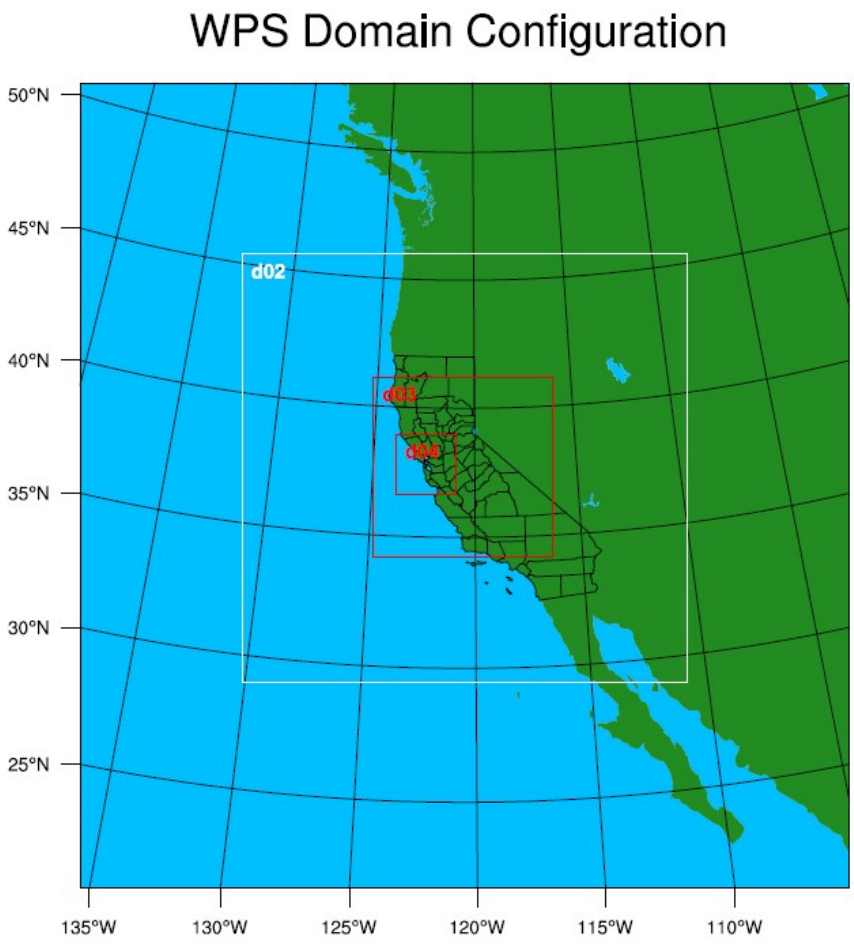


Figure 3.4: Nested WRF modeling domains.

These plots were also qualitatively evaluated for known meteorological features of the modeling domain, especially at 4-km and 1-km resolutions. These features include slope flows, channeled flows, sea breeze and low-level jet. The vertical profile of observed and simulated meteorological fields was compared at several upper air meteorological stations, including Oakland, Medford, Reno and Las Vegas, and at a temporary station established at Bodega Bay. Ramboll's METSTAT program (Emery et al., 2001) was used to statistically evaluate the performance of WRF.

The WRF model performed reasonably well in every evaluation category. The estimated bias, gross error, root mean square error (RMSE), and index of agreement (IOA) are within established criteria for acceptable model performance for every day of 2016. In other words, performance obtained from the Bay Area applications of WRF is similar or slightly better than performance obtained from applications elsewhere, available from literature. Additional information on model application and evaluation can be found in Tanrikulu et al., 2019.

3.3 Air Quality Modeling

U.S. EPA's Community Multiscale Air Quality (CMAQ) modeling system version 5.2 was used to simulate gaseous and particulate air toxics. The modeling domain is similar to that used for the District's previous air toxics modeling (Tanrikulu et al., 2009; 2011), focusing on the Bay Area at 1-km horizontal grid resolution, but extending further inland to include more surrounding regions (Figure 1.1). The vertical grid has 28 layers that extend to the lower stratosphere (~18 km) with a surface layer thickness of about 25 m. Below 1,500 m, the CMAQ layers match the WRF layers, while above 1,500 m, CMAQ layers span several meteorological model layers, , which is a common practice in air quality modeling to improve computational efficiency.

The initial and boundary conditions for the 1-km modeling domain were primarily derived from the District's recent regional air quality modeling that simulated ozone and PM over the Bay Area, San Joaquin Valley and Sacramento Valley at 4-km grid resolution (Tanrikulu et al., 2019).

The standard Statewide Air Pollution Research Council Toxics Species version 2007 (SAPRC07TC) chemistry mechanism implemented in CMAQ v5.2 includes gaseous air toxics such as formaldehyde, acetaldehyde, acrolein, benzene and 1,3-butadiene (Hutzell et al., 2012). It also separately tracks direct emissions of formaldehyde, acetaldehyde and acrolein, since these compounds include a significant proportion of chemical production in the atmosphere (i.e., "secondary" production) from the oxidation of other organic compounds.

For the Bay Area application, the standard chemistry mechanism was modified to include atmospheric mercury and chemical reactions that oxidize elemental mercury to divalent mercury in both gaseous and particle-bound forms. Gaseous elemental mercury, the predominant form in the atmosphere, is relatively inert and can be transported over long distances with an atmospheric lifetime ranging from several months to a year, while both forms of oxidized mercury (often referred to as gaseous oxidized mercury and particulate bound mercury) are quickly removed from the atmosphere via wet and dry deposition, limiting their impact to a local/regional scale (AMAP/UNEP, 2013).

Formation of methylmercury by microorganisms and its bioaccumulation in the aquatic food chain are not addressed in this study. Other toxic metals added to the mechanism for the Bay Area applications include hexavalent chromium, nickel, cadmium and lead. Explicit particle emission components from diesel exhaust were also added to separately track diesel PM. The initial and boundary concentrations for the newly added species were set to a lower bound value (a negligible, but non-zero value) to avoid potential numerical problems in the model.

The CMAQ modeling was conducted for the whole year of 2016 using the complete air toxics emissions inventories described in Section 3.1 (base case) and with all anthropogenic emissions from West Oakland removed (control case). The base case represents ambient concentrations of the air toxics for 2016 over the entire Bay Area, which will be used for model evaluation and health impact assessment. The control case estimates background levels of the air toxics in

West Oakland, which will complement local-scale air dispersion model simulations to determine detailed source-receptor relationships for the area.

The simulated annual average concentrations of gaseous air toxics are discussed in section 3.3.1, diesel PM in section 3.3.2, and toxics metals in section 3.3.3.

3.3.1 Gaseous Air Toxics

Figures 3.5 through 3.9 show annual average concentrations of five gaseous air toxics (formaldehyde, acetaldehyde, acrolein, 1,3-butadiene, and benzene) from the base case CMAQ simulation over the 1-km modeling domain. The annual average concentrations are a total of primary and secondary components for species with secondary production pathways.

The highest annual average formaldehyde concentration is simulated at Martinez in the vicinity of the Shell Refinery, reaching 15.7 $\mu g/m^3$. Other hot spots are simulated near a wastewater treatment facility in northern San Jose (8.7 $\mu g/m^3$), at San Francisco International Airport (8.2 $\mu g/m^3$), in northwestern Petaluma near a regional landfill (6.6 $\mu g/m^3$), and near Emeryville (5.1 $\mu g/m^3$). Simulated concentrations range from 2 to 5 $\mu g/m^3$ in the areas surrounding these hot spots as well as at a landfill east of Livermore, and near Richmond, Oakland International Airport, Redwood City and southern San Jose. Similar concentrations are simulated along the Delta, the I-580 corridor in Livermore, and the I-880 corridor between San Leandro and San Jose.

The annual average acetaldehyde concentrations are highest at San Francisco International Airport (2.7 $\mu g/m^3$). Concentrations are also high (above 0.8 $\mu g/m^3$) on the east side of the Bay Bridge, at Oakland International Airport, and in San Jose. Portions of I-80, I-880, I-680, I-101, and I-580 have elevated concentrations.

While formaldehyde and acetaldehyde in most of the modeling domain are largely due to secondary production, hot spot areas tend to exhibit relatively higher primary fractions, indicating significant contributions of local sources (see Appendix B for a discussion of primary vs. secondary toxics formation).

Concentration patterns of acrolein and 1,3-butadiene are similar, with both showing the highest annual average concentration at San Francisco International Airport (1.1 $\mu g/m^3$ for acrolein and 0.9 $\mu g/m^3$ for 1,3-butadiene). Secondary production pathways of acrolein include atmospheric oxidation of 1,3-butadiene.

For benzene, annual average concentrations above 1 $\mu g/m^3$ occur in Richmond, Martinez, northern San Jose, Mountain View, and at the San Francisco International Airport.

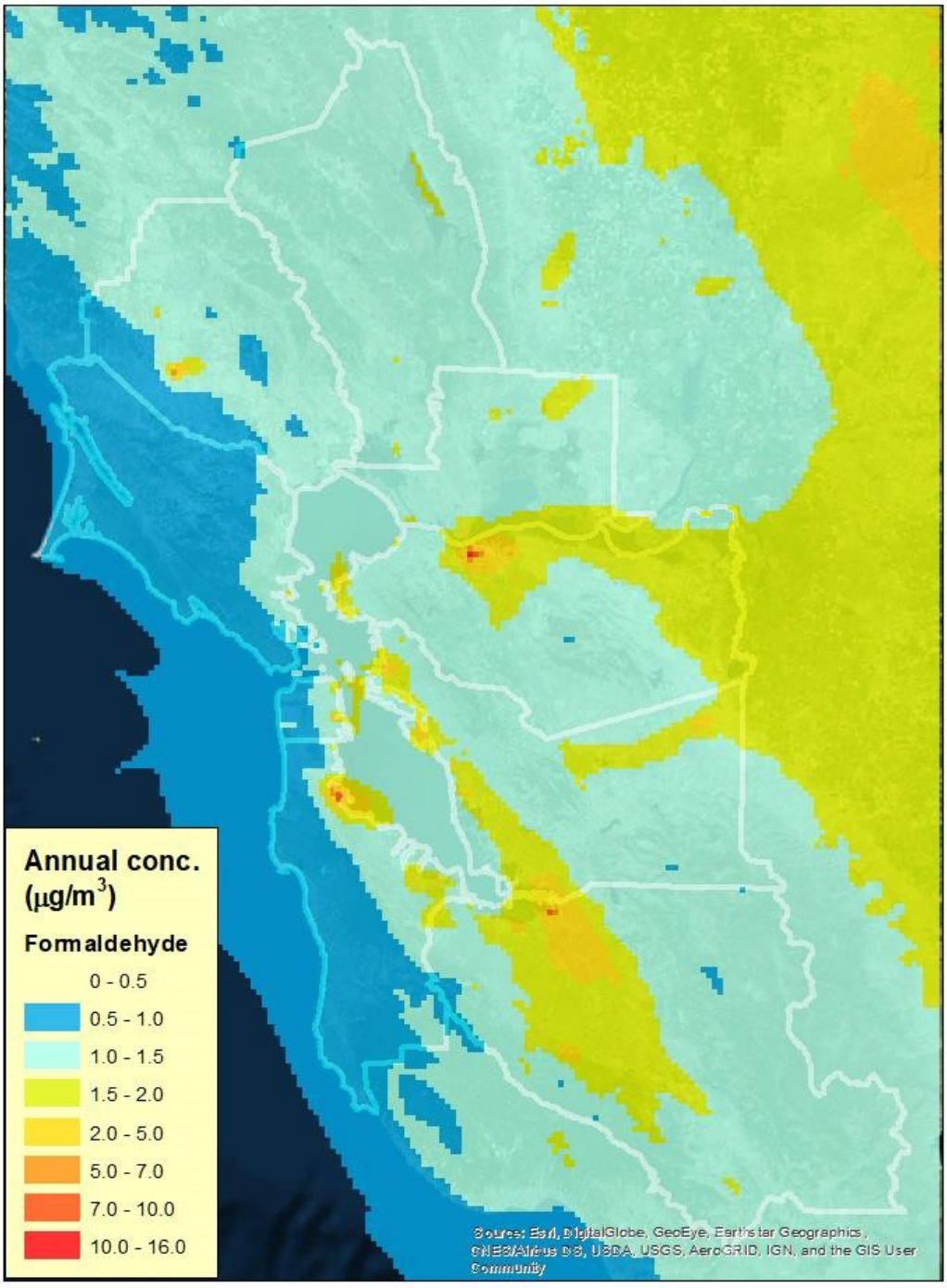


Figure 3.5: Annual average simulated formaldehyde concentrations for 2016.

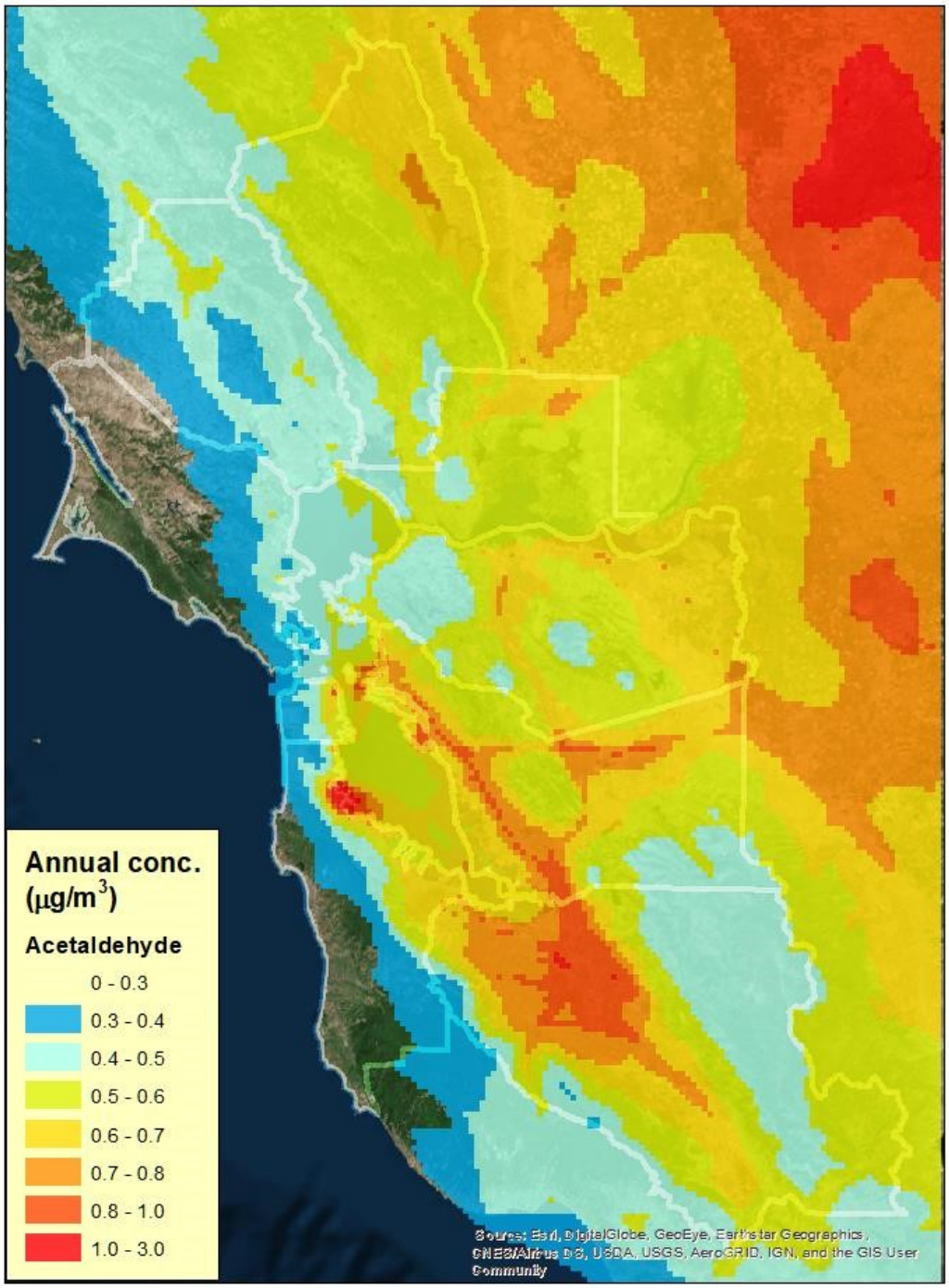
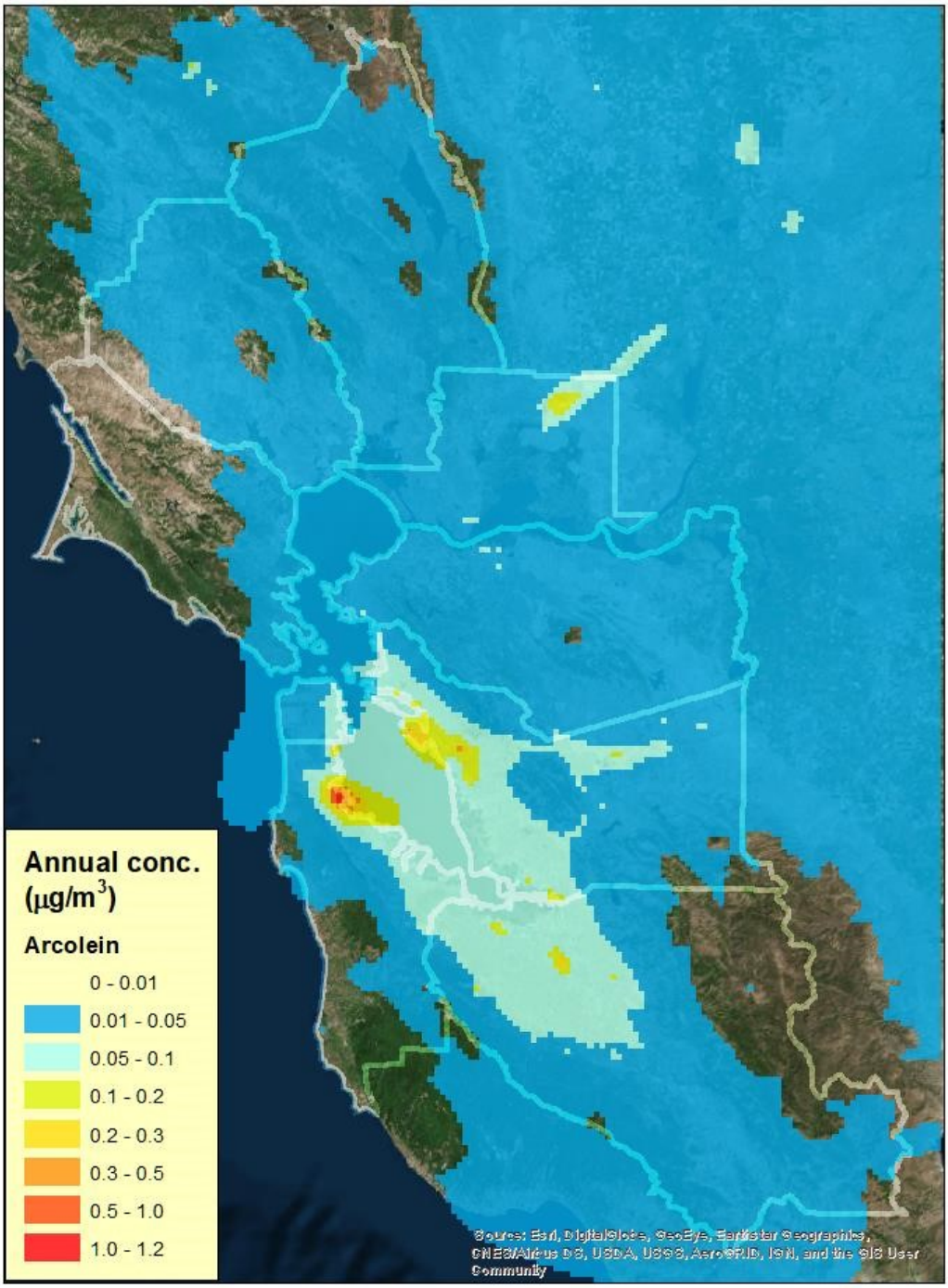
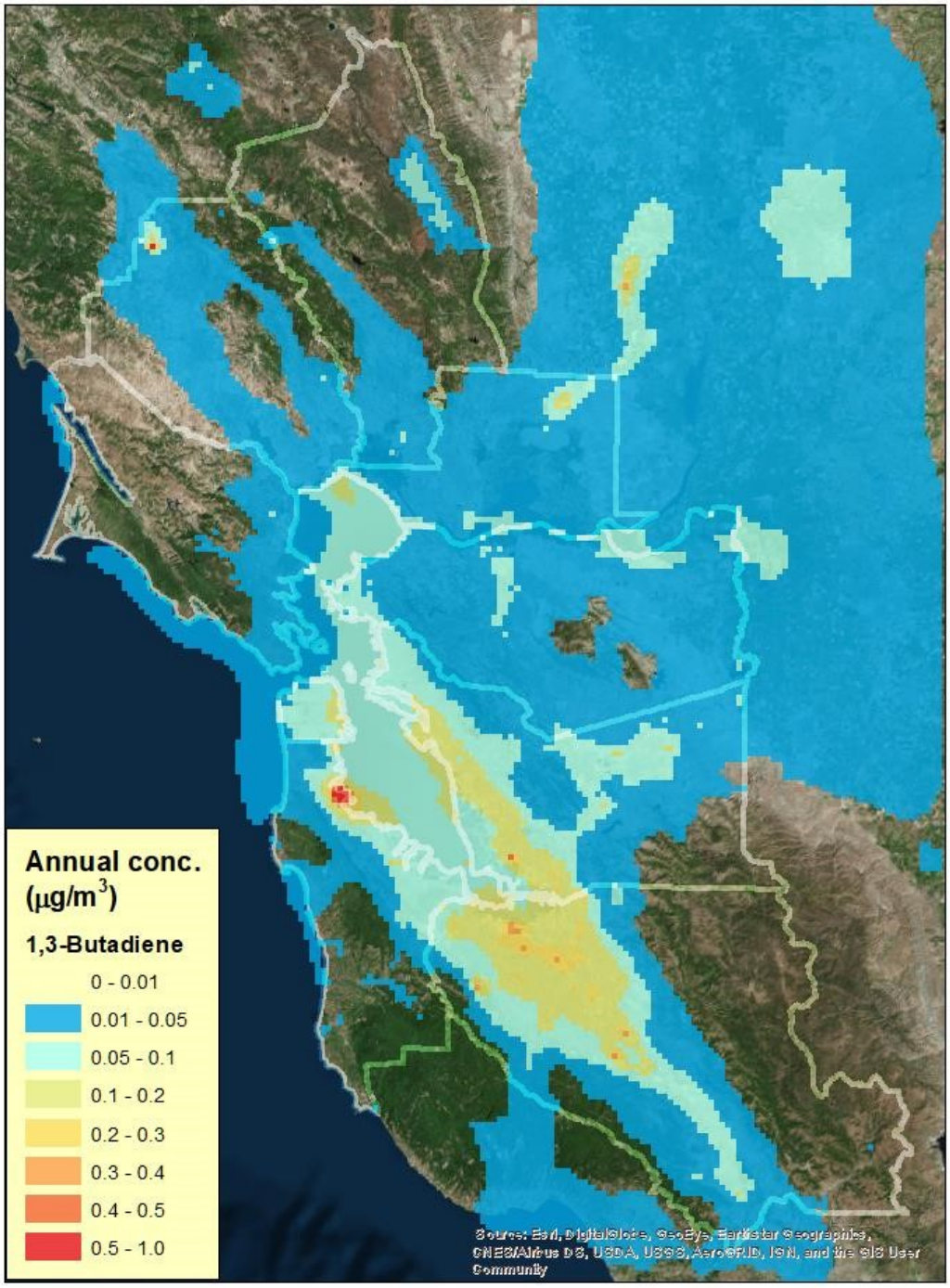


Figure 3.6: Annual average simulated acetaldehyde concentrations for 2016.



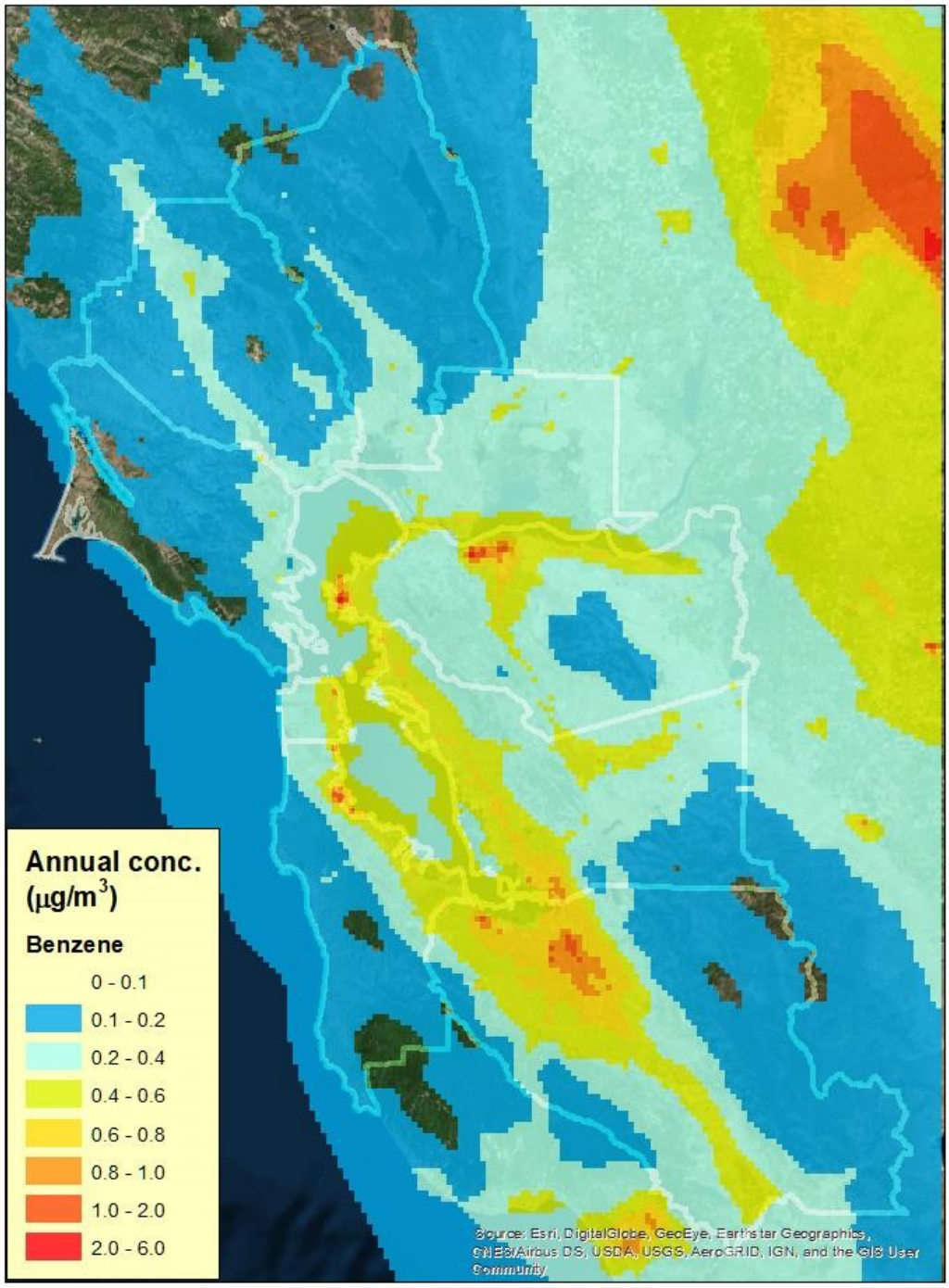
Maximum: 1.1

Figure 3.7: Annual average simulated acrolein concentrations for 2016.



Maximum: 0.9

Figure 3.8: Annual average simulated 1,3 butadiene concentrations for 2016.



Maximum: 5.5

Figure 3.9: Annual average simulated benzene concentrations for 2016.

3.3.2 Diesel PM

Figure 3.10 shows the annual average concentrations of diesel PM. The highest concentration is 2.7 $\mu g/m^3$ at San Francisco International Airport. Concentrations are also high (above 1 $\mu g/m^3$) along the Bay Area ship routes, peaking at 2.6 $\mu g/m^3$ near Yerba Buena Island, as well as in downtown Oakland and San Jose International Airport. Concentrations at Oakland International Airport reach 0.9 $\mu g/m^3$. Concentrations along I-880 between Oakland and San Jose range mostly from 0.6 to 0.8 $\mu g/m^3$ with some grid cells having concentrations above 0.8 $\mu g/m^3$. The northern edge of San Pablo Bay, a portion of I-580 around Dublin, the Dumbarton Bridge, and a portion of US 101 north of Sunnyvale also show concentrations of 0.6 to 0.8 $\mu g/m^3$.

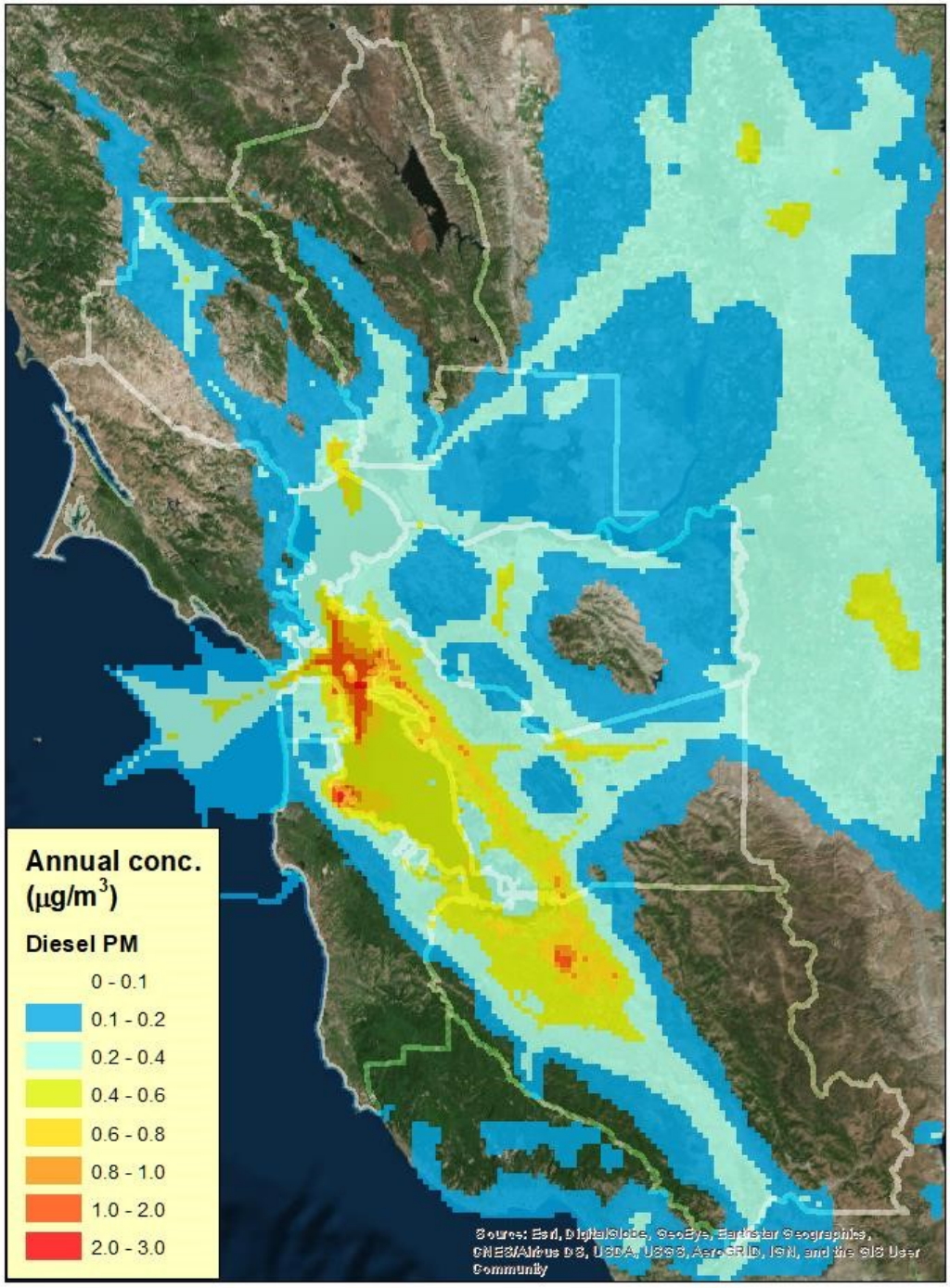


Figure 3.10: Simulated annual average diesel PM concentrations for 2016.

3.3.3 Toxic Metals

Five toxics metals (hexavalent chromium, cadmium, lead, nickel, and mercury) were simulated, and their annual average concentrations were estimated. Emission estimates for these metals were taken from the EPA's 2014 National Air Toxics Assessment (NATA) inventory and may not

be representative of Bay Area emission levels for 2016. Therefore, the estimated annual average concentrations are considered to be preliminary. A summary of simulated metal concentrations is presented in Appendix C.

4. Model Performance Evaluation

The simulated air toxics concentrations were compared against available observations for the purpose of evaluating the CMAQ model. The District collects ambient air toxics data at 20 air monitoring stations, as discussed in Section 2.1. Locations of these stations are shown Figure 4.1. Samples of elemental carbon (EC) were used as a surrogate for evaluating diesel PM since diesel PM cannot be directly distinguished in the measurements.

Figure 4.2 shows scatter plots of observed vs. modeled formaldehyde and acetaldehyde concentrations at the San Jose-Jackson Street air monitoring station. The model tends to underestimate concentrations of these species but shows reasonable agreement with observations, aside from a few outliers.

Figure 4.3 shows scatter plots of observed vs. modeled benzene and 1,3-butadiene at the 20 toxics monitoring sites. Again, the model performance is reasonable but with slight underestimation. The underestimation biases at Oakland West are somewhat higher than the overall biases across all 20 sites, but agreement between the model and observations is still reasonable.

Figure 4.4 presents scatter plots of observed EC vs. modeled diesel PM. At Oakland West and San Jose-Jackson Street, modeled diesel PM concentrations are generally higher than observed EC. Assuming the predominant source of observed EC is diesel exhaust, this is expected because simulated diesel PM consists of PM components other than EC (e.g., organic carbon).

The modeled diesel PM tends to be lower than observed EC at Vallejo and Livermore, especially in winter and fall, suggesting EC sources other than diesel exhaust are influencing these sites (e.g., wood smoke). These discrepancies are also an indication of pollutant transport from outside the region defined in the modeling domain. While observations included the impact of such transport, the modeled concentrations did not because no diesel PM concentrations are specified along the model boundary. Overall, modeled diesel PM and observed EC are close enough to demonstrate their correlation.

Figure 4.5 compares observed and modeled concentrations of nickel, cadmium, lead and particulate-bound mercury. The model greatly underestimates the observed metal concentrations, indicating substantial uncertainty in emissions estimates for metals. This finding indicates that modeled cancer risks associated with toxic metals are also underestimated.

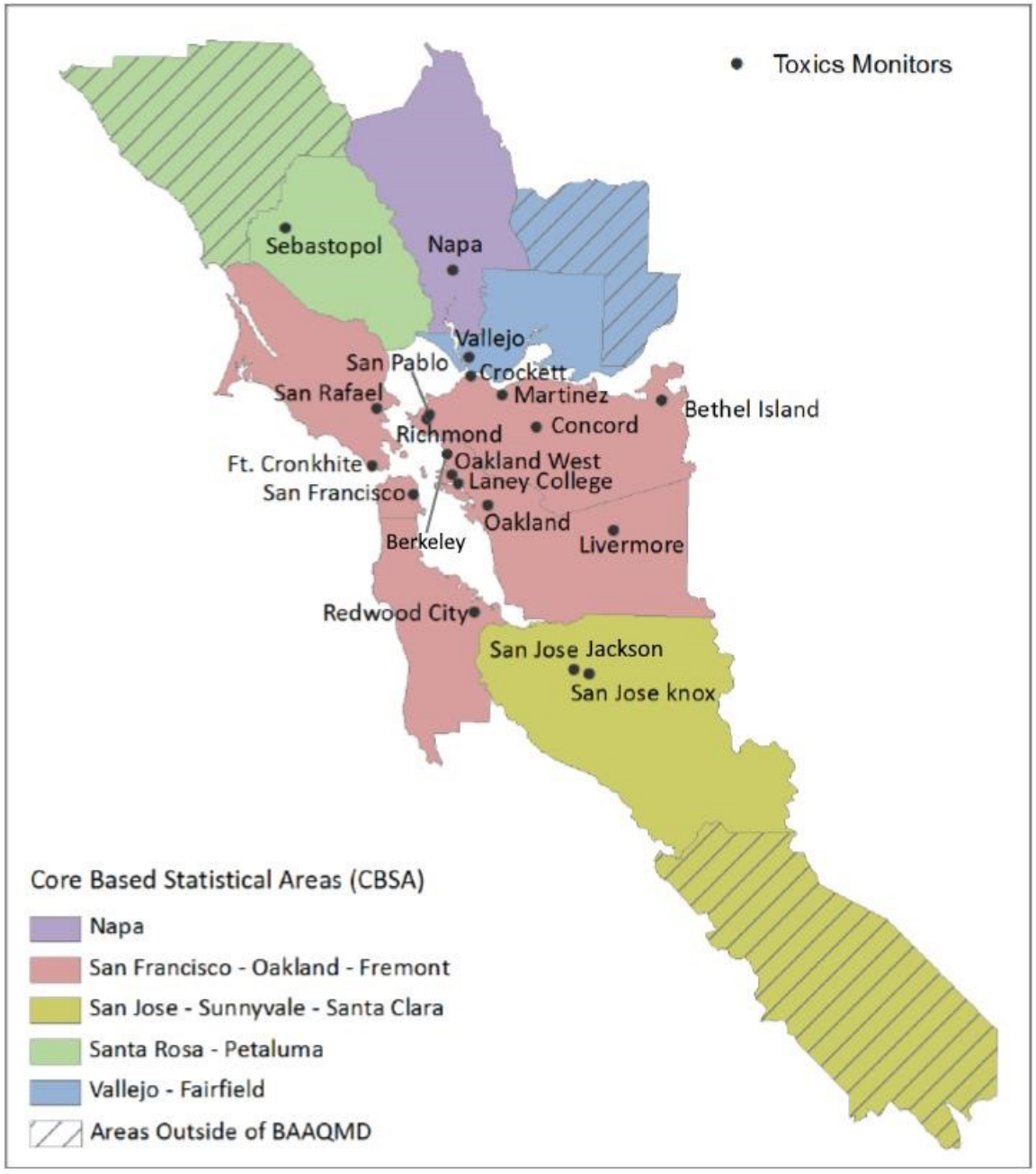
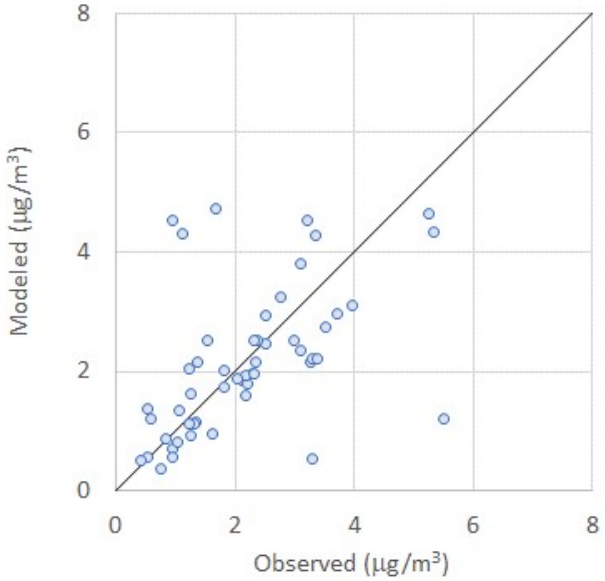


Figure 4.1: Map of BAAQMD toxics monitoring sites in 2016; reprinted from Knoderer et al. (2017). The location of the Berkeley site, which began operation on July 1, 2016, was added.

(a) Formaldehyde

NMB	-1.8%
NME	35%



(b) Acetaldehyde

NMB	-31%
NME	46%

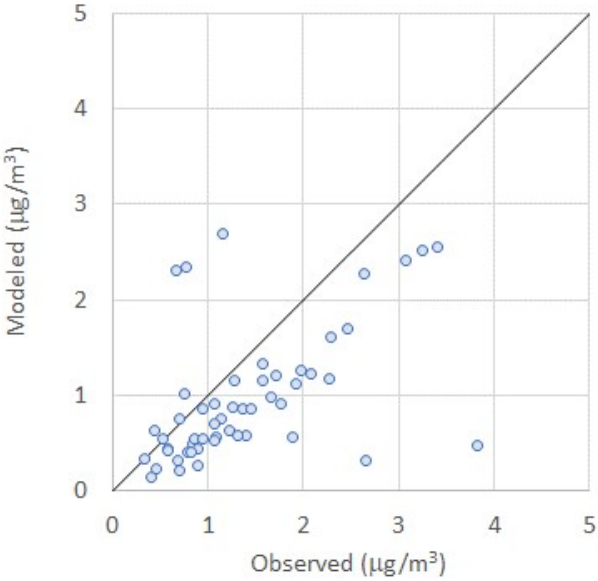


Figure 4.2: Observed vs. modeled 24-hr average concentrations of formaldehyde and acetaldehyde at the San Jose-Jackson St. site. Performance statistics shown are normalized mean bias (NMB) and normalized mean error (NME).

(a) Benzene

	All Sites	Oakland West
NMB	-16%	-29%
NME	40%	34%

(b) 1,3-butadiene

	All Sites	Oakland West
NMB	-5.7%	-28%
NME	44%	36%

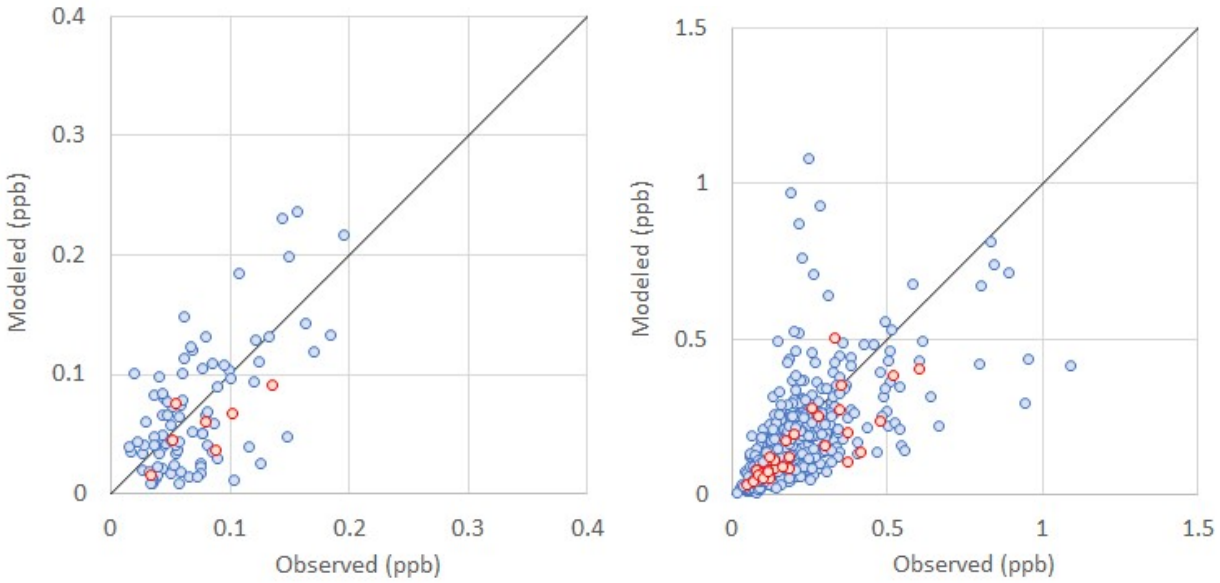


Figure 4.3: Observed vs. modeled 24-hr average concentrations of benzene and 1,3-butadiene at 20 toxics monitoring sites (values at the Oakland West site are shown in red). Normalized mean bias (NMB) and normalized mean error (NME) were calculated over all 20 sites, as well as at the Oakland West site alone.

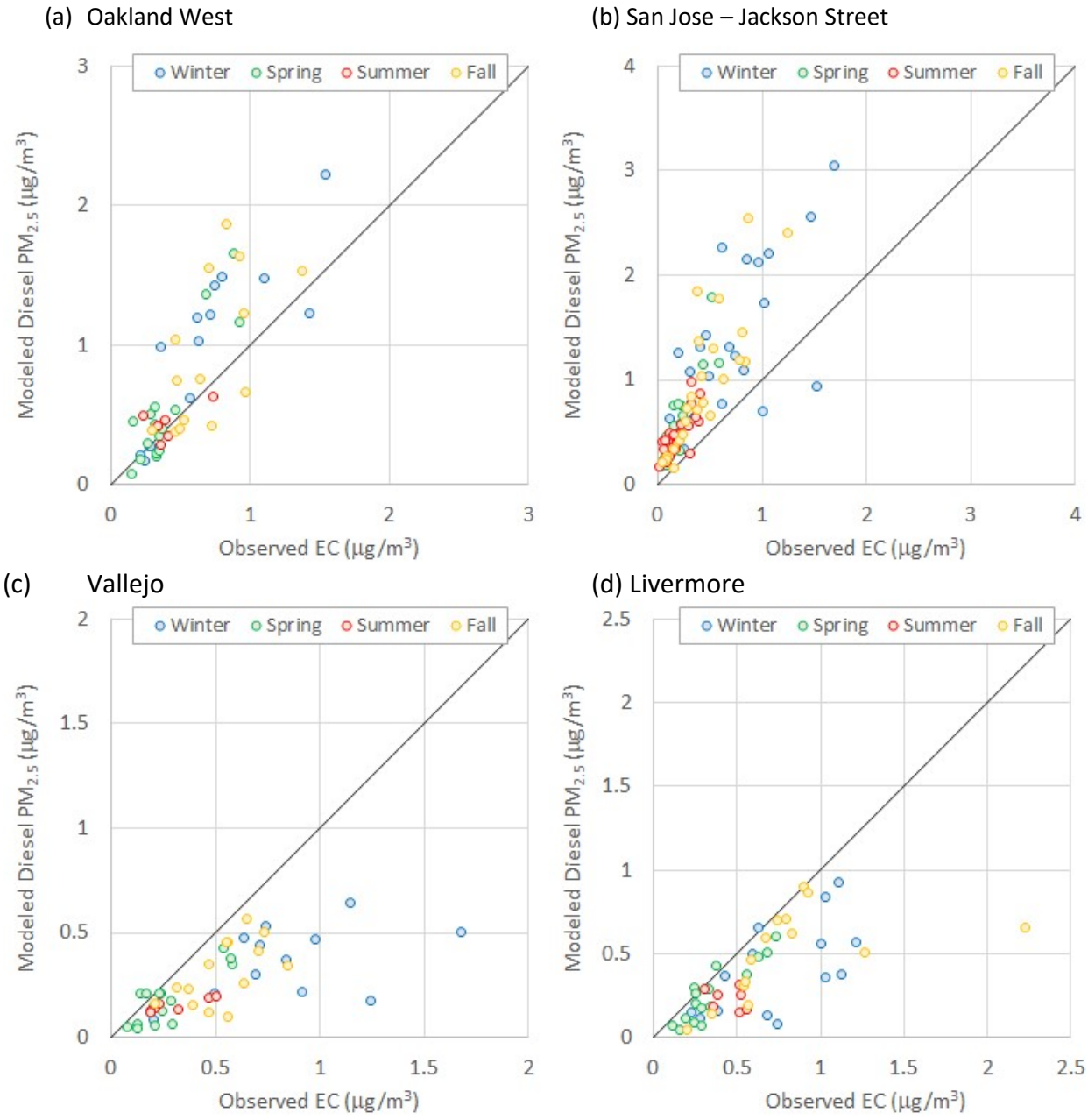
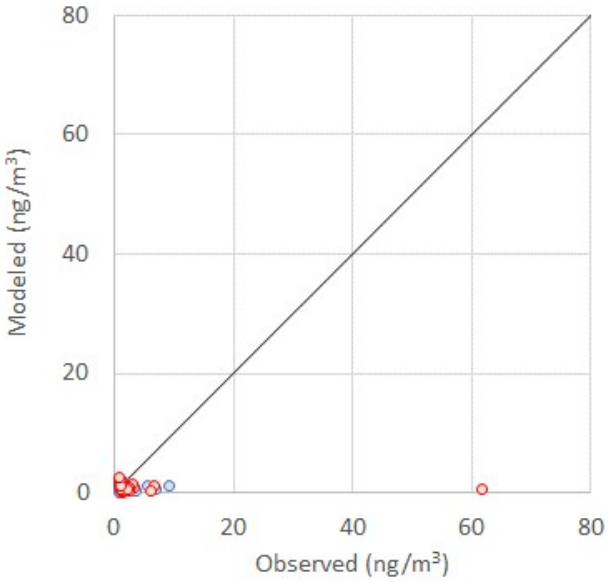
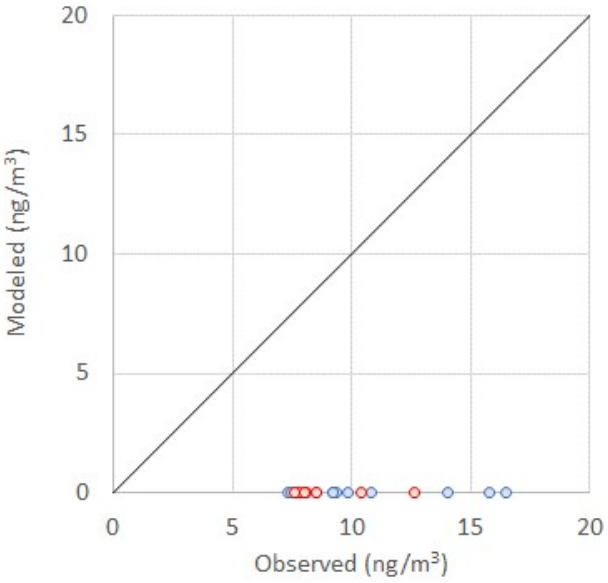


Figure 4.4: 24-hr average concentrations of observed $PM_{2.5}$ EC vs. modeled diesel $PM_{2.5}$ at Oakland West, San Jose-Jackson St., Vallejo and Livermore. Winter, spring, summer, and fall are defined as January-February-December, March-April-May, June-July-August, and September-October-November, respectively.

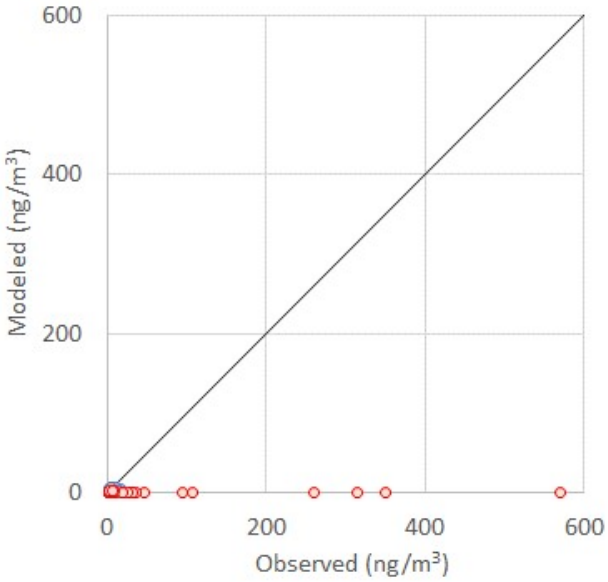
(a) Nickel



(b) Cadmium



(c) Lead



(d) Particulate bound mercury

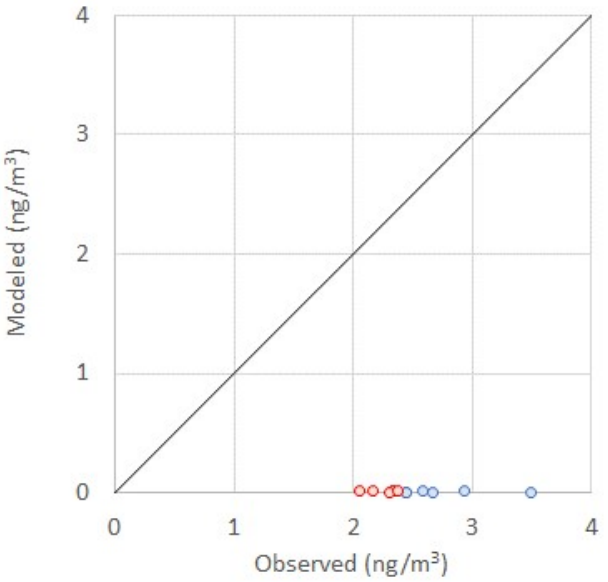


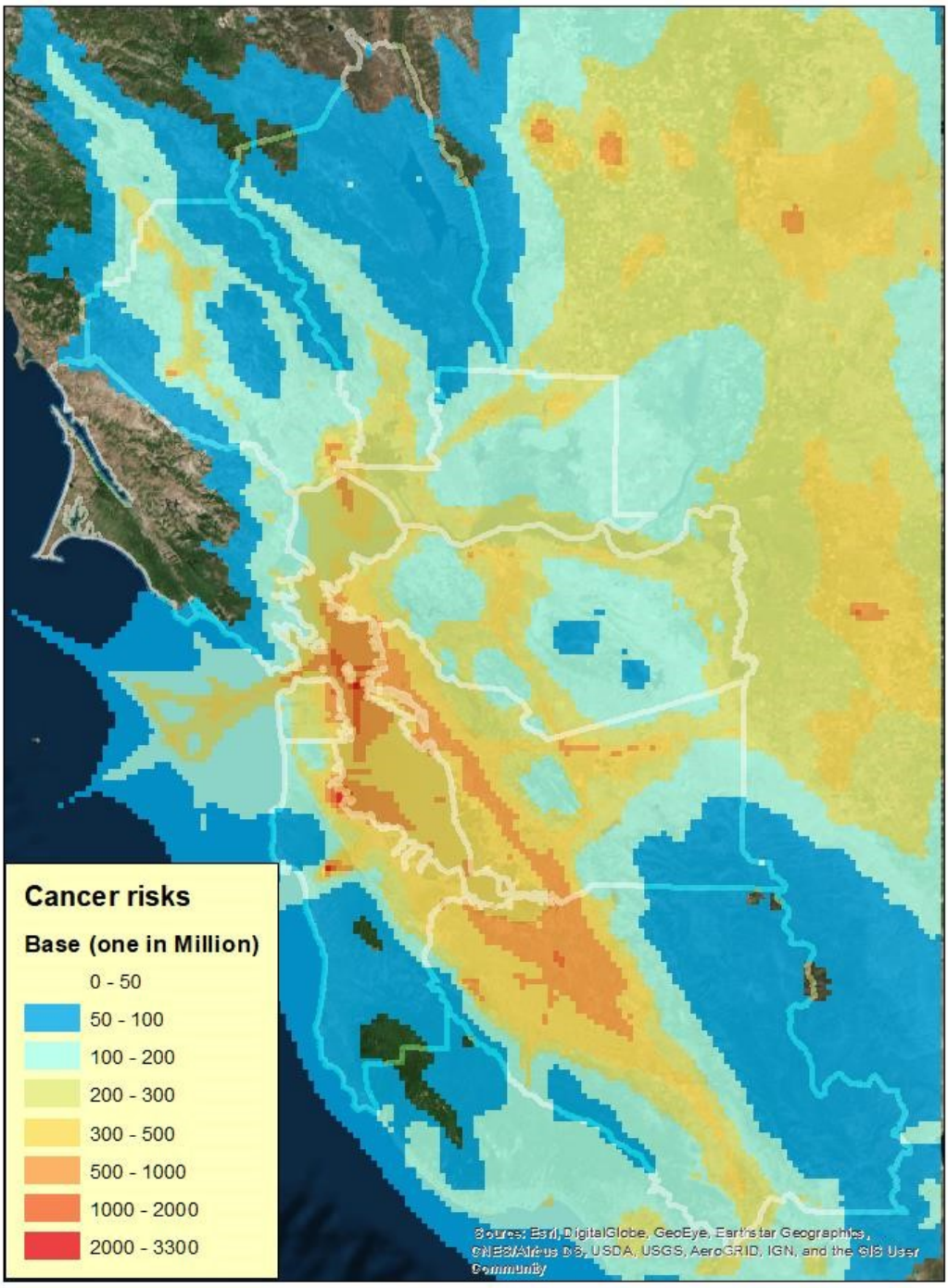
Figure 4.5: Observed vs. modeled 24-hr average concentrations of $PM_{2.5}$ nickel, cadmium, lead and mercury at Oakland West, Vallejo, Livermore, and San Jose-Jackson St. (values at the Oakland West site are shown in red).

5. Risk Evaluation

As described in Section 1.1, cancer risk estimates for the modeled air toxics were calculated using inhalation unit risk factors. Cancer risk associated with modeled air toxics was calculated by multiplying annual average concentrations of each air toxic compound with its respective unit risk factor (Table 1.1) and then the resulting values were summed. The results were expressed as the number of expected excess cancer incidences per million people and are shown in Figure 5.1.

The highest number of estimated excess cancer incidences are modeled to occur east of Half Moon Bay (around 3,200 per million) which coincides with the location having the highest concentration of hexavalent chromium.[3] Other than that, the spatial distribution of cancer risk in the Bay Area is similar to that of diesel PM concentrations (Figure 3.10), with the next highest cancer risks occurring at the San Francisco International Airport (about 2,600 per million). The number of estimated excess cancer incidences ranges from 1,000 to 2,000 per million at San Jose International Airport as well as in the area surrounding San Francisco International Airport. The excess cancer incidence estimates along the I-880 corridor connecting Oakland and San Jose, and along the US-101 corridor between San Jose and Palo Alto range from 500 to 1,000 per million.

[3] The largest source of hexavalent chromium emissions in the emissions inventory is mineral processes, an area source that is spatially distributed based on the location of sand and gravel facilities.



Maximum: 3210

Figure 5.1: Expected excess cancer incidences per million.

6. Summary and Discussion

A total of 11 air toxics were simulated for 2016 over the entire Bay Area using the US EPA's CMAQ model at 1-km grid. Toxic included diesel particulate matter (DPM), 5 toxic gases (acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde), and 5 trace metals (cadmium, chromium VI, lead, mercury, and nickel). Excess cancer risks were estimated for individual air toxics species as well as for all species combined. Previous analyses have indicated that DPM and the 5 toxic gases cumulatively account for more than 90% of toxic air contaminant emissions in the Bay Area (Tanrikulu et al., 2011).

Toxics measurement stations are sparsely distributed in the Bay Area, and samples are collected on a schedule of either 1 in 6 days or 1 in 12 days. A significant number of toxics measurements are below the instrument minimum detection limit, which makes it difficult to develop a conceptual model of air toxics formation and transport in the Bay Area. Nevertheless, comparisons between simulated and the available observed concentrations show reasonable agreement.

The District simulated DPM and the same five toxics gases for 2005 (Tanrikulu et al., 2009) and with projected emissions for 2015 (Tanrikulu et al., 2011) and estimated associated excess cancer risk. Both simulations were performed with the Comprehensive Air Quality Model with Extensions (CAMx). Because of limited computational resources, the prior simulations were conducted for only 2 weeks in January and 2 weeks in August.

Findings of this recent simulation were compared against the previous simulations and the recent simulations are determined to be improved estimates. Comparison between the new and old simulations, however, was not discussed in this report because the old simulations did not cover the entire year and their emission estimates relied on an older version of air toxics speciation.

Future related work includes updates to the spatial distribution of emissions data and to estimates of residential woodburning emissions. Recent PM modeling (Tanrikulu et al., 2019) showed that woodburning emissions may be significantly underestimated in the North Bay. As a result, concentrations of EC, formaldehyde and acetaldehyde, as well as associated cancer risk, may be underestimated.[4]

[4] Note that the CMAQ modeling does not account for emissions from wildfires, which also have health impacts. However, the episodic and variable nature of these emissions present challenges for evaluating long-term exposures.

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Appendix A – Toxics Emissions Inventory

This appendix provides additional information on the emissions inventory used for the 2016 air toxics modeling, including summary tables and emissions density plots (note that tables and plots for DPM are provided in the main body of the report).

A1. Gaseous Species

Five gaseous air toxics were modeled explicitly in CMAQ: acetaldehyde, acrolein, benzene, 1,3-butadiene, and formaldehyde. Tables A1 through A5 show emissions of these species by geographic area and source sector. Figures A1 through A5 show the spatial distribution of these species across the 1-km modeling domain.

Table A1: Summary of 2016 acetaldehyde emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.04	0.08	0.30	0.03	0.45
Contra Costa	0.03	0.04	0.14	0.02	0.23
Marin	0.01	0.02	0.03	0.00	0.06
Napa	0.00	0.01	0.03	0.00	0.05
San Francisco	0.02	0.09	0.07	0.00	0.18
San Mateo	0.02	0.19	0.07	0.02	0.29
Santa Clara	0.04	0.06	0.23	0.02	0.35
Solano	0.01	0.04	0.06	0.01	0.11
Sonoma	0.01	0.03	0.08	0.00	0.12
BAAQMD Subtotal	*0.18*	*0.55*	*1.01*	*0.09*	*1.84*
Non-BAAQMD Counties	0.13	0.16	0.69	0.45	1.44
Domain Total	**0.31**	**0.72**	**1.71**	**0.54**	**3.28**

Table A2: Summary of 2016 acrolein emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.03	0.02	0.03	0.05	0.13
Contra Costa	0.02	0.00	0.01	0.01	0.05
Marin	0.00	0.00	0.00	0.00	0.01
Napa	0.00	0.00	0.00	0.00	0.01
San Francisco	0.01	0.00	0.01	0.00	0.02
San Mateo	0.01	0.08	0.01	0.01	0.11
Santa Clara	0.02	0.02	0.02	0.01	0.06
Solano	0.01	0.02	0.00	0.01	0.03
Sonoma	0.01	0.00	0.01	0.00	0.02
BAAQMD Subtotal	*0.11*	*0.14*	*0.09*	*0.09*	*0.43*
Non-BAAQMD Counties	0.04	0.02	0.06	0.11	0.23
Domain Total	**0.15**	**0.16**	**0.15**	**0.20**	**0.66**

Table A3: Summary of 2016 benzene emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.19	0.10	0.39	0.20	0.89
Contra Costa	0.20	0.08	0.25	0.49	1.01
Marin	0.03	0.04	0.08	0.03	0.18
Napa	0.03	0.02	0.04	0.01	0.10
San Francisco	0.06	0.05	0.09	0.02	0.22
San Mateo	0.09	0.11	0.15	0.09	0.43
Santa Clara	0.21	0.11	0.40	0.26	0.98
Solano	0.05	0.03	0.08	0.07	0.23
Sonoma	0.05	0.03	0.11	0.01	0.21
BAAQMD Subtotal	*0.90*	*0.57*	*1.60*	*1.19*	*4.25*
Non-BAAQMD Counties	0.96	0.30	0.90	5.57	7.73
Domain Total	**1.86**	**0.87**	**2.50**	**6.76**	**11.99**

Table A4: Summary of 2016 1,3-butadiene emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.07	0.10	0.04	0.05	0.25
Contra Costa	0.02	0.08	0.02	0.02	0.14
Marin	0.00	0.04	0.01	0.00	0.05
Napa	0.00	0.03	0.00	0.01	0.04
San Francisco	0.01	0.05	0.01	0.00	0.07
San Mateo	0.01	0.10	0.01	0.02	0.14
Santa Clara	0.14	0.10	0.04	0.03	0.30
Solano	0.01	0.03	0.01	0.01	0.05
Sonoma	0.01	0.03	0.01	0.02	0.07
BAAQMD Subtotal	*0.28*	*0.56*	*0.14*	*0.15*	*1.13*
Non-BAAQMD Counties	0.08	0.20	0.08	0.20	0.56
Domain Total	**0.36**	**0.76**	**0.22**	**0.35**	**1.69**

Table A5: Summary of 2016 formaldehyde emissions (tons/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.09	0.24	0.22	0.68	1.23
Contra Costa	0.19	0.12	0.11	1.79	2.21
Marin	0.02	0.05	0.03	0.06	0.16
Napa	0.01	0.04	0.02	0.07	0.14
San Francisco	0.05	0.25	0.05	0.20	0.54
San Mateo	0.06	0.60	0.06	0.18	0.88
Santa Clara	0.10	0.19	0.18	1.02	1.49
Solano	0.07	0.12	0.04	0.10	0.33
Sonoma	0.03	0.08	0.06	0.32	0.48
BAAQMD Subtotal	*0.60*	*1.68*	*0.76*	*4.42*	*7.47*
Non-BAAQMD Counties	0.43	0.61	0.49	1.56	3.09
Domain Total	**1.04**	**2.29**	**1.25**	**5.97**	**10.55**

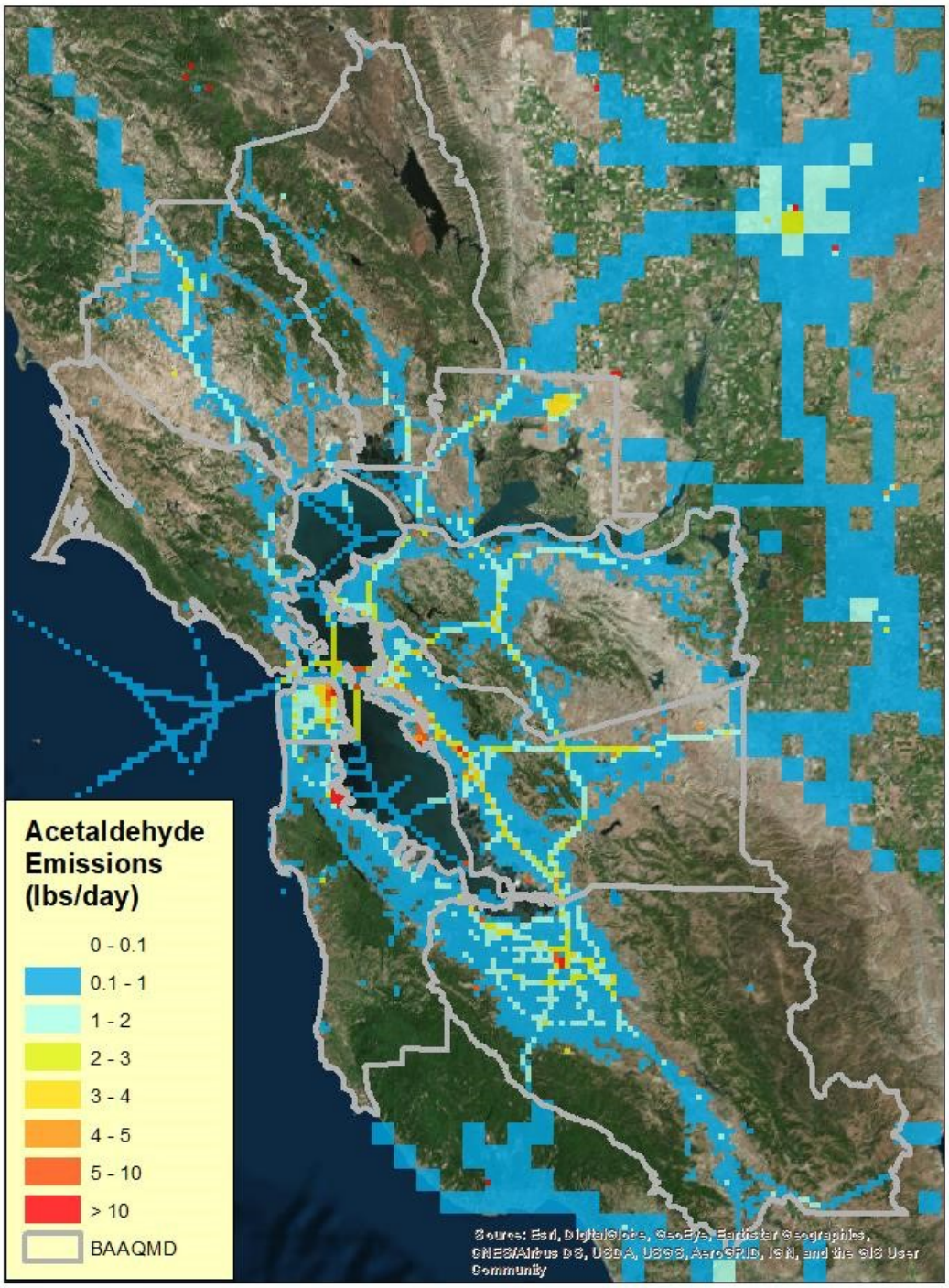


Figure A1: Spatial distribution of 2016 annual average acetaldehyde emissions for the 1-km modeling domain.

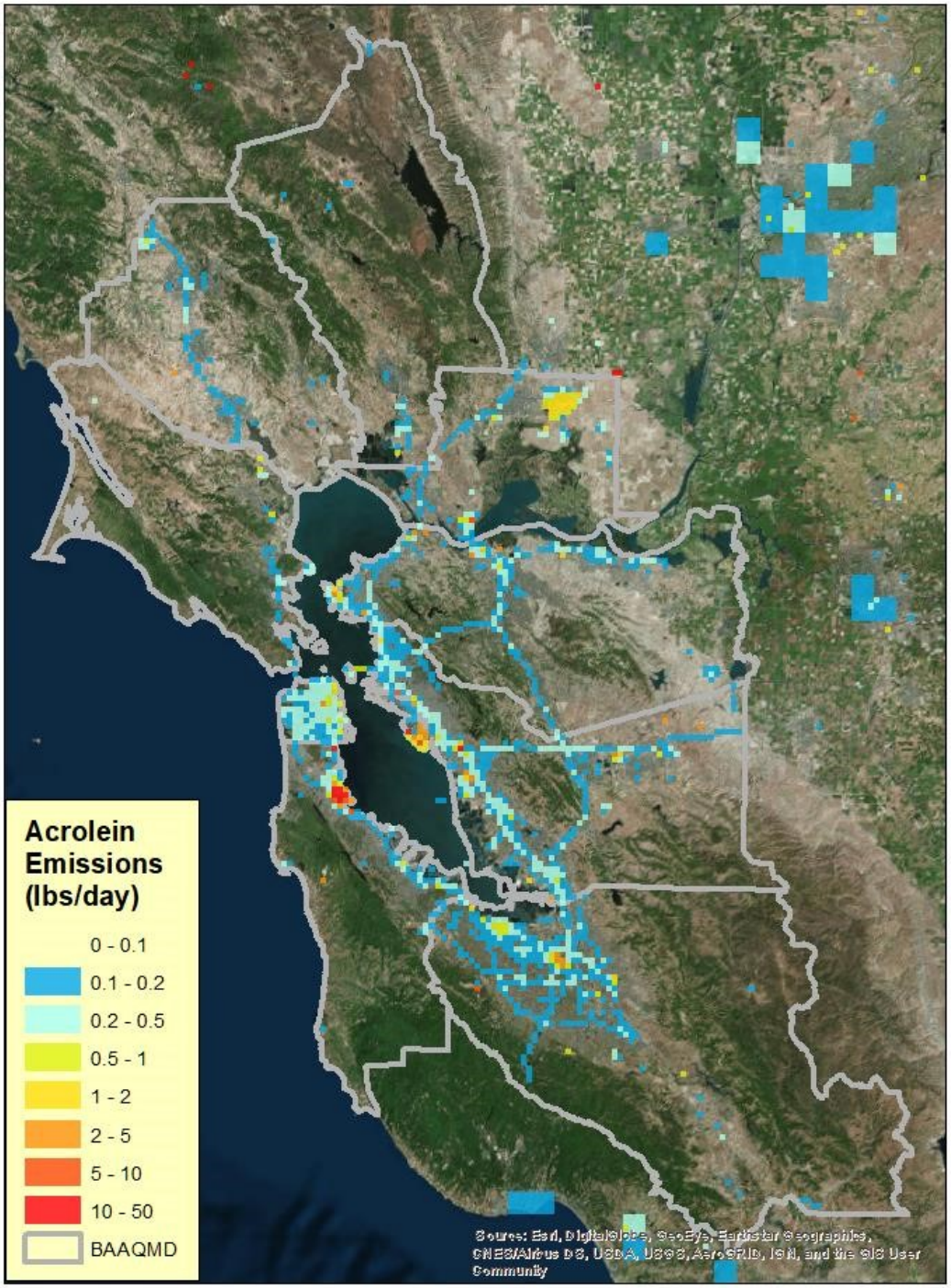


Figure A2: Spatial distribution of 2016 annual average acrolein emissions for the 1-km modeling domain.

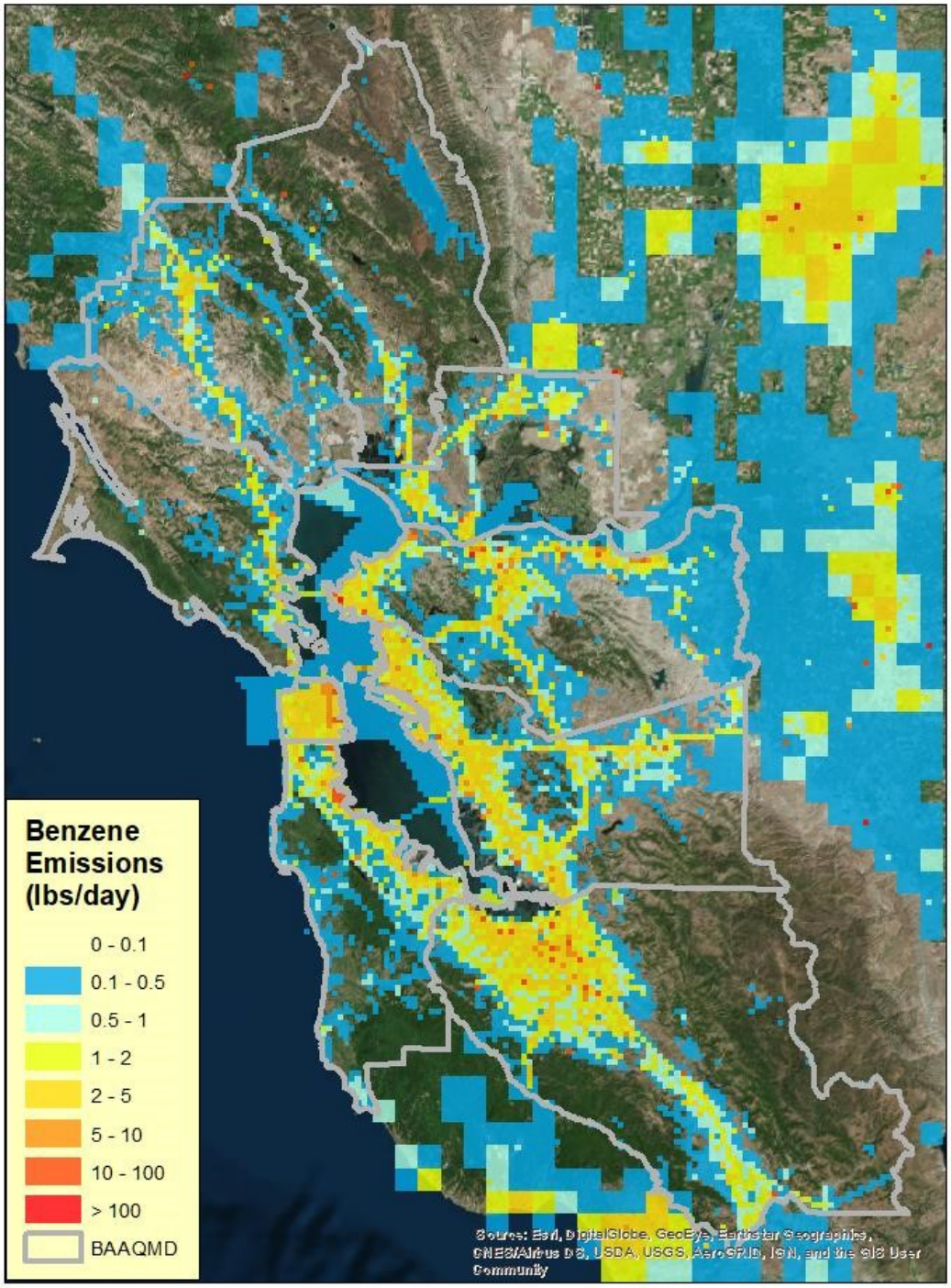


Figure A3: Spatial distribution of 2016 annual average benzene emissions for the 1-km modeling domain.

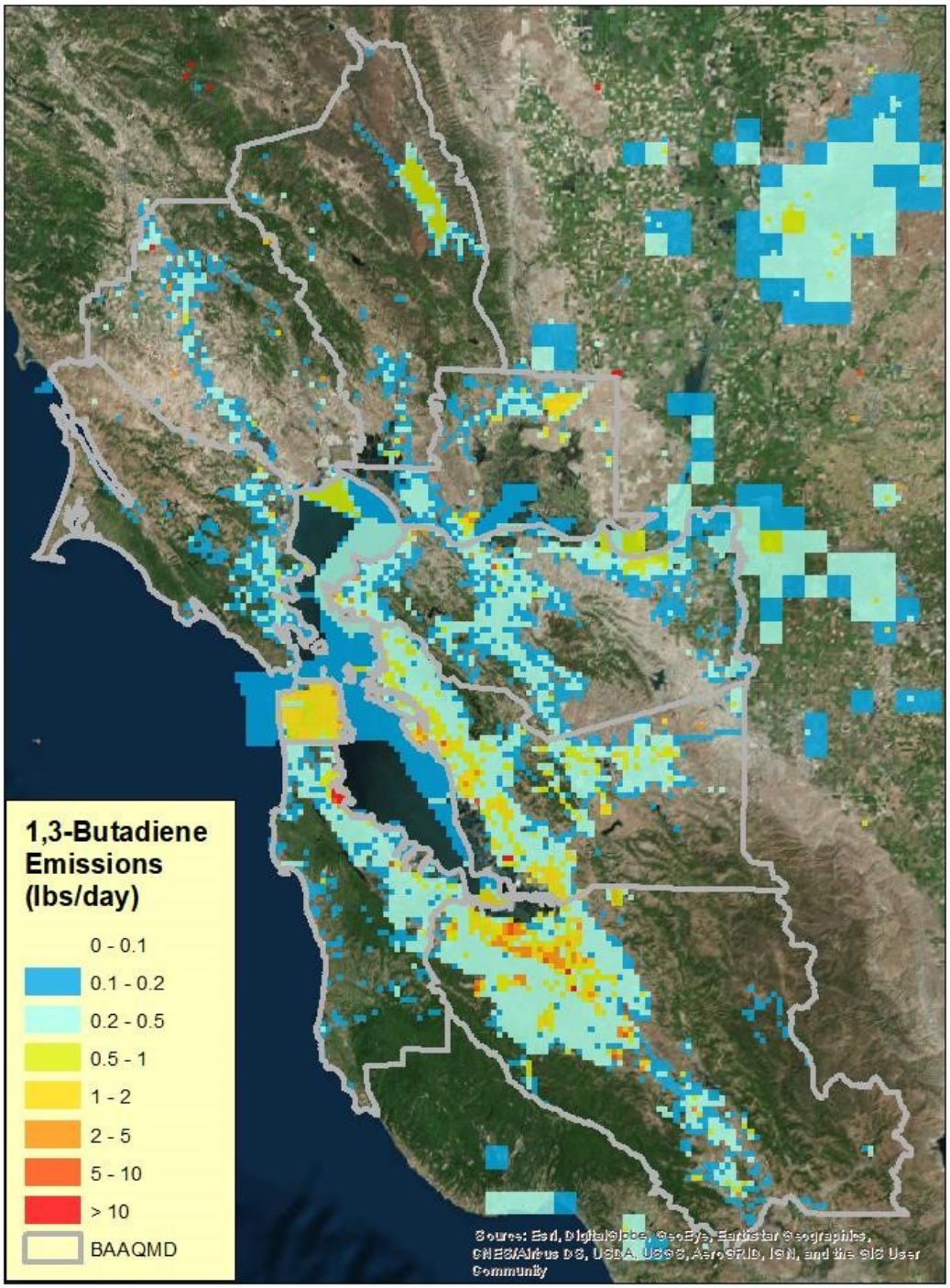


Figure A4: Spatial distribution of 2016 annual average 1,3-butadiene emissions for the 1-km modeling domain.

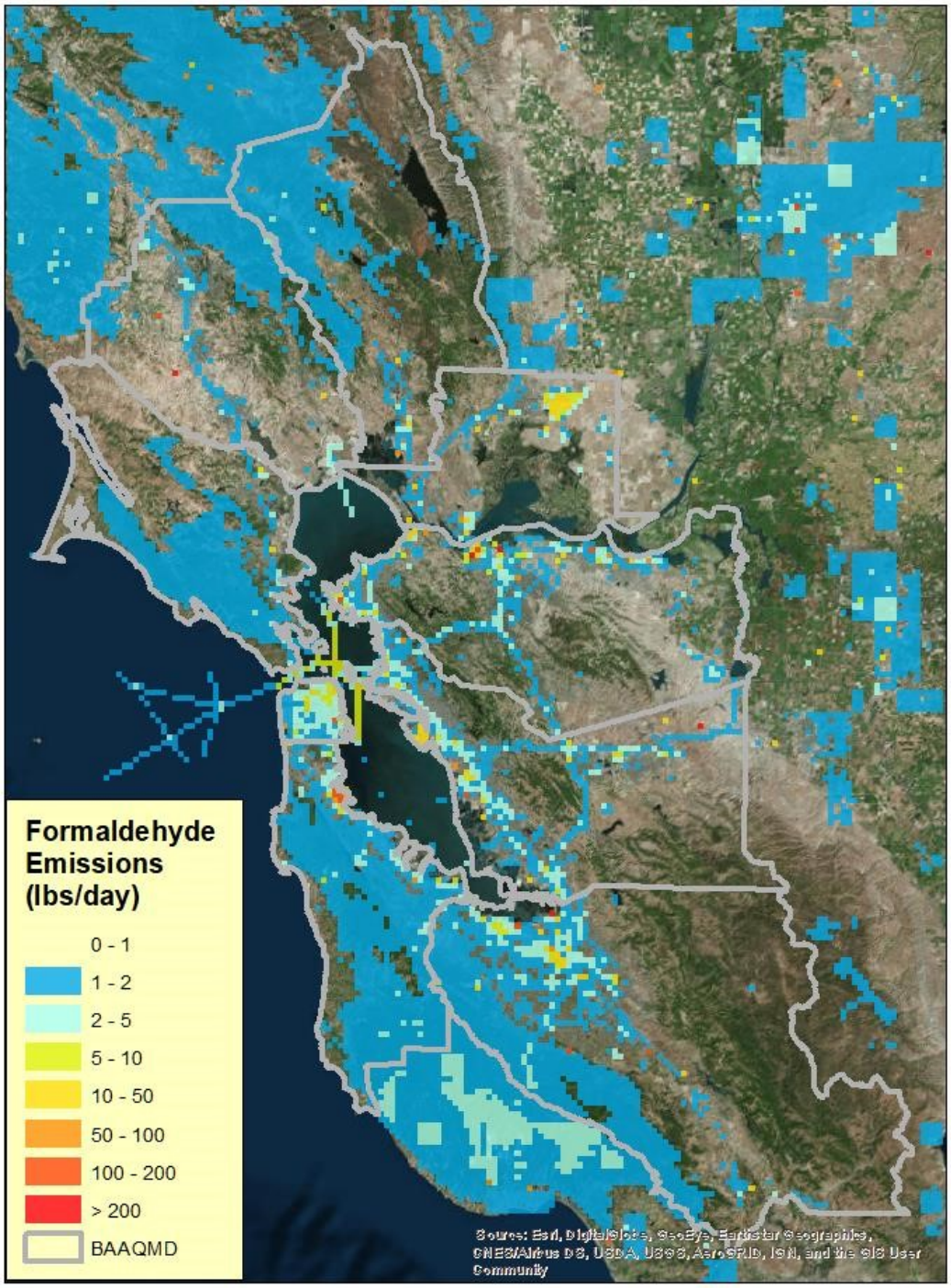


Figure A5: Spatial distribution of 2016 annual average formaldehyde emissions for the 1-km modeling domain.

A2. Trace Metals

Five trace metals were modeled explicitly in CMAQ: cadmium, chromium VI, lead, mercury, and nickel. Tables A6 through A10 show emissions of these species by geographic area and source

sector. Figures A6 through A10 show the spatial distribution of these species across the 1-km modeling domain.

Table A6: Summary of 2016 cadmium emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.03	0.00	0.00	0.00	0.04
Contra Costa	0.03	0.00	0.00	0.01	0.05
Marin	0.01	0.00	0.00	0.00	0.01
Napa	0.01	0.00	0.00	0.00	0.01
San Francisco	0.02	0.02	0.00	0.00	0.04
San Mateo	0.02	0.00	0.00	0.00	0.02
Santa Clara	0.09	0.00	0.00	0.00	0.09
Solano	0.01	0.00	0.00	0.00	0.02
Sonoma	0.02	0.00	0.00	0.00	0.02
BAAQMD Subtotal	*0.24*	*0.04*	*0.00*	*0.02*	*0.29*
Non-BAAQMD Counties	0.13	0.01	0.00	0.16	0.31
Domain Total	**0.36**	**0.05**	**0.00**	**0.19**	**0.60**

Table A7: Summary of 2016 chromium VI emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.05	0.00	0.01	0.00	0.07
Contra Costa	0.01	0.00	0.01	0.12	0.14
Marin	0.01	0.00	0.00	0.00	0.01
Napa	0.00	0.00	0.00	0.00	0.00
San Francisco	0.01	0.01	0.00	0.00	0.02
San Mateo	0.64	0.00	0.01	0.00	0.65
Santa Clara	0.35	0.00	0.01	0.01	0.37
Solano	0.00	0.00	0.00	0.02	0.03
Sonoma	0.15	0.00	0.00	0.00	0.15
BAAQMD Subtotal	*1.22*	*0.02*	*0.05*	*0.15*	*1.44*
Non-BAAQMD Counties	1.30	0.01	0.03	0.14	1.48
Domain Total	**2.52**	**0.03**	**0.08**	**0.29**	**2.92**

Table A8: Summary of 2016 lead emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.39	0.00	0.00	5.93	6.33
Contra Costa	1.30	0.01	0.00	3.12	4.43
Marin	0.08	0.00	0.00	1.72	1.81
Napa	0.07	0.00	0.00	0.79	0.86
San Francisco	0.25	0.01	0.00	0.00	0.26
San Mateo	0.39	0.00	0.00	3.02	3.40
Santa Clara	0.71	0.00	0.00	6.11	6.82
Solano	0.17	0.00	0.00	2.20	2.38
Sonoma	0.17	0.00	0.00	1.84	2.01

BAAQMD Subtotal	*3.53*	*0.02*	*0.00*	*24.73*	*28.29*
Non-BAAQMD Counties	1.70	0.03	0.00	13.59	15.32
Domain Total	**5.22**	**0.05**	**0.00**	**38.32**	**43.60**

Table A9: Summary of 2016 mercury emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	0.16	0.01	0.01	0.00	0.19
Contra Costa	0.08	0.01	0.00	0.15	0.24
Marin	0.02	0.00	0.00	0.00	0.02
Napa	0.01	0.00	0.00	0.00	0.02
San Francisco	0.06	0.01	0.00	0.00	0.07
San Mateo	0.06	0.00	0.00	0.00	0.06
Santa Clara	0.14	0.01	0.01	0.41	0.57
Solano	0.02	0.00	0.00	0.01	0.04
Sonoma	0.03	0.00	0.00	0.00	0.03
BAAQMD Subtotal	*0.58*	*0.05*	*0.04*	*0.57*	*1.25*
Non-BAAQMD Counties	0.18	0.04	0.02	0.07	0.31
Domain Total	**0.76**	**0.09**	**0.06**	**0.65**	**1.56**

Table A10: Summary of 2016 nickel emissions (lbs/day) by geographic area and source sector.

Geographic Area	Area	Nonroad	Onroad	Point	Total
Alameda	1.79	1.41	2.51	0.05	5.76
Contra Costa	0.85	1.55	1.38	1.75	5.54
Marin	0.07	1.74	0.41	0.00	2.22
Napa	0.03	0.81	0.20	0.00	1.03
San Francisco	0.17	1.37	0.59	0.01	2.15
San Mateo	0.16	1.03	1.00	0.02	2.21
Santa Clara	1.45	1.16	2.45	0.10	5.16
Solano	0.07	0.73	0.47	1.12	2.39
Sonoma	0.28	0.67	0.45	0.00	1.41
BAAQMD Subtotal	*4.87*	*10.46*	*9.47*	*3.06*	*27.86*
Non-BAAQMD Counties	5.17	3.82	4.82	3.89	17.71
Domain Total	**10.04**	**14.29**	**14.29**	**6.95**	**45.57**

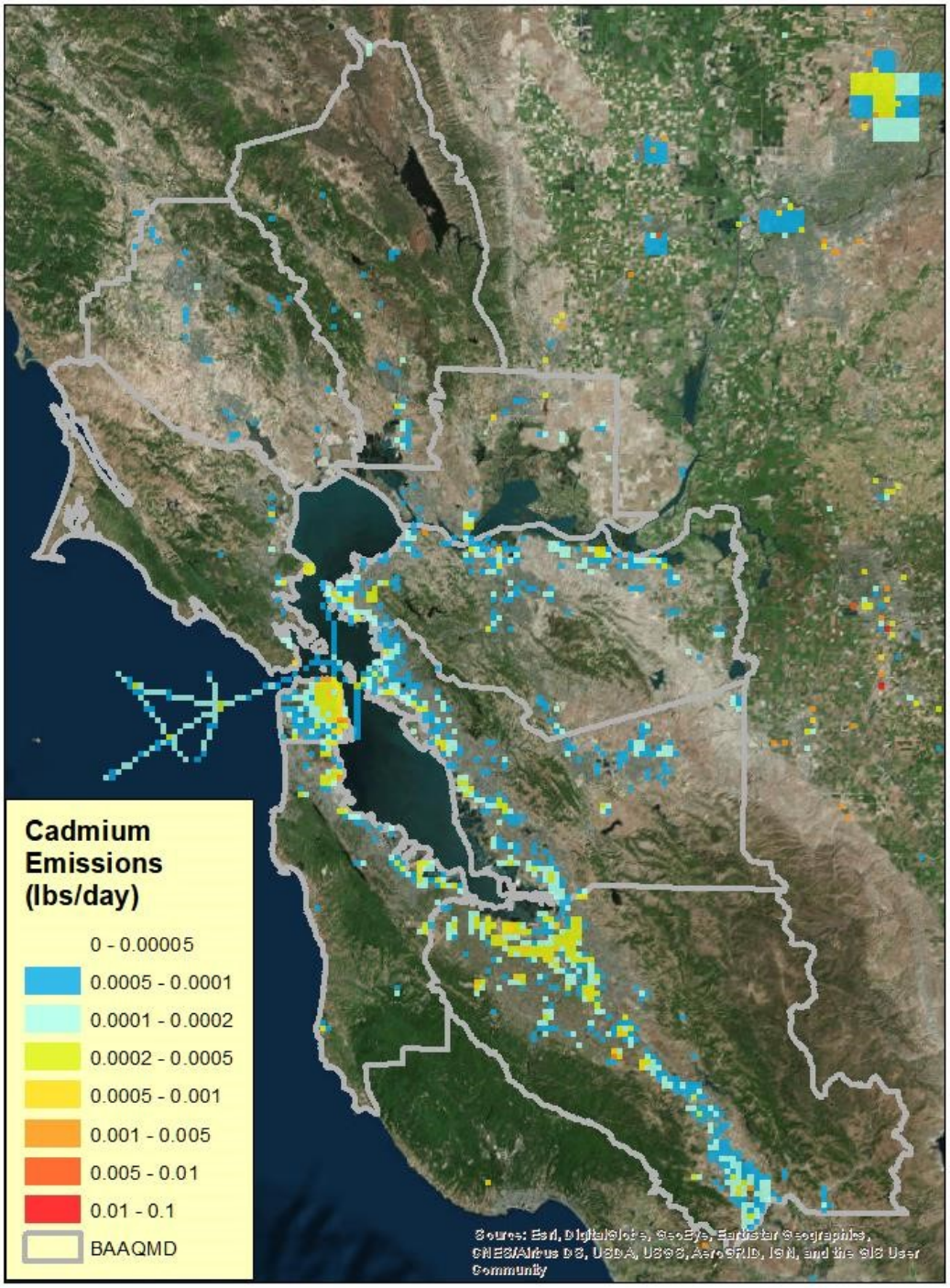


Figure A6: Spatial distribution of 2016 annual average cadmium emissions for the 1-km modeling domain.

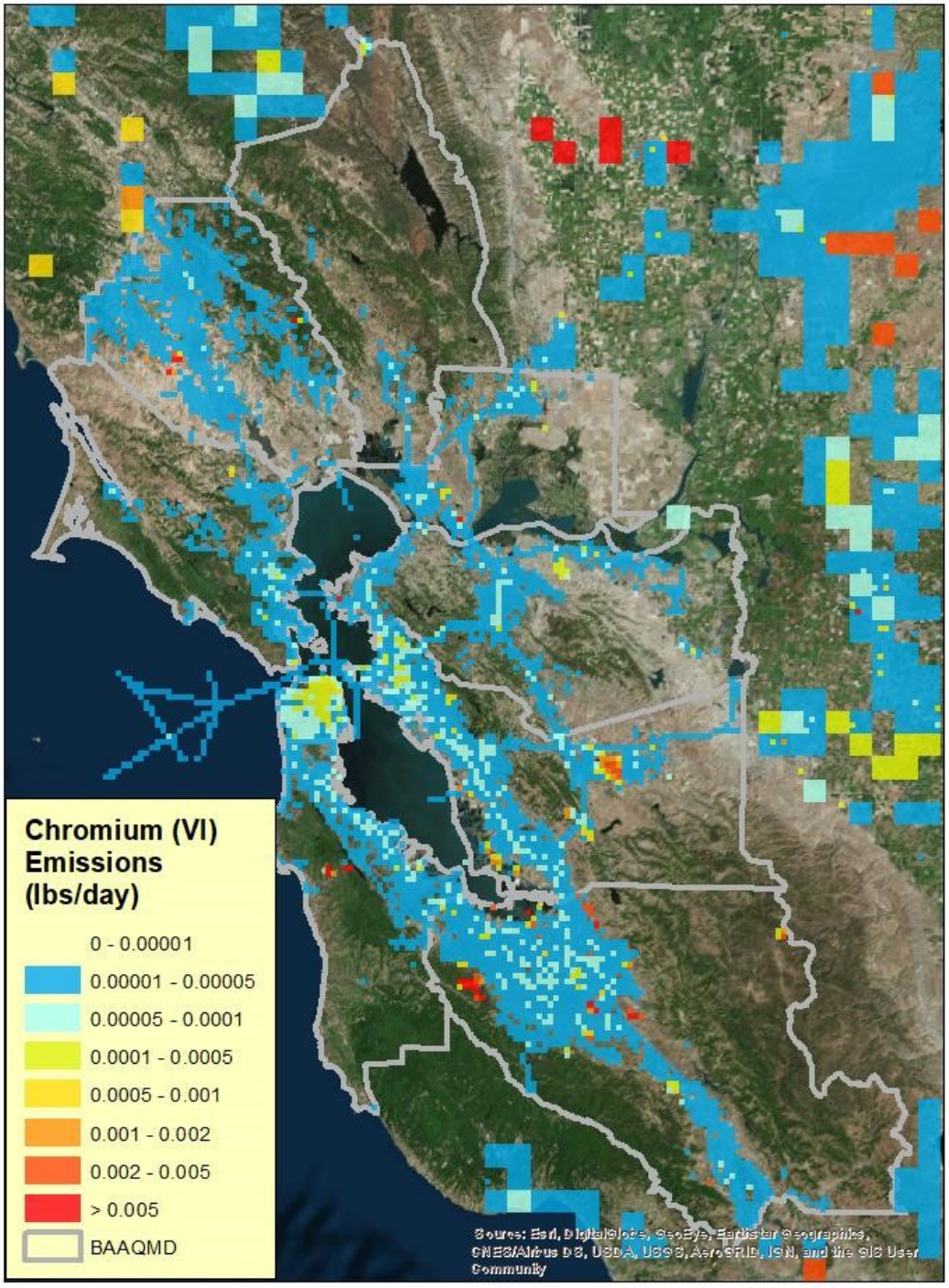


Figure A7: Spatial distribution of 2016 annual average chromium VI emissions for the 1-km modeling domain.

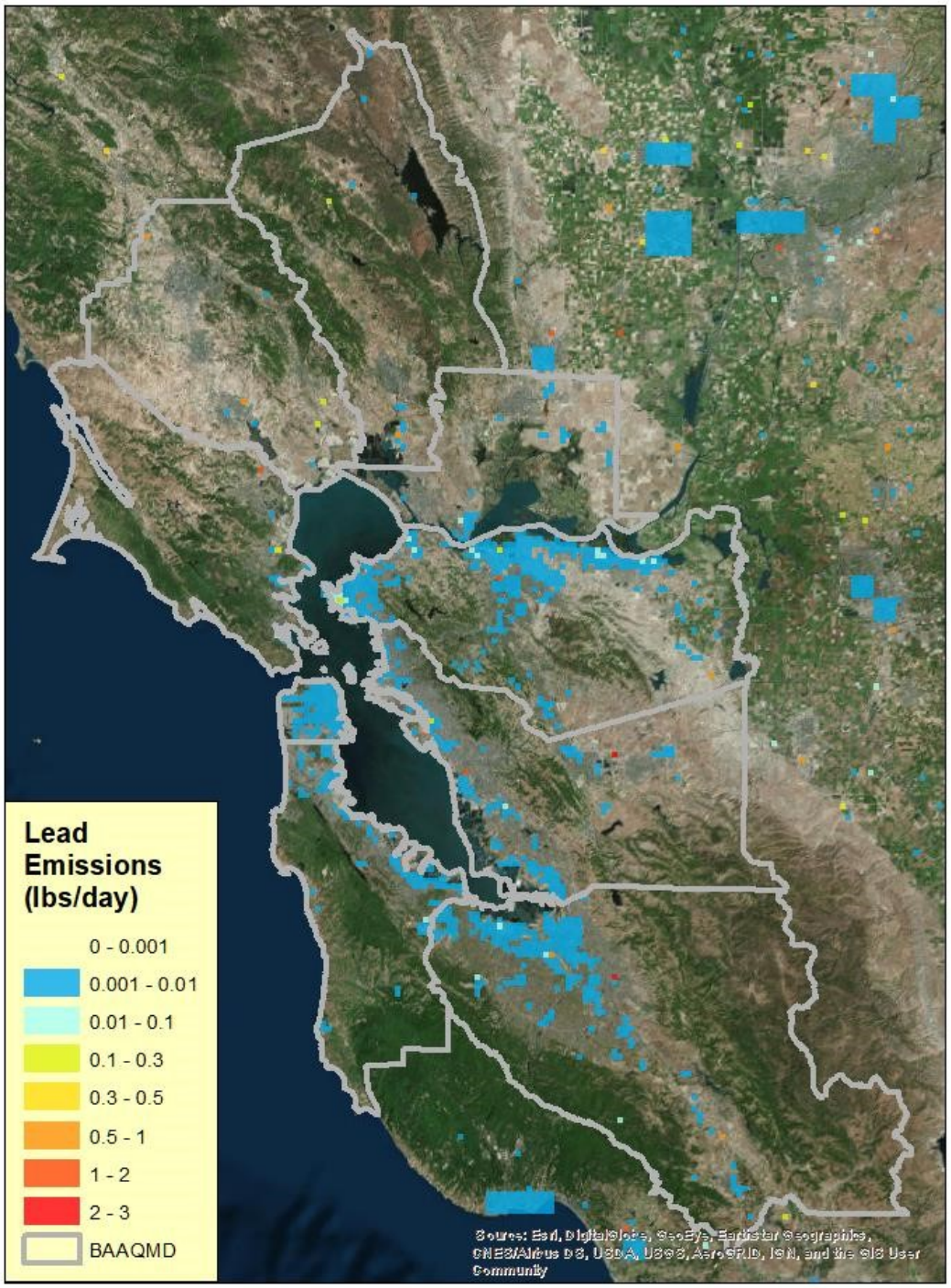


Figure A8: Spatial distribution of 2016 annual average lead emissions for the 1-km modeling domain.

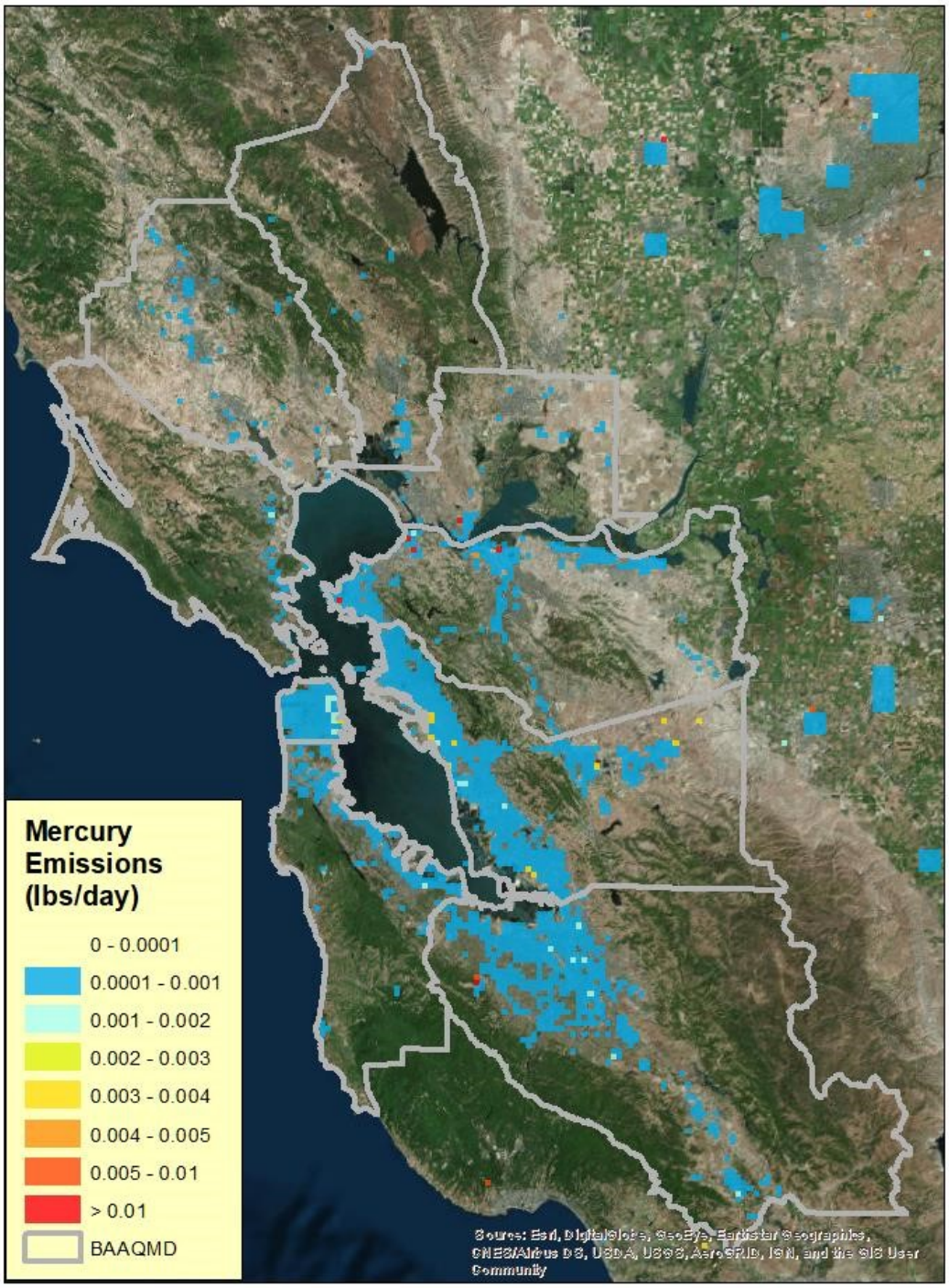


Figure A9: Spatial distribution of 2016 annual average mercury emissions for the 1-km modeling domain.

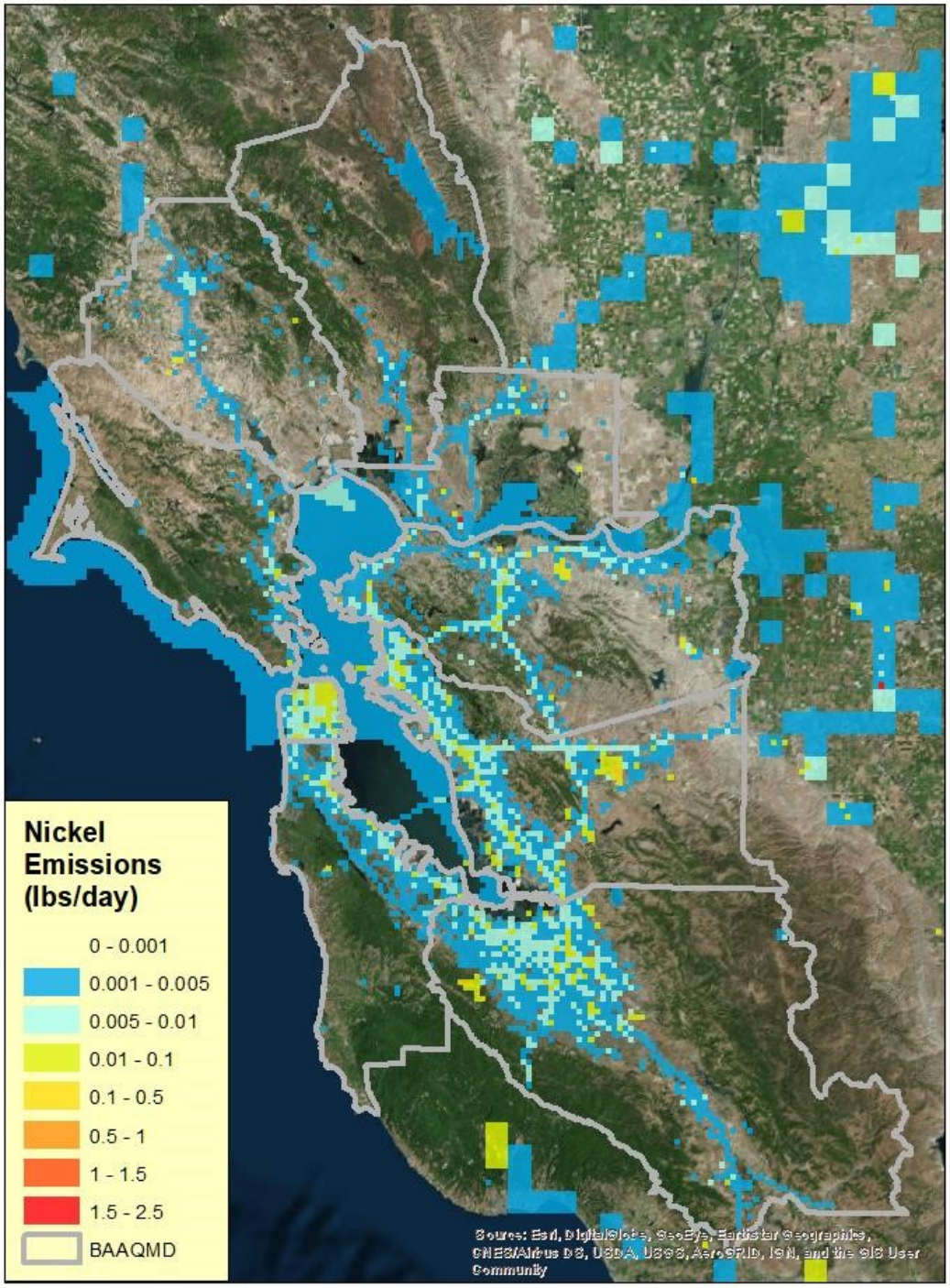


Figure A10: Spatial distribution of 2016 annual average nickel emissions for the 1-km modeling domain.

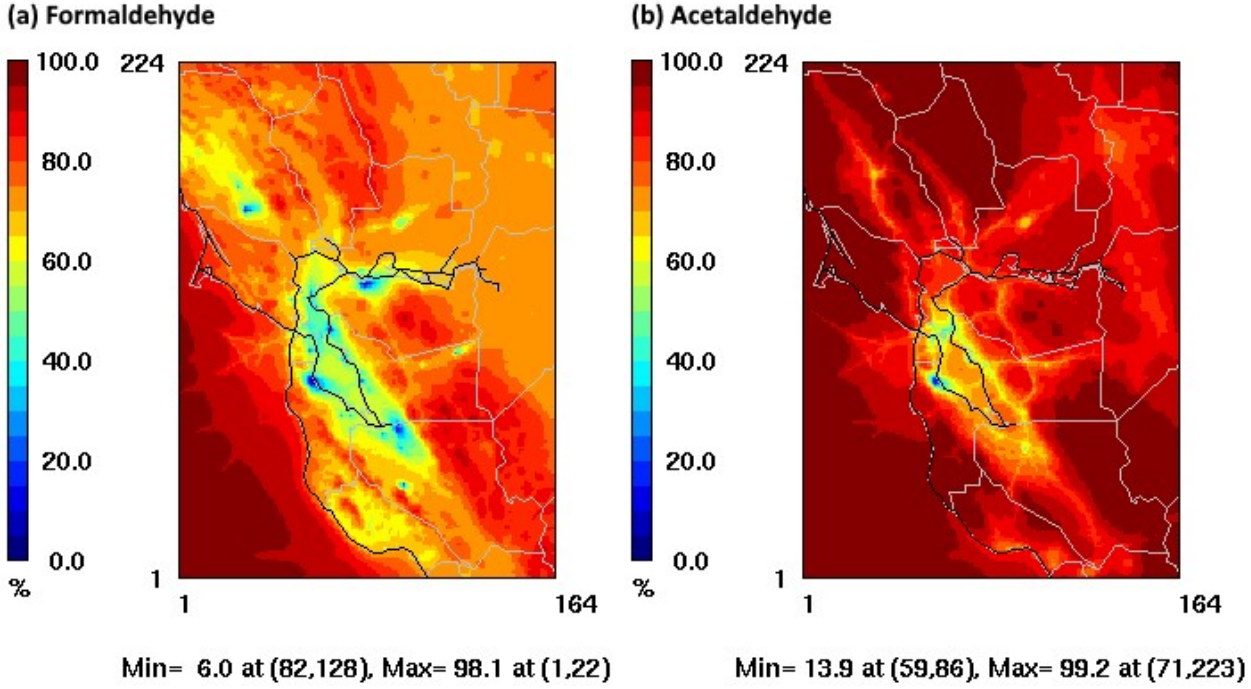
Appendix B: Simulated Primary vs Secondary Air Toxics

Some air toxic compounds have both primary components (i.e., direct emissions) and secondary components (i.e., production in the atmosphere via chemical reactions of other hydrocarbons). For example, formaldehyde and acetaldehyde are primarily formed from atmospheric oxidation of other biogenic (e.g., isoprene emitted from plants) and anthropogenic (e.g., ethene and propene from petrochemical facilities) VOCs. Acrolein is one of the major products of the photochemical oxidation of 1,3-butadiene.

To assess the relative importance of the primary and secondary contributions, CMAQ's SAPRC07TC chemistry mechanism explicitly tracks primary emissions of formaldehyde, acetaldehyde and acrolein, as well as their photochemical production.

Figure B1 shows fractions of secondary contributions to annual average formaldehyde, acetaldehyde and acrolein concentrations in the 1-km modeling domain. Secondary production is the predominant source of formaldehyde and acetaldehyde in most areas of the modeling domain except in the immediate vicinity of emissions sources. Contributions of primary acrolein are generally higher than those of primary formaldehyde and acetaldehyde.

Figure B2 displays relative contributions of primary and secondary formaldehyde, acetaldehyde and acrolein over the West Oakland receptor domain. The primary contributions are relatively higher in this area, which indicates substantial local source influences.



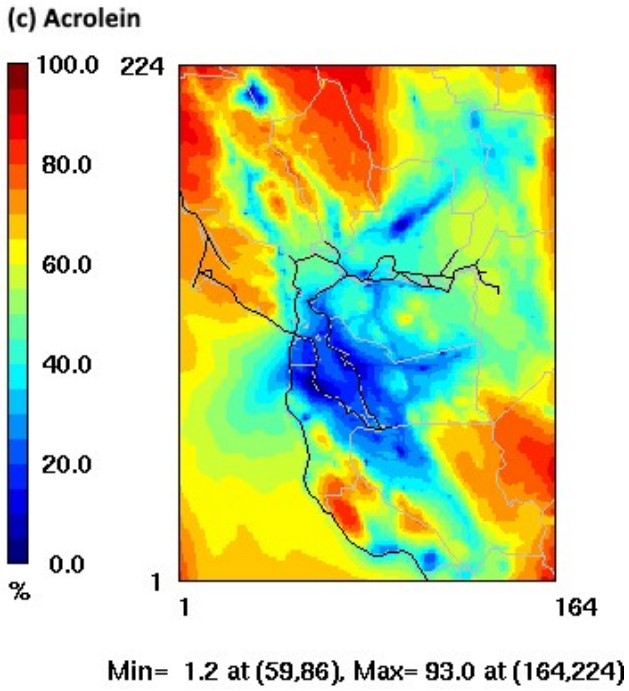
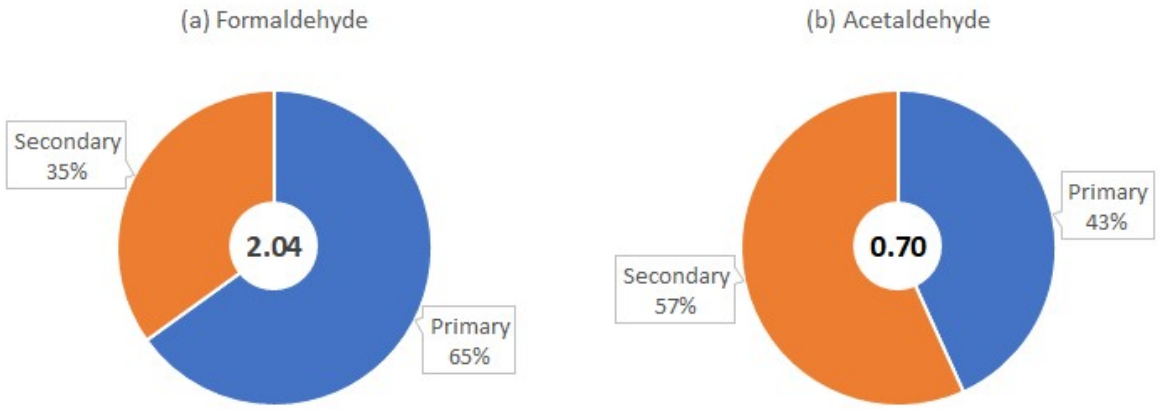


Figure B1: Percent contributions of secondary production to annual average formaldehyde, acetaldehyde and acrolein concentrations in the 1-km modeling domain.



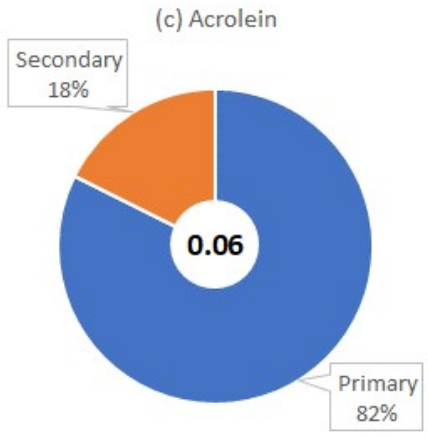


Figure B2: Percent contributions of secondary production to annual average formaldehyde, acetaldehyde and acrolein concentrations over the West Oakland Receptor domain. The numbers in the center represent total (primary plus secondary) concentrations.

Appendix C: Simulated Trace Metals

Figures C1 through C5 show the annual average concentrations of hexavalent chromium, cadmium, lead, nickel, and mercury, respectively. Mercury concentrations are shown as sum of all three forms of atmospheric mercury (gaseous elemental mercury, gaseous oxidized mercury, and particulate bound mercury). Note that the trace metal concentrations in these figures are given in nanograms per cubic meter (ng/m^3) to better represent their typical atmospheric concentration ranges.

The highest annual average concentration of hexavalent chromium is simulated to occur east of Half Moon Bay (8.3 ng/m^3). Concentrations above 1 ng/m^3 are seen northwest of Petaluma and west of Cupertino. Each of these areas are associated with mineral processing activities in the NATA area source inventory. Outside of the Bay Area, the Stockton and Sacramento areas also show above 1 ng/m^3 concentrations.

The simulated annual average cadmium concentration peaks at Lathrop (0.9 ng/m^3). Simulated concentrations are below 0.05 ng/m^3 in the Bay Area except for Islais Creek Channel (0.06 ng/m^3).

Simulated hot spots for lead are located at local airports such as Reid-Hillview Airport (39.0 ng/m^3), Palo Alto Airport (37.0 ng/m^3), Livermore Municipal Airport (33.9 ng/m^3), Watsonville Municipal Airport (28.2 ng/m^3), San Carlos Airport (25.2 ng/m^3), Hayward Executive Airport (23.6 ng/m^3), Nut Tree Airport (23.1 ng/m^3) and Buchanan Field Airport (22.9 ng/m^3). Lead concentrations quickly diminish as distance from the source increases.

The simulated annual average nickel concentration is highest at Lathrop (31.5 ng/m^3). The second highest is at Benicia near the Valero Refinery (17.9 ng/m^3). Other hot spots in the Bay Area are Livermore (7.8 ng/m^3), Richmond (6.1 ng/m^3) and west of Cupertino (5.4 ng/m^3).

The highest annual average mercury concentration of 1.8 ng/m^3 is simulated to occur just west of Cupertino, with the surrounding areas showing above 0.5 ng/m^3. Simulated concentrations are below 0.5 ng/m^3 for all other areas except for Rodeo which shows 0.6 ng/m^3.

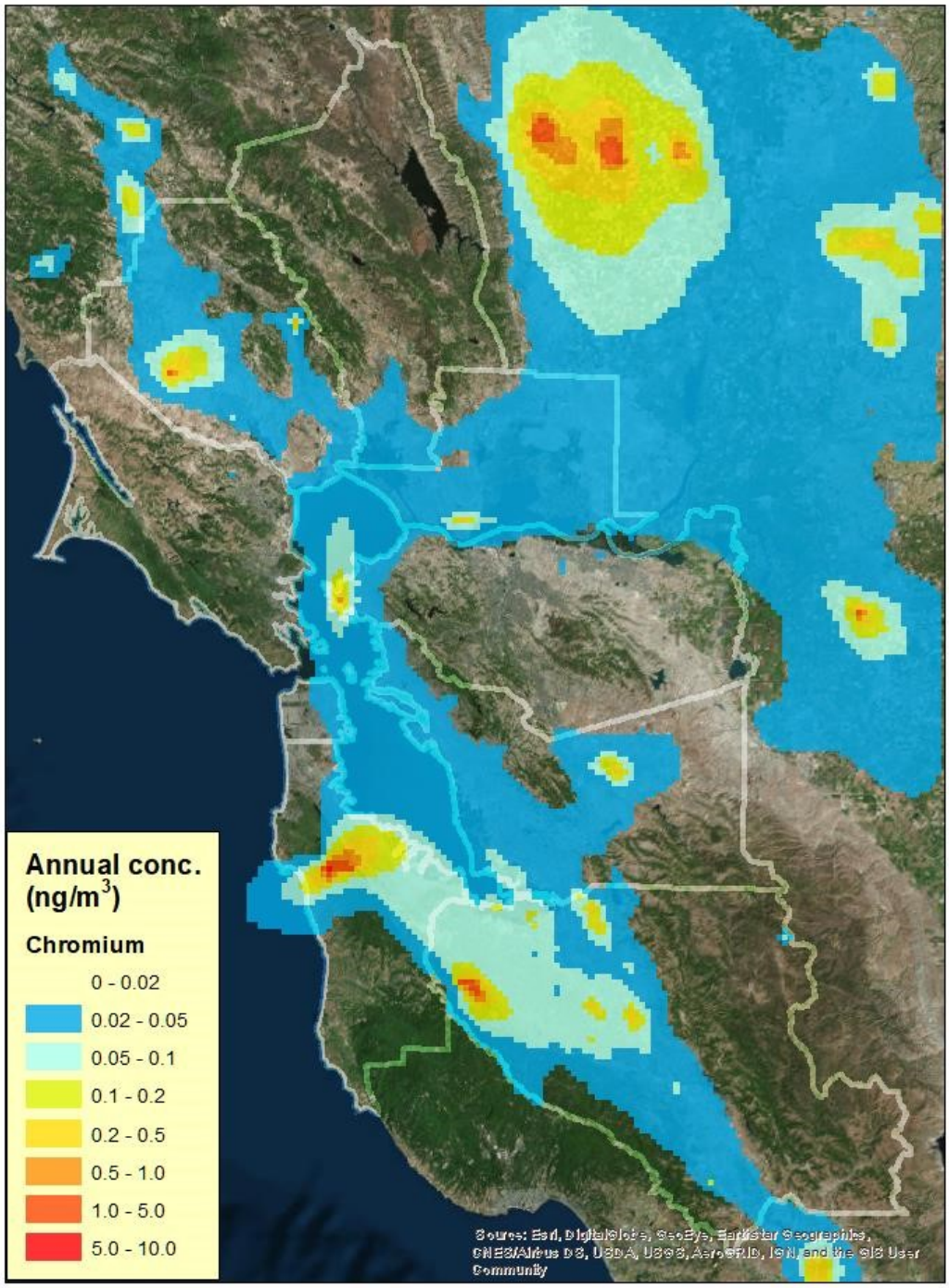
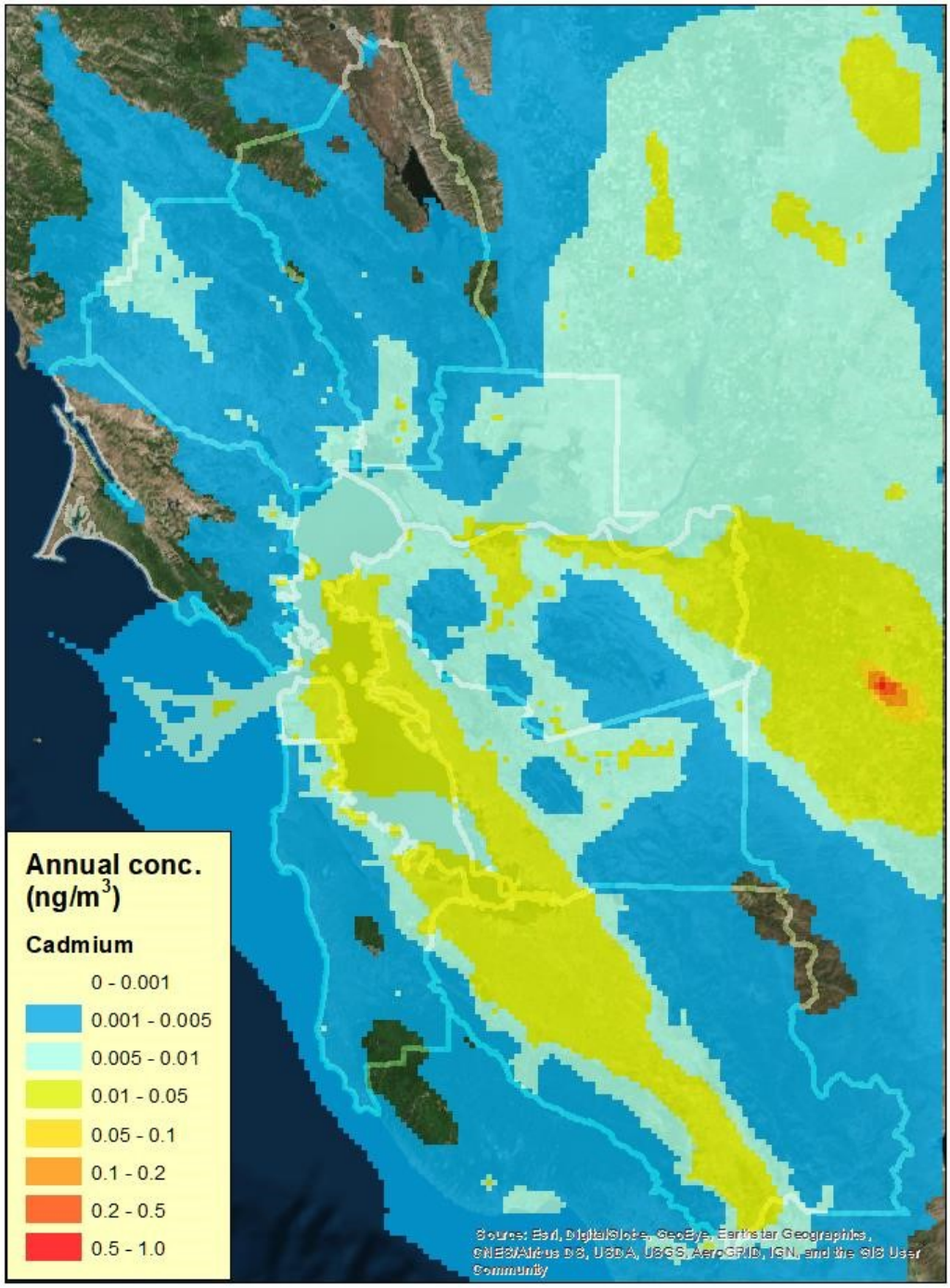
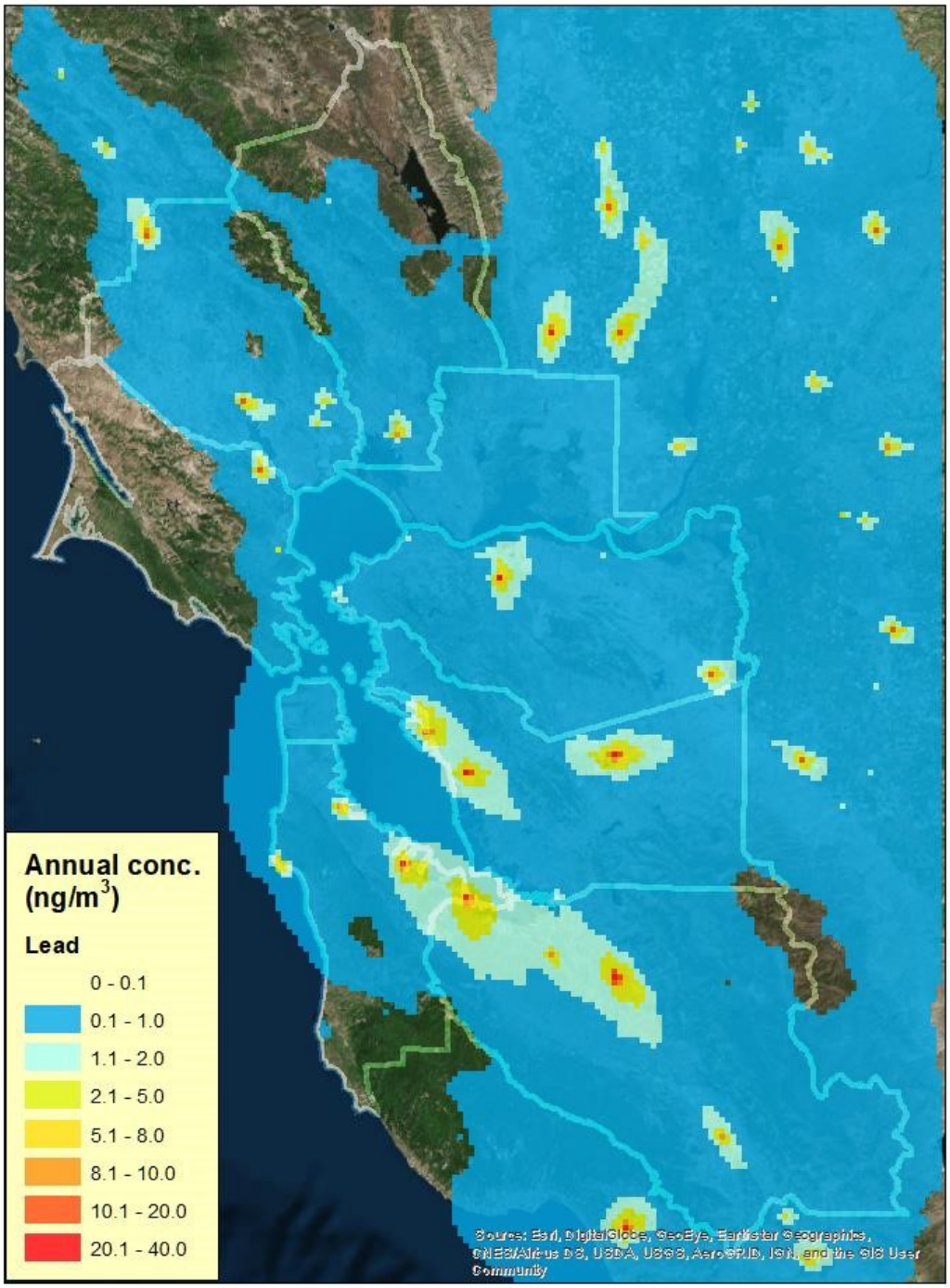


Figure C1: Simulated annual average hexavalent chromium concentrations for 2016.



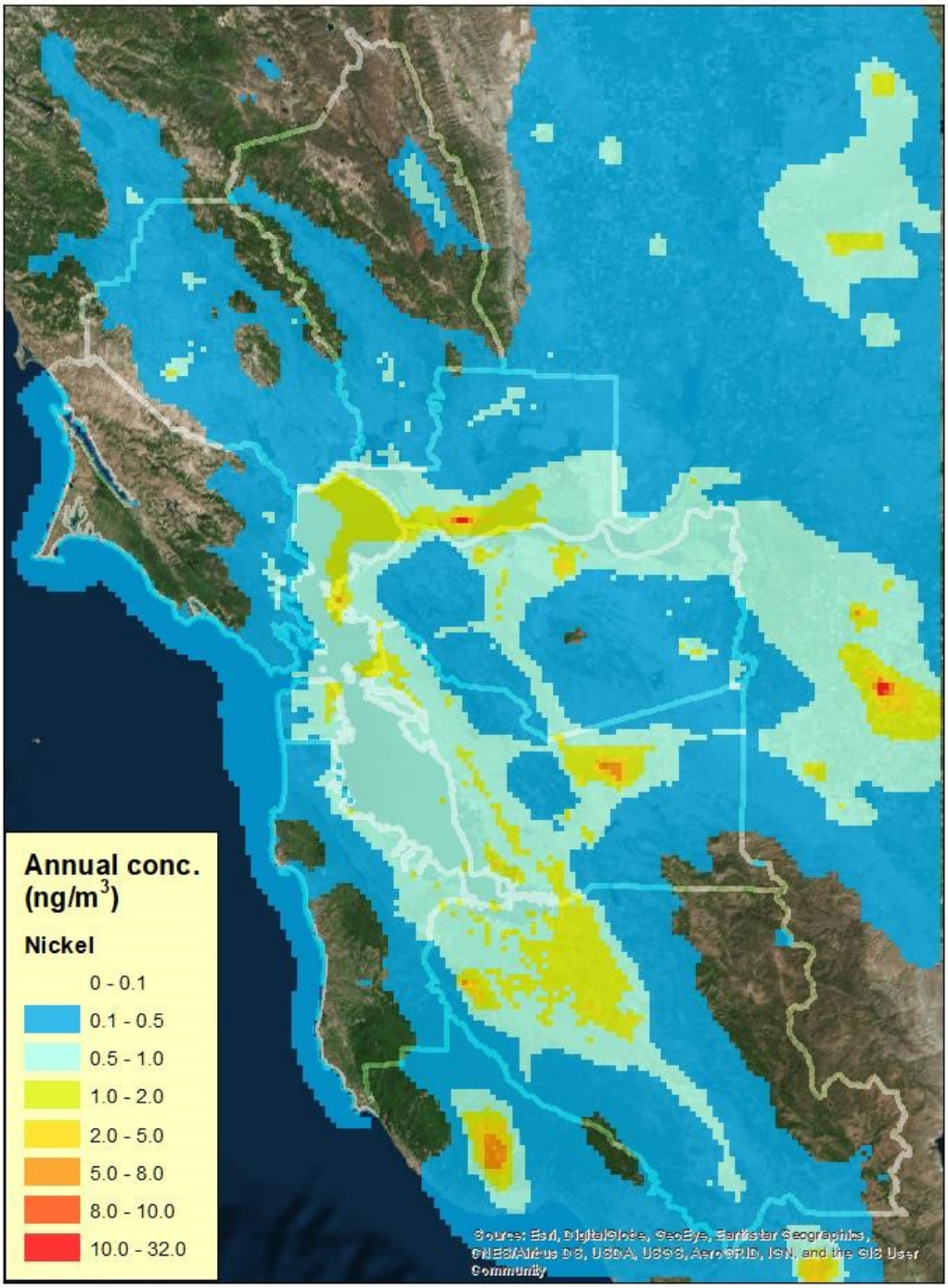
Maximum: 0.9

Figure C2: Simulated annual average cadmium concentrations for 2016.



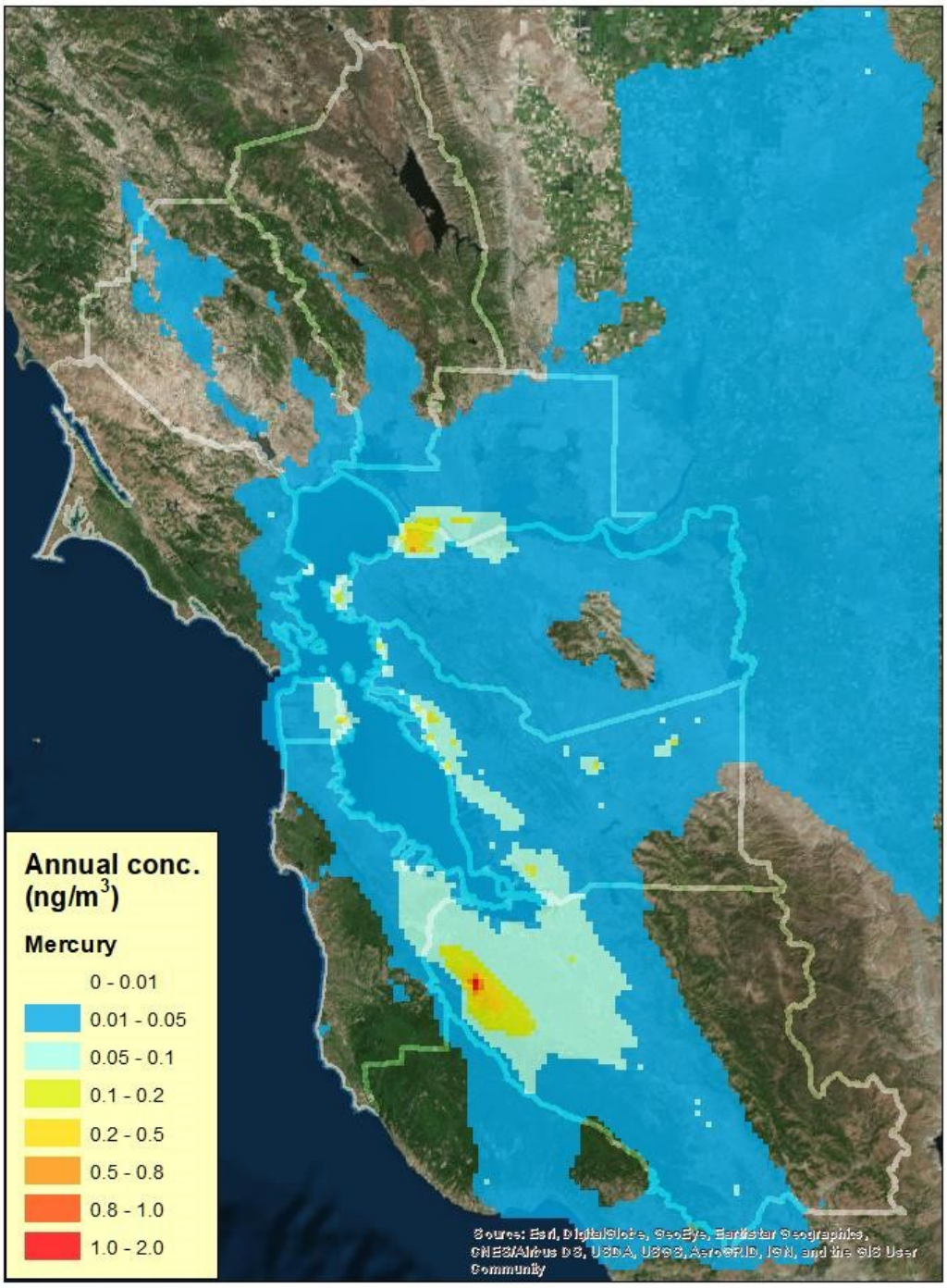
Maximum: 39.0

Figure C3: Simulated annual average lead concentrations for 2016.



Maximum: 31.5

Figure C4: Simulated annual average nickel concentrations for 2016.



Maximum: 1.8

Figure C5: Simulated annual average mercury concentrations for 2016.

Appendix D: Excess Cancer Risk in West Oakland

As mentioned in Section 3, in addition to the base case, a "control case" simulation was conducted with all anthropogenic emissions from the West Oakland source domain removed, which provides regional background contributions to air toxics in the West Oakland. The differences between the base and control cases represent contributions from the local anthropogenic sources in West Oakland.

Figures D1 through D4 present the base case annual average concentrations of the air toxics and show significant mass concentrations in the West Oakland receptor domain (formaldehyde, acetaldehyde, benzene, and diesel PM). Annual average formaldehyde concentrations range from 1.3 to 5.1 $\mu g/m^3$. The northwestern section of the West Oakland community (the community border is indicated by the red line in the figure) shows the highest concentration.

The highest annual average acetaldehyde concentration (0.83 $\mu g/m^3$) within the West Oakland receptor domain is located outside of the West Oakland community, at a grid cell in the northwestern corner of the receptor domain. The concentration gradient of acetaldehyde is not as dramatic as that of formaldehyde. The highest acetaldehyde concentration in the West Oakland community is 0.75 $\mu g/m^3$.

The annual average benzene concentration is highest (0.68 $\mu g/m^3$) at the northeastern corner of the West Oakland receptor domain. Within the West Oakland community border, the concentration ranges from 0.4 to 0.6 $\mu g/m^3$ except for the small area in the northeastern corner of the community.

The annual average diesel PM concentrations peak at the northwestern corner of the receptor domain (1.3 $\mu g/m^3$), suggesting significant contributions from diesel traffic over the Bay Bridge. Within the West Oakland community, the concentration remains below 0.9 $\mu g/m^3$.

Figure D5 shows relative fractions of individual air toxics mass concentrations averaged over the 5x4 grid cells within the West Oakland receptor domain. Formaldehyde accounts for almost half of the total air toxic concentration. The next highest is diesel PM, which makes up 19% of the total mass concentration, followed by acetaldehyde (17%) and benzene (13%). The combined toxic metals contribute less than 0.1%.

Figure D6 shows expected excess cancer incidences per million people for the base case, which was calculated as described in Section 4, combining impacts from all the air toxics. The spatial pattern of the cancer risk is similar to that of diesel PM concentrations, with the highest number of excess cancer incidences (1069 per million) occurring at the northwestern corner of the receptor domain, and the lowest (496 per million) occurring at the grid cell that partially overlaps the southwestern tip of the West Oakland community. This is expected, as more than 80% of the combined cancer risk is attributed to diesel PM (see Figure D7). Although formaldehyde is the largest contributor in terms of mass concentration in the area, excess cancer risk is dominated by diesel PM due to its high risk factor.

Figure D8 shows the same plot as Figure D6, but for the control case. The spatial gradient of the excess cancer risk somewhat decreased compared to Figure D6, but the northwestern corner grid cell still shows the highest value, indicating the importance of non-local contributions from the Bay Bridge.

Figure D9 shows the differences in the excess cancer risk between the base and control cases. The Chinatown area (the southeastern corner of the West Oakland receptor domain) would benefit the most (485 cancer incidences per million avoided) from eliminating all anthropogenic emissions in the West Oakland source domain. Similarly, significant benefit is expected at the northwestern corner of the receptor domain, although the population in this grid cell is very small. Within the West Oakland community, the cancer incidences avoided range from 174 to 365 per million.

Figure D10 is the same as Figure D9 except the relative contributions of local vs. background toxics to excess cancer risks is shown on a percentage basis. Local sources account for about 50% of cancer risk in the China Town area, and about 40% in the West Oakland community. The lowest local source contribution to cancer risk is about 27% and is located at a cell in the southwestern corner of the domain.

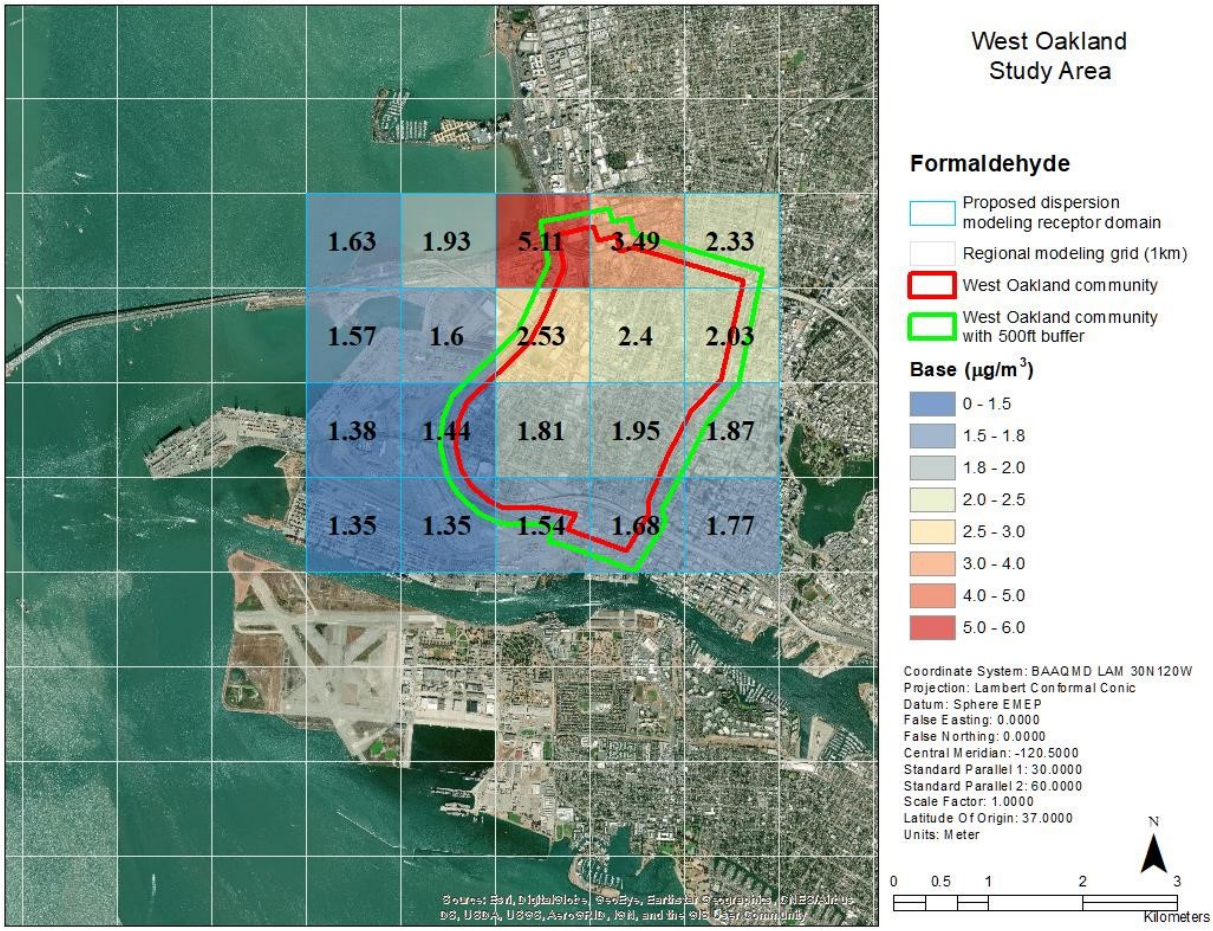


Figure D1: Annual average concentrations of formaldehyde in the West Oakland receptor domain for the base case.

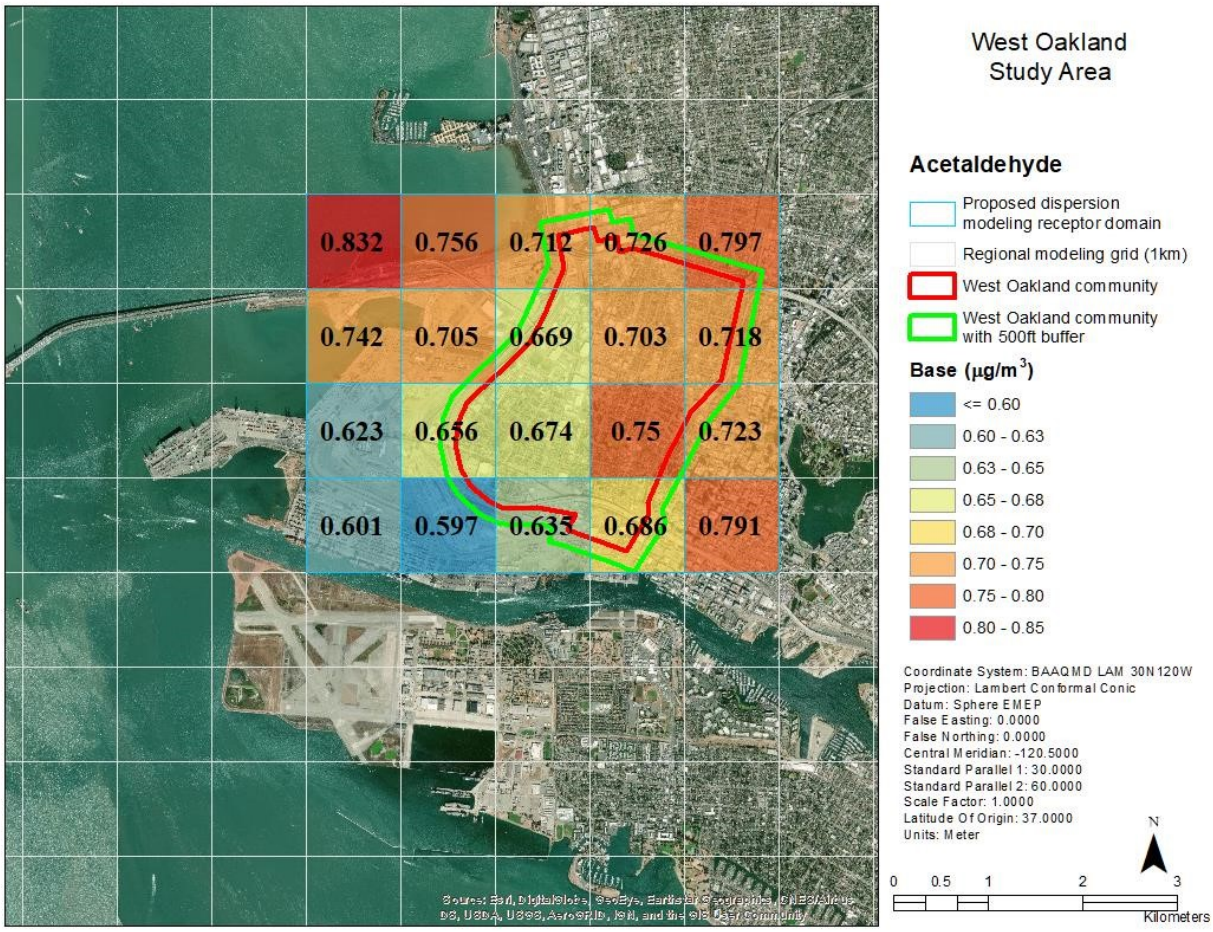


Figure D2: Annual average concentrations of acetaldehyde in the West Oakland receptor domain for the base case.

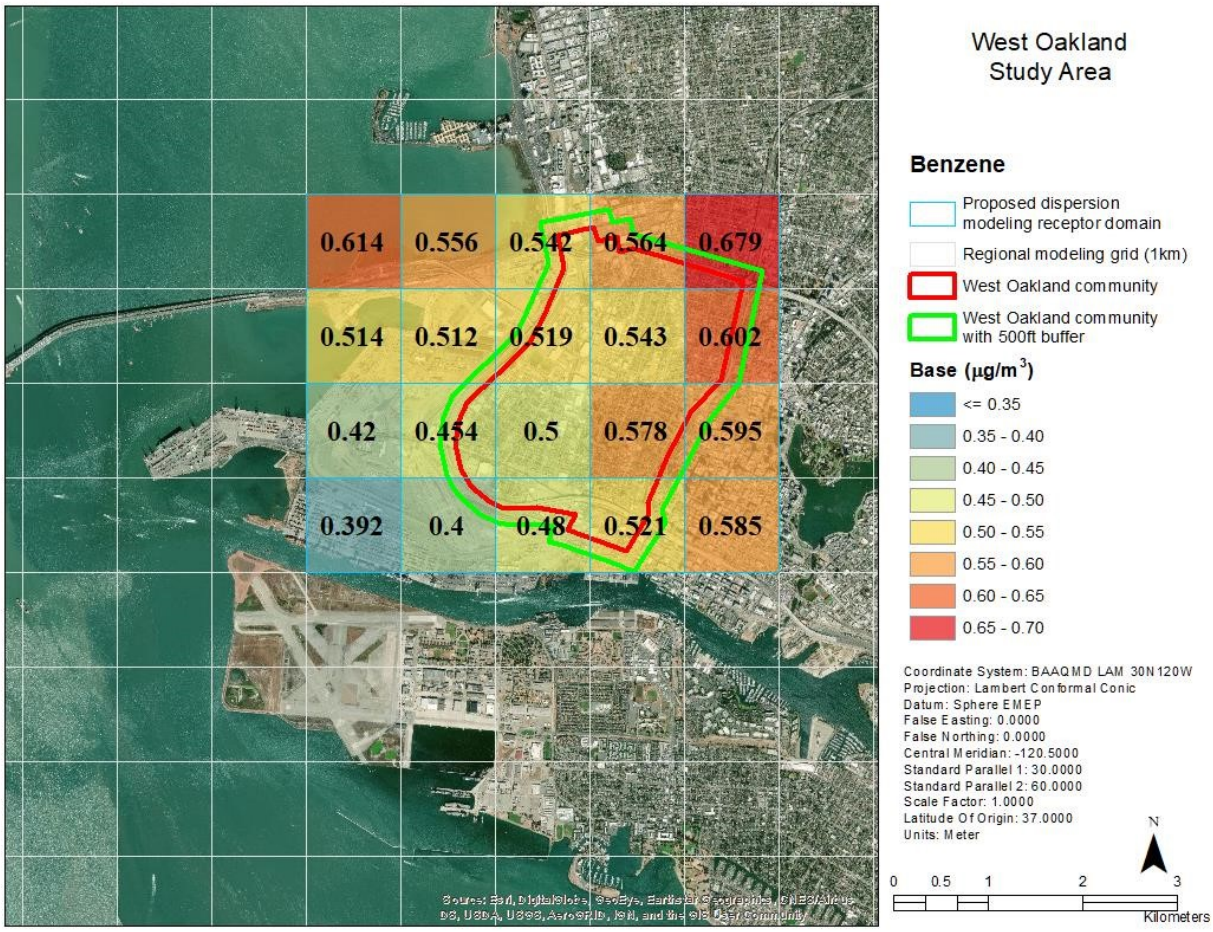


Figure D3: Annual average concentrations of benzene in the West Oakland receptor domain for the base case.

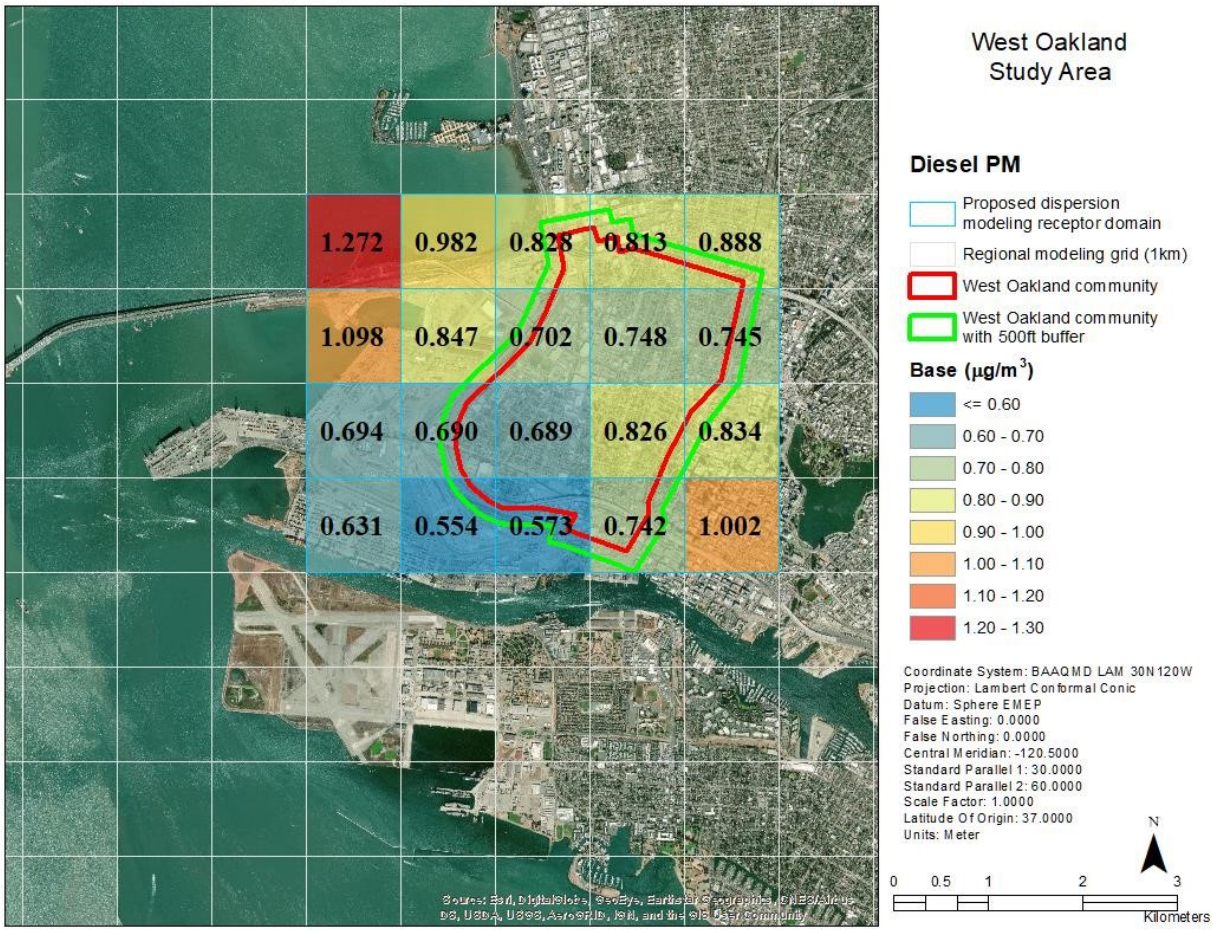


Figure D4: Annual average concentrations of diesel PM in the West Oakland receptor domain for the base case.

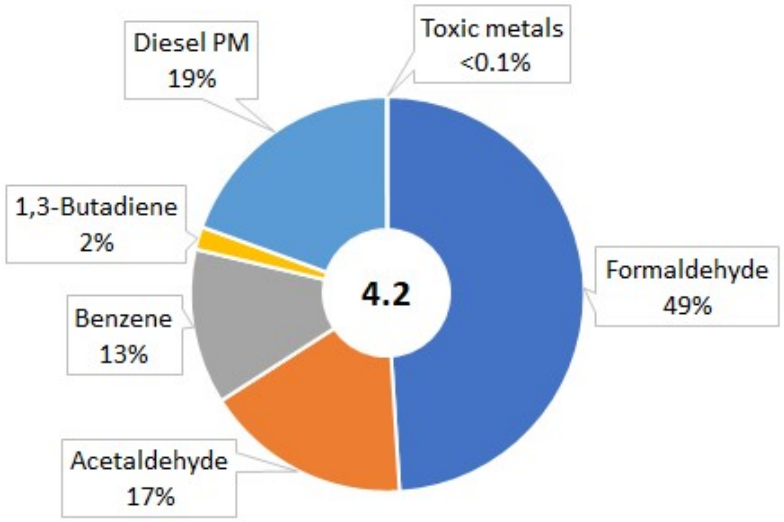


Figure D5: Relative contributions of individual air toxics to total air toxics mass concentration in West Oakland. The number in the center represents the combined annual average concentration ($\mu g/m^3$) of all air toxics modeled, averaged over the 5x4 grid cells within the West Oakland receptor domain.

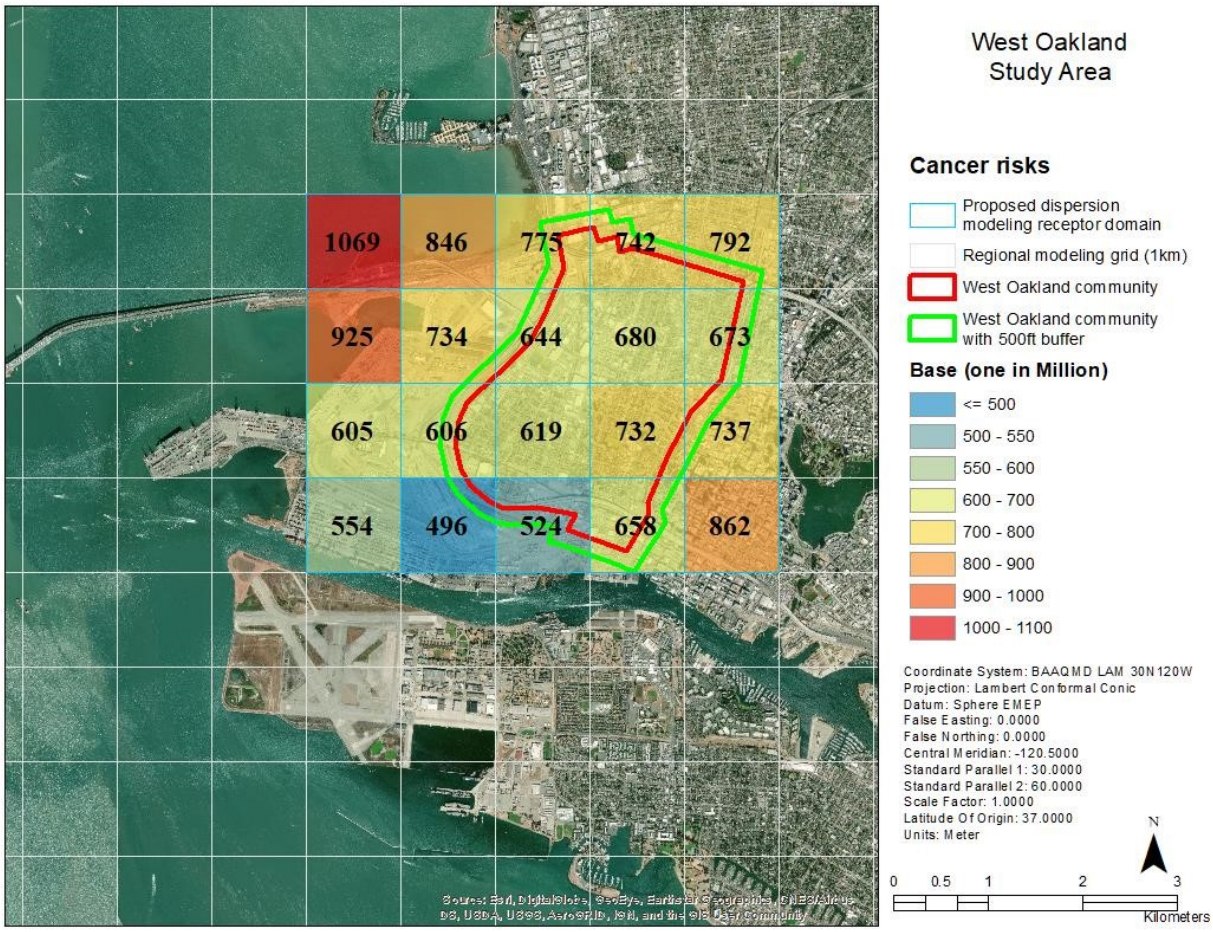


Figure D6: Expected excess cancer incidences per million in the West Oakland receptor domain (base case).

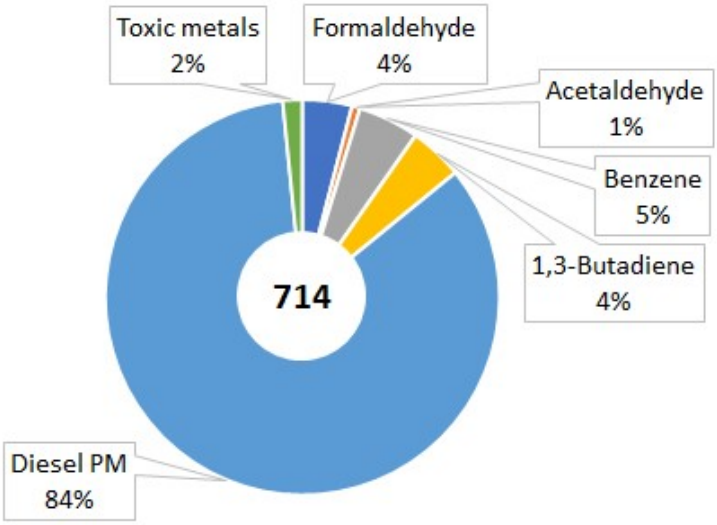


Figure D7: Relative contributions of individual air toxics to total excess cancer risk in West Oakland. The number in the center represents the combined excess cancer incidences (per million people) due to all air toxics modeled, averaged over the 5x4 grid cells within the West Oakland receptor domain.

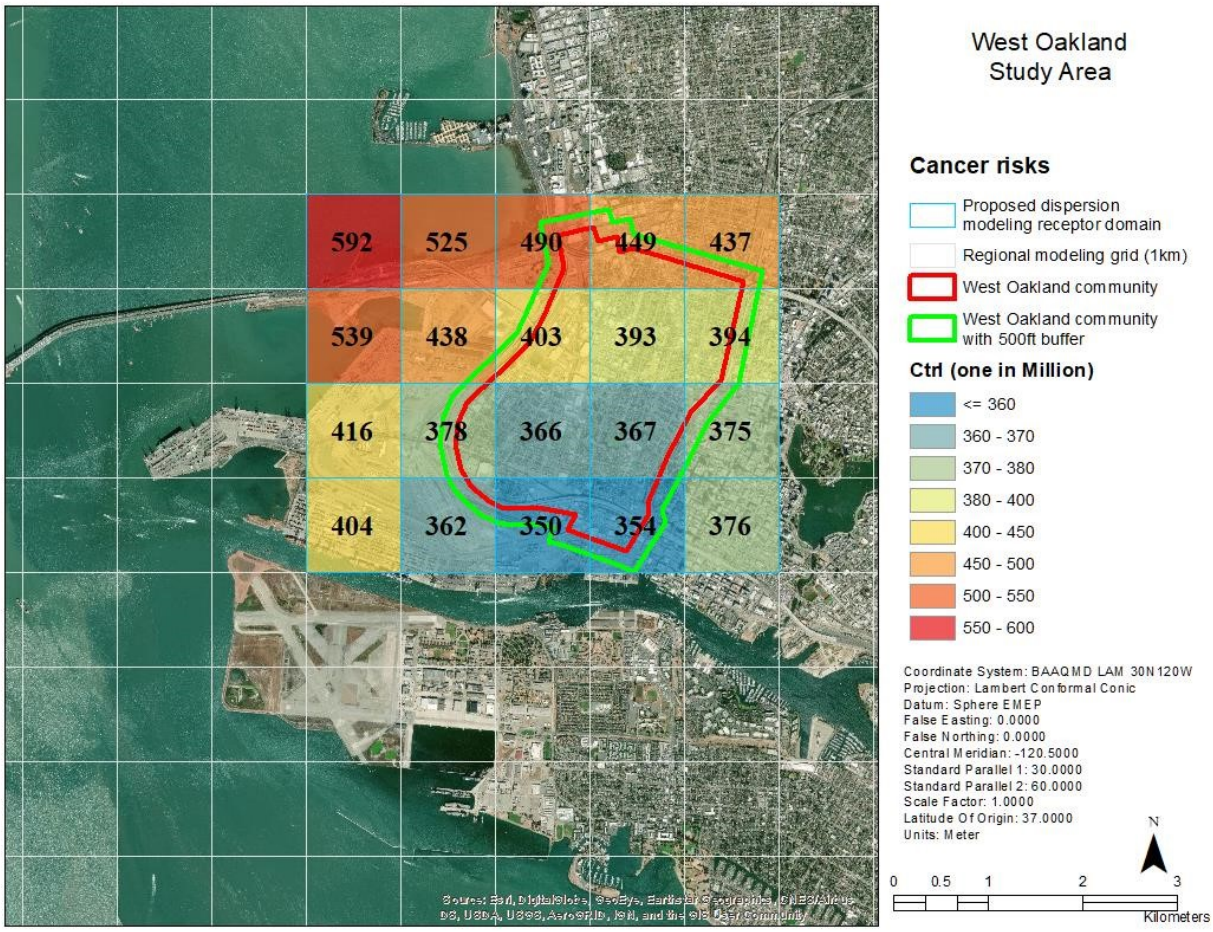


Figure D8: Expected excess cancer incidences per million in the West Oakland receptor domain (control case).

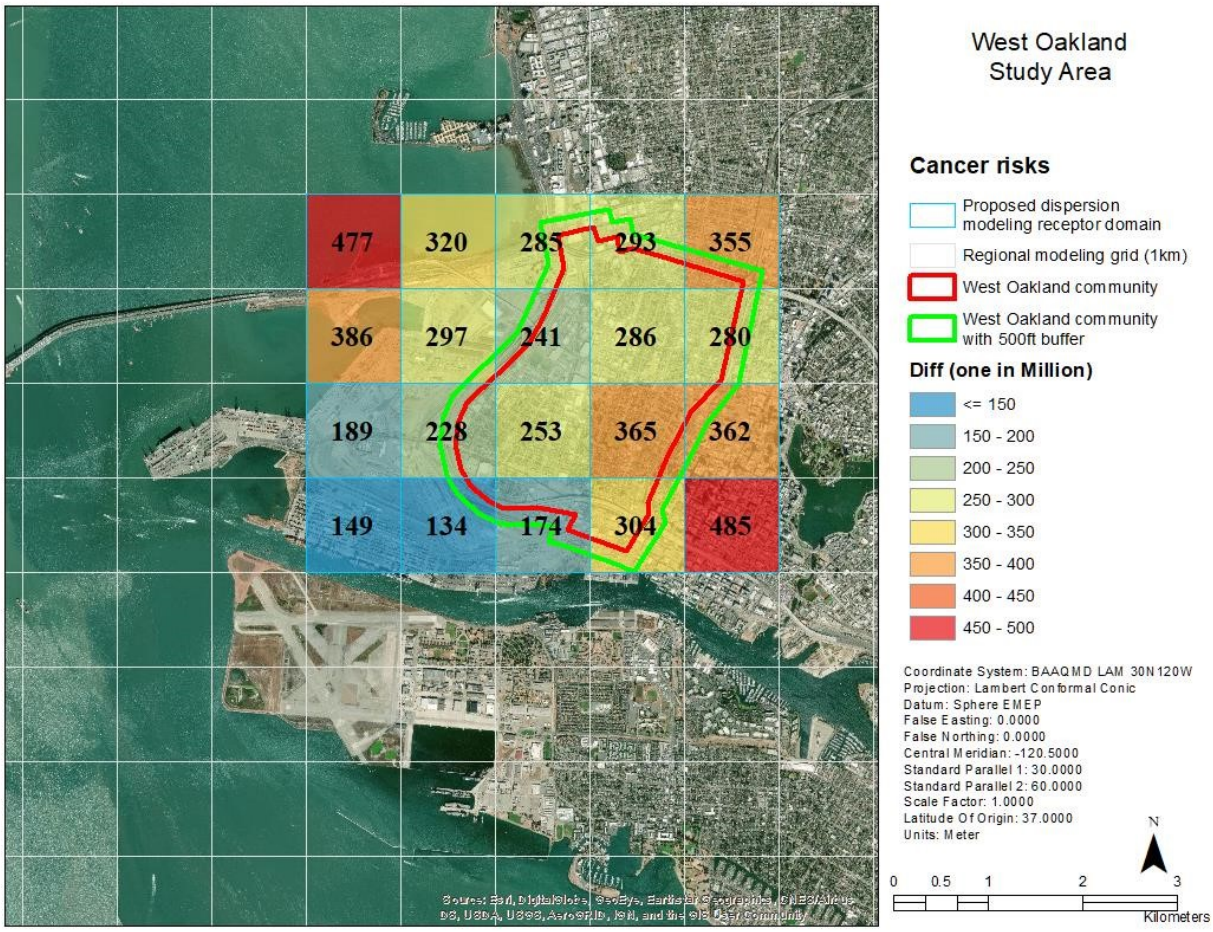


Figure D9: Differences in expected excess cancer incidences per million in the West Oakland receptor domain between the base and control cases.

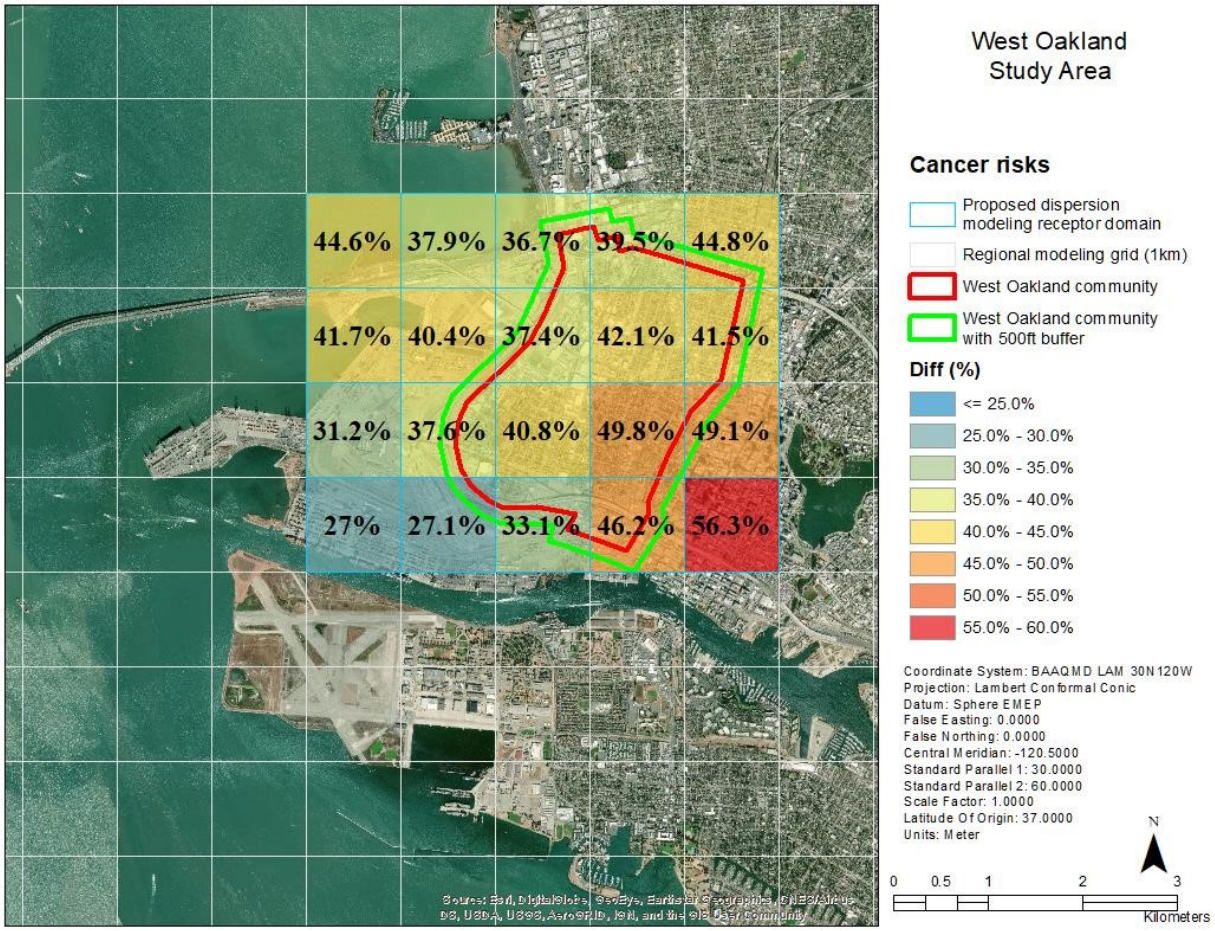


Figure D10: Percentage contribution of cancer risks due to the local anthropogenic emissions within West Oakland.

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Environmental Health

REVIEW Open Access

A review of health effects associated with exposure to jet engine emissions in and around airports

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Abstract

Background: Airport personnel are at risk of occupational exposure to jet engine emissions, which similarly to diesel exhaust emissions include volatile organic compounds and particulate matter consisting of an inorganic carbon core with associated polycyclic aromatic hydrocarbons, and metals. Diesel exhaust is classified as carcinogenic and the particulate fraction has in itself been linked to several adverse health effects including cancer.

Method: In this review, we summarize the available scientific literature covering human health effects of exposure to airport emissions, both in occupational settings and for residents living close to airports. We also report the findings from the limited scientific mechanistic studies of jet engine emissions in animal and cell models.

Results: Jet engine emissions contain large amounts of nano-sized particles, which are particularly prone to reach the lower airways upon inhalation. Size of particles and emission levels depend on type of aircraft, engine conditions, and fuel type, as well as on operation modes. Exposure to jet engine emissions is reported to be associated with biomarkers of exposure as well as biomarkers of effect among airport personnel, especially in ground-support functions. Proximity to running jet engines or to the airport as such for residential areas is associated with increased exposure and with increased risk of disease, increased hospital admissions and self-reported lung symptoms.

Conclusion: We conclude that though the literature is scarce and with low consistency in methods and measured biomarkers, there is evidence that jet engine emissions have physicochemical properties similar to diesel exhaust particles, and that exposure to jet engine emissions is associated with similar adverse health effects as exposure to diesel exhaust particles and other traffic emissions.

Keywords: Jet engine emissions, Airports, Occupational exposure, Particulate matter, Polycyclic aromatic hydrocarbons, Biomarkers

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Background

Exposure to air pollution, including ultrafine particulate matter (UFP), from industry and traffic is associated with adverse health effects [1–4]. Airports are significant high-emission sources and human exposure to these emissions is a growing health concern. Importantly, airport personnel are at risk of occupational exposure to jet engine emissions [5]. More knowledge is needed on exposure risks, adverse health effects, biomarkers and risk management options related to the diverse factors influencing human exposure to airport emissions [6] (Fig. 1).

However, data collection seems challenging. Commercial airports are large, complex and diverse work places, where aircraft, ground-support equipment (GSE), and related vehicles all contribute to mixed emissions [7, 8]. In turn, commercial airports as well as military air stations are year-round active high security areas with restricted access, which can reduce the options for external researchers to collect optimal or sufficient measurements. Consensus or formal guidelines for optimal measurement design, instrumentation and analysis methods for the different emission components are lacking, which further complicates comparison of data and risk assessment [5, 9].

With this review, we seek to compile available studies in the open scientific literature on health effects of jet engine emissions in occupational settings and in residential areas around airports, along with mechanistic effects studied in animal and cell models. The studies were selected based on key papers and systematic searches (search terms, method and selection criteria are disclosed in the Additional file 1). We briefly summarize the characteristics of jet engine emissions and highlight the complexity of this field of research, but detailed research on emissions and physical-chemical studies is beyond the scope of this review.

Toxicity of jet fuel exposure

The toxicity of (unburned) jet fuel as such has been considered in many studies (reviewed in [10]) since the early 1950's, where the specifications of the hydrocarbon-based jet fuel, JP-4 (jet propellent-4), was published by the US air force. Major toxic effects reported for JP-4 were skin irritation, neurotoxicity, nephrotoxicity, and renal carcinogenicity in rats [11]. Jet fuels are mixtures of gasoline and kerosene with performance additives [10]. In 1994, US Air Force converted to JP-8, developed to be less volatile and less explosive upon crash incidents compared to JP-4. JP-8 (NATO F-34) is equivalent to Jet A-1 fuel used in commercial aircraft. A range of other kerosene-based jet fuels are in use, depending on aircraft type and differing in kerosene ratio and requirements for additives [5]. Measurements of a range of the common aircraft pollutants such as benzene, toluene, and chlorinated compounds in breath samples from exposed personnel on an airbase before and after work tasks showed significant exposure for all subjects, ranging from minor elevations up to > 100 times the values of

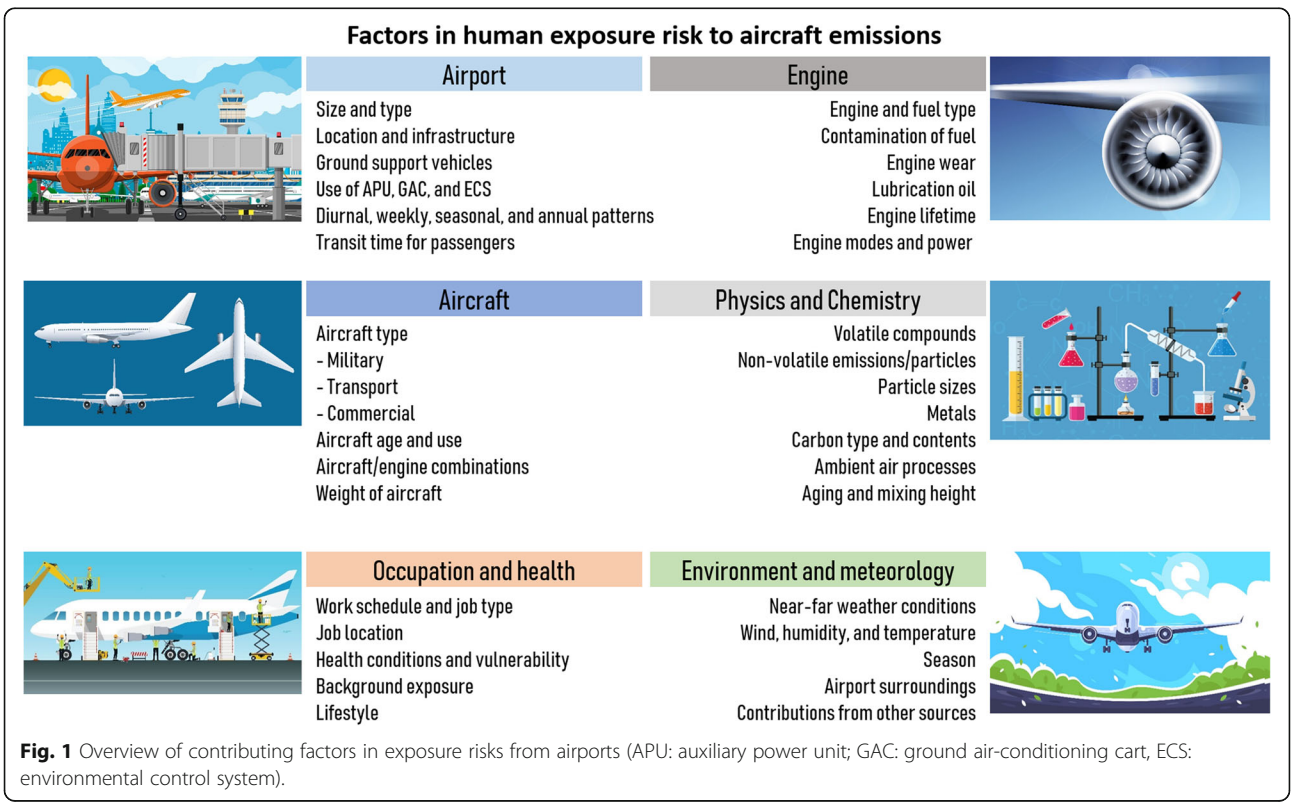

Fig. 1 Overview of contributing factors in exposure risks from airports (APU: auxiliary power unit; GAC: ground air-conditioning cart, ECS: environmental control system).

the control group for fuel workers [12]. The uptake of JP-8 components both occur via inhalation and dermal contact, and apart from benzene, naphthalene in air and in exhaled breath condensate (EBC) may be useful as a biomarker of exposure to and uptake of JP-8 fuel components in the body [13]. Although most studies report low acute toxicity for both JP-4 and JP-8, JP-8 was reported to show effects such as respiratory tract sensory irritation [11], inflammatory cytokine secretion in exposed alveolar type II epithelial cells and in pulmonary alveolar macrophages [14], increased pulmonary resistance and decreased weight gain in rats upon inhalation exposure for 7 or 28 days [15, 16]. Subchronic 90-days studies with rats with various exposure levels of JP-4 and JP-8 showed little toxicity, apart from male rat hydrocarbon nephropathy [11]. However, JP-8 fuel exposure has been linked to noise-activated ototoxic hearing loss in animal studies [17, 18] and in occupational exposure cases [19, 20], and to immunotoxicity [21, 22].

It is likely that fuel refinements will advance in the future and be an important factor in emission reductions. A newer synthetic jet fuel (Fischer-Tropsch Synthetic Paraffinic Kerosene) under development to replace JP-8 in the future, was evaluated for toxicity in the required range of tests used to develop occupational exposure limits (OELs). The highest exposure level of 2000 mg/m^3 (6 h per day, 5 days a week for 90 days) produced multifocal inflammatory cell infiltrations in rat lungs, whereas no genotoxicity or acute inhalation effects were observed, and the sensory irritation assay indicated that the refined synthetic fuel was less irritating than JP-8 [23]. Evidence of cancer risk is, however, normally evaluated in two-year inhalation studies in rats.

Characteristics of jet engine emissions

Like other combustion engines, jet engines produce volatile organic compounds (VOC) such as CO_2, NO_x, CO, SO_x and low molecular weight polycyclic aromatic hydrocarbons (PAH), and particulate matter (PM) with associated PAH, and metals [24]. Incomplete combustion of fossil fuels, including kerosene, results in the formation of carbon-rich (> 60%), aromatic bi-products called char, and condensates, which are known as soot. Char and soot can either be measured as elemental carbon (EC, used in atmospheric sciences) or black carbon (BC, used in soil and sediment sciences) [25]. This terminology originates from their measurement methods (BC is light-absorbing, determined by optical methods and EC is refractory, determined by thermo-optical and oxidizing methods) [26]. BC is often used in physical/chemical aerosol studies of airport- and urban emissions, such as in Costabile et al. [27] and Keuken et al. [28]. However, there is no apparent consistent correlation between BC concentrations and particle number concentrations across exposure studies at airports, but data is limited as noted by Stacey [9].

In general, emission levels are high, but vary depending on engine conditions and fuel type, as well as on operation modes such as idling, taxi, take-off, climb-out and landing [29].

Particulate matter (PM)

PM is divided by size ranges according to the aerodynamic diameter of the particles, where UFP are in the nanoscale of < 100 nm. Several studies have shown that aircraft emissions are dominated or even characterized by high concentrations of very small particles. This was underlined in a recent study by Stacey, Harrison and Pope carried out at Heathrow London in comparison to traffic background [30]. Some report particles in the range of 5–40 nm [31], and others particle diameters of 20 nm as compared to larger particles of > 35 nm measured at surrounding freeways [32]. Campagna et al. studied the contributions of UFP from a military airport to the surrounding area, by sampling on the airport grounds during flight activities, nearby the airport, in an urban area and in a rural area. The smallest primary particles were found within the airport (~ 10 nm) and the largest in the urban area (~ 72 nm). The highest UFP levels inside the airport were measured during taxi and take-off activities (4.0×10^6 particles/cm^3) [33]. Westerdahl et al. reported very high particle number concentrations at take-off of a single jet aircraft, with a 10 s peak of 4.8 million particles/cm^3 together with elevated NO_x and BC levels [34].

The small particles are emitted in large numbers and tend to form complex agglomerates in ambient air that can be detected in larger particle size modes [35, 36] (see [5] for elaboration). In a recent study in Montreal-Pierre-Elliott-Trudeau International Airport, the total particle number concentration over all sizes at the airport apron reached 2.0×10^6/cm^3, which was significantly higher compared to downtown Montreal (1×10^4/cm^3). The geometric mean of observed ultrafine particle number density of nanoparticles was 1×10^5/cm^3 at the apron and 1.1×10^4/cm^3 outside the Departure Level entrance [37]. We recently published exposure measurements conducted at a commercial airport and non-commercial airfield, where air concentrations were measured to 7.7×10^6 particle/cm^3 or 1086 μg/m^3 of total particles during take-off of one single jet plane [36]. The majority of these particles were below the size detection limit of 10 nm for the instruments [36], which was also shown, and highlighted as a general challenge, by others [38].

The nanostructure of carbon particles are influenced by fuel type and combustion processes. Low thrust settings are associated with the smallest particle sizes. In

one of their studies, Vander Wal et al. characterized the aircraft particles as predominantly organic carbon at low thrust and EC at higher thrust settings [38]. In turn, it was reported that soot reactivity, characterized by an outer amorphous shell, of soot particles from a turbofan test engine was lower in particles from ground idle as compared to particles from climb-out engine mode for two fuel types. Biofuel blending slightly lowered this soot reactivity at ground idle, but had the opposite effect at the higher power condition of climb-out. The authors comment that for soot reactivity, measured by an outer amorphous shell in the study, biofuels may be beneficial in airports where ground idle engine conditions are often in use, but the effect on emissions in climb-out conditions is undetermined [31]. According Moore et al., a 50:50 biofuel blending reduces particle emissions from aircraft with 50–70%, compared to conventional Jet-A fuel [39]. Another study did extensive analyses of emissions from four on-wing commercial aircraft turbo engines (two newer CFM56–7 engines and two CFM56–3 engines), also demonstrating that the type of emissions were significantly dependent on power. PM emission indices (g/kg $^{-1}$ fuel) were reported to increase from 0.011 to 0.205 g/kg $^{-1}$ fuel with a power increase from idle to 85%. In turn, the data showed that hydrocarbons are mostly emitted at ground idle engine conditions, as opposed to PM emissions being more significant at higher power thrusts, such as take-off and landing. EC fraction of PM also increased with increase in power [40]. Targino et al. measured large EC (BC) concentrations during boarding and disembarking (mean 3.78 μg/m^3), at the airport concourse (mean 3.16 μg/m^3) and also inside an aircraft on the ground with open doors (mean 2.78 μg/m^3) [41].

Lubrication oil and organophosphate esters

A recent study found that intact forms of unburned jet engine lubrication oil was a major component of emissions from aircraft [42]. Organophosphate esters (OPEs) are a large group of chemicals with toxic properties used as stabilizing agents in numerous consumer – and industrial products, including in aircraft lubricating oil and hydraulic fluids. Airplane emissions are thought to be an important source of OPEs in the environment. Not only does these chemicals accumulate in ecosystems, but it is also a concern due to the location of airports near populated areas [5]. Li et al. recently studied the concentrations of 20 OPEs in ambient air, soil, pine needles, river water, and outdoor dust samples collected around an airport in Albany, New York, and reported elevated total OPE concentrations in all samples. The spatial distribution of OPEs in air, soil, and pine needles correlated with distance to the airport. The average daily intake of OPEs via air inhalation and outdoor dust ingestion in the vicinity of the airport was up to 1.53 ng/kg bw/day for children and 0.73 ng/kg bw/day for adults [43]. Another study examined organophosphates, such as tri-n-butyl phosphate, dibutyl phenyl phosphate, triphenyl phosphate and tricresyl phosphate from turbine and hydraulic oils, as well as oil aerosol/vapors and total volatile organic compounds (VOC) in air with potential for occupational exposure for airport ground personnel. The measured exposure levels were mainly below the limit of quantification during work tasks, but provoked exposure situations resulted in significantly higher exposure levels compared to normal conditions, illustrated by oil aerosol up to 240 mg/m^{-3} and and tricresyl phosphate concentrations up to 31 mg/m^{-3}. Highest exposure levels were measured during loading from jet engine aircraft [44].

Exposure to toxic compounds via contaminated bleed air (from engine compressors), including OPEs, has been widely studied among cabin crew and pilots, and has been associated with adverse neurological effects and respiratory illness [45, 46].

Metals and other elements

Metals which might be specific to airport emissions, either by abundance or type, such as the heavy-metal vanadium [47], could be potential chemical fingerprints. Abegglen et al. applied single particle mass spectrometry to investigate metal content and sources in emissions from different jet engines at various combustion conditions, and Mo, Ca, Na, Fe, Cu, Ba, Cr, Al, Si, Mg, Co, Mn, V, Ni, Pb, Ti and Zr were found to be significant frequently occurring metals. Fuel, lubrication oil, grease and engine wear are potential sources, but several metals were allocated to multiple sources [48].

In the studies of He et al and Shirmohammadi et al, particles were collected at Los Angeles Airport (LAX) and central Los Angeles (LA) and among other analyses, allocated according to elements associated with different sources [49, 50]. S was considered as aviation-related and particle-bound Na was viewed as ocean-related, due to sea salt from the ocean near by LAX. Al, Ca, Ti and K were considered as trace elements for road dust from LAX and central LA. Mn, Fe, Cu, Zn, Ba, Pb, Ni, and Mg were associated with traffic emissions, including fuel and lubricating oil combustions and brake abrasions, engine and tire wear. In LAX particles, S accounted for the largest fraction (49.5%), followed by road dust elements (21.8%) and traffic-related elements (15.9%). In particles from central LA, elements from traffic, road dust, and aviation were represented equally (28.5, 31.5, and 33.4%, respectively) [49, 50]. In a study from Montreal-Pierre-Elliott-Trudeau International Airport, several metals were found to be abundant in the particle fraction, such as Fe, Zn, and Al, and the authors speculate, that

airports in fact may be hotspots for nanoparticles containing emerging contaminants [37]. A recent study investigated the levels of 57 elements at five sampling sites within the vicinity of Eskisehir Hasan Polatkan Airport in Turkey, based on moss bag biomonitoring using Sphagnum sp. in combination with chemical analyses of lubrication oil and aviation gasoline fuel used by general aviation, piston-engine, and turboprop aircraft. Moss bag biomonitoring was a useful tool in identification of the elements that accumulated downwind of the airport emissions. Characterization of the metal contents in moss bags and oil and fuel were in agreement, showing that Pb, along with Cd, Cu, Mo, Cr, Ni, Fe, Si, Zn, Na, P, Ca, Mg, and Al were dominating elements in the general aviation aircraft emissions [51].

Polycyclic aromatic hydrocarbons/volatile organic compounds

Polycyclic aromatic hydrocarbons (PAH), including several known carcinogens, are also candidates for chemical airport emission tracers. PAH are semi-volatile compounds, in between the gaseous and particulate phases. Lighter-weight PAHs (< 4 rings) present almost exclusively in the vapour-phase and PAHs with higher molecular weights (> 4 rings) are almost completely particle-bound [5]. It was reported that the apron of the Fiumicino Airport in Rome had higher levels of measured PAH (27.2 μg/m^3) compared to PAH levels in the airport building and terminal [52]. Another study of PAH in airport emissions at the apron reported that the five most abundant species of particle bound-PAHs for all sampling days were naphthalene, phenanthrene, fluoranthene, acenaphthene, and pyrene, with total concentrations between 0.152 μg/m^3 - 0.189 μg/m^3 (152.21–188.94 ng/m^3) depending on season. The most abundant fractions of benzo(a)pyrene (BaP) equivalent concentration (BaPeq) in different molecular weights were high-weight PAHs (79.29%), followed by medium-weight PAHs (11.57%) and low-weight PAHs (9.14%). The percentages of total BaPeq in the very small particles < 0.032 μm were 52.4% (mean concentration 0.94 ng/m^3) and 70.15% in particles < 100 μm (mean concentration 1.25 ng/m^3) [53]. Studies of the emissions from a helicopter engine at different thrusts included analysis of 22 PAH compounds, where 97.5% of the total PAH emissions were two- and three-ringed PAHs, with a mean total PAH concentration of 843 μg/m^3 and a maximum of 1653 μg/m^3 during ground idle. This was 1.05–51.7 times higher compared to a heavy-duty diesel engine, a motor vehicle engine, and an F101 aircraft engine. In turn, total level of BaP during one landing and take-off cycle (LTO) (2.19 mg/LTO) [54] was higher than the European Commission emission factor of 1.24 mg/LTO, stated in their PAH position paper, where emission factors are used to calculate the degree to which a source contributes to the total emission of a specific pollutant [55]. The Danish occupational exposure limit for PAH is 200 μg/m^3 [56], and reported PAH concentrations in ambient air across studies were below this level.

Volatile organic compounds (VOC) comprise a diverse group of organic chemicals, with different physicochemical and toxicological properties. Scientific studies of these emission compounds were meticulously reviewed by Masiol et al. [5], and as noted by the authors there is insufficient knowledge in terms of the significance of these compounds for airport exhaust health impacts [5]. Some VOC have known toxicities and other are suspected to have adverse health effects, and among the hydrocarbons found in aircraft exhaust, 14 single or complex compounds are listed as hazardous by the Federal Aviation Administration, which in addition to PAH compounds comprise benzene, styrene, xylene, toluene, acetaldehyde, 1,3-butadiene, n-hexane, acrolein, propionaldehyde, ethylbenzene, formaldehyde, and lead compounds [57]. A recent study assessed 46 VOC in the indoor air of the control tower maintenance room, potentially affecting employees, where a correlation was found between aircraft number and concentrations of light aldehydes/ketones [58].

Summary and perspectives

Emission measurement studies are continuously conducted at international airports, such as Amsterdam Airport Schiphol (AMS) [28, 59], Rome Ciampino (CIA) [60], London Heathrow (LHR) [61, 62], Beirut-Rafic Hariri International Airport (RHIA) [63], Hartsfield-Jackson Atlanta International Airport [64], Los Angeles International Airport (LAX) [32, 49, 65], and other large airports in California [66] which besides measurements of the previously mentioned compounds, also often include analyses of emission patterns and weather conditions, and characterizations of particle size- and mass distributions [67]. The data from these emission studies and physical-chemical studies of emissions including particle matter (PM), from which we referenced some in the previous sections, were recently reviewed thoroughly [9]. To summarize the previous section, we repeat some selected important points regarding airport-sourced particles that were deducted from the available data by Stacey [9]:

1) *Particle numbers near airports are significantly higher than away from airports and jet engines are a significant source of UFP.* This means that urban areas in the vicinity of airports are at risk of increased exposure to UFP in addition to normal daily background and traffic-related emissions, but airport personnel working on the ground are in significant risk of exposure, simply due to proximity.

2) *The highest concentrations of UFP are measured downwind of aircraft.* Due to the occupational potential of exposure for airport ground workers there is a growing necessity of further studies of dispersion, size distributions and environmental factors affecting these emissions. Stacey [9] highlights that measurements at longer distances are highly influenced by physical and chemical processes affecting the emissions in the air, including volatile compounds. As such, there is a need for increased standardization of methods and instruments to facilitate valid comparisons between studies within this field, as has been established in general for environmental particulate matter (PM) measurements.
3) *Aircraft emissions are dominated by very small particles of < 20 nm.* This may be a way to separate these from other emission sources, such as road traffic, where the main particle fraction are of larger sizes. Smaller particle size means higher specific surface area. Smaller particles deposit in the deep end of the lung during inhalation and the total surface area of the deposited nanoparticles has been suggested to be predictive of toxicological potential in the lung [68].
4) *The majority of non-volatile airport emission particles are carbonaceous (consisting of elemental and organic carbon compounds).*The emissions from aircraft consists of high numbers of soot particles with associated PAHs and metals, and thus, their physico-chemical composition is similar to diesel exhaust particles [36].

Diesel exhaust is classified as carcinogenic to humans by IARC [69], and cause lung cancer, systemic inflammation, and inflammatory responses in the airways [70]. Animal studies have shown that the particulate fraction of diesel exhaust is mutagenic and carcinogenic [71], whereas filtered diesel exhaust does not cause cancer [72]. Exposure to standard reference diesel particle SRM1650b and carbon black (CB) induce pulmonary acute phase response, neutrophil influx, and genotoxicity in mouse models [73–78]. Genotoxicity has been observed even at very low doses of CB [79]. In a meta-analysis of exposure to diesel exhaust and lung cancer occurrence in three occupational studies, the identified dose-response relationship showed that occupational exposure to 1 μg EC/m^3 during a 45 year work life would cause 17 excess lung cancers per 10,000 exposed using the EC content of diesel exhaust as metric [80]. Another recent analysis of 14 case-control studies estimated exposure to diesel exhaust particles using job-exposure matrices. In this study, occupational exposure to 1 μg EC/m^3 during a 45 year work life would cause 4 excess lung cancers per 10,000 exposed using the EC content of diesel exhaust as metric [81].

Carcinogenic substances are evaluated and listed by the International Agency of Research in Cancer (IARC) under WHO according to accumulated scientific findings in cellular, animal and human studies. Group 1 entails substances with sufficient evidence of carcinogenicity in humans and group 2 includes substances that IARC has classified as probably (2A) or possibly (2B) carcinogenic to humans [82]. As almost all current aviation fuel/jet fuels are extracted from the middle distillates of crude oil (kerosene fraction), which is between the fractions for gasoline and diesel [5] (whose combustion emissions are classified as group 2B and group 1 carcinogens, respectively [69]), there is cause for concern in terms of the potential carcinogenicity of exposure to jet fuel combustion products.

Exposure studies

Reported exposure levels for PAH, BC and UPF in the studies below are presented in Table 1.

Occupational exposure

Childers et al. (2000): An extensive study of PAH concentrations at an airbase was carried out, using real-time monitors and air samplers on different locations and in different flight-related and ground-support activities. Airborne and particle-bound PAH were measured in a break room, downwind from an aircraft (C-130H) during engine tests, in a maintenance hangar, in an aircraft (C-130H) cargo bay during cargo-drop training and during engine running on/off loading and backup exercises, and downwind from aerospace ground equipment (diesel-powered electrical generator and a diesel-powered heater). Measurements were carried out with three different monitors. Total PAH concentrations followed a general trend of downwind from two diesel aerospace ground equipment units > engine on/off-loading exercise > engine tests > maintenance hangar during taxi and takeoff > background measurements in the maintenance hangar. Reported mean total PAH concentrations in integrated air samples (vapor phase) were 0.6011 μg/m^3 (hangar background), 1.0254 μg/m^3 (hangar taxiing), 2.8027 μg/m^3 (engine test), 6.7953 μg/m^3 (engine running on/off) and 9.8111 μg/m^3 (aerospace ground equipment). Dominating PAH in all exposure scenario was naphthalene, the alkyl-substituted naphthalenes, and other PAHs in the vapor phase. Particle-bound PAHs, such as fluoranthene, pyrene, and benzo[a]pyrene were also found. During flight-related exercises, PAH concentrations were 10–15 higher than in ambient air, and it was found that PAH contents fluctuated rapidly from < 0.02 to > 4 μg/m^3 during flight-related activities [83].

Iavicoli et al. (2006): In this study, occupational exposure risk to PAH and biphenyl was evaluated in an Italian airport during winter. Concentration and purification of 12 samples of 25 PAH by gas chromatography-ion trap

Table 1 Overview of reported levels of occupational exposures of PAH, BC, and particles in airports. *Mean levels are presented if reported. For detailed data, see references*

Description	*Reported mean levels Ambient air*	*Reported mean levels Personal monitors*	Reference
PAH			
Total mean PAH concentrations in integrated air samples at an airbase on different locations and in different flight-related and ground-support activities	601.1 ng/m^3 (hangar background) 1025.4 ng/m^3 (hangar taxiing) 2802.7 ng/m^3 (engine test) 6795.3 ng/m^3 (engine running on/off) 9811.1 ng/m^3 (diesel-fueled aerospace ground equipment) *During flight-related exercises, PAH concentrations were 10–15 times higher than in ambient air*	*NA*	Childers et al. (2000) [83]
PAH compounds of highest levels measured for 24 h in three different locations	130–13,050 ng/m^3 (naphthalene) 64–28,500 ng/m^3 (2-methylnaphthalene) 24–35,300 ng/m^3 (1-methylnaphtalene) 24–1610 ng/m^3 (biphenyl) 54.2 ng/ m^3 (fluoranthene) 8.6 ng/m^3 (benzo[a]pyrene)	*NA*	Iavicoli et al. (2006) [84]
Total mean of 23 PAH (vapor and particle-bound) measured during 24 h of 5 work days at the airport apron, airport building and terminal/office area	27.703 μg/m^3 (apron) 17.275 μg/m^3 (airport building) 9.494 μg/m^3 (terminal departure area) *Highest levels in the airport apron particularly for 1 and 2-methylnaphthalene and acenaphthene*	*NA*	Cavallo et al. (2006) [52]
Total mean particle-bound PAH measured in the vicinity of LAX to assess the spread of airport emissions in up – and downwind ambient air to the immediate neighborhood	18.2 ng/m^3 (upwind from the airport) 24.6 ng/m^3 (downwind from the airport) 50.1 ng/m^3 (at the taxiway) 60.1 ng/m^3 (terminal region) *Particle-bound PAH mean levels measured on two freeways were 47.0 ng/m^3 and 169.4 ng/m^3*	*NA*	Westerdahl et al. (2008) [34]
Black carbon			
Mean black carbon concentrations measured at different micro-environments of airports and in commercial flights	3.78 μg/m^3 (during boarding/disembarking) 3.16 μg/m^3 (airport concourse) 2.78 μg/m^3 (inside aircraft with open doors) 0.81 μg/m^3 (inside aircraft on the ground with closed doors)	*NA*	Targino et al. (2017) [41]
BC levels measured in the vicinity of LAX to assess the spread of airport emissions in up – and downwind ambient air to the immediate neighborhood	0.3 μg/cm^3 (upwind from the airport) 0.7 μg/cm^3 (downwind from the airport) 1.8 μg/cm^3 (at the taxiway) 3.8 μg/cm^3 (terminal region)	*NA*	Westerdahl et al. (2008) [34]
Contributions of airport activities to measured BC levels at Amsterdam Schiphol were measured for 32 sampling days over 6 months	Mean BC: 0.6 mg/m^3	*NA*	Pirhadi et al. (2020) [85]
Particles			
UFP and size distributions measured in the vicinity of LAX to assess the spread of airport emissions in up – and downwind ambient air to the immediate neighborhood	Average UFP counts of 5×10^4 particles/cm^3 (500 m downwind of the airport), which were significantly influenced by aircraft operations where peaks were observed Maximum UFP measured was 4.8×10^6 particles/m^3 downwind from a jet aircraft taking off Particle size: 90 nm (upwind from airport) 10–15 nm (downwind from airport)	*NA*	Westerdahl et al. (2008) [34]
Total mean concentration of 10 daily UFP samples with personal monitors placed with crew chief and hangar operator	6.5×10^3 particles/cm^3 (downwind site)	2.5×10^4 particles/cm^3 (crew chief) 1.7×10^4 particles/cm^3 (hangar operator) *Median number concentrations for 2 months measurement period*	Buonanno et al. (2012) [86]
Geometric means of personal exposure to particle number concentration carried out in five different occupational groups	*NA*	37×10^3 UFP/cm^3 (baggage handlers) 5×10^3 UFP/cm^3 (landside security) $12–20 \times 10^3$ UFP/cm^3 (catering drivers, cleaning staff and airside security)	Møller et al. (2014) [87]
Particle and metal exposure in ambient air and in airport workers using exhaled breath condensates	$1.0 \times 10^4–2.1 \times 10^7$ particles/cm^3 (apron workers) $10^3–10^4$ (office staff) *Airport workers were exposed to significantly smaller particles (mean geometric size: 17.7 nm) compared*	Particulate content was found in exhaled breath condensates, but no difference was found between the two study groups	Marie-Desvergne et al. (2016) [88]

Table 1 Overview of reported levels of occupational exposures of PAH, BC, and particles in airports. *Mean levels are presented if reported. For detailed data, see references (Continued)*

Description	*Reported mean levels Ambient air*	*Reported mean levels Personal monitors*	Reference
	to office workers (mean geometric size: 23.7 nm).		
Number concentrations and size distributions inside the cabin of an aircraft waiting for take-off compared to outdoor	$10–40 \times 10^3$ particles/cm^3 *A 40 min wait 100 m downwind of the runway was calculated to be equal to 4 h exposure in a clean urban background environment away from the airport*	*NA*	Ren et al. $(2018)_a$ [89]
Potential exposure to passengers and indoor airport staff investigated by $PM_{2.5}$ concentrations in the terminal building at three seasons	*Arrival hall:* 337 μg/m^3 (Winter) 105 μg/m^3 (Spring) 167 μg/m^3 (Summer) *Departure hall:* 385 μg/m^3 (Winter) 130 μg/m^3 (Spring) 170 μg/m^3 (Summer) *Ambient airport air:* 400 μg/m^3 (Winter) 156 μg/m^3 (Spring) 216 μg/m^3 (Summer) *1.9–5.9 times higher particles number concentrations in the terminal buildings than measured in a normal urban environment* *Total UFP exposure during an entire average waiting period (including in the terminal building and airliner cabin) of a passenger was estimated to be equivalent to 11 h of exposure to normal urban emissions*	*NA*	Ren et al. $(2018)_b$ [90]
UFP monitoring at several sampling sites in the vicinity of Lisbon Airport for 19 non-consecutive days	Downwind average particle number concentration range: 3.3×10^4 cm^3 to 5.9×10^4 particles per cm^3 Measured range of peaks: 2.3×10^5 particles per cm^3 to 3.4×10^5 particles per cm^3	*NA*	Lopes et al. (2019) [91]
Maximal measurements at a commercial airport and exposure assessment at a non-commercial airfield	10^6 -10^8 particles/cm^3 (main combustion events of plane leaving and arriving) 1086 μg/m^3 (single peak event of plane leaving) *10.7% was predicted to deposit in the alveolar lung regions*	*Personal exposure levels were similar to air concentrations*	Bendtsen et al. (2019) [36]
Maximal UFP number concentration of UFP exposures investigated for 33 male employees working in an airport taxiway	9.59×10^6 (during support tasks in taxiing and taking off of the aircraft)	2.44×10^3 particles/cm^3 *Median UFP number concentration*	Marcias et al. (2019) [92]
Contributions of airport activities to measured particle number concentrations (PNCs) at Amsterdam Schiphol were measured for 32 sampling days over 6 months	Mean total PNC: 35,308 particles/cm^3 *Aircraft departures and aircraft arrivals contributed to 46.1 and 26.7% of PNC, respectively. Ground support equipment and local road traffic accounted for 6.5% of PNC and were characterized by diameters of 60–80 nm. Traffic from surrounding freeways was characterized by particles of 30–40 nm and contributed to 18% of PNC* Mean $PM_{2.5}$: 7.4 mg/m^3 Particle size range: 10–20 nm	NA	Pirhadi et al. (2020) [85]

mass spectrometry sampled for 24 h in three different locations of the airport showed general low levels, with highest levels of naphthalene (0.13–13.05 μg/m^3), 2-methylnaphthalene (0.064–28.5 μg/m^3), 1-methylnaphtalene (0.024–35.3 μg/m^3), and biphenyl (0.024–1.610 μg/m^3). Measured levels of the carcinogens benzo[b + j + k]fluoranthene and benzo[a]pyrene were 0.0542 μg/m^3 and 0.0086 μg/m^3 respectively [84].

Buonanno et al. (2012): Occupational exposure and particle number distributions were studied at an aviation base on a downwind site, close to the airstrip and by 10 daily UFP samples with personal monitors placed with a crew chief (assists the pilots during ground activities) and a hangar operator (aircraft maintenance). Particle number distribution averaged a total concentration of 6.5×10^3 particles/cm^3 at the downwind site. Short-term peaks during the working day mainly related to takeoff, landing and pre-flight operations of jet engines were measured in the proximity of the airstrip. Personal exposure concentrations were higher than stationary monitoring measurements. Personal exposure of workers were at a median number concentration of 2.5×10^4

particles/cm^3 for the crew chief and 1.7×10^4 particles/cm^3 for the hangar operator during the 2 months measurement period. The crew chief experienced the highest exposures, with maximum values at approximately 8×10^4 particles/cm^3 [86].

Møller et al. (2014): Personal exposure monitoring of particle number concentration was carried out in five different occupational groups, namely baggage handlers, catering drivers, cleaning staff, airside security and landside security in CPH, for 8 days distributed over 2 weeks. The study reported significant differences among the occupational groups. Highest exposures were found in baggage handlers (geometric mean: 37×10^3 UFP/cm^3), which was 7 times higher in average compared to landside security which are indoor employees (geometric mean: 5×10^3 UFP/cm^3). In between highest and lowest exposure groups, were catering drivers, cleaning staff and airside security with similar exposure levels (geometric mean: $12–20 \times 10^3$ UFP/cm^3) [87].

Targino et al. (2017): Black carbon (BC) particle concentrations were measured within different microenvironments of 12 airports and on 41 non-smoking commercial flights. Great variability was seen depending on environment measured. 70% of personal exposure during a journey occurred in the airport concourses and during transit to/from the aircraft. 18% was contributed to the waiting time onboard an aircraft with open doors waiting for loading. Largest BC exposure were found during boarding and disembarking (mean BC = 3.78 μg/cm^3; 25th, 50th, 75th percentiles: 1.29, 2.15, 4.68), at the airport concourse (mean BC = 3.16 μg/cm^3; 25th, 50th, 75th percentiles: 1.20, 2.15, 4.0) and inside parked aircraft with open doors (mean BC = 2.78 μg/cm^3; 25th, 50th, 75th percentiles: 0.35, 0.72, 2.33). BC levels were low in the aircraft on the ground with closed doors (mean BC = 0.81 μg/cm^3; 25th, 50th, 75th percentiles: 0.2, 0.35, 0.72, respectively). Lowest concentration was found during flights in the air [41].

Ren et al. (2018)[a]: The number concentrations and size distributions inside the cabin of an aircraft waiting for take-off were investigated and analyzed in comparison to outdoor UFP and the use of the ground air-conditioning cart (GAC) and environmental control system (ECS), which are used to provide conditioned air between boarding and doors closing to prepare for take-off. The study showed that environmental particle number concentration varied significantly, ranging from 10 to 40×10^3 particles/cm^3 depending on wind, and take-off and landing activities. When the GAC was on, the indoor particle numbers followed those outdoors, with the ECS providing protection factors for crew and passengers from 1 to 73% for 15–100 nm particles, and from 30 to 47% for 100–600 nm particles. A 40 min wait 100 m downwind of the runway was calculated to be equal to 4 h exposure in a clean urban background environment away from the airport [89].

Ren et al. (2018)[b]: In this study, the potential exposure to passengers as well as indoor airport staff was investigated by measurements in the terminal building of Tianjin Airport in Beijing of CO_2, $PM_{2.5}$, and UFP concentration and particle size distribution during three seasons. The effects on the indoor air quality of airliner-generated particles penetrating from the outdoor environment through open doors and by heating, ventilation and air-conditioning systems was studied.

$PM_{2.5}$ concentrations in the terminal building varied during the seasons of winter, spring and summer with 337–105-167 μg/m^3 in the arrival hall, 385–130-170 μg/m^3 in the departure hall, and 400–156-216 μg/m^3 in ambient airport air, respectively. These were significant higher levels compared to Chinese standard and WHO annual mean value of 10 μg/m^3 during all the tested seasons. The indoor environment was significantly affected by the outdoor air levels (Spearman: $p < 0.01$). Particle number concentration in the terminal building displayed two size distribution, with one mode at 30 nm and a mode at 100 nm, which was significantly different from the size distribution measured in a normal urban environment, which had one peak at 100 nm. The study reports particle number concentrations of 1.9–5.9 times higher in the terminal buildings than the concentrations measured in a normal urban environment by different size bins. Measured total UFP exposure during an entire average waiting period (including in the terminal building and airliner cabin) of a passenger was estimated to be equivalent to 11 h of exposure to normal urban emissions [90].

Bendtsen et al. (2019): In this study, the occupational exposure levels to particles was evaluated by measurements at a non-commercial airfield and particles were collected and characterized at a non-commercial airfield and from the apron of a commercial airport.

Electron microscopy showed that the aerosol at the non-commercial airfield appeared to be mainly aggregates of soot, whereas the aerosol at the apron of the commercial airport appeared much more complex dominated by agglomerated soot particles, salt crystals and pollen. At the commercial airport, particles were mainly below 300 nm in diameter and distributed in two modes with geometric mean diameters of < 20 nm and approximately 140 nm. At the non-commercial airfield, two full cycles of a normal workflow of plane leaving, plane arriving and refueling by were recorded in a jet shelter using stationary and portable devices including in the breathing zone of personnel. Average particle number concentration for a full workflow cycle of 170 min were 1.22×10^6 particles/cm^3. For take-off and landing of one jet plane, average particle number concentrations and mass were 7.7 particles/cm^3 and 1086 μg/m^3 and 2.67

particles/cm^3 and 410 μg/m^3, respectively. During the main combustion events of plane leaving and arriving, the instruments reached their upper detection limits of 10^6 particles/cm^3 (DiSCmini, which measures particle number concentration, mean particle size and lung-deposited surface area) and 10^8 particles/cm^3 (ELPI, which monitors real-time particle levels), including in the breathing zone monitor of the personnel. Prevalent particle sizes suggested that the jet engine combustion particles were < 10 nm in aerodynamic diameter [36].

Mokalled et al. (2019): In this study, 48 volatile organic compounds (VOC) from approximately 100 commercial aircraft during real operations of different engine modes at Beirut Rafic Hariri International Airport were assessed to identify specific markers, together with measurements of Jet A-1 kerosene fuel vapors and gasoline exhaust.

Heavy alkanes (C8-C14, mainly n-nonane and n-decane) contributed to 51–64% of the total mass of heavy VOCs emitted by aircraft. Heavy aldehydes (nonanal and decanal) was reported as potential tracers for aircraft emissions due to their exclusive presence in aircraft-related emissions in combination with their absence from gasoline exhaust emissions. Total concentration of heavy alkanes in the ambient air was 47% of the total mass of heavy VOCs measured. No aircraft tracer was identified among the light VOCs (≤ C7). VOC compositions in jet exhaust varied with combustion power, and it was shown that light VOC emissions decrease as the engine power increases. Auxiliary power unit (APU) emissions were identified to be of the same order of magnitude as main engine emissions [93].

Marcias et al. (2019): In this study, occupational exposure to ultrafine particles and noise was investigated for 33 male employees working in an airport taxiway in a smaller Italian airport. Job categories represented were aircraft ground equipment personnel, firefighting officer, flight security agent, and aviation fuel administration staff. Both stationary sampling (ELPI) and personal particle measurements were included. The morphology and chemical composition was determined by EM and EDS, and showed small soot particles in aggregates with sodium, potassium, magnesium, calcium, aluminium, carbon, nitrogen, silicon, oxygen, fluorine, chlorine and sulphur. The maximal UFP number concentration (9.59×10^6 particles/cm^3) on stationary equipment was measured during support tasks in taxiing and taking off of the aircraft. Median UFP number concentration measured with personal monitors on the 33 operators was 2.44×10^3 particles/cm^3 and a maximum of 13×10^3 particles/cm^3. Average size range was 35–103 nm. A significant difference in mean size and distributions was found between job tasks, where flight security officers were exposed to particles with lower mean sizes as compared to aircraft ground equipment operators [92].

Residential exposure

Westerdahl et al. (2008): Air measurements were carried out in the vicinity of LAX to assess the spread of airport emissions in downwind ambient air to the immediate neighborhood. Ultrafine particle numbers (UFP), size distributions, particle size, black carbon (BC), nitrogen oxides (NOx), and particle-bound PAH were measured. The lowest levels of pollutants were measured upwind of the airport, where UFP ranged from 580 to 3800 particles/cm^3, black carbon from 0.2 to 0.6 μg/m^3, and particle-bound PAH from 18 to 36 ng/m^3. In contrast, at 500 m downwind of the airport, average UFP counts of 50,000 particles/cm^3 were observed, which were significantly influenced by aircraft operations where peaks were observed. Black carbon, particle-bound PAH, and NO_x were also elevated, although not in the same extent, and the authors observed that BC, particle numbers, and NOx levels varied together in similar patterns indicating they were associated with similar sources. Black carbon concentrations varied across the measurement sites, with a mean of 0.3 μg/cm^3 upwind from the airport, 0.7 μg/cm^3 downwind from the airport, 1.8 μg/cm^3 at the taxiway, and 3.8 μg/cm^3 in the terminal region. Mean PM-PAH levels were 18.2, 24.6, 50.1 and 60.1 ng/m^3 at the measurement sites, respectively. PM-PAH mean levels measured on two freeways were 47.0 ng/m^3 and 169.4 ng/m^3. The maximum UFP measured was 4.8×10^6 particles/m^3 downwind from a jet aircraft taking off. NOx levels before the take-off were around 8 ppb and increased to 1045 ppb, mostly due to NO. Black carbon rose from approximately 800 to 9550 ng/m^3, and PM-PAH values increased from 37 to 124 ng/m^3. Significant variations were observed in particle sizes, where upwind measurements were dominated by particles of 90 nm, and downwind particles were of 10–15 nm in size. The author noted that UFP levels from aircraft were measured to persist up to 900 m from the runways, indicating potential risks for the nearby communities [34].

Lopes et al. (2019): In this study, data is presented from UFP monitoring at several sampling sites in the vicinity of Lisbon Airport in 2017 and 2018, for 19 non-consecutive days. Measurements included sites further away from the airport, under the landing/take-off path. Correlation analysis between air traffic activity and UFP concentrations was conducted and show the occurrence of high UFP concentrations in the airport vicinity. The particle counts increased 18–26 fold at locations near the airport, downwind, and 4-fold at locations up to 1 km from the airport. Results show that particle number increased with the number of flights and decreased with the distance to the airport [91].

Pirhadi et al. (2020): In this study, the contributions of airport activities to particle number concentrations (PNCs) at Amsterdam Schiphol was quantified by use of

the positive matrix factorization (PMF) source apportionment model. Various pollutants were measured, including NOx and CO, black carbon, PM2.5 mass, and the number of arrivals and departures were measured for 32 sampling days over 6 months. Airport activities accounted for 79.3% of PNCs divided in aircraft departures, aircraft arrivals, and ground service equipment (GSE) (with contributions of local road traffic, mostly from airport parking areas). Aircraft departures and aircraft arrivals contributed to 46.1 and 26.7% of PNCs, respectively, and were characterized by particle diameters < 20 nm. GSE and local road traffic accounted for 6.5% of the PNCs and were characterized by diameters of around 60–80 nm. Traffic from surrounding freeways was characterized by particles of 30–40 nm and contributed to 18% of PNCs. In comparison, the urban background emissions dominated the mass concentrations with 58.2%, but had the least contribution to PNCs with 2.7% [85].

Summary of exposure studies

Occupational exposure to increased levels of nanosized particles [36, 85–90, 92], increased levels of PAH including known human carcinogens [52, 83, 84], and black carbon [41] were reported in the literature. Levels of exposure reported in these studies are summarized in Table 1. One study reported that personnel monitors measured higher levels compared to stationary equipment [87], and it was shown that ground support equipment, such as diesel-powered electrical generators and heaters [83] and auxiliary power units [93] contribute significantly to emissions.

Three important main factors were identified which significant influenced occupational exposure: *proximity to emission sources*, where levels were generally higher in close proximity and down-wind to aircraft, *fluctuations in emission levels*, characterized by exposure peak events such as landing- or take-off, and *job type*, where outdoor ground-affiliated work types are at highest risk of exposure. As such, airport personnel can likely be grouped in low (office staff/landside jobs with indoor work, far away from emission sources), medium (catering/cleaning/landside security staff with intermittent outdoor work) and high (baggage handlers/aircraft mechanics/ crew chief) exposure groups.

The majority of studies on the contribution of airport emissions to air pollution in the surrounding environment are physical/chemical studies of particle numbers, mass and related air pollutants, which are reviewed elsewhere as previously described.

More studies reported increased risk of exposure correlating with decreased distance to airports [94–96] and time spent downwind from an airport [97], hence a significant factor for potential health effects for neighboring residential areas based on these studies is *distance to airports*, which relating to wind and atmospheric conditions is an important determinant for pollution levels.

Health effects

Here we present studies in which direct health effects have been assessed in humans, including in biomonitoring and epidemiological studies, and biological mechanisms-of-action assessed in animal or cell studies. Our main focus is particle exposure, however, studies focusing more on VOC/PAH are also presented.

Occupational studies

Møller et al. (2017 and 2019): A prospective, occupational cohort study in CPH, encompassing 69,175 men in unskilled positions as baggage handlers or in other outdoor work used register information of socioeconomic, demographic and health data together with a job-exposure matrix was based on GPS measurements within the airport, detailed information on tasks from 1990 to 2012, exposure to air pollution at home, and lifestyle details. Occupational exposure groups were categorized according to work time at the apron, "apron-years" (non-exposed, 0.1–2.9, 3.0–6.9 and ≥ 7 years). The reference group comprised different low-exposure occupational groups [98]. A follow-up study was conducted on an exposed group of 6515 male airport workers at 24–35 years of age in unskilled positions with a reference group of 61,617 men from greater Copenhagen area in unskilled jobs. Exposure was assessed by recordings of time spent on the airport apron and diagnoses of ischemic heart disease and cerebrovascular disease was obtained from the National Patient Register. No associations between cumulative apron-years and the two disease outcomes were found. On the other hand, since the exposed group had a mean age of 24–35 years, a 22-year follow-up may have been too short to detect cardiovascular effects [99].

Lemasters et al. (1997): In this early study, mixed low-level exposure to fuel and solvent was studied in a repeated measures design with male aircraft workers at a military air station serving as their own controls from pre-exposure to 30 weeks post-exposure. The study group consisted of six aircraft sheet metal workers mainly exposed to solvents, adhesives and sealants, six aircraft painters exposed to solvents and paints, 15 jet fueling operations personnel ($n = 15$) responsible for fuel delivery, fueling and defueling aircraft and repairing fuel systems, and 23 workers in the flight line crew exposed to jet fuel, jet exhaust, solvents and paint, and included ground crew and jet engine mechanics. Expired breath analysis was carried out for different trace compounds, but was found to have low values (< 25 parts per billion). An increase in sister chromatid exchange (SCE)

compared to pre-exposure was found after 30 weeks of exposure for sheet metal workers (mean SCE per cell increased from 6.5 (SD: 0.8, range: 5.5–7.7) to 7.8 (SD: 0.3, range: 7.4–8.2) and painters (mean SCE per cell increased from 5.9 (SD: 0.7, range: 5.0–6.8) to 6.7 (SD: 1.0, range 5.3–7.8)), indicating exposure to genotoxic substances for these subgroups [100].

Tunnicliffe et al. (1999): In Birmingham International Airport, occupational exposure to aircraft fuel and jet stream exhaust was evaluated in terms of respiratory symptoms and spirometry in 222 full-time employees according to job title. Data was collected by questionnaire and with on-site measurement of lung function, skin prick tests, and exhaled carbon monoxide concentrations. Occupational exposure was assessed by job title, where baggage handlers, airport hands, marshallers, operational engineers, fitters, and engineering technicians were considered as high exposure groups, security staff, fire fighters, and airfield operations managers as medium exposure group, and low exposure groups consisted of terminal and office workers. Upper and lower respiratory tract symptoms were commonly reported in the questionnaire and 51% had one or more positive allergen skin tests. Cough with phlegm and runny nose were found to be significantly associated with high exposure (adj. OR = 3.5, CI: 1.23–9.74; adj. OR = 2.9, CI: 1.32–6.4, respectively). Upper and lower respiratory symptoms were common among exposed workers, but no significant difference was found in lung function. The authors conclude that it is more likely that these symptoms reflect exposure to exhaust rather than fuel [101].

Yang et al. (2003): The aim of this study was to evaluate self-reported adverse chronic respiratory symptoms and acute irritative symptoms among 106 airport workers in risk of exposure to jet fuel or exhaust (jet fuel handlers, baggage handlers, engineers etc.) compared to 305 terminal or office workers (control group) at Kaohsiung International Airport (KIA) in Taiwan. The odds ratio analyses were adjusted for possible confounding factors, such as age, marital status, education, duration of employment, smoking status, and previous occupational exposure to dust or fumes. The prevalence of acute irritative symptoms was not significantly different, whereas chronic respiratory symptoms such as cough (adj. OR = 3.41, CI: 1.26–9.28) and dyspnea (adj. OR = 2.34, CI: 1.05–5.18) were significantly more common among airport workers. The study did not report exposure measurements, but the authors conclude that the expected higher exposure of aviation fuel or exhaust in the ground personnel is the likely explanation for the increased incidence of self-reported chronic respiratory health-effects compared to the office personnel [102].

Whelan et al. (2003): Prevalence of respiratory symptoms among female flight attendants along with teachers was investigated by self-reported questionnaire in comparison to database-derived data on blue collar workers with no known occupational exposures, and it was found that female flight attendants and teachers were significantly more likely to report work related eye (12.4 and 7.4%), nose (15.7 and 8.1%), and throat symptoms (7.5 and 5.7%), and more episodes of wheezing and flu, compared to other female workers (2.9% eye, 2.7% nose, and 1.3% throat symptoms). Female flight attendants were significantly more likely than teachers and controls to report chest illness 3 years in retrospective (flight attendants: 32.9%, teachers: 19.3%, female workers: 7.2%) [103].

Cavallo et al. (2006): In this study, 41 airport employees in jobs with very close proximity to aircraft in service (fitters, airport hands, marshallers, baggage handlers) or in jobs with some proximity to aircraft (security staff, maintenance service personnel, cleaning staff, air field operations managers, runway shuttle drivers) in Leonardo da Vinci airport in Rome were evaluated for exposure to aircraft emissions along with biomarkers of genotoxicity in comparison to a control group of 31 office workers at the same airport. Job tasks in very close proximity to aircraft in service were considered to be high exposure jobs. Urinary PAH metabolites were used as biomarker of endogenous PAH exposure in parallel with PAH analyses of air samples. Exfoliated buccal cells and blood were evaluated for DNA damage, e.g. micronuclei, chromosomal aberrations and sister chromatid exchange (SCE). PAH exposure was measured during 24 h of 5 work days at the airport apron, airport building and terminal/office area from January to February 2005. Total mean of 23 PAHs (particle and vapour) at the apron, airport building and terminal departure area were 27.7, 17.2, and 9.5 $\mu g/m^3$, respectively, with a prevalence of 2–3 ring PAHs with highest levels in the airport apron particularly for 1- and 2-methylnaphthalene and acenaphthene. Urinary PAH metabolite levels were similar for high exposure job groups and controls. The exposed group showed increased SCE (mean number: 4.61 ± 0.80) compared to control group (3.84 ± 0.58) and increased levels of chromosomal aberrations and DNA strand breaks in the Comet assay in both buccal cells and lymphocytes, indicating genotoxic exposures [52].

Radican et al. (2008): A follow-up study of 14,455 workers from 1990 to 2000 evaluated the mortality risk from trichloroethylene and other chemical exposures in aircraft maintenance workers. Relative risk (RR) for exposed compared to unexposed workers were calculated, and positive associations with several cancers were observed, but mortality had not changed substantially since 1990, with increased risk of all-cause mortality (RR = 1.04, CI: 0.98–1.09) or death from all cancers (RR = 1.03, CI: 0.91–1.17) [104].

Erdem et al. (2012): A study group consisting of 43 aircraft fuel maintenance staff, fuel specialists, and mechanics occupationally exposed to JP-8 fuel directly or via engines of jet planes were evaluated for the metabolites 1- and 2-naphthol and creatinine in urine as biomarkers of exposure to jet fuel. In turn, sister chromatid exchange (SCE) and micronuclei were evaluated in blood-derived lymphocytes as biomarkers of genotoxic exposure. Urinary markers and SCE were significantly increased in exposed workers (1-naphthol: 99.01 μmol/mol creatinine; 2-naphthol: 77.29 μmol/mol creatinine), by 10-fold as compared to a control group of 38 employees working in the same area without any work-related exposure to JP-8 fuel [105].

Marie-Desvergne et al. (2016): In this study, exposure to airport nanoparticles and metals was evaluated in airport workers by exhaled breath condensate (EBC) as a non-invasive representative of the respiratory system. EBC was collected from 458 airport workers from Marseille Provence Airport and Roissy Charles de Gaulle Airport in Paris, working directly on the apron (exposed) or in the offices (less exposed). In addition, ambient nanoparticle exposure levels were characterized in terms of particle number concentration, size distribution and by electron microscopy.

The study showed that airport workers were exposed to significantly higher particle numbers (1.0×10^4–2.1×10^7 particles/cm^3) compared to office staff (10^3–10^4 range equivalent to background traffic emissions), although office workers were periodically exposed to peaks of 10^4–10^5 when the building doors were open. Airport workers were exposed to significantly smaller particles (mean geometric size: 17.7) compared to office workers (mean geometric size: 23.7). EBC was characterized by volume, total protein content, and a multi-elemental analysis was used to.

measure Na, Al, Cd, and Cr. Particles in EBC were analyzed with dynamic light scattering and electron microscopy (SEM-EDS).

A significantly higher concentration of Cd was found in apron worker EBC (mean: 0.174 ± 0.326 μg/l) in comparison with office workers (mean: 0.108 ± 0.106 μg/l). Particulate content in EBC was confirmed by DLS and SEM-EDS, but no differences were found between the two study groups, and measured EBC particle contents did not correlate with ambient exposure levels [88].

Studies on effects of residential exposure to airport emissions

Visser et al. (2005): In this population-based study, it was investigated if the residents living around Amsterdam Schiphol Airport were at higher risk of developing cancer compared to the general Dutch population. The regional cancer registry was used, estimating the cancer incidence from 1988 to 2003 in the population residing near the airport compared to the national cancer incidence. The exposure was defined by aircraft noise and postal code areas, as historical data on ambient air pollution were unavailable. The study did not include information on lifestyle factors, and therefore, did not control for smoking and other potential confounders. A core zone closest to the airport and a remaining ring zone was studied. Thirteen thousand two hundred seven cancer cases were identified in the study area, and a significant increase in the incidence of hematological cancers (standardized incidence ratio, SIR = 1.12, CI: 1.05–1.19) was found, mainly due to non-Hodgkin lymphoma (SIR = 1.22, 95% CI: 1.12, 1.33) and acute lymphoblastic leukemia (SIR = 1.34, CI: 0.95, 1.83). Respiratory system cancer incidence was significantly decreased (SIR = 0.94, CI: 0.90, 0.99), due to the low rate in males (SIR = 0.89). The study concludes that the overall cancer incidence in the residential areas closest to Amsterdam Schiphol Airport was similar to the national incidence. The increase in the risk of hematological cancers could not be explained by higher levels of ambient air pollution in the area [106].

Lin et al. (2008): In this cross-sectional study, it was assessed whether residents living near commercial airports had increased rates of hospital admissions due to respiratory diseases compared to those living further away. The study included all residents living within 12 miles from the center of each of three airports (Rochester in Rochester, LaGuardia in New York City and MacArthur in Long Island). Hospital admission data were collected by the New York State Department of Health for all residents who were hospitalized for asthma, chronic bronchitis, emphysema, chronic obstructive pulmonary disease and, for children aged 0–4 years, bronchitis and bronchiolitis during 1995–2000. Exposure indicators were distance from the airport and dominant wind patterns from the airports.

The relative risks of hospital admissions due to respiratory conditions for residents living < 5 miles from the airport were 1.47 (CI: 1.41–1.52) for Rochester and 1.38 (CI: 1.37–1.39) for LaGuardia, as compared to those living > 5 miles from the airports. No differences were observed for MacArthur airport. When considering hospital admission rates by distance for 12–1 miles towards the airports, a significant trend of increasing hospital admissions with closer distance to the airport was observed for the Rochester airport. The authors reported a stronger effect for traditionally lower socio-economic groups [94], which may be of more relevance in the US, due to the medical insurance system.

Habre et al. (2018): In this study, 22 non-smoking volunteers with mild to moderate asthma were recruited to do scripted mild walking activity in parks inside or outside a zone of high airport-related ultrafine particle

exposure downwind of LAX. Physiological parameters were measured before and after exposure, and the study was conducted as a cross-over study, such that the participants served as their own controls. Personal exposure to black carbon, PAH, ozone, and $PM_{2.5}$ were measured and combined with source appointment analysis and health models. A difference in PM exposure was found between the high (mean particle number concentration of 53,342 particles/cm^3 and mean particle size of 28.7 nm) and the low exposure zone (mean particle number concentration of 19,557 particles/cm^3 and mean particle size of 33.2 nm). It was reported that IL-6 levels in blood were increased after the walk in the high exposure zone compared to the low exposure zone. Airport-related PM was distinguished from roadway traffic emissions by principal component analysis, and increase of airport-related PM was significantly associated with increased IL-6 levels [107].

Amsterdam Schiphol report (2019): Based on three studies with 191 primary school children from residential areas near Schiphol Airport, 21 healthy adults living adjacent to the airport [108], and an in vitro study [109], respectively, this Dutch report (not subjected to peer review) describes the findings of reduced lung function in children and adults following higher short-term exposure to ultrafine particles near Schiphol Airport. On days with high exposure, children suffered more from respiratory complaints and used more medicine. In the adults, short-term reductions in heart function were also found. The authors note that these effects may be larger for individuals already suffering from medical conditions. The authors point out that the effects are results of ultrafine particles from both air and road traffic, and that there are no indications that health effects of air traffic emissions are different from those caused by road traffic [59].

Lammers et al. 2020: This study investigated the health effects of controlled short-term exposure of 21 healthy non-smoking volunteers aged 18–35 years to UFP near Shiphol Airport Amsterdam. The volunteers were exposed 2–5 times to ambient are for 5 h while cycling. Cardiopulmonary outcomes such as spirometry, forced exhaled nitric oxide, electrocardiography and blood pressure were measured before and after exposure, and compared to measured total- and size-specific particle number concentrations (PNC). Average PNC was 53,500 particles/cm^3 (range 10,500–173,200). Increase in exposure to UFP was associated with a decrease in FVC and a prolongation of the corrected QT interval, which were associated with particle sizes < 20 nm (UFP from aviation), but not with particles > 50 nm (UFP from road traffic). Although the effects were relatively small and measured after single exposures of 5 h in young healthy adults [108], such effects could be important in susceptible sub-populations.

Animal studies and in vitro studies

Ferry et al. (2011): Immature primary human monocyte-derived dendritic cells (DCs) from healthy donor blood were exposed for 18 h to different doses of experimental jet exhaust particles in absence or presence of *E. coli* lipopolysaccharides (LPS). Antigen-presenting and stimulatory molecules were measured along with tumor necrosis factor (TNFα) and IL-10. The effects were assessed on immature and mature DCs as well as on cells during the maturation process.

The primary particles collected from the jet exhaust by direct impaction were found to be spherical and carbonaceous primary particles of ~ 10 nm and aggregates up to ~ 93 nm. No toxic effects were observed for doses below of 100 μg/mL jet engine particles. Maturation of immature dendritic cells by LPS stimulation induced a significant 500-fold increase in TNFα and 30-fold increase in IL-10. Immature dendritic cells produced low amounts of TNFα (fold change from LPS: 0.006) and IL-10 (fold change from LPS: 0.11), which increased non-significantly upon stimulation with particles (fold change from LPS: TNFα: 0.11, IL-10: 0.19). However, simultaneous exposure to LPS and a high particle dose of 100 μg/ml induced a 2-fold increase in TNFα production compared to LPS-maturation ($p = 3 \times 10^{-5}$). Different activation patterns were seen for the expression of HLA DR and CD86, which are dendritic cell maturation markers. It was concluded that jet exhaust particles may act as adjuvants to endotoxin-induced dendritic cell maturation, which may influence potential effects on human health [110].

Shirmohammadi et al. (2018): $PM_{0.25}$ collected at the vicinity of Los Angeles Airport (LAX) and from central Los Angeles (LA) close to and downwind from major freeways, from stationary sampling stations used for air quality control, were investigated. The particles were subjected to source allocation analyses of elements and carbon contents (see Introduction), and ROS formation was compared in rat alveolar macrophage cells (NR8383).

ROS activity measured as units of Zymosan equivalents were normalized by total PM0.25 mass to represent the intrinsic toxicity of the particles, and this mass-normalized ROS activity was similar for LAX (4600.93 ± 1516.98 μg Zymosan/mg PM) and central LA (4391.22 ± 1902.54 μg Zymosan/mg PM). According to the authors, volume-normalization of the ROS activity can be used as a metric for comparison of inhalation exposures, as an indicator of exposure severity. A slightly higher PM0.25 mass concentration in central LA meant overall similar volume-normalized ROS activity levels with no significant difference between the observed averages (LAX: 24.75 ± 14.01 μg Zymosan/m^3, central LA: 27.77 ± 20.32 μg Zymosan/m^3). Thus, there were similar levels of ROS activity and similar toxic potential of the PM in the vicinity of LAX and in the vicinity of freeways in central LA [49].

He et al. (2018): $PM_{0.25}$ collected at Los Angeles Airport (LAX) and from central Los Angeles (LA) close to and downwind from major freeways (similar collection sites as in [49]) were investigated and compared. Particles were source-allocated by analyzing elements (see Introduction). Particles collected at LAX were primarily associated with aircraft emissions, and particles from central LA with urban traffic, road and dust emissions. The reactive oxygen species (ROS) potential was evaluated intracellularly in human bronchial epithelial cells (16HBE) after 1, 2, and 4 h of exposure, and IL-6, IL-8 and TNF were measured as markers of inflammation.

Exposure of 16HBE cells to 10 μg/mL particles produced significantly elevated ROS levels for both samples compared to unexposed cells. Particles from central LA generated slightly more ROS than LAX samples per mass unit, and both were at negative control level after 20 h recovery. ROS potential in PM from both airport and central LA correlated with some of the measured traffic-related transition metals (Fe and Cu). Particles from LAX induced increased expression of IL-6, IL-8 and TNFα compared to the negative control (1.7, 1.8, and 1.4-fold, respectively), whereas central LA-particles induced slightly lower expressions (1.3, 1.3, and 1.1-fold, respectively). Hence, overall LAX particles had similar inflammatory potency as particles from central LA, showing that airport $PM_{0.25}$ contributions to urban emission PM pollution possess similar inflammatory properties [50].

Jonsdottir et al. (2019): In this study, aerosol was collected from the world's most used aircraft turbine (CFM56–7B26, run-in and airworthy) in a test cell at Zurich Airport. The test cell is open to the ambient environment and the aerosol was collected from both standard Jet A-1 fuel and a HEFA fuel blend. The toxicity of the non-volatile PM emissions was studied by direct particle deposition onto air-liquid interface cultures of human bronchial epithelial cells (BEAS-2B).

Cytotoxicity was evaluated by the release of cytosolic LDH from damaged cells, expression of the oxidative stress marker HMOX-1 and inflammatory cytokines IL-6 and IL-8.

Single, short-term (1 h) exposure to PM increased cell membrane damage, lead to oxidative stress and increased pro-inflammatory cytokines in bronchial epithelial cells, depending on fuel type and combustion conditions from which the particles were produced. PM from conventional fuel at ground-idle conditions was most potent, and the authors comment that PM from aircraft turbine exhaust may be a risk to respiratory health, also by making airway epithelia vulnerable to secondary exposure of other air pollution compounds and pathogens [111].

Bendtsen et al. (2019): In this study, the toxicity of particles collected in a commercial and a non-commercial airport were evaluated in vivo by intratracheal instillation in mice (see section 2.3 for occupational exposure measurements). Adult female C57BL/6 mice were exposed to 6, 18, and 54 μg particles/mouse dispersed in Nanopure water by sonication. The exposure doses were calculated on the basis of worst case scenario: of the maximum exposure level measured at the non-commercial airport of 1086 μg/m^3 at the peak event of plane departure, 9.6% were estimated to deposit in the alveolar lung regions. This was adjusted to the volume of a mouse lung and to 8 h of work, estimating exposure of 4, 12, and 39 days of work, respectively. Control mice were exposed to Nanopure water, and positive controls were carbon black Printex90 nanoparticles and SRM2975 diesel particles. Exposed mice were euthanized on day 1, 28, and 90 post-exposure. Inflammation was measured as inflammatory cell influx in bronchoalveolar lavage fluid as well as by the acute-phase response marker *serum amyloid A* (*Saa*) in lung (mRNA), liver (mRNA) and blood (protein). Genotoxicity was assessed by the comet assay on lung and liver tissue and cells from the bronchoalveolar lavage fluid. Analysis of the particles by scanning and transmission electron microscopy showed small primary particles and agglomerates of soot, which appeared uniform for non-commercial airport particles (mainly from jet engine emissions) and more heterogenous for the commercial airport particles (emissions from aircraft, ocean, traffic and background). Pulmonary exposure to particles from both airports induced genotoxicity and dose-dependent acute phase response, and inflammation at same levels as standard diesel exhaust particles and carbon black nanoparticles [36].

He et al. 2020: In this study, UFPs from aviation or road traffic emissions were collected near the major international airport, Amsterdam-Schiphol airport (AMS), along with UFPs from an aircraft turbine engine at low and full thrust. The toxicity of the particles was tested in human bronchial epithelial cells (Calu-3) combined with an air-liquid interface (ALI) system with exposure to UPFs at low doses from 0.09 to 2.07 μg/cm^2. Cell viability, cytotoxicity and IL-6 and -8 secretion were assessed after 24 h exposure. Cell viability was < 80% for all doses. LDH release as measure of cytotoxicity was observed at the highest exposure dose around 1.5 μg/cm^2 together with increased production of IL-6 and IL-8 compared to control exposure (blank filter extraction or re-suspension solution). It was concluded that airport and road traffic UFP as well as UFP samples from the turbine engine had similar inflammatory properties [109].

Summary of health effect studies

Increased levels of metabolites in urine as biomarkers of internal exposure to jet fuel [105] were reported in biomonitoring studies of occupational exposure to airport emissions. Exposure to airport emissions was associated with increased levels of biomarkers of genotoxicity, in

terms of increased levels of SCE [52, 100, 105] and DNA strand breaks in the Comet assay [52], which indicates exposure to genotoxic and potential carcinogenic agents in the emissions. In turn, there were occupational studies reporting increased levels of self-reported respiratory complaints [101–103].

We identified a limited number of studies and one report reporting correlations between airport emission levels and health effects of residents in the vicinity of airports: Aircraft emission levels were associated with increased hospitalization for asthma, respiratory, and heart conditions especially in susceptible subgroups such as children below 5 years of age, elderly above 65 years of age [66, 94] and lower socioeconomic groups [97, 112]. A Dutch report on Schiphol similarly reported that school children and adults took more medication and had more respiratory complaint on days with increased exposure to aircraft emissions and concludes that health effects of air traffic emissions are similar to those caused by road traffic [59]. A biomonitoring study showed increased blood levels of the inflammatory marker IL-6 in volunteers with mild to moderate asthma after a walk in a zone with high levels of aircraft emissions [107]. It is well-known that other types of air pollution including diesel exhaust cause morbidity and mortality [113]. Taken together, these results suggest that the exposure to aircraft emissions induce pulmonary and systemic inflammation, which potentially contributes to cancer, asthma, respiratory and coronary heart disease.

Five mechanistic studies on the toxicity of airport particles were identified, one animal study in mice and four cell studies: Airport particles were reported to act as adjuvants in the activation of inflammatory cells or pathways [110] and induce pro-inflammatory cytokines [111]. Airport particles were shown to have similar inflammatory potency and similar ability to induce DNA damage as traffic emission particles [50], such as diesel exhaust particles [36]. In turn, airport particles induced significant levels of the biomarker Saa following intratracheal instillation in mice, associated with risk of cardiovascular disease [36], and they have the potential to generate ROS at similar levels as traffic emission particles [49, 50]. Thus, the conclusions from these in vitro and in vivo studies support the overall concern addressed in previous sections that airport emission particles are capable of inducing toxic responses comparable to the responses observed for other air pollution particles such as diesel exhaust particles.

Discussion

Although a range of kerosene-based aircraft fuel types are in use, they are overall similar in chemical composition [24, 29]. Kerosene lies between the distillated crude oil fractions of gasoline (gasoline combustion exhaust, IARC group 2b) and diesel (diesel combustion exhaust, IARC group 1) and the carcinogenic potential of jet fuel combustion products could be anticipated given the reported similarities to diesel exhaust particles. We highlight two important reported characteristics of airport particles:

- The majority of non-volatile airport emission particles are carbonaceous and aircraft engines emit large amounts of nanoparticles, which are dominated by very small particles of < 20 nm, which form aggregates/agglomerates in ambient air
- Particle numbers near airports are significantly higher than away from airports and jet engines are a significant source of UFP in ambient air. The highest concentrations of UFP are measured downwind of aircraft

The reported PAH levels [52, 83, 84] were all below the current Danish occupational exposure limit of 200 μg/m^3. One study reported BC levels at the apron of 3.78 μg/m^3 and particle levels was overall reported to be between ~ 10^3 and 10^8 particles/cm^3 for exposed airport personnel (Table 1). The new exposure limit for diesel exhaust particles in EU is defined by the elemental carbon (EC) level and is 50 μg EC/m^3 [114]. The Netherland recently endorsed an OEL for diesel exhaust particles at 0.01 mg/m^3 measured as respirable EC. This was based on socioeconomic considerations and the Dutch prohibition risk level (OEL) is at 1.03 μg EC/m^3 [115], a level corresponding to 4 extra death cases of lung cancer per 1000 exposed, for 40 years of occupational exposure. Thus, the reported BC level [41] are well below the new EU OEL for diesel exhaust as well as the Dutch OEL, but exceed the Dutch prohibition risk level. Recently published data on the dose-response relationship between exposure to diesel exhaust particles and lung cancer in epidemiological studies estimated that occupational exposure to 1 μg/m^3 EC would cause 4 to17 excess lung cancer cases per 10,000 exposed [80, 81].

The particle exposure levels can be compared to nanoparticle reference values used in The Netherlands, Germany and Finland as a provisional substitute when nano-specific OELs or DNELs for engineered nanoparticles are not available [116]. For low density insoluble nanomaterials such as carbon-based nanoparticles, the reference value is 40,000 particles/cm^3. Compared to this reference value for engineered nanoparticles, the reported occupational exposure levels are high for some job groups.

Significant variations in emission levels are observed between airports, depending on factors such as size, type, location, and wind direction. However, the closer to the source of emissions, the higher the exposure. Proximity to

exposure peak events such as landing and take-off is also an important determinant of high exposure. This is evident from the combined literature of occupational exposure measurements and ambient air measurements in residential areas around airports. As such, the highest levels of occupational exposure is found for airport personnel working at the apron, in close proximity to running jet engines. Airport personnel can likely be grouped in low (office staff/landside jobs with indoor work, far away from emission sources), medium (catering/cleaning/landside security staff with intermittent outdoor work) and high (baggage handlers/aircraft mechanics, crew chiefs) exposure groups [52, 86–88, 92, 98, 100–102]. To reduce occupational exposure, emission sources can be moved, the distance to emission sources can be increased, time spent in proximity to emission sources can be reduced and personal protection equipment can be used during peak exposures. Personal exposure may be higher than measured by stationary monitors, and thus, routine monitoring of personal exposure levels could be suggested.

Workplace experts, airport leaders and personnel groups have the necessary intrinsic knowledge and experience to suggest feasible, realistic options for reducing the exposure for specific job functions at individual airports.

The similarity of airport emission particles with diesel exhaust particles and pure carbon nanoparticles, with respect to physico-chemical properties as well as specific toxicological parameters was demonstrated in the animal study from our laboratory [36], and a growing number of studies report similar toxicity and health effects of emissions from airports and traffic. Airport emission particles likely have similar physico-chemical properties as diesel exhaust particles even though the primary particle size of jet engine emissions is somewhat smaller than the primary size of diesel exhaust particles. Diesel exhaust is classified as carcinogenic to humans by IARC [69], cause lung cancer, systemic inflammation, and inflammatory responses in the airways [70].

Aircraft emissions are associated with biomarkers of exposure, biomarkers of disease and health outcomes both for exposed workers [36, 41, 52, 83, 84, 86–90, 92, 100–103, 105] and for the general population living down-wind of airports [59, 66, 94–97, 107, 112]. Occupational exposure to aircraft emissions were associated with:

- Biomarkers of exposure to jet fuel emissions
- Biomarkers of genotoxic exposure
- Self-reported respiratory distress

The reported adverse effects correlate with effects demonstrated in animal studies and in in vitro studies, where aircraft emission particles caused inflammation [50, 110, 111], acute phase response [36], reactive oxygen species [49, 50] and DNA damage [36], which are biomarkers of risk of cancer, cardiovascular disease and respiratory disease. This supports the notion of a causal relationship between exposure to airport emissions and the observed health effects. Although mechanistic studies on airport emissions are scarce, knowledge from other closely related scientific areas still applies, such as particle toxicity, carcinogenicity/toxicity of VOCs and OPEs and epidemiological studies of health effects caused by air pollution [117].

Another relevant concern to raise in this context is the adverse health effects of low-level chronic occupational exposure to these chemicals, which is difficult to study [118]. OPEs have been associated with adverse health effects reported from cabin crew and pilots after occupational exposure to bleed air and fume events during flights, with symptoms of respiratory illness and neurological effects [119]. The dominant OPE used in lubrication oil is tricresyl phosphate (TCP), which are among the highly neurotoxic OPEs [120]. It has been suggested that brain exposure may occur via inhalation of circulating small jet particles associated with OPEs, crossing the blood-brain barrier [121] – neurotoxic effects of OPEs may also be an understudied occupational risk of apron staff.

It has been shown that air pollutants worsen pre-existing diseases, such as allergy or other inflammatory (airway) or cardiovascular conditions [2–4, 122–124]. One example is a study examining the relationship between personal exposure to traffic emissions and acute respiratory health in school children with asthma residing in the Bronx, New York, which have the highest asthma incidence in New York City and state [125]. Personal samples of $PM_{2.5}$, including the EC fraction, were collected 24 h daily for 40 school children with asthma from four schools, with spirometry and symptoms assessed several times daily. The study found increased relative risks of different airway symptoms, such as wheeze (RR = 1.45, CI: 1.03–2.04), shortness of breath (RR = 1.41, CI: 1.01–1.99), with relative risk of total symptoms of 1.30 (CI: 1.04–1.62). Interestingly, the symptoms were associated with increase in average 2-day school site and personal EC levels, but not mass of $PM_{2.5}$ [125]. As such, as demonstrated in asthmatic volunteers, residents living near airports, and supported by inflammatory effects shown in available in vitro studies, airport UFP and associated pollutants are, in addition to their direct adverse effects, likely to have the ability of worsen pre-existing disease.

Conclusion

The reported adverse health effects of jet engine emissions are similar to those caused by exposure to diesel exhaust and air pollution. However, given the lack of

consensus on optimal measurement methods, equipment and quality control for near- and far field airport emissions and human risk assessments markers, more studies of exposure and of toxicological mechanisms are necessary.

These drawbacks are summarized efficiently by Lighty et al. in their paper on combustion compounds and health: "*There is a need for better integration of the combustion, air pollution control, atmospheric chemistry, and inhalation health research communities. Epidemiology has demonstrated that susceptible individuals are being harmed by ambient PM. Particle surface area, number of ultrafine particles, bioavailable transition metals, polycyclic aromatic hydrocarbons (PAH), and other particle-bound organic compounds are suspected to be more important than particle mass in determining the effects of air pollution. Time- and size-resolved PM measurements are needed for testing mechanistic toxicological hypotheses, for characterizing the relationship between combustion operating conditions and transient emissions, and for source apportionment studies to develop air quality plans*" [24].

Based on the accumulated knowledge so far, measures to reduce occupational exposure and emission levels at airports should be increased.

Supplementary Information

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Additional file 1.

Authors' contributions

Conceptualization, Methodology, Data Curation, and Writing – Original Draft and Review and Editing: KMB; Conceptualization and Methodology: UBV, Data Curation (Systematic Database Search): EB; Writing – Review and Editing: ATS and UBV. The authors read and approved the final manuscript.

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Availability of data and materials

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Competing interests

The authors declare that they have no competing interests.

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Authorship and Uses

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List of Terms and Acronyms

ACRONYM	DEFINITION
AQMP	Air Quality Management Plan
AFI	Aviation Facilities, Inc.
ASTM	ASTM International
ATAG	Air Transport Action Group
CARB	California Air Resources Board (Also “ARB")
BAAQMD	Bay Area Air Quality Management District
CAAFI	Commercial Aviation Alternative Fuels Initiative
CI	Carbon Intensity
CJF	Conventional Jet Fuel
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
CORSI	Carbon Offsetting and Reduction Scheme for International Aviation
CEC	California Energy Commission
DPM	Diesel Particulate Matter
EPA	U.S. Environmental Protection Agency
FOGs	Fats, Oils and Greases
GHGs	Greenhouse Gases
GPY	Gallons per Year
HAP	Hazardous Air Pollutants
HEFA	Hydroprocessed Esters and Fatty Acids
ICAO	International Civil Aviation Organization
ICCT	International Council for Clean Transportation
IBAC	International Business Aviation Council
KM SFPP	Kinder Morgan Santa Fe Pacific Pipeline
LCFS	Low Carbon Fuel Standard (California)
LTOs	Landings and Take Offs (Aircraft)
MJ	Megajoule
NAAQS	National Ambient Air Quality Standards
NO_x	Oxides of Nitrogen
OAK	Oakland International Airport
PM / $PM_{2.5}$	Particulate Matter / PM smaller than 2.5 microns in size
RD	Renewable Diesel
RFS	Renewable Fuel Standard (federal)
SFBAB	San Francisco Bay Air Basin
SAF	Sustainable Aviation Fuel
SFO	San Francisco International Airport
SJC	San Jose International Airport
SIP	State Implementation Plan
SO_x	Sulfur Oxides
UA	United Airlines
UFP	Ultrafine Particles
W2W	Well-to-Wheels

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Executive Summary

Sustainable aviation fuel (SAF) is a drop-in replacement for conventional jet fuel (CJF) that can significantly reduce full-fuel-cycle greenhouse gas (GHG) emissions from jet aircraft engines. Currently, SAF is required to be blended with CJF, at up to 50 percent SAF by volume. Of the seven certified processes to produce SAF, one pathway (hydroprocessing of esters and fatty acids, or HEFA) currently accounts for more than 95 percent of the SAF used in commercial aviation. Neat SAF produced using the HEFA process currently reduces full-fuel-cycle GHG emissions from jet aircraft by approximately 60 percent compared to using baseline CJF. SAF that will be available in the near future (from HEFA or other pathways) will likely provide even greater GHG-reduction benefits.

The world's commercial aviation sector contributes roughly two-to-three percent of combustion-related GHG emissions. In California's Bay Area (greater San Francisco-Oakland), aviation contributes about six percent of transportation-related GHG emissions. Compared to surface (ground and water) transportation modes, the aviation sector presents greater challenges to decarbonize. Commercial aviation companies have made important strides to reduce carbon emissions through aircraft fleet efficiency improvements, but SAF has emerged as the leading approach to further reduce GHG emissions from jet aircraft.

There are currently four LCFS-certified "pathways" to produce SAF; all four use the HEFA process and animal tallow feedstock at World Energy's biorefinery in Paramount, CA. These pathways provide full-fuel-cycle GHG reductions ranging from 52 to 73 percent relative to baseline CJF. Although SAF must currently be blended with CJF (having higher carbon intensity), each SAF gallon ultimately displaces one CJF gallon, and therefore provides GHG reductions based on the relative carbon intensities of the two neat fuels.

SAF blends can also improve local ambient air quality, especially within airport boundaries and adjacent areas in close proximity to large numbers of jet "Landing and Take Off" (LTO) events. Specifically, SAF blends can significantly reduce direct aircraft emissions of fine particulate matter (PM), sulfur oxides (SOx) and carbon monoxide (CO). Although more studies are needed, displacing neat CJF with SAF blends also appears to reduce black carbon emissions and provide beneficial alterations of ultrafine particle emissions from jet engines. Based on studies to date, it appears that SAF does not significantly change NOx emissions from the jet engines, and therefore it does not seem to advance ozone-reduction strategies in the Bay Area or other urban areas.

A few million gallons of neat SAF are being used in the U.S. today. The largest SAF volumes are being dispensed in California at Los Angeles International Airport (LAX) and San Francisco International Airport (SFO), which have become proving grounds for SAF use in North America. SAF-fueled jet departures at these airports accelerated in 2019, when SAF became active as a credit-generating fuel under California's landmark Low Carbon Fuel Standard (LCFS) program.

While the societal benefits offered by SAF are compelling -- and demand from airlines is growing – currently this "premium" jet fuel is neither available nor affordable for wide-scale use. It costs at least two

times as much to produce SAF compared to CJF, using the leading HEFA pathway and assuming a typical SAF yield of less than 15 percent, with renewable diesel (RD) being the dominant co-product. While the SAF yield can be increased up to 50 percent, this entails greater incremental cost and appears to compromise the market value of the overall biofuel products (RD and SAF, plus renewable naphtha and propane).

An equally important market barrier is that, once produced, a gallon of neat SAF's current market value in California is about eight percent lower than a gallon of RD, even though they are co-produced from the same feedstock and HEFA process. Consequently, SAF producers are likely to continue gearing their biofuel production to maximize the yield of RD – the more valuable co-product – unless and until SAF becomes a more highly valued biofuel (monetarily, environmentally, or both).

This combination of higher cost / lower market value has implications on airlines that purchase SAF. Supplies can be constrained, and incremental fuel cost can be high. Airlines using SAF at San Francisco International Airport (SFO) reportedly pay a premium of about $1.25 per gallon, under a best-case scenario that includes buydown of SAF costs using LCFS credits as well as "RIN" values under the federal Renewable Fuel Standard (RFS). Nonetheless, demand for SAF has been fairly strong in California – specifically at SFO and LAX. Roughly five million gallons of SAF blends (30 % SAF / 70% CJF appears to be typical) were dispensed at these two airports in 2019.

Despite higher costs to produce and purchase SAF, the industry and its airline customers anticipate major growth. Based on known "offtake" agreements, at least 350 million gpy of neat SAF will be produced and available for dispensing at U.S. airports by the 2023 timeframe. It is not yet known if that will continue to be dispensed into aircraft at or below a 50/50 ratio, as the blending requirement is largely a safety precautionary measure. In fact, aircraft flights have been successfully and safely demonstrated on neat SAF.

SFO – the nation's seventh busiest airport – has been a world leader to foster large-scale use of SAF. For several years, the airport has been working with its airline partners to test SAF blends and develop innovative ways to increase supply, while lowering costs. Under a Memorandum of Understanding (MOU) with airlines as well as SAF providers, SFO has established the goal to procure and dispense enough neat SAF within three to five years to displace about two percent of its CJF use (30 million gallons per year), and 17 percent (300 million gallons per year) within about a decade. While this near-term goal may have been significantly set-back by the unprecedented COVID-19 pandemic, it is too soon to know the impact on meeting the longer-term goal (a decade out).

Oakland International Airport (OAK) is the other Bay Area airport that has made progress to pilot test the benefits of SAF blends in commercial aviation. At least six million gallons per year of neat SAF have been committed to FedEx and Southwest Airlines for dispensing out of the OAK fuel farm facility. There appears to be significant synergy between SFO, OAK and SJC to share delivery and storage logistics for large-scale

SAF usage in the Bay Area, as SFO has invited both airports to join its MOU and interdisciplinary Stakeholder Working Group (SWG).

Over the longer term (about a decade), industry estimates indicate that one to six billion gallons of neat SAF may be available for the U.S. commercial aviation sector. This will be supplied by a combination of key existing SAF producers (primarily World Energy and Neste) as well as newcomers to SAF production such as Fulcrum BioEnergy, Red Rock Biofuels, Phillips 66 and others. The vast majority of this appears likely to be targeted for consumption in California, due to monetary incentives offered under the LCFS. A significant portion – perhaps half or more – may be used in the Bay Area at SFO and OAK, with potential synergy for use at SJC.

A high-level estimate was performed to roughly calculate the full-fuel-cycle GHG reductions that could be realized by widely using SAF blends at the three largest Bay Area airports. The assumptions were that pre-pandemic demand will return for jet fuel at SFO, OAK and SJC; and that 100 percent of the flights at all three airports will use SAF blends instead of neat CJF. A range of blends – SAF5, SAF25, and SAF50 – were evaluated. It is estimated that GHG reductions from SAF blends would range from 0.47 million metric tons per year (SAF5) up to 4.7 million metric tons per year (SAF50), based on 2019 emissions estimates. Notably, these combined GHG reductions reflect emissions from all fuel loaded at these three Bay Area airports, i.e., they are not constrained to reductions that would occur within BAAQMD boundaries.

A similar analysis was performed to estimate criteria pollutant emission reductions that could be realized within BAAQMD boundaries under the same SAF blend deployment scenarios. For the best-case scenario, it is estimated that displacing all CJF use at the three major airports with a SAF50 blend could provide reductions in CO emissions of 2.27 tons per day, SOx emissions of 0.39 tons per day, and PM10 emissions of 0.28 tons per day.

A number of challenges and barriers exist that currently hinder SAF producers from providing commercial aviation operations at SFO and other California airports with the large volumes they ultimately seek. The three key (related) impediments under current dynamics are 1) higher cost/price of SAF relative to CJF; 2) reduced value of SAF on a per-gallon basis compared to its more-dominant co-product RD (which disfavors gearing the production process for a higher SAF yield versus RD); and 3) federal and state policies that generally favor using limited biofuel resources to decarbonize surface transportation more than the aviation sector.

A fourth impediment has been the global COVID-19 pandemic, which has dramatically decreased aircraft departures at large coastal airports (nearly 70 percent at SFO at its peak), thereby greatly reducing demand for CJF and lessoning the need for airlines to continue switching to SAF blends.

A fifth impediment is the potential for California to be "outcompeted" for limited available SAF supplies, because other nations (or even regions of the U.S.) now offer – or may offer in the near future -- more

favorable incentives and/or policies, which could make it increasingly difficult for airlines serving the Bay Area to procure large volumes of the fuel.

To address these barriers currently impeding wider-scale use of SAF at Bay area airports – thereby helping to achieve its GHG-reduction objectives for the commercial aviation sector -- the BAAQMD may wish to further develop and implement the following actions, in conjunction with various stakeholders.

- Engage with CARB and other relevant state or federal agencies about how to 1) improve the relative value of SAF through changes in the monetization metrics of key programs (LCFS, Cap and Trade, RFS2, etc.), and 2) generally modify California's GHG-reduction policies to more favorably treat SAF production and/or end use.

- Further evaluate the pros and cons of channeling more types of support (policy, incentive funding, permitting requirements, etc.) towards SAF as the leading available strategy to further decarbonize the Bay Area's aviation sector.

- Consider exploring new pilot program incentives for SAF production and end use, based on air qualify benefits associated with reducing criteria pollutants and air toxics in DAC / EJ areas near Bay Area airports.

- Consider creative methods to incentive larger-scale production and use of SAF, such as fast-track permitting and/or CEQA approval for new biofuel production facilities or conversion of conventional refineries to biorefineries.

- Commission a study (e.g., using the UC system) that corroborates and further quantifies SAF's effects on criteria and toxic air pollutants from commercial aircraft, which can help ensure that grant funding achieves its intended use (i.e., to reduce surplus, quantifiable emissions.

- Establish (or join existing) regular working groups with SFO and other major Bay Area Airports (OAK, SJC) to monitor SAF-related progress, developments and status of key impediments (including Covid-19 impacts).

SAF Potential for Reducing GHG Emissions at Bay Area Airports

1. Background / Introduction

1.1. Commercial Aviation Market and Contributions to GHG Inventories

Global aviation entails nearly 32,000 aircraft from 1,300 airlines that annually carry about 4.4 billion passengers covering 45,000 routes. Worldwide, commercial aviation (passenger and freight airlines) consume as much as 90 billion gallons of jet fuel annually, while emitting an estimated 918 metric tons of CO_2 (about 2.4 percent of global CO_2 emissions from fossil fuel use).[1] Relative to 2016, it has been projected (pre-pandemic) that international air traffic at North American airports will grow annually by an average of 2.7 percent over the next two decades. International flights at airports in Asia and the Middle East are expected to experience even greater annual growth,[2] with average global air traffic expected to increase as much as 4 to 5 percent annually.[3]

Collectively over the last decade, U.S. commercial airlines annually consumed an average of about 20 billion gallons of Jet Fuel A (also called conventional jet fuel, or CJF). Total CJF consumption in 2018 was nearly 27 billion gallons across all U.S. aviation uses.[4] The Department of Energy has projected that the CJF market in the U.S. will reach 54 billion gallons per year by 2040.[5]

At San Francisco International Airport (SFO) -- the largest airport in the San Francisco Bay Area -- airlines annually dispense approximately one billion gallons of CJF, with 2019 reaching about 1.2 billion gallons.[6] No public records were found for typical annual volumes of CJF dispensed at the other two large commercial aviation airports in the Bay Area, Oakland International (OAK) and San Jose International (SJC). Simplistically using greenhouse gas (GHG) emissions data provided by Bay Area Air Quality Management District staff (BAAQMD) associated with Landings and Take-Offs (LTOs)[7] – reported as metric tons of CO_2 equivalent ("$MTCO_2e$") – rough estimates for annual CJF dispensing at the other two airports have been derived proportionally, using the ratio of SFO's fuel use (the lower end, at 1 billion gallons per year) to its LTO GHG emissions. Table 1 summarizes estimated volumes of CJF dispensed at these three airports (see the * in the table).

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[1] International Council on Clean Transportation, "CO2 Emissions from Commercial Aviation: Fact Sheet, September 2019, https://theicct.org/sites/default/files/ICCT_CO2-commrcl-aviation-2018_facts_final.pdf.

[2] Haldane Dodd, Air Transport Action Group, "Aviation's Climate Action Plan," Presentation at ACT Expo "Greening Aviation" session, April 26, 2019.

[3] Dr. Alan H. Epstein (Prat & Whitney) and John Mandyck (United Technologies Corporation), "The Future of Sustainable Aviation: Betting on Jet Propulsion and Lower Net Carbon Fuels," Power Point presentation, 2016, http://naturalleader.com/wp-content/uploads/2016/10/UTC-7612-FutureSustainableAviationWhitePaper_3.pdf.

[4] Energy Information Administration, Table F1: Jet fuel consumption, price and expenditure estimates, 2018, https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_jf.html&sid=US.

[5] U.S. Department of Energy, Bioenergy Technologies Office's Efforts on SAJF,: presentation by Jonathan Male to CAAFI General Meeting, December 4, 2018, http://www.caafi.org/resources/pdf/1.2_Value_Proposition.pdf.

[6] Personal communication to GNA from Erin Cooke of San Francisco International Airport, September 2020.

[7] Notably, SFO operates many more long-haul flights than OAK and SJC, and thus dispenses greater volumes of CJF on a per-flight basis. Using a simplistic ratio of LTO GHG emissions does not capture this difference. However, GNA has received corroboration from knowledgeable sources that this rough approximation (as noted in Table 1 below) is reasonably accurate.

Table 1. Estimated annual dispensing of CJF (Jet A) at three largest Bay Area airports

Bay Area Airport	LTO CO_2 Emissions (mtCO2e/yr)	% of Total	Estimated Jet A Use (gal/yr)	Source of Estimate
San Francisco Int'l (SFO)	1,332,084	71.8	1 billion	Cited by SFO officials
Oakland Int'l (OAK)	334,029	18.0	251 million	CO_2e emissions (from LTOs) relative to SFO
San Jose Int'l (SJC)	188,270	10.2	141 million	
Totals	**1,854,383**	**100.0**	**1.4 billion**	
LTO GHG Source: "2019 Large Jet Aircraft GHG Emissions" (BAAQMD – Base Year 2011), provided by BAAQMD staff, July 2020.				
*This is a rough approximation; GHG emissions are from LTO events and may not include general or business aviation flights. SFO's annual fuel demand (used to estimate OAK and SJC) entails all fuel dispensed at SFO, most of which is combusted beyond the Bay Area. Consequently, it is possible that these estimates understate or overstate dispensing CJF dispending at any of these three airports.				

As shown in the table, based on GHG (CO_2e) emissions from aircraft during LTO events, roughly 1.4 billion gallons per year of Jet A fuel (CJF) are collectively dispensed at these major Bay Area airports (pre-pandemic). SFO, OAK and SJF account for about 72, 18 and 10 percent of this CJF use, respectively.

1.2. Initiatives to Reduce Aviation-Related GHG Emissions

U.S. Federal and International

About a dozen years ago (2008-2009), the commercial aviation sector joined the business aviation sector in efforts to significantly reduce aircraft emissions of CO_2 and other GHGs, to mitigate the industry's contributions to climate change. Drivers for these initiatives primarily came from the U.S. Federal Aviation Administration (FAA), the International Civil Aviation Organization (ICAO), the General Aviation Manufacturers Association (GAMA), the International Business Aviation Council (IBAC), the International Air Transport Association (IATA), the Air Transport Action Group (ATAG), and other organizations. ICAO in particular has been a major drive to reduce aviation-related GHG emissions (see for example https://www.icao.int/environmental-protection/Pages/ClimateChange_ActionPlan.aspx).

While there are some differences and nuances in the goals of these various organizations, there are key common elements, such as those codified in a joint November 2009 press release[8] calling for adoption of specific initiatives and goals, which included the following:

- Phasing in of carbon-neutral growth
- Annual improvements in fuel efficiency
- A 50 percent reduction in total carbon emissions by 2050, relative to 2005

In 2015, the FAA and other federal agencies joined with aviation companies and stakeholders to adopt the *United States Aviation Greenhouse Gas Emissions Reduction Plan.* This collaboration was designed to help U.S. commercial aviation achieve the "aspirational goal" of carbon-neutral growth by 2020, using

[8]General Aviation Manufacturers Association and the International Business Aviation Council, "Global Business Aviation Community Announces Commitment On Climate Change," press release, November 24, 2009, https://gama.aero/news-and-events/press-releases/global-business-aviation-community-announces-commitment-on-climate-change/.

2005 as the baseline year. The plan included specific approaches to reduce the carbon footprint of U.S. aviation, including support to develop and deploy "sustainable alternative jet fuels with lower life-cycle GHG emissions than conventional petroleum fuel."[9]

The next year these initial efforts in the U.S. were combined with similar goals of the international aviation industry, resulting in adoption of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA is a global market-based initiative that seeks to mitigate annual increases in total CO_2 emissions from international civil aviation. (Note: CORSIA does not specify mitigating CO_2e emissions.) Using emissions offsets as the basic approach to reducing CO_2 emissions, CORSIA focuses on civil aviation flights that depart in one country and arrive in a different country. The objective is to aggressively reduce aircraft-related GHG emissions below baseline levels, while also considering "special circumstances and respective capabilities" of different countries and airlines.[10]

CORSIA's initial "monitoring, reporting and verification" phase took effect in 2019. As of mid-2020, 82 countries (acknowledged as "Member States") are participating in this voluntary "pre-phase" of CORSIA. Under CORSIA's voluntary pre-phase, all ICAO Member States that operate international flights track and report CO_2 emissions from their international flights. CORSIA's "first phase" begins January 1, 2021; it will require covered aviation operations to begin offsetting GHG growth when operating on covered routes. By 2035, CORSIA requires substantial GHG offsets through this market-based system (with recent adjustments due to the COVID-19 pandemic).

One key way for commercial airlines to achieve their CORSIA offsetting requirements is to use a "CORSIA eligible" fuel, which includes sustainable aviation fuel (SAF) that meets certain certification criteria.[11] CORSIA's route-based approach applies to aircraft operators that annually emit more than 10,000 metric tons of CO_2 during international flights. (Globally, the average commercial aviation flight in 2018 emitted an estimated 24 metric tons of CO_2.[12]) Operators with lower annual emissions on international flights can still participate in the market-based program to monitor and trade their international CO_2 emissions. An in-depth discussion about CORSIA and its specific requirements involving SAF is beyond the scope of this memo; details can be found at the ICAO Environment website.[13]

Largely in response to the initial actions of 2009 and then subsequent adoption of CORSIA, the world's major commercial aviation companies have made tangible accomplishments to reduce GHG emissions over the last decade. In the U.S., major airlines are driven to reduce GHG emissions by at least two

[9] U.S. Government, "United States Aviation Greenhouse Gas Emissions Reduction Plan," submitted to the International Civil Aviation Organization, June 2015.
[10]Timothy Obitts, Chief Operating Officer and General Counsel, National Air Transportation Association, "Green Aviation: Funding and Regulatory Drivers," Presentation at ACT Expo "Greening Aviation" session, April 26, 2019.
[11] Federal Aviation Administration, "ICAO and Alternative Jet Fuels," presentation by Dr. James I. Hileman, July 29, 2020, accessed from CAAFI website at http://www.caafi.org/resources/pdf/CAAFI_Webinar_CORSIA_Eligible_Fuels_07_29_2020.pdf.
[12] International Council on Clean Transportation, "CO2 Emissions from Commercial Aviation: Fact Sheet, September 2019, https://theicct.org/sites/default/files/ICCT_CO2-commrcl-aviation-2018_facts_final.pdf.
[13]See https://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx).

separate (but related) needs: 1) to achieve corporate sustainability goals (including CORSIA); and 2) to avoid regulatory restrictions on future air traffic growth (e.g., adoption of indirect source rules focused on airports). Additionally, airlines are driven to reduce or offset GHG emissions to help passengers "feel better" about the environmental implications of their air travel (especially discretionary).

State of California

GHG-reduction efforts in California are driven by the California Global Warming Solutions Act of 2006 (the Act), which was born out of Assembly Bill 32. The Act calls for the California Air Resources Board (CARB) and other State agencies to adopt sweeping efforts to reduce GHG emissions emitted from "all sectors of the economy." Specific strategies are laid out in California's 2017 Climate Change Scoping Plan (soon to be updated), which specifically targets a 40 percent reduction in GHG emissions by 2030, relative to the 1990 baseline. Given that California's transportation sector contributes about 40 percent of the State's GHG emissions (2017 inventory[14]), the Scoping Plan makes it a high priority to rapidly reduce GHG emissions for all modes of transportation, including aviation.

In 2009 under the umbrella of AB 32, CARB adopted the landmark Low Carbon Fuel Standard (LCFS) program, as one pillar of California's efforts to decarbonize the state's vast transportation sector. Using a combination of market pull and regulatory requirements, CARB designed the LCFS to systematically reduce the average carbon intensity (CI) of mainstream transportation fuels, with certain exceptions.

Originally, CARB excluded aviation fuel from participating under the LCFS. However, in 2018 CARB approved amendments that (among other things) allowed producers of low-carbon aviation fuels to voluntarily "opt into" the LCFS. This meant that renewable jet fuel dispensed at California airports could start generating valuable LCFS credits, as long as the fuel's life-cycle "pathway" has an CARB-certified CI rating below that of CJF. CARB set-up declining CI "benchmarks" for CJF, specifically to enable the calculation of credits that can be generated by voluntarily substituting low-CI "alternative jet fuel" (AJF).[15] According to a coalition of SAF producers, CARB's actions to add SAF into the LCFS "firmly established" California as America's "leading SAF state from both a supply and demand standpoint," and also put it "in the top tier of locations globally supporting the expansion of SAF."[16]

Under the LCFS regulation, AJF does not necessarily refer to renewable or "sustainable" jet fuel. CARB defines AJF as "a drop-in fuel, made from petroleum or non-petroleum sources, which can be blended and used with conventional petroleum jet fuels without the need to modify aircraft engines and existing fuel distribution infrastructure." As these words indicate, AJF does not need to be made from renewable, sustainable feedstock to generate LCFS credits.[17] However, the practical implication is that AJF now

[14] See https://ww2.arb.ca.gov/ghg-inventory-graphs.
[15] CARB, "Low Carbon Fuel Standard Basics," https://ww2.arb.ca.gov/sites/default/files/2020-06/basics-notes_1.pdf.
[16] Letter to CARB from Graham Noyes (Noyes Law Corporation), representing the "SAF Producer Group," September 21, 2020, provided to GNA from a leading SAF producer.
[17] CARB, "Low Carbon Fuel Standard Basics Proposed New Temporary Pathway: Alternative Jet Fuel," July 31, 2019, https://ww2.arb.ca.gov/sites/default/files/classic//fuels/lcfs/fuelpathways/comments/ajf_temp.pdf.

generating credits under the LCFS is essentially synonymous with SAF (also see the discussion in Section 2.1).

Section 2.3 of this report further defines and describes SAF's GHG-reduction benefits, by key variables. Section 7 provides CARB's CI benchmark curve and discusses the relative value of LCFS credits generated with SAF used for aviation versus renewable diesel used for ground transportation.

Bay Area Air Quality Management District

In April 2017, BAAQMD approved its 2017 Clean Air Plan. The Plan's overarching objective is to "lead the (Bay Area) to a post-carbon economy, to continue progress toward attaining all State and federal air quality standards, and to eliminate health risk disparities from exposure to air pollution among Bay Area communities." The Plan includes a comprehensive strategy of 85 proposed control measures to simultaneously reduce ozone and fine particle pollution, reduce air toxics, and meet the State's long-term GHG reduction targets. [18]

Aviation contributes about six percent of the Bay Area's transportation-related GHG emissions. For all transportation sources (ground, air and marine), the Plan prioritizes reducing emissions of GHGs, criteria pollutants, fine particulate matter, and toxic air contaminants. It seeks to decrease fossil fuel combustion, and increase use of renewable energy (including development of local production capacity). The Plan notes that "by 2050, Bay Area industries will need to be powered by renewable electricity wherever feasible with renewable fuels making up the difference." Noting that CJF is considered a "hard-to-replace" and/or "specialty" fuel, the Plan acknowledges that oil companies will likely continue to supply liquid aviation fuel, but it will need to transition to renewable, non-petroleum forms (i.e., SAF).

In fact, as one of many potential future control measures for mobile sources, the Plan calls out increased use of SAF to help simultaneously achieve climate change goals and ambient air quality goals. Specifically, Transportation Control Measure (TCM) TR17 calls for BAAQMD to "work with the appropriate partners to increase the use of cleaner burning jet fuel and low-NOX engines in commercial jets arriving and departing the Bay Area." [19]

Additional localized efforts to reduce aviation-related GHG emissions within the BAAQMD's jurisdiction are discussed in the context of the Bay Area's three major airports (see Section 7.1).

[18] Bay Area Air Quality Management District, "Final 2017 Clean Air Plan, adopted April 19, 2017, http://www.baaqmd.gov/~/media/files/planning-and-research/plans/2017-clean-air-plan/attachment-a_-proposed-final-cap-vol-1-pdf.pdf?la=en.

[19] Bay Area Air Quality Management Plan, "Draft 2017 Clean Air Plan: Spare the Air, Cool the Climate;" presentation to Board of Directors by Henry Hilken, Director of Planning and Climate Protection, March 1, 2017, http://www.baaqmd.gov/~/media/files/board-of-directors/2017/bod_presentations_030117-pdf.pdf?la=en.

2. SAF Description and Characteristics

2.1. General Description, Basic Production Processes

Broadly defined, SAF[20] refers to certified distillate aviation fuels "produced sustainably from renewable resources (in whole or in part)."[21] More technically, SAF is "drop-in" alternative aviation fuel produced using a renewable pathway approved by ASTM International (ASTM), which ensures key standards are met for fuel quality, sustainability, safety and performance characteristics. Specifically, ASTM D7566 ("Specification for Aviation Turbine Fuels Containing Synthesized Hydrocarbons") sets requirements for 100 percent (neat) SAF, as well as blended portions. First published in 2009, ASTM D7566 includes a series of annexes that lay out the most-current requirements for SAF to be deemed a drop-in substitute for CJF.

Table 2 lists all seven SAF-production pathways (by annex number) approved under ASTM D7566 and/or ASTM D4054 (the fast-track process recently enacted). Annex 2, the "HEFA SPK" pathway (hydro-processing of fats and oils) has been, and continues to be, the dominant method to produce SAF. In fact, this pathway is estimated to account for more than 95 percent of the SAF that has been used in commercial aviation, to date.[22] Section 4 discusses specific producers using this dominant pathway.

Table 2. ASTM D7566 and D4064 (fast-track) approved pathways for SAF

Technology Code	Pathway Code ASTM Annex	Feedstock	Max Blend %	Status
Fischer-Tropsch Synthetic Paraffinic Kerosene	FT SPK **A1**	All biomass and household waste	50%	Approved 2009 (ASTM D7566), currently no technical barriers to widespread implementation. Commercial facilities starting production in 2020-2021.
HEFA Synthetic Paraffinic Kerosene	**HEFA SPK** **A2**	Renewable fat, oil and grease	50%	Approved 2011 (ASTM D7566), **Commercially produced/supplied at scale**
Hydroprocessed Synthesized Isoparaffins	HFS-SIP **A3**	Sugars	10%	Approved 2014 (ASTM D7566), currently no technical barriers to widespread implementation.
FT Synthesized Paraffinic Kerosene plus Aromatics	FT-SPK/A **A4**	All biomass and household waste	50%	Approved 2015 (ASTM D7566), currently no technical barriers to widespread implementation.
Alcohol to Jet Synthetic Paraffinic Kerosene	ATJ-SPK **A5**	Sugars, biomass, waste gases	50%	Approved 2016 (ASTM D7566), commercially produced/supplied at low volume.
Catalytic Hydrothermolysis Synthesized Kerosene	CH-SK or CHJ **A6**	Renewable fat, oil and grease	50%	Approved 2020 (ASTM D7566), currently no technical barriers to widespread implementation.
Synthesized Paraffinic Kerosene from HC-HEFA	HC-HEFA SPK **A7**	Renewable fat, oil and grease	10%	Approved, first pathway under ASTM D4054 fast track review process

Source: Inputs from ASTM Inter'l; table reproduced from Atlantic Council, "Sustainable Aviation Fuel Policy in the United States: A Pragmatic Way Forward, by Fred Ghatala, April 2020 and Green Car Congress, https://www.greencarcongress.com/2020/05/20200514-ihi.html.

[20] SAF is also commonly called "sustainable alternative jet fuel" (SAJF), "renewable jet fuel" (RJF), and "alternative jet fuel."
[21] Commercial Aviation Alternative Fuels Initiative, "Glossary," http://www.caafi.org/resources/glossary.html.
[22] Atlantic Council, "Sustainable Aviation Fuel Policy in the United States: A Pragmatic Way Forward, by Fred Ghatala, April 2020.

Regardless of the production pathway, before SAF can be used in U.S. aircraft, it must be blended with CJF and certified under ASTM D7566 as well as D1655 ("Standard Specification for Aviation Turbine Fuels"). SAF blends that meet ASTM D1655 "can be handled in the same fashion as the equivalent refined D1655 aviation turbine fuel," [23] so it can be inserted into a manifold upstream via an on-airport hydrant system, or directly into an aircraft. (In addition, ASTM D4054 encumbers a fast-track evaluation process to determine if emerging alternative jet fuels are equivalent to CJF.)

> ***Definition:*** *drop-in jet fuel blend:*
>
> *A substitute for conventional jet fuel that is completely interchangeable and compatible with conventional jet fuel when blended with conventional jet fuel. A drop-in fuel blend does not require adaptation of the aircraft/engine fuel system or the fuel distribution network, and can be used "as is" on currently flying turbine-powered aircraft.*
>
> -CAAFI, http:// www.caafi.org/resources/glossary.html

Currently, the maximum amount of SAF allowed under the dominant HEFA pathway (and most others) is 50 percent by volume. As described below by the Air Transport Action Group (ATAG), the 50 percent blending limit was adopted as an initial precautionary safety measure, but it is not likely to cap long-term use of SAF.

> *"The reasons for the current blend limits are to ensure the appropriate level of safety and compatibility with the aircraft fueling systems (mainly due to the level of aromatics which are necessary for the different systems). It is, however, likely that higher blend limits will be approved in the future."*[24]

In fact, aircraft have been flown on 100 percent SAF, such as demonstration flights by Boeing and Airbus. And, jet engine OEM Rolls-Royce announced in late 2020 that it will "ground test" SAF100, "to determine whether the unblended biofuel can be used in its next-generation engine technology."[25] Currently, SAF is blended with at least 50 percent CJF largely as a precautionary measure. As noted, ASTM is the organization that sets standards for aviation fuels, and it appears to be actively working towards testing and verifying the safety of higher blend limits. More information about ASTM's process to maintain the safety of aircraft fuels, including SAF, can be obtained from ASTM's website.[26]

Notably, it appears that blends well below 50 percent may be leading the early years of SAF usage. Supplies of neat SAF are constrained, and it is a premium-priced fuel even when blended at 50 percent (see Section 7). Used in blend ratios well below the current 50 percent limit, SAF can still provide significant GHG reductions (proportional to the blend ratio). As further discussed, some early-adopter airlines are commonly using SAF in a 30 percent blend with CJF, and some may be using lower percentage

[23] ASTM, "Active Standard ASTM D7566," https://www.astm.org/Standards/D7566.htm.
[24] Air Transport Action Group (ATAG), "Beginner's Guide to Sustainable Aviation Fuel," Edition 3, November 2017, https://aviationbenefits.org/media/166152/beginners-guide-to-saf_web.pdf.
[25] Opisnet.com, "Rolls-Royce to Ground Test 100% SAF in Next-Generation Engines, reporting by Aaron Alford, November 16, 2020,
[26] For example, see ASTM's brochure "Keeping Aircraft Safe," https://www.astm.org/ABOUT/OverviewsforWeb2014/AviationOverviewSept2018.pdf.

blends.[27] Blending to low SAF levels extends the limited SAF supply and makes it more affordable. Although blending results in proportionally lower GHG-reduction benefits (as further evaluated), it is noteworthy that each gallon of neat SAF provides a certain GHG reduction benefit, regardless of the ratio at which it ultimately gets blended.

2.2. Performance and Combustion

As summarized by the National Renewable Energy Laboratory, jet fuels are "mostly defined in terms of required performance properties." Per the ASTM approval process and pathways noted above, all jet fuels (fossil or renewable) are required to meet specifications for parameters that include: (1) minimum energy density by mass, (2) maximum allowable freeze point temperature, (3) maximum allowable deposits in standard heating tests, (4) maximum allowable viscosity, (5) maximum allowable sulfur and aromatics content, (6) maximum allowable amount of wear in standardized test, (7) maximum acidity and mercaptan concentration, (8) minimum aromatics content, (9) minimum fuel electrical conductivity, and

Table 3. Comparison of typical CJF to SAF (neat, HEFA pathway) for key properties

Key Fuel Properties	Typical Measured Values	
	Conventional Jet Fuel* (CJF)	Sustainable Aviation Fuel (SAF)
Density (kg/m3)	800	772
Flash point (deg C)	42	47
Total aromatic content (%)	15%	0.10%
Freeze point (deg C)	-40	-50
Specific Energy (MJ/kg)	43	44
Sulfur content (ppm)	700	< 1
Derived Cetane number	46	60
Source: Neste communication to GNA (citing CRC and AFRL reports, Jan. 2020) ***Jet A**		

(10) minimum allowable flash point.[28]

The net result is that SAF is substantially similar to CJF, and provides excellent overall properties for use as a safe, high-performance substitute jet fuel. In fact, as shown in Table 3, SAF produced by the dominant HEFA pathway offers certain combustion characteristics that are advantageous over CJF for operating aviation

[27] Notably, it appears to be rare for SAF to be directly delivered to aircraft. More typically, SAF gets to the airport fueling system through a pipeline or local fuel farm / hydrant system (which has lifecycle GHG benefits vs. delivering by tanker), where it may be further blended with CJF before being dispensed into individual aircraft.

[28] National Renewable Energy Laboratory, "Review of Biojet Fuel Conversion Technologies," Wei-Cheng Wang, Ling Tao, Jennifer Markham, Yanan Zhang, Eric Tan, Liaw Batan, Ethan Warner, and Mary Biddy, NREL Technical Report NREL/TP-5100-66291, July 2016.

engines. These include a higher cetane number, lower aromatic content, and lower sulfur content[29] – all of which help to contribute to SAF's lower GHG and criteria pollutant emissions profiles (see Section 2.4) and higher performance. Notably, while SAF's lack of aromatics help provide its good emissions profile, it also raises materials compatibility issues, which is one key reason that ASTM currently requires SAF to blended with CJF.[30]

Although HEFA-SPK SAF has a slightly greater fuel density by mass than CJF, its volumetric energy density is about 4 percent lower than CJF. This means that (all else being equal) SAF use could result in proportional reductions in aircraft flying range compared to burning CJF. However, the lower volumetric energy density only impacts aircraft that are flying on (or close to) a fuel capacity limit. That rarely happens in practice, as aircraft are more typically limited by maximum takeoff weight (MTOW) restrictions.[31]

Major jet engine manufacturers like Pratt & Whitney (a United Technologies company) have clearly sanctioned use of SAF blends in their engines, while also noting important challenges that need to be overcome to achieve wide-scale use (limited supply, high costs).[32] Notably, the Sustainable Aviation Fuel Users Group (SAFUG), formed in September 2008, includes "25 members airlines (representing 33% of commercial aviation fuel demand)" and five "affiliates" organizations from the aviation industry (Boeing, Airbus and Embraer). Reportedly, SAFUG members including the airlines and manufacturers have signed a sustainability pledge acknowledging that advancing and adopting SAF is "a key driver to a carbon neutral industry."[33]

In sum, SAF is not only a drop-in replacement for CJF; in several important ways it is a superior jet fuel.

2.3. Carbon Intensity, Effects on Life-Cycle GHG Emissions and Sustainability

SAF's primary environmental benefit is that it provides a cost-effective, compelling in-sector GHG-reduction strategy for airlines and aircraft OEMs alike (consistent across turbine and piston types). A commonly cited figure is that neat SAF can reduce lifecycle GHG emissions by "up to 80 percent" compared to petroleum-based CJF.[34] However, as further described below, SAF's actual GHG-reduction benefits depend on the specific production pathway and feedstock type. Notably, on a *per-gallon basis*

[29] Pearlson, M. N., "A Techno-Economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels," Master of Science, Massachusetts Institute of Technology, 2007.
[30] For additional information, see IATA's "Fact Sheet 2 - Sustainable Aviation Fuel: Technical Certification," https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-technical-certifications.pdf.
[31] Personal communication to GNA from CAAFI, September 2020.
[32] Dr. Alan H. Epstein (Prat & Whitney) and John Mandyck (United Technologies Corporation), "The Future of Sustainable Aviation: Betting on Jet Propulsion and Lower Net Carbon Fuels," Power Point presentation, 2016, http://naturalleader.com/wp-content/uploads/2016/10/UTC-7612-FutureSustainableAviationWhitePaper_3.pdf.
[33] International Civil Aviation Organization, "Sustainable Aviation Fuel User Groups (SAFUG)," https://www.icao.int/environmental-protection/GFAAF/Pages/Project.aspx?ProjectID=13.
[34] This "up to 80 percent" is frequently cited by fuel producers, end users, SAF proponents, and in aviation sector publications. For example, see the commentary from Neste at https://www.aviationpros.com/gse/fueling-equipment-accessories/fuel-distributors-suppliers-manufacturers/article/21144761/neste-north-america-now-is-the-time-to-let-sustainable-aviation-fuel-take-off.

the GHG reductions for a given type of neat SAF are independent of the degree to which it is ultimately blended with CJF.

In California where SAF use is strongest, CARB measures the GHG-reduction potential of all transportation fuels by their carbon intensity (CI) value (in grams of carbon dioxide equivalent per mega Joule, or

Table 4 All Current LCFS-Certified Pathways for Alternative Jet Fuel (SAF), as of August 2020

Fuel Producer / Production Location	Feedstock / Pathway Process	Location of Feedstock	Carbon Intensity (gCO2e/MJ)
AltAir LLC (World Energy) Paramount, CA	Animal Fat (Tallow) / Hydrotreatment using natural gas, grid electricity and hydrogen	Colorado	23.93
		Canada	25.08
		North America	37.13
		Australia	42.91
		Avg CI (Unweighted)	**32.26**

gCO2e/MJ). The baseline aviation fuel to which SAF is compared for relative GHG emissions is CJF, which currently has a CI value of 89.37 gCO2e/MJ.

Starting in late 2019 and culminating in June 2020, one company and biofuels facility – World Energy's Paramount, California plant – certified four distinct (but similar) Tier 2 production pathways for SAF ("Alternative Jet Fuel" using CARB's nomenclature). As shown in Table 4, all four pathways entail hydrotreatment of tallow feedstock (animal fat from cattle and poultry). The CI ratings range from 23.93 to 42.91 gCO2e/MJ. One key CI determinant is the geographical location of the feedstock, and how far it must be shipped to reach World Energy's Paramount biofuels plant in Southern California. The average CI of World Energy's four CARB-certified pathways is 32.26 gCO2e/MJ (unweighted for production volumes). Notably, this is almost identical to the volume-weighted average CI for renewable diesel (RD) transacted under the LCFS program in 2019. This reflects the fact that SAF is co-produced with RD, using the same feedstocks and hydrotreatment process -- although it is not incentivized at the same rate as RD (see Section 4).

As indicated, the CI ratings for currently available SAF sold under a CARB-certified pathway (i.e., being supplied today by World Energy's Paramount biorefinery) range from 42.91 gCO2e/MJ down to 23.93 gCO2e/MJ.[35] In this comparison, neat (100 percent) SAF provides reductions in carbon intensity ranging

[35]California Air Resources Board, "LCFS Current Pathways as of April 2020," downloaded from https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm.

from 52 to 73 percent, relative to baseline CJF. Notably, World Energy is working on HEFA pathways with feedstocks other than tallow that may eventually achieve "carbon negative" CI values.[36]

It is important to stress that these potential GHG reductions associated with using SAF are based on the CI values of unblended (neat) SAF. As noted, ASTM requirements currently limit SAF content to 50 percent (or less) by volume, blended with CJF. Moreover, blends well below 50 percent SAF are being used to extend limited supply of neat SAF. Thus, accounting of actual GHG reductions from SAF use must consider the degree to which each neat gallon is blended. (See the analysis in Section 7.)

For SAF from not-yet-certified pathways (i.e., SAF not supplied by World Energy), CARB staff has established "temporary" CI ratings. To build-up these temporary CI values, CARB used "the most conservative data from LCFS certified renewable diesel pathways that produce (SAF) as a co-product."[37] Pending full pathway certification by the producer, some SAF supplied to airlines at Bay Area airports has been assigned CARB's temporary CI of 50 gCO2e/MJ; this provides about a 44 percent GHG reduction for each gallon of neat SAF relative to CJF.[38]

It appears that the GHG-reduction benefits of SAF may increase as new production pathways and feedstocks become commercialized and/or greater utilized. The International Council on Clean Transportation (ICCT) notes that SAF produced through "advanced fuel conversion processes" such as gasification and cellulosic alcohol-to-jet "can deliver 80% to 90% reductions in fuel carbon intensity, and their production could be greatly increased in the upcoming decades."[39] A recent publication by the National Academy of Sciences indicates that SAF's fuel-fuel-cycle GHG-reduction benefits may be even greater:

> *The potential GHG emissions reduction benefits from using (SAF) could be significant when compared to conventional jet fuel, and in some cases could exceed 100% (e.g., with biochar sequestration, or avoidance of other GHGs associated with the feedstock).*[40]

This concurs with World Energy management's previously noted statement that they are working on "negative carbon" pathways for the SAF they produce in Paramount, California – using the well-established and proven HEFA pathway. In addition, the ICAO cites at least three carbon-negative "CORSIA eligible" SAF pathways that use Fischer-Tropsch and Alcohol-to-Jet processes.[41] Again, these estimated

[36] World Energy's Bryan Sherbacow, personal communication to Jon Leonard of GNA, August 2020.
[37] California Air Resources Board, "Low Carbon Fuel Standard Proposed New Temporary Fuel Pathway: Alternative Jet Fuel," July 31, 2019, https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/comments/ajf_temp.pdf.
[38] California Air Resources Board, "Low Carbon Fuel Standard Proposed New Temporary Fuel Pathway: Alternative Jet Fuel," July 31, 2019, https://ww2.arb.ca.gov/sites/default/files/classic//fuels/lcfs/fuelpathways/comments/ajf_temp.pdf.
[39] International Council for Clean Transportation, "Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities," January 2019, https://theicct.org/sites/default/files/publications/Alternative_fuel_aviation_briefing_20190109.pdf.
[40] National Academy of Sciences, "Sustainable Alternative Jet Fuels and Emissions Reduction: February 2019 Factsheet," summary of ACRP Web-Only Document 41, accessible from www.trb.org/main/blurbs/179509.aspx.
[41] International Civil Aviation Organization, CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels, November 2019, https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions.pdf.

potentials for carbon reduction refer to use of SAF in its neat form, as a drop-in unblended replacement for CJF. Under current ASTM requirements, for any production pathway SAF must be blended with CJF for safety and general precautionary reasons. This also improves economics and extends the limited supply of SAF.

Several key mechanisms are in place to ensure that SAF used in California (as well as Oregon) is produced using sustainable, environmentally sound pathways. First, the LCFS and its counterpart in Oregon encourage "good behavior" by suppliers throughout the entire feedstock and supply chain processes for their biofuel products. This is because low CI values associated with sustainable pathways generate the highest credit values. Second, there are enforcement mechanisms in place to ensure sustainability. CARB has taken aggressive action to monitor the origins of biofuels (SAF, RD and others) dispensed in California. Reportedly, the agency has hired large numbers of third-party certifiers around the world, who help ensure sustainable sourcing for imported biofuels that generate credits under the LCFS, while also corroborating CI ratings for steps in the process that occur abroad. These actions by CARB have helped keep SAF and RD out of California if they have not been produced sustainably.[42]

Section 4 further discusses the implications of the relative CI ratings for CJF and SAF, in terms of potential GHG emissions in the Bay Area, and how they can impact the price of SAF blends to end users.

2.4. Effects on Aircraft Emissions of Criteria and Hazardous Air Pollutants

In addition to strong GHG-reduction benefits, substituting SAF blends for neat CJF can provide important improvements in ambient air quality. As noted above, SAF's high cetane number, lack of aromatic hydrocarbons and near-zero sulfur content generally help reduce aviation engine emissions of criteria pollutants and toxic air contaminants. A key Airport Cooperative Research Program (ACRP) study was conducted in 2018-2019 to assess the status of knowledge regarding emission reductions achievable by using SAF blends in commercial aircraft. Known as ACRP 02-80, the study was sponsored by the National Academy of Science and its Transportation Research Board. Under this study, the selected expert (Booz Allen Hamilton) collected, reviewed, and compiled data from emissions tests sponsored by a large government-industry-academia consortium. The results were derived from analysis using an Aviation Environmental Design Tool considering data from "representative airports" across various operational characteristics and fleet mixes (i.e., the numbers of jet, turboprop, and/or piston aircraft).[43]

In 2019, a "final" version of the ACRP 02-80 report was completed and issued as "Web-Only Document 41" (aka ACRP 41). This report included a second phase of ACRP 02-80 that further analyzed data compiled in the initial phase. This second part analyzed other blend levels of SAF (as low as 5%), and also explored

[42] Personal communications from state officials and SAF producers to GNA, July 2020.
[43] National Academies of Sciences, Engineering, and Medicine 2018, "*State of the Industry Report on Air Quality Emissions from Sustainable Alternative Jet Fuels*," **(Phase 1 of ACRP 02-80)**, Washington, DC: The National Academies Press, April 2018, https://doi.org/10.17226/25095, https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4238.

SAF benefits related to ultra-fine particles (UFP) in terms of particle mass (nvPM mass) and particle number (nvPM #).

Using the new analysis, the report authors developed "uncertainty in impact factors" for the emissions reductions found under Phase 1. The study reported important reductions in CO, SOx and PM emissions from jet aircraft fueled with SAF blends, although it found that no statistically significant NOx emissions

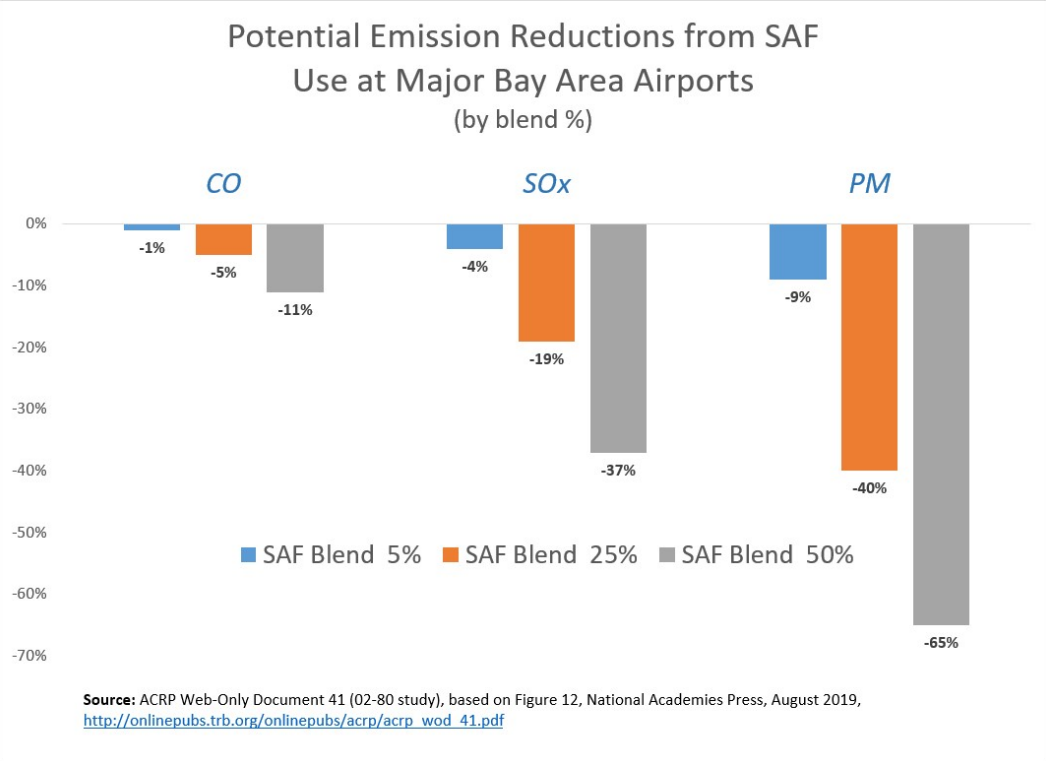

Figure 1. ACRP findings on potential criteria pollutant reductions from using SAF blends (see text reference)

reductions are realized. Figure 1 summarizes key findings for reducing these pollutants as a function of SAF blend percentage. These results are specific to airports that have a high percentage of turbine jets (relatively few piston engine aircraft), as is the case for the Bay Area's three largest airports. In Section 7.2, these emissions reduction factors are applied to quantify potential SAF-related reductions in criteria pollutant emissions at SFO, OAK and SJC.

In a separate "Fact Sheet"[44] that addresses the entire ACRP 02-80 study, the authors summarized estimated emission reductions from using SAF at "12 representative airports," paraphrased as follows.

[44] National Academy of Sciences, "Sustainable Alternative Jet Fuels and Emissions Reduction: February 2019 Factsheet," summary of ACRP Web-Only Document 41, accessible from www.trb.org/main/blurbs/179509.aspx.

SAF blends:

- Significantly reduce emissions of PM and sulfur oxides
- Achieve "moderate" reductions of carbon monoxide and unburned hydrocarbons"
- Reduce emissions of "ultrafine particles, not just the regulated larger particles"
- Minimally reduce, or have no effect on, emissions of NOx and hazardous air pollutants (HAPs)

The study notes that "these reductions could give airports flexibility to grow under their State Implementation Plan (SIP) constraints." For example, one key element of the BAAQMD's work to reduce local particulate matter emissions in the Bay Area is to prepare an "abbreviated" SIP that addresses EPA "planning requirements" associated with $PM_{2.5}$ attainment.[45] Expanded use of SAF feeds into the objectives of such a plan.

As one means to facilitate this process, the ACRP 02-80 study authors developed "a simplified tool that will allow airports to easily estimate emission reductions from use of (SAF) at their airport." As is further described in Section 6.1, SFO is already using significant volumes of SAF blends. While airport staff have not yet applied this tool to estimate the associated emissions reductions, they are using an internal methodology for this purpose, based on other industry data and within the framework of SFO's annual Climate Action Plan.[46]

[45] BAAQMD, "Particulate Matter Planning Activities," https://www.baaqmd.gov/plans-and-climate/air-quality-plans/current-plans.
[46] Personal communication from Erin Cooke and John Galloway (Environmental Dept at SFO) to GNA, telephone interview, August 12, 2020.

3. Emergence as a Leading Approach to Reduce Aviation-Related GHG Emissions

3.1. Previous Efforts Focused on Airline Fleet Efficiency

Historically, U.S. commercial airlines have focused on fuel efficiency improvements to reduce their aircraft fleet GHG emissions. Primarily, they have increased aircraft fuel economy by upgrading to newer planes (fleet modernization), and improving aerodynamics of in-use aircraft. Major GHG reductions have been achieved, but it appears this twin approach is now providing diminishing returns (see below). Consequently, the world's major aviation companies increasingly began to explore fuel-related strategies as a leading approach to reduce GHG emissions, beyond reductions enabled by fleet modernization.

As early as 2006, the U.S. Government began to take significant interest in SAF as a drop-in low-GHG replacement for CJF. Among the first steps taken was to form the Commercial Aviation Alternative Fuels Initiative (CAAFI) — a public-private partnership between the U.S. government, airlines, aircraft manufacturers, airports, and fuel producers. CAAFI was designed to lead SAF-related RD&D efforts, environmental assessments, commercialization efforts, fuel testing and other activities.

While test flights using SAF blends have been conducted in the U.S. for commercial, business and military aircraft for more than a decade, major momentum for SAF commercialization began about five years ago. A number of key SAF-related regulatory and sustainability initiatives have been adopted over the last half decade. Most of these are related to CORSIA, or at least complementary to its objectives. For example, in the 2010 timeframe FAA began "working to enable" U.S. aviation companies to consume one billion gallons per year of SAF blends by 2018.[47] Although that goal fell far short, the upshot in mid-2020 is that major commercial aviation companies in the U.S. and worldwide now seek to obtain and test SAF blends, to simultaneously comply with initiatives like CORSIA and achieve corporate sustainability goals.

SAF's emerging importance to reduce global aviation GHG emissions has been emphasized by the General Aviation Manufacturers Association (GAMA), acting jointly with the National Air Transportation Association and other stakeholders. In 2018 (and just updated for 2020), these stakeholders jointly produced a SAF use "guide,"[48] which includes the following sweeping statement (emphasis added):

> *"The single largest potential reduction in aviation's GHG emissions, and the key to reaching our goals for reducing them, will come about through the broad adoption of sustainable aviation fuel (SAF) in place of conventional jet fuel in use today."*

3.2. Current SAF Use at Demonstration Scale

NOTE: This report focuses on SAF use for commercial passenger aviation. However, it is important to note

[47] Federal Aviation Administration, "Sustainable Alternative Jet Fuels," https://www.faa.gov/about/office_org/headquarters_offices/apl/research/alternative_fuels/.

[48] "Fueling the Future: Sustainable Aviation Fuel Guide, Edition 2, 2020, https://www.futureofsustainablefuel.com/guide.

that business aviation and commercial aviation also constitute important sectors for SAF adoption. In fact, some SAF stakeholders consider these smaller aviation sectors to be more ready and conducive to adopt SAF than the big passenger airlines, due to "a more extensive supply chain" that is less dependent on the fuel pipelines that are often used to supply jet fuel to commercial flights.[49]

Notwithstanding this significant progress to systematically shift commercial airlines over to SAF, worldwide use remains very limited (see ATAG callout quote). Moreover, at this relatively early stage it can be challenging to find verifiable information about specific volumes of SAF currently produced and consumed. The Rocky Mountain Institute estimated that during 2018, SAF constituted "less than 0.01% of global consumption" for aviation fuel, equating to "about 5 million gallons per year."[50] Neste Corporation, with the world's largest capacity to produce SAF and other biofuels for transportation, stated in 2018 that "a mere 6.6 million gallons" of SAF are produced annually "on a commercial scale" (globally).[51] Although the U.S. Energy Information Administration (EIA) does not report SAF production or consumption, EPA reports RFS RIN data, "which indicate that the United States consumed 2.4 million gallons" of neat SAF in 2019.[52] While 2020 RIN data are not yet complete, it appears that roughly 3.6 million gallons of neat SAF were produced through August 2020. [53]

> *"For mid- and long-haul flying, an energy transition away from fossil-based fuels and towards sustainable sources of liquid fuel is needed. Luckily, the industry has already been hard at work in this area. Over 200,000 commercial flights have now taken place since we gained certification for the use of sustainable aviation fuel in 2011. It is in regular use at five global airports, but the percentage of total fuel use is still very small."*
>
> *-Air Transport Action Group, September 2019*

Part of the uncertainty about actual SAF usage may involve inconsistent nomenclature. First, statements about SAF volumes often do not specify if they refer to neat (100 percent SAF), or to ASTM-compliant blends (up to 50 percent). Second, fuel producers tend to emphasize emerging or future production "capacity," rather than actual current production, with some exceptions. Similarly, end-users (airlines) tend to speak about future (and confidential) "commitments" to use SAF, rather than current actual use. Based on various public sources of information, a reasonable estimate is that roughly 8 to 9 million gallons per year of SAF blends are currently being dispensed in the U.S. commercial aviation sector, with typical blends constituting 30 percent SAF. This does not take into account the impact of Covid-19, which has resulted in major reductions of CJF use since Q1 of 2020, but may be reducing SAF blend use at a much lower rate.

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[49] Personal correspondence to GNA from a SAF supplier for general and business aviation flights, October 2020.
[50] Craig Schiller, Rocky Mountain Institute, "Greening Aviation: Sustainability Takes Flight with Leading Airlines," Presentation at ACT Expo "Greening Aviation" session, April 26, 2019.
[51] Neste Corporation, "Renewable Jet Fuel, why does it cost more, August 30, 2018, https://www.neste.com/blog/aviation/renewable-jet-fuel-why-does-it-cost-more.
[52] National Renewable Energy Laboratory, "Renewable Hydrocarbon Biofuels," https://afdc.energy.gov/fuels/emerging_hydrocarbon.html.
[53] https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rins-generated-transactions

3.3. Key Drivers for Expanded Use

According to EIA's (pre-COVID) estimate, U.S. consumption of jet fuel will grow more than any other transportation energy source over the next 30 years, with the exception of electricity. EIA notes that increased demand for air transportation will "outpace" improvements in aircraft fuel efficiency.[54] In fact, the limits of using aircraft fuel efficiency improvement to offset growing jet fuel use – and therefore to mitigate aviation-related GHG emissions under CORSIA and other key initiatives -- is becoming a key driver for expanded SAF production and use. As many aviation stakeholders have noted – and common-sense dictates – it is harder to reduce GHG emissions from aircraft compared to key other modes of transportation, i.e., ground vehicles and water vessels. Especially notable is that combustion-free aircraft (e.g., powered with batteries and/or hydrogen fuel cells) are in the very early stages of research and development. Once prototypes are developed, the technology will need to overcome major safety barriers due to the nature of air travel. By contrast, "zero-emission" heavy-duty battery-electric and fuel cell platforms have now been conceptually proven for ground transportation applications, and their commercialization is progressing rapidly – as are government goals, incentives and requirements applied to them.

Notably, non-U.S. companies and governments are also keenly aware that SAF can provide hard-to-obtain GHG reductions in commercial aviation. While California currently offers the most-attractive market for SAF due to its LCFS program, this landscape may be changing as international aviation companies also seek to procure growing volumes of SAF. Other nations – particularly those in the European Union – already have favorable policies and may allow begin to "outpace" California as a market draw for SAF. This could make it increasingly difficult for airlines serving California airports – in particular SFO in the Bay Area -- to procure the large volumes of SAF they seek.

But for now, a key dynamic for SAF supply available at California airports relates to its close ties with RD production. A key question: is there greater potential societal benefit in maximizing SAF production to help decarbonize commercial aviation, while reducing volumes of co-produced RD for use in heavy-duty ground transportation? According to LCFS data for 2019, the volume of RD supplied for ground transportation applications in California currently exceeds the volume of SAF ("AJF") by a factor of approximately 300 to 1.[55] What is the future mix of these two renewable transportation fuel that will best and most cost effectively advance California's GHG-reduction goals, while accounting for the relative difficulty of decarbonizing the aviation sector? These complex questions are reportedly under discussion at high levels by CARB officials and state officials. Key overarching issues are further discussed in Sections 4 and 9.2.

[54]U.S. Energy Information Administration, "Annual Energy Outlook 2019 with Projections to 2050," January 4, 2019, https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

[55]CARB, Low Carbon Fuel Standard, Alternative Fuel Volumes and Credit Generation, averaging of Q3 and Q4 data, datasheet downloaded at https://ww3.arb.ca.gov/fuels/lcfs/dashboard/dashboard.htm.

4. Supply Side: Feedstock, Producers, and Production Pathways

4.1. Feedstock Types

SAF (like the RD with which it is co-produced), can be made from a wide variety of non-petroleum renewable resources. Generally, feedstocks that can be used to produce SAF certifiable under ASTM D7566 fall in these categories:

- Fats, oils, and greases (FOGs),
- Carbohydrates/sugars (e.g., corn or sugarcane)
- Lignocellulosic (plant dry matter)
- Industrial wastes

One particular type of "FOG" – animal tallow from beef, sheep or chicken processing – is currently the leading feedstock used to co-produce RD and SAF. Animal tallow is fat (triglycerides) recovered by a rendering process. The animal residues are cooked, and the fat is recovered as it rises to the surface. Since animal tallow is a waste by-product, it is widely available in the U.S. as a relatively affordable feedstock. It can be harvested sustainably, as long as robust markets exist for meat and other animal products. While tallow dominates today, CARB has indicated that others (e.g., soybean oil) may be key feedstocks of the future for California's supply of both RD and SAF.

It is important to reiterate that the same feedstocks and process are currently used to co-produce RD and SAF. As described below, fuel producers control the relative yields of the two fuels, subject to limitations and tradeoffs. Additionally, the same feedstocks used to co-produce RD and SAF are also used to produce biodiesel. This general issue of feedstock competition as a potential barrier to wider use of SAF is further discussed in Section 9.2.

4.2. Production Processes and Pathways

As was described in Section 2.1, the current dominant method to produce SAF (as a co-product with RD) is "FOG" hydrotreatment (a HEFA process). Other SAF production pathways that have been approved under ASTM D7566 include -- but are not limited to -- 1) catalytic upgrading of sugars, 2) Fischer-Tropsch solid biomass-to-liquid 3) biogas-to-liquid, and 4) alcohol-to-jet. However, most of these other processes are not yet used to produce SAF (and RD) on a commercial scale.[56] As noted, neat SAF from any production pathway must be blended with conventional aviation turbine fuel and certified under ASTM D1655 before it can be dispensed into aircraft.

[56] National Renewable Energy Laboratory, "Renewable Diesel Fuel," Robert McCormick and Teresa Alleman, July 18, 2016, https://cleancities.energy.gov/files/u/news_events/document/document_url/182/McCormick___Alleman_RD_Overview_2016_07_18.pdf.

Importantly, the relative percentage varies for how much SAF these pathways produce. Subject to various limits and tradeoffs, producers can maximize the SAF yield relative to RD and other co-products. The International Council on Clean Transportation (ICCT) examined four processes and pathways to produce SAF, including the dominant HEFA pathway.[57] Figure 2 highlights "typical product slates" in terms of RD as the dominant co-product, with SAF being a sub-dominant co-product. Other subdominant co-products are renewable naphtha and propane. The first bar in the chart illustrates a typical product slate from a RD/SAF production facility using the HEFA process. As shown, this pathway produces about 75 percent of its total biofuel (by mass) as "Road fuels" (RD); "Jet fuel" (SAF) constitutes about 15 percent by mass. The remaining 10 percent are "Other products" (renewable propane and naphtha).

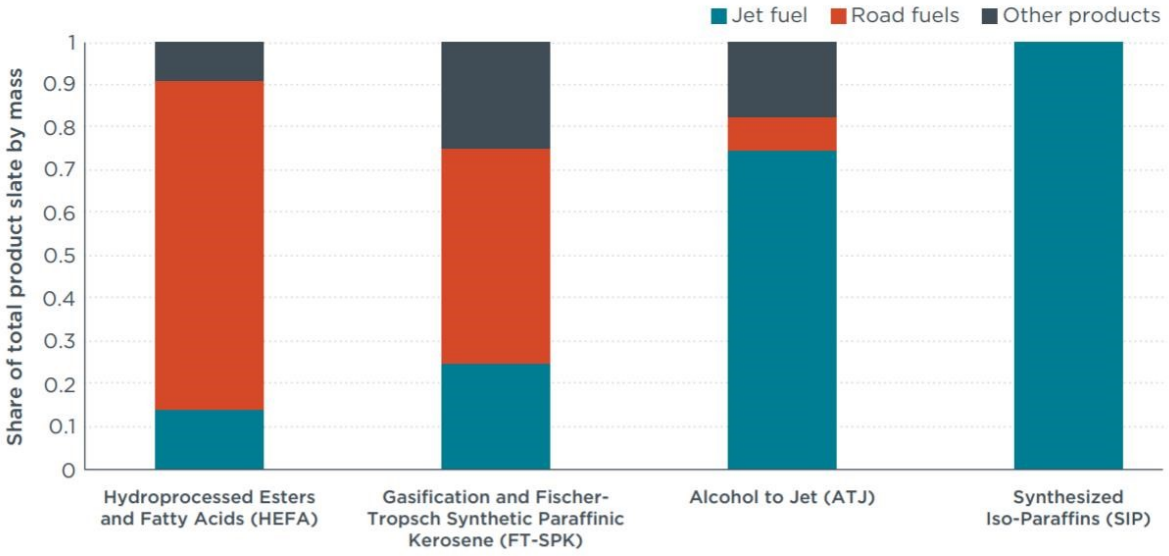

Figure 2. Typical product slates for SAF pathways (ICCT)

According to interviews with producers, this HEFA example reflects the high end of SAF yield that is regularly achieved today (up to about 15 percent by mass). In this case, the HEFA process has been geared towards producing RD for ground transportation as the dominant co-product. At this "typical" yield, SAF is reportedly produced at roughly the same cost as RD on a volumetric basis. However, the biofuel producer can choose to co-produce SAF at a much higher fraction of the product slate (up to about 50 percent). For example, as described below, producers can vary the type and/or loading of catalyst used during the HEFA process to increase the SAF yield (referred to below by its range of carbon atoms, C11 to C13), relative to the yield of RD (C14-C20) or the other co-products. (Note: they appears to be overlap

[57] ICCT, "Long-term aviation fuel decarbonization: Progress, roadblocks and policy opportunities," January 2019. https://theicct.org/sites/default/files/publications/Alternative_fuel_aviation_briefing_20190109.pdf.

here; SAF is also listed today as being C8-16 or C8-18, with a significant percentage of molecules in the higher range.)[58]

> *"During hydroprocessing of triglycerides, the type of catalyst is one of the most important factors to determine the yield and composition of liquid products, such as green naphtha (C5-C10), green jet fuel (C11-C13), and green diesel (C14-C20), and even green liquid petroleum gas (LPG). A severe hydrocracking catalyst would lead to a high production of green naphtha whereas a mild-hydrocracking catalyst is prone to produce mainly green diesel. The reaction temperature plays an important role for the yield and quality of hydroprocessed oils as well."*[59]

Increasing the relative yield of SAF (and therefore reducing the RD yield) entails higher costs and other tradeoffs (see Section 8). Leading U.S.-based SAF producer World Energy confirms that its Paramount HEFA plant could produce SAF at 50 percent of the total yield. However, in current markets for biofuels, World Energy chooses to favor a high RD yield. Increasing the SAF yield requires "cracking" more longer-chain (C14+) RD molecules, which raises costs and may lower the overall biofuel yield. Moreover, SAF (and other lighter hydrocarbons that are increased) "trade at lower values" than RD. Thus, the aggregate value of the HEFA yield decreases.[60] Speaking about one specific HEFA pathway, Pearlson et al corroborate this by noting that choosing to maximize jet fuel production imposes higher costs "due to increased hydrogen use and decreased diesel and jet fuel yield."[61]

Notably, World Energy and other producers are continually seeking technological and economic solutions to improve their SAF yield, while minimizing such tradeoffs. If SAF becomes more valuable through technology, market and/or policy changes, producers will find it more attractive to increase the relative yield percentage for SAF.

Greater details about and repercussions of this differing value for SAF vs RD – and the tradeoffs associated with increasing the SAF yield – are discussed further in Section 8.

4.3. Major Producers and Production Volumes (Existing and Planned)

Figure 3, prepared by CAAFI as of June 2019, graphically depicts the location of the SAF production facilities in the U.S. that are commercially producing SAF today (green dots), under construction (blue dots), or planned (red dots).[62] As noted, the dominant current U.S. SAF production facility is World Energy's plant in Paramount, California. GEVO in eastern Texas is also producing commercial SAF, in small

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[58] Neste Corporation, personal communication to GNA, September 2020.
[59] "Hydroconversion of Triglycerides into Green Liquid Fuels," Rogelio Sotelo-Boyás, Fernando Trejo-Zárraga and Felipe de Jesús Hernández-Loyo, published October 2012, https://www.intechopen.com/books/hydrogenation/hydroconversion-of-triglycerides-into-green-liquid-fuels
[60] Personal communication from World Energy to GNA, August 2020.
[61] Matthew Pearlson, Wollersheim C, Hileman J.,"A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production," January 2013, https://onlinelibrary.wiley.com/doi/abs/10.1002/bbb.1378.
[62] CAAFI, "Current State of Alternative Jet Fuel Deployment," Power Point presentation, July 16, 2019, http://www.caafi.org/focus_areas/docs/Alternative_Jet_Fuel_Deployment_Status_July%202019.pdf.

volumes. Red Rock Biofuels (Nevada) and Fulcrum Bioenergy (Oregon) both anticipate bringing SAF production facilities online in late 2020 or early 2021. Within two years new SAF productions facilities in the Midwest and East Coast are expected to become operational from Gevo, Fulcrum Bioenergy, SG Preston, and Lanza Tech. (The information below is now becoming out of date, although -- as of this writing -- CAAFI has not updated the map version.)

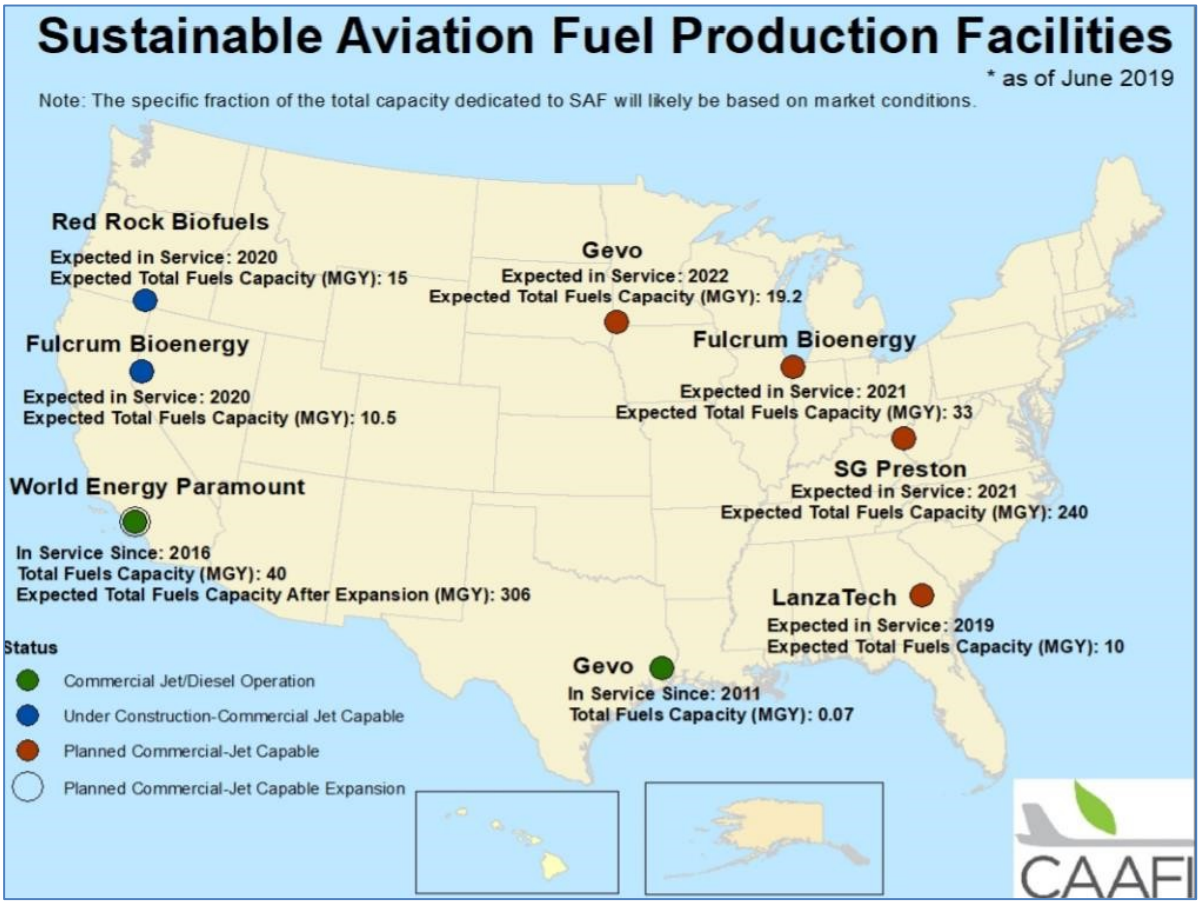

Figure 3. CAAFI's mid-2019 map of SAF production facilities (operating, under construction, and planned)

Other companies that produce (or plan to produce) SAF for U.S. commercial aviation include Neste and Velocys, which are both located outside the United States. Like World Energy, Neste is an important producer for SAF being dispensed at Bay Area airports. Neste, World Energy, Fulcrum and other key SAF producers (existing or planned) are further described below in the context of end use in the Bay Area.

Neste Corporation

Neste is the world's largest producer of biomass-based diesel (BBD) fuels used in high-horsepower compression-ignition engines for on-road and off-road transportation applications. Neste currently specializes – and leads the world in – producing RD via the HEFA pathway for heavy-duty ground

transportation applications. In recent years Neste has increasingly focused on marketing and selling the co-produced kerosene jet fuel from this process, after upgrading it into ASTM-compliant SAF. Neste has branded this as Neste MY Renewable Jet Fuel™.

Currently, Neste has capacity at its three major production plants (Europe and Asia) to annually produce about 3.2 million tons (roughly 1 billion gallons) of biofuels for transportation. However, by expanding production capacity at Neste's Singapore biofuels, the company is in the process of increasing annual production capacity for all biofuel types by 50 percent, up to 4.8 million tons (about 1.6 billion gallons).

Currently, the vast majority of Neste's production capacity is dedicated to making RD for ground transportation. Only about 3.3 percent (~100,000 tons / 34 million gallons) of Neste's annual biofuel production capacity appears to be geared for making SAF. This capacity primarily exists at the Porvoo (Finland) production facility. However, as part of the Singapore plant expansion (to be completed in the 2023 timeframe), it appears that Neste is planning a 10-fold increase in its annual capacity to produce SAF (increasing from 100,000 to 1 million tons).[63] Neste is also conducting a feasibility study to potentially add major SAF production capacity at its Rotterdam biofuels production facility.[64]

It is important to note that these numbers refer to current and future production capacities, but not necessarily actual fuel production. Like the airline industry, Neste believes SAF has emerged as "the most effective method for decarbonizing aviation today." [65] However, as further described in Section 8.3, a gallon of RD currently has greater market value than a gallon of SAF. Ultimately, Neste (and other existing or potential SAF producers) will rely on dynamic market conditions to determine how much of their transportation biofuel production should be geared towards SAF vs RD.

Previously, Neste facilitated single test flights of its SAF blends with major airlines that include Qantas, Virgin Atlantic, JAL, KLM, Air New Zealand, and the U.S. Air Force. Neste now supplies (or expects to soon supply) SAF at a variety of airports around the world; U.S. locations include SFO, Chicago O'Hare and LAX.[66] In fact, as further discussed in Section 6, Neste is becoming a major supplier of SAF at SFO in the Bay Area. According to public statements, Neste's SAF product (RJF) "is already available at industrial scale," and "successful commercial use has been achieved." While Neste estimates that "widespread continuous use" of SAF is imminent, the company also stresses that this will require greater policy and stakeholder support.

World Energy

Boston-based World Energy is the U.S. leader for *actual production* of SAF, and possibly the world's leading producer. (Note: Neste does not disclose actual production volumes, but the company is "very confident" it has become the world's largest SAF producer.[67]) In March 2018, World Energy acquired all

[63] Neste Corp., "Neste's role in sustainable aviation," accessed July 2020, https://www.neste.com/companies/products/aviation/neste-my-renewable-jet-fuel.
[64] Neste Corp., personal communication to GNA, September 2020.
[65] Neste Corp., https://www.youtube.com/watch?time_continue=77&v=mOTp6x0LWFM.
[66] Lana Van Marter, Commercial Development Manager, Neste Corp., presentation at ACT Expo "Greening Aviation" session, April 26, 2019.6
[67] Neste Corp., personal communication to GNA, September 2020.

assets of AltAir's Paramount (California) biorefinery, for a cost that was reportedly $72 million.[68] Today, World Energy makes approximately 45 million gallons of BBD fuels, using four different CARB-certified HEFA pathways (refer back to Table 4). The bulk of the BBD fuel that World Energy produces at the Paramount plant is RD for ground transportation, which is primarily sold to big fleet customers like UPS.

No firm numbers are provided by World Energy, but it appears that SAF constitutes less than 10 percent of its current BBD production at the Paramount plant. Most of this (up to 5 million gallons per year) is purchased by United Airlines. In fact, World Energy has executed an agreement that makes United Airlines its exclusive SAF customer for U.S. based commercial passenger aviation. To date, most of the SAF that World Energy supplies to United Airlines is dispensed at nearby LAX. However, World Energy has also been supplying SAF to SFO "for many years," [69] and international airline SAF customers have included Singapore, Finnair and Air France.[70] Some (if not all) of World Energy's SAF currently going to SFO appears to be sold to international carriers like these, as well as cargo airlines (see Section 6).

In late 2018, World Energy announced a $350 million expansion of the Paramount biorefinery, which will increase annual production of all BBD fuels to 306 million gallons. World Energy notes that about half of this increased production capacity (150 million gallons per year) will be dedicated to SAF; the remainder will be for RD and renewable propane.[71] However – similar to the case with Neste's expanded production in Singapore – World Energy will rely on market dynamics (including but not limited to relative values) to guide the ultimate percentages of SAF, RD and renewable propane it produces at the Paramount production plant (see Section 8.3).

Apparently, World Energy will distribute at least some of this new, much-larger SAF production through its new partnership with a major, long-standing aviation fuel provider. In January 2020, World Energy and Shell Aviation jointly announced a collaboration to "develop a scalable supply" of SAF. The multiyear effort between the two companies will supply "up to one million gallons" of SAF to the SFO operations of Lufthansa Airlines (notably, not a North American airline, so this stays within World Energy's agreement with United Airlines). The SAF will be blended with CJF "at a ratio of up to 30%" into a CARB-certified low-CI aviation fuel. [72] Lufthansa has also partnered

Figure 4. World Energy's Paramount plant (photo by GNA)

[68] GreenAironline.com, "World Energy acquires AltAir's world-first commercial scale renewable jet fuel refinery," March 2018, https://www.greenaironline.com/news.php?viewStory=2465.
[69] Personal communication from World Energy to GNA, August 2020.
[70] Personal communication from Erin Cooke of SFO to GNA, September 2020.
[71] Biomass Magazine, "World Energy Invests $350M to Expand Paramount Biofuel Production, article by World Energy, October 4, 2018, http://biomassmagazine.com/articles/15699/world-energy-invests-350m-to-expand-paramount-biofuel-production.
[72] Shell Aviation, "Shell Aviation and World Energy Collaborate to Increase Supply of Sustainable Aviation Fuel," press release, January 7, 2020, https://www.shell.com/business-customers/aviation/news-and-media-releases/news-and-media-2020/shell-aviation-and-world-energy-collaborate-to-increase-supply-of-sustainable-aviation-fuel.html.

with Neste since 2011 to pilot SAF use in European commercial flights; the two companies announced further collaboration in October 2019.[73]

World Energy's SAF will also be used by Amazon Corporation, which has committed to achieve carbon neutrality by 2024. Reportedly, Amazon "aims to compete with FedEx and UPS in the logistics and shipping industry," and its emerging airline Prime Air has tested out SAF blends on at least two flights. In July 2020, Amazon announced that the company "has secured up to six million gallons" of blended SAF under a year-long procurement deal with World Energy as the fuel producer, and Shell Aviation as the supplier. Thus, it appears that Amazon Prime Air may be the largest offtake customer for SAF produced and supplied under the above-noted World Energy-Shell Aviation partnership. Amazon's press release is not clear whether the SAF it procures will be dispensed at one or more Bay Area airports. Notably, Amazon's major hub for air operations will be in Kentucky.[74]

Amazon states that the blended SAF it procures will reduce carbon emissions in the range of 20 to 22 percent.[75] As noted above, World Energy's approved LCFS pathways have carbon intensity (CI) values that range from 52 to 73 percent lower than the current CI of CJF. Assuming World Energy's best-case CI pathway for producing SAF, it can be deduced that Amazon will operate its cargo jets on a blend of about 30 percent SAF mixed with CJF, as follows:

SAF at -73% CI x 30% SAF blend = ~ -22% carbon emissions (full fuel cycle)

Based on this and the Lufthansa case described above, an approximate blend of 30 percent SAF / 70 percent CJF appears to be commonly used by World Energy's aviation customers. Notably, this is largely an academic estimate. Jet fuel is typically dispensed to aircraft using an underground common hydrant system, which "begins where fuel enters one or more tanks from an external source such as a pipeline, barge, rail car, or other motor fuel carrier."[76] This type of system is how SAF is now (or will be) introduced into the CJF supply at large airports like SFO. In this process, the SAF delivered by the supplier is blended into the hydrant system, and the percentage of SAF that ultimately reaches a given aircraft's fuel tanks may vary significantly.

Other Producers with Announced Plans or Potential to Supply Bay Area Airports

In addition to Neste and World Energy, other companies that currently produce SAF consumed at Bay Area airports – and/or have announced plans to build production facilities for this purpose – include Fulcrum BioEnergy, Red Rock Biofuels, SG Preston, and Phillips 66. Notably, two major domestic RD producers in the U.S. – Diamond Green Diesel and Renewable Energy Group – are likely working on their own efforts to produce and market SAF, which may ultimately be consumed at Bay Area airports.

[73]Neste Corporation, "Neste and Lufthansa aim for a more sustainable aviation," press release, October 2, 2019, https://www.neste.com/releases-and-news/aviation/neste-and-lufthansa-collaborate-and-aim-more-sustainable-aviation.
[74] Amazon Corporation, "Promoting a more sustainable future for Amazon Air," The Amazon Blog, July 8, 2020, https://blog.aboutamazon.com/operations/promoting-a-more-sustainable-future-through-amazon-air .
[75] Amazon's web blog states "up to 20 percent;" the accompanying video on SAF states a 22 percent reduction.
[76] U.S. EPA, "Field-Constructed Tanks and Airport Hydrant Systems – 2015 Requirements, https://www.epa.gov/ust/field-constructed-tanks-and-airport-hydrant-systems-2015-requirements#ahs.

SAF producer developments relevant (or potentially relevant) to the Bay Area include:

- Red Rock Biofuels is building its production plant in Lakeview, Oregon. It will reportedly convert "136,000 tons of waste woody biomass into 15.1 million gallons/year of renewable fuels;" it's unclear how much will be RD for ground transportation versus SAF for aviation, but it appears that about 6 million gallons per year will be dedicated as SAF. Red Rock will focus on a Fischer-Tropsch pathway (FT-SPK) to make this biofuel.[77] It seems likely that a significant portion of this will be used at SFO and OAK.

- Fulcrum BioEnergy's plant near Reno, Nevada will be the nation's first commercial-scale plant to convert landfill waste into renewable fuel (RD as well as SAF). The resulting fuel will provide a "more than 80% reduction in lifecycle CO2 emissions." In 2014, Cathay Pacific made an undisclosed equity investment in Fulcrum.[78] In 2015, United Airlines made a $30 million equity investment in Fulcrum. Under the deal with United, Fulcrum will also build a SAF production facility in Gary, Indiana.[79] United Airlines has executed an offtake agreement with Fulcrum that appears to include up to 180 million gallons per year of SAF blends. It seems likely that a significant portion of this will be used for United's operations at SFO, or other Bay Area airports.

- Phillips 66's announced plans are of particular interest, to both SFO and the BAAQMD. Section 6 further discusses this case, in the context of SAF use at SFO.

- In the Pacific Northwest, the U.S. Department of Agriculture has joined with Alaska Airlines and SeaTac International Airport in an R&D project to convert local poplar trees to SAF. This type of alcohol-to-jet production pathway could eventually help bring SAF to the Bay Area. However, this process and project in particular do not yet appear to be producing significant volumes of SAF. [80]

4.4. Production Targets for Near and Longer Term

[77] Red Rock Biofuels, "Lakeview Project Summary," https://www.redrockbio.com/lakeview-site.html.
[78] Cathay Pacific, https://fulcrum-bioenergy.com/partners/cathay-pacific/.
[79] Ibid.
[80] Advanced Hardwood Biofuels Northwest, "Bridge to Biofuels: Renewable Biofuels and Biochemicals from Poplar Trees – Part 3 – Biojet Fuel, https://www.youtube.com/watch?v=pLye9duz1nU.

SAF Potential for Reducing GHG Emissions at Bay Area Airports

The Air Transport Action Group (ATAG)[81] considers SAF to be the key "long-term solution " for reducing commercial aviation GHG emissions, combined with "radical advances in technology."[82] As shown in Table 5, ATAG estimates that by 2025, the worldwide total "capacity of potential SAF production" will reach about 923 million neat gallons per year. (This is approximately equal to the current actual worldwide RD production). ATAG estimates it would take roughly twice that amount of SAF supply – about 1.85 billion neat gallons per year, or "around 2% of the overall jet fuel supply" – to "enable a tipping point in the supply / price balance, allowing more rapid deployment" of SAF. ATAG notes that this can only be achieved with "the right policy support."[83]

Table 5. ATAG Estimated SAF worldwide production capacity: mid-2020 and 2025

Parameter	2020 Estimated Actual	2025 ATAG: "Expected"*	2025 ATAG: Needed to "Enable Tipping Point" in Supply/Price
SAF Worldwide Production Capacity **(Neat)**	~6 to 7 Mgpy	923 Mgpy	1847 Mgpy
% of Current **CJF** Production	~0.01%	~1%	~2%
*SAF production plants and refineries "currently operating, under construction or advanced planning" **Source:** Air Transport Action Group (ATAG), May 2020 "Fact Sheet" on SAF (see text for full reference)			

CAAFI, which leads a government-industry consortium to make SAF a widely used alternative to CJF in commercial aviation, estimates number that are in the same ballpark as ATAG. As of mid-2020, CAAFI reports that "several producers" plan to collectively produce approximately one billion gallons per year of neat SAF by 2026.[84] Blended at 30 percent SAF, this would result in more than three billion gallons of SAF fuel for use in the commercial aviation sector.

[81] ATAG (www.atag.org) "represents the entire aviation sector: airlines, airports, air traffic management organizations and the makers of aircraft and engines. It coordinates common industry positions on the sustainable future of air transport."
[82] ATAG, "Aviation Industry Welcomes Progress in CORSIA, Despite Global Emergency," press release, March 16, 2020.
[83] Air Transport Acton Group, "Aviation's Energy Transition, FACT SHEET #5," May 2020, http://www.caafi.org/resources/pdf/FACT_SHEET_5_Aviations_Energy_Transition.pdf.
[84] Personal communication from CAAFI to GNA, September 2020.

5. Demand Side: Commercial Aviation SAF Users

5.1. Overview

According to statistics provided (and continually updated) within ATAG's Aviation Benefits Beyond Borders report,[85] roughly 266,000 commercial flights have been operated (worldwide) on SAF blends since 2011. At least six airports "are currently regularly supplied with SAF," and at least nine airlines have arranged "significant off-take agreements" to purchase it. CAAFI calculates from actual SAF use reports that "procurements" of SAF have been steadily growing since 2016, especially in the commercial aviation sector. As shown in Figure 5, 2019 neat SAF procurements by U.S. airlines reached nearly 2.5 million gallons, and 2020 procurements are on track to exceed 4 million neat gallons.

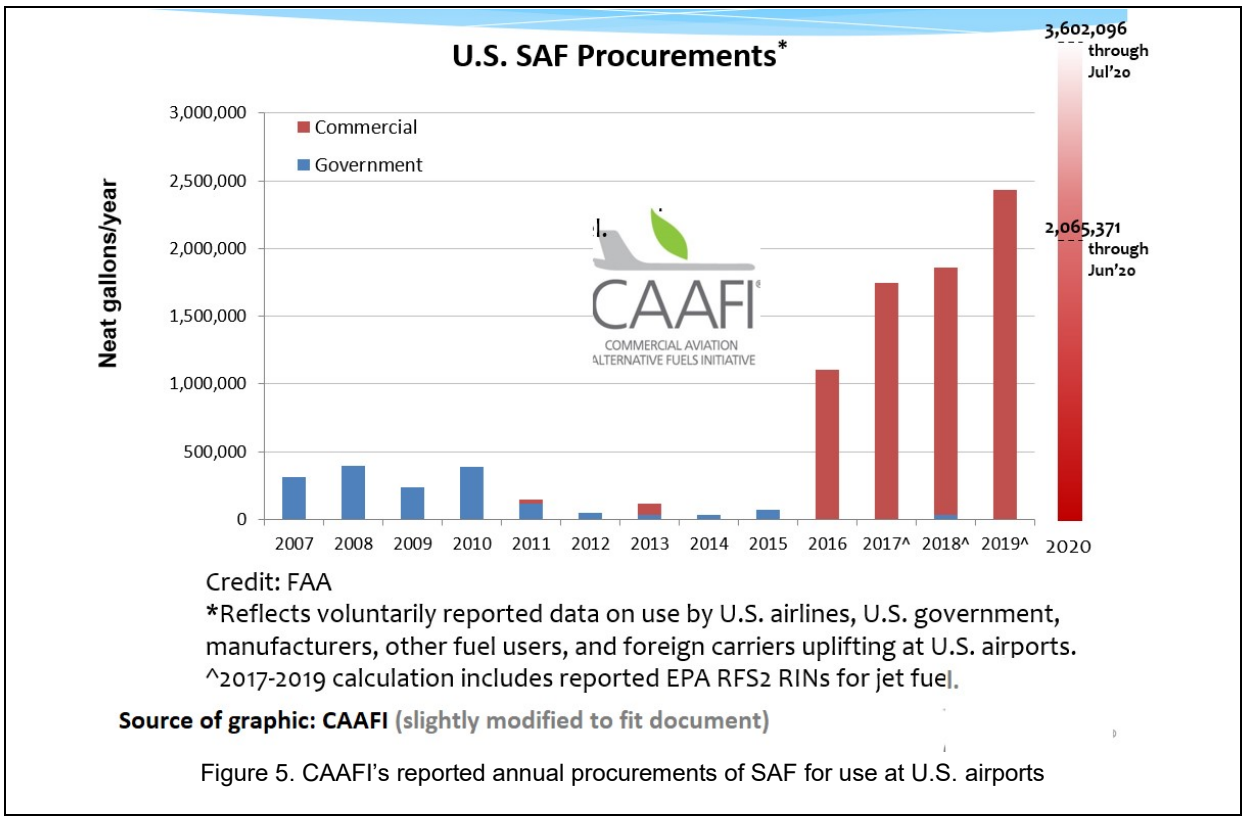

Figure 5. CAAFI's reported annual procurements of SAF for use at U.S. airports

5.2. Major Airlines Using SAF in California

Commercial Passenger Airlines

United Airlines is currently the largest user of SAF in North America, and possibly worldwide. United consumes about four billion gallons of CJF annually. CJF combustion makes up 99 percent of its carbon

[85] Aviation Benefits Beyond Borders, "Sustainable Aviation Fuel," accessed September 2, 2020, https://aviationbenefits.org/environmental-efficiency/climate-action/sustainable-aviation-fuel.

footprint, which the airline has committed to reduce by 50 percent before 2050. To date, United has reduced GHG emissions by about 10 percent (relative to 2007 levels), but most of this was done through efficiency measures (e.g., a $2 billion investment per year to purchase more-fuel-efficient aircraft). Over the last five years, United has increasingly relied on fuel-related strategies to reduce aircraft-related GHG emissions. In March 2016, the airlines made its first flight on a SAF blend (LAX to San Francisco route). Since then, United has operated well over 4,000 flights on SAF blends, and it claims to currently consume as much as 50 percent of the U.S. SAF supply.[86]

United is now aggressively "scaling up biofuel use," to achieve its planned GHG reductions. This has necessitated active seeking of other SAF suppliers beyond Neste and World Energy, as well as investing in Fulcrum BioEnergy's greenfield production facility. United claims to have locked up "over half of the (airline) industry's biofuel commitments"[87] encumbered under offtake agreements, which it estimates at about 1.5 billion gallons over multiple years. Table 6 in the next subsection provides three different estimates for off-take agreements, including data provided by United Airlines.

As of July 2020, CAAFI indicated that United is "the only U.S. airline flying on SAF on a continuous basis."[88] However, that appears to be changing, with multiple airlines moving towards regular operation of certain flights on SAF blends. In fact, at least eight other passenger airlines are also testing SAF blends in flights departing from U.S. airports, including several that are operated out of SFO and other Bay Area airports. These include Alaska Airlines, American Airlines, and Cathay Pacific, which have joined United in striking deals with Neste and other suppliers for SFO flights. Section 6 further discusses various key Bay Area operations on SAF blends, in the context of the three major Bay Area commercial airports.

Commercial Cargo Airlines

Package and freight airlines have also initiated test programs to determine if SAF is an economically and technically feasible replacement for CJF. For example, in 2018 FedEx's "ecoDemonstrator" Boeing 777F became the company's first aircraft to fly on neat SAF. (Notably, this was a demonstration / R&D flight; use of neat SAF is not approved for commercial use in the U.S., primarily due to caution about materials compatibility issues that could compromise safety.) As further described, FedEx is now dispensing SAF blends at Bay Area airports, at demonstration scale.

Similar to the case with passenger airlines, use of SAF blends to date has primarily been a secondary strategy for package and freight airlines to reduce aviation-related footprints. FedEx and other carriers have achieved the bulk of their GHG reductions through efficiency improvements obtained via aircraft fleet modernization.[89] However, SAF is playing an increasing role in the sustainability strategies of cargo

[86]Ibid.
[87]Aaron Stash, United Airlines Manager of Environmental Strategy and Sustainability, "Greening Aviation: Sustainability Takes Flight with United Airlines," Presentation at ACT Expo "Greening Aviation" session, April 26, 2019.
[88] CAAFI, "Current State of Alternative Jet Fuel Deployment," Power Point presentation, July 16, 2020, http://www.caafi.org/focus_areas/docs/Alternative_Jet_Fuel_Deployment_Status_July%202019.pdf.
[89]Allison Bird, FedEx, "Championing Sustainability in Air Freight," ACT Expo "Greening Aviation" session, April 26, 2019.

airlines. Amazon Prime, UPS and other cargo airlines are also testing and procuring SAF, with a focus on Bay Area airports (see Section 6).

5.3. Near-Term Expanded Use: Announced Offtake Agreements

At least nine airlines have negotiated "current forward purchase agreements" with SAF suppliers; these collectively encumber as much as 1.6 billion gallons of SAF over roughly a decade.[90] Table 6 summarizes three different sources that breakout rough estimates for airlines that have negotiated long-term off-take agreements, and their associated SAF producers/suppliers.

[90] Aviation Benefits Beyond Borders, "Sustainable Aviation Fuel," accessed September 2, 2020, https://aviationbenefits.org/environmental-efficiency/climate-action/sustainable-aviation-fuel.

Table 6. Estimated neat SAF volumes for announced commitments / offtake agreements

End User Airline *(Suppliers)*	United Airlines: Announced SAF Commitments	CARB: "Examples of Airline Partnerships with Producers"	CAAFI "SAF Offtake Agreements Beyond Numerous Demonstration Programs"
United ***(World Energy and Fulcrum BioEnergy)***	915 M gal (unspecified time)	• 5 mgpy from World Energy (unspecified time) • 90 to 180 mgpy (over 10 yrs) from Fulcrum	• 5 mgpy from World Energy (unspecified time) • 90 to 180 M gpy (10 yrs) from Fulcrum BioEnergy
Cathay Pacific ***(Fulcrum BioEnergy)***	375 M gal (unspecified time)	375 M gal (over 10 years)	• 37.5 M gpy (10 years)
JetBlue ***(SG Preston, Neste)***	99 M gal (unspecified time)	10 M gal (over 10 years)	• 10 M gal (10 years, JFK) • Unspecified volume from Neste
Quantas ***(SG Preston)***	40 M gal (unspecified time)	No information reported	• 4 M gpy (10 years, LAX)
Lufthansa / Austrian/ Brussels / Eurowings / Swiss ***(Gevo)***	40 M gal (unspecified time) for all	40 M gal (over 5 yrs) just for Lufthansa	• Unspecified volume from Neste for SFO operations
FedEx / Southwest ***(RedRock Biofuels)***	"Not publicly available"	• 3 mgpy for 8 yrs (Southwest)	• 3 M gpy each (7 yrs, Bay Area)
Air Canada / Japan / Alaska / KLM/ British Airways / Scandinavian / Delta ***(Neste, Other Suppliers)***	"Not publicly available"	• Unspecified small volumes	• KLM: 24 M gpy (10 years) • Delta: 10 M gpy (2022-23, term/blend unspecified) • Unspecified volume from Neste for SFO operations
Virgin Atlantic ***(LanzaTech/LazaJet)***	• No information	• No information	• 100 M gpy by 2023 from 4 facilities
Amazon Prime Air ***(World Energy)***	• No information	• No information	• 1.8 M g over 12 months
Air British Petroleum ***(Fulcrum BioEnergy, Neste)***	• No information	• No information	• 50 M gpy (over 10 years) from Fulcrum • Unspecified volume from Neste for SFO operations
American ***(Neste)***	• No information	• No information	• 9 M gal over 3 years (source for this is American Airlines)
Alaska ***(Neste)***	• No information	• No information	• Undisclosed volume /term (source for this is Neste)
Signature Flight Support ***(Neste)***	• No information	• No information	• 5 M gal / undisclosed term (source for this is Neste)

Source cited by UA: see text footnote, citing industry press releases and UA's assumptions for scale-ups
Source for CARB: https://ww3.arb.ca.gov/fuels/lcfs/lcfs_meetings/031717presentation.pdf
Source for CAAFI (except as indicated): "SAF offtake agreements," July 22, 2020 Power Point presentation provided to GNA by Steve Csonka of CAAFI

Like current use, it can be challenging to accurately tally how much SAF will actually be consumed in U.S. commercial aviation within the next few years, due to hazy terminology. As of mid-2020, CAAFI estimates that ">350 M gpy" of neat SAF are committed for near-term purchase under existing airline offtake agreements, "with more in development."[91]

[91] CAAFI, "U.S. SAF Procurements" as of September 16, 2020, Power Point slide provided by CAAFI to GNA.

6. A Closer Look: SAF Use at Major Bay Area Airports

6.1. San Francisco International Airport

San Francisco International Airport (SFO) is the nation's seventh largest airport for annual passenger throughput.[92] SFO is by far the largest airport in the Bay Area, annually serving roughly 58 million incoming and outgoing passengers with at least 58 different airlines. Each year, airlines operating at SFO dispense approximately one billion gallon of conventional jet ("Jet A") fuel.[93] (Notably, in 2019 this reached 1.2 billion gallons.[94] Of the three largest Bay Area commercial airports (SFO, OAK and SJC), nearly two-thirds of the annual landings and takeoffs (LTOs) occur at SFO, accounting for 72 percent of the GHG ("CO_2e") total emissions (Scopes 1, 2, and 3) at these three airports.[95]

SFO has adopted a five-year Strategic Plan that includes a goal to achieve "carbon neutrality" and reduce "SFO-controlled" (Scope 1, 2) GHG emissions by 50 percent. This feeds into California's overarching State policy to achieve a 40 percent reduction in all GHG emissions from a 1990 baseline by 2030. SFO notes that a key GHG-reduction strategy within its annual Climate Action Plan is to support its commercial aviation airline partners in obtaining and using SAF. In fact, SFO states that

> *"Aircraft are overwhelmingly the single largest source of emissions at SFO. To address this, SFO is leading the world's largest initiative to develop and deploy SAF at an airport. In FY 2020, SFO expects to be a leading airport for SAF deliveries, and is leading a coalition of airlines, fuel producers, and NGOs to expand SAF industry incentives and investment to drive the market in California and beyond."*[96]

SFO was one of the first airports in the world to recognize the potential of SAF as a clean alternative fuel for commercial aviation operations. In 2017, the SFO Airport Commission adopted an "Airport Policy on the Advancement" of SAF, to further explore SAF's potential to reduce aircraft-related emissions of GHGs, as well as criteria pollutants (specifically, particulate matter and sulfur oxides). By that same year, SFO had "facilitated a series of twelve SAF demonstration flights" in partnership with Singapore Airlines. SFO also began partnering with the City of San Francisco's Department of Environment to "carefully analyze the use and adoption of SAF in the context of international, federal, state and local sustainability and environmental requirements and best practices for organizational and infrastructure resilience."[97]

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[92] World Airport Codes, "US Top 40 Airports, https://www.world-airport-codes.com/us-top-40-airports.html.
[93] Erin Cooke, Sustainability Director, SFO, "Sustainable Aviation Fuel: State of the Industry and California's Emerging Opportunities," Power Point slide presentation, circa 2017 (undated).
[94] Personal communication to GNA from Erin Cooke, SFO, September 2020.
[95] Airport LTO and GHG data provided to GNA by BAAQMD via personal communication, July 2020.
[96] San Francisco International Airport, "Climate Action Plan 2019," https://www.flysfo.com/sites/default/files/media/sfo/community-environment/SFO_Climate_Action_Plan_FY19_Final.pdf.
[97] San Francisco International Airport, "Director's Recommendation: Adopt Airport Policy on the Advancement of Sustainable Aviation Fuels," Memorandum to Airport Commission, December 19, 2017.

SAF Potential for Reducing GHG Emissions at Bay Area Airports

In September 2018, SFO signed a memorandum of understanding (MOU) with four airlines (United, Alaska, American, and Cathay Pacific) and four fuel producers (Shell, Chevron, Neste and LanzaTech) to work cooperatively on expanding SAF use at the airport. According to SFO's press release, this agreement was "the first of its kind to include fuel suppliers, airlines, and airport agencies in a collaborative effort to accelerate the global transition to sustainable fuels."[98] SFO has since added Gevo, ANA and San Diego Airport to its list of MOU signatories, while continuing to court other parties.

In 2019 -- as an extension of previous collaborative work by SFO, airlines, and aviation partners -- SFO commissioned a "Sustainable Aviation Fuel (SAF) Feasibility Study." [99] This study provided new assessments regarding SAF's commercial feasibility, viability, and infrastructure needs at SFO. Key findings of the study are summarized (paraphrased) as follows:

- **Current supply chain** - SFO currently has approximately 750,000 bbls (31.5 million gallons) of fuel storage "available" for storing SAF. Additional storage volume is needed over the "medium to long term."
- **Multi-modal transport** - Trucking, pipeline, rail, and waterborne pathways exists at SFO for potential SAF delivery, although they are not yet "ideal" and/or fully suitable for transporting SAF.
- **SAF production and supply** – Supply of SAF available to SFO -- as well as means of SAF production -- are currently limited. However, significant growth for both production and supply is underway. Some involves expansion of foreign facilities, although imported SAF will be "more difficult to rely upon."
- **Potential storage and blending sites** - The study identified nine "short list" sites that need "infrastructure and supply chain modifications" to enable wider use of SAF at SFO. For the mid and long term, "existing refinery sites" were ranked the highest (based on criteria including site development, logistics, planning/permitting, environmental, community acceptance, and contingency/operational risk). Three Northern California refinery sites (Chevron in Richmond, PBF Energy in Martinez, and Phillips 66 in Rodeo) were noted for strong potential for both on-site production and storage in the future. (See the discussion below about Phillips' August 2020 announcement that it will "reconfigure" its Rodeo petroleum refinery into a biofuels production facility for RD and SAF, using a HEFA pathway.)
- **Funding Mechanisms and Support** – The study identified various state, federal and local sources of potential funding that can be used to help facilitate expanded use of SAF at SFO.

[98] San Francisco International Airport, "SFO Announces Landmark Agreement for Use of Sustainable Aviation Fuels," press release, September 5, 2018.
[99] San Francisco International Airport, "Sustainable Aviation Fuel Feasibility Study," Final Report, September 2019, provided to GNA by SFO staff, July 2020.

SAF Potential for Reducing GHG Emissions at Bay Area Airports

The SFO study identified "volume targets" for phasing in use of SAF to displace CJF, from the near term (3 to 5 years) into the long term (10+ years). As shown in Table 7, roughly within the next five years, the target for SFO is approximately 30 million "neat" (unblended) gallons per year of SAF; this equates to about 2 percent of current SFO CJF use (pre-pandemic). Over the mid-to-long term (5 to 10 years, and beyond), the target is approximately 300 million neat gallons of SAF per year; this is about 17 percent current CJF use. Notably, at the current ASTM-approved blend limit for SAF (50% SAF, 50% CJF), these volumes can be doubled to arrive at the targeted volumes of blended SAF. For a 30 percent SAF blend, these volumes can be tripled.

Table 7. Low/High SAF volume targets at SFO compared to CJF
Millions of gallons per year

	Short Term (3-5 yrs)		Mid Term (5–10 yrs)		Long Term (10+ yrs)	
Type of Aviation Fuel	**Low**	**High**	**Low**	**High**	**Low**	**High**
Conventional Jet Fuel	**1200**	**1400**		**1800**	**>1800**	
Sustainable Aviation Fuel (Neat*)	**0**	**30**		**300**	**>300**	
% SAF use of current CJF use	NA	2.1%		~16.7%	16.7%+ (?)	
SAF Production Source	Existing and Planned Facilities (U.S., Global)		Demand / Price Induced (West Coast, Global)		Mainstream California Production	

Source: adapted from SFO "Sustainable Aviation Fuel Feasibility Study," September 2019 (Fig. 10, p. 17)
*Unblended (100%) SAF; at current ASTM-approved blend (50% SAF), these volumes can be doubled for useable SAF.

SFO's 2019 study identified likely sources of production for the targeted volumes of SAF over these same time periods. As indicated in the table, SFO's long-term plan is to transition toward getting all of its SAF from "mainstream California production" facilities.

Since the 2019 SAF study was commissioned, SFO has been implementing actions designed to make progressively larger SAF volumes available to its airline partners, under the airport's overarching "push towards net-zero carbon." In July 2020, SFO announced it joined with Neste Corporation to deliver an initial "batch" of SAF to select SFO airlines via an existing "multiproduct" pipeline. In an SFO / Neste press release, specific SAF quantities were not disclosed, but "high volumes" of SAF are reportedly already being transported via this system. In an August 2020 press release, Neste announced it is now supplying unspecified volumes of SAF blends to three airlines at SFO – Alaska, American and JetBlue -- as part of the umbrella MOU signed in 2018.[100]

Neste's raw biofuel product is shipped from its Porvoo (Finland) biofuels plant to Houston, where it undergoes final refining into SAF and RD. Neste uses Crowley to transport fully-conditioned and blended SAF from Houston to the Bay Area via a short-sea shipping tanker, where it is introduced into the pipeline

[100] Neste Corporation, "Neste to supply sustainable aviation fuel to three major U.S.airlines," press release of August 13, 2020, https://www.neste.us/www.neste.us/about-neste/news-inspiration/articles/Neste-supplies-sustainable-aviation-fuel-to-major-US-airlines.

that serves SFO's Fuel Farm.[101] Specifically -- based on detailed discussion from SFO's September 2019 "Feasibility" report about SAF – it appears that Neste's SAF is being delivered via part of the Kinder Morgan Santa Fe Pacific Pipeline (KM SFPP) network. Notably, only blended SAF (certified to ASTM 1655) can be introduced into the KM SFPP, which is regulated by the California Public Utility Commission. The KM SFPP also serves fuel farms at (or near) Oakland International Airport and San Jose International Airport.[102] (Extensive discussion of the KM SFPP's relevance as a potential SAF supply and distribution network for SFO -- as well as other parts of the Bay Area -- is provided in SFO's September 2019 SAF "Feasibility" Study.[103])

In mid-2020, Phillips 66 announced it will "reconfigure" its Bay Area refinery (Rodeo) to produce renewable fuels. As noted above, SFO's detailed SAF "Feasibility" study (September 2019) "short listed" this traditional petroleum refinery as one of several sites having good mid- and long-term potential for "storing, blending, and supplying SAF to SFO" (as well as other Bay Area airports, like Oakland International).[104] According to Phillips' press release, it will discontinue producing transportation fuels from crude oil, and transition the refinery to produce biofuels. Specifically, Phillips will co-produce RD, SAF and other products from feedstock that include used cooking oil, fats, greases and soybean oils. While not stated, this appears to be a HEFA pathway.

Phillips indicates that 1) the modified refinery will eventually produce 680 million gallons per year of these various renewable transportation fuels, although the SAF portion is not estimated. It states that the reconfigured Rodeo plant will become "the world's largest facility of its kind," with a total renewable fuel production "exceeding 800 million gallons per year when combined with the production of renewable fuels from an existing project in development." Production of RD, SAF and the other co-products is expected to begin in early 2024, "if approved by Contra Costa County officials and the Bay Area Air Quality Management District."[105]

It also appears that airlines seeking to use SAF at SFO may source it from Red Rock Biofuel's production plant in Oregon, once that facility is completed and starts production. Initially, it appears that Red Rock's SAF production will be used at Oakland International Airport (see below). SFO notes that "there will likely be opportunities to integrate supply chains, including blending and storage, with the supply to Oakland International Airport."[106]

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[101] San Francisco International Airport, "A Milestone for SFO: Neste Makes First Pipeline Delivery of Sustainable Aviation Fuel," joint press release with Neste Corp., July 7, 2020.
[102] According to Kinder Morgan (www.kindermorgan.com), its "Pacific Operations" pipeline network transports "more and one million barrels per day of gasoline, jet fuel, and diesel fuel" to western U.S. customers.
[103] San Francisco International Airport, "Sustainable Aviation Fuel Feasibility Study," Final Report, September 2019, provided to GNA by SFO staff, July 2020.
[104] See Table 6 on page 18 of SFO's 2019 SAF Feasibility study.
[105] Phillips 66, "Phillips 66 Plans to Transform San Francisco Refinery into World's Largest Renewable Fuels Plant, press release, August 12, 2020, https://www.wsj.com/articles/u-s-refiners-embrace-greener-fuels-11597251600.
[106] Ibid.

6.2. Oakland International Airport

Oakland International (OAK) is the second busiest airport in the Bay Area, and the fourth largest in California. This "primarily commercial service" airport serves more than "60 nonstop destinations on 14 different airline brands."[107] To date, it appears that use of SAF at OAK has been focused on FedEx's air cargo operations. Specifically, FedEx has announced plans to use up to three million gallons per year of SAF at its OAK air cargo hub. Additionally, but at least one passenger airline, Southwest, will also get SAF at OAK. Per CAAFI's estimate noted above, both FedEx and Southwest have signed offtake agreements with Red Rock Biofuels to each receive three million gallons per year of SAF, over seven years. Neat SAF supply will be shipped from the Red Rock refinery by truck or rail to a blending location and then "trucked to the Oakland International Airport fuel farm."[108]

The Red Rock SAF production plant in Lakeview was scheduled to begin operation in the Spring of 2020, but it appears to be significantly behind schedule.[109] Thus, it is not clear when FedEx and Southwest jets serving Oakland International will start using SAF blends from Red Rock Biofuels, but a start in 2021 seems likely.[110]

6.3. San Jose International Airport

San Jose International Airport (SJC) -- self-described as "Silicon Valley's Airport -- serves approximately 16 million passengers per year. Roughly, SJC is comparable to Oakland International in terms of market share for Bay Area passengers.[111] SJC has a "comprehensive" alternative fuels program that focuses on achieving GHG and criteria pollutant reductions, but this appears to be solely focused on ground transportation serving the airport. Based on extensive searching of SJC's website (mid-2020), the airport has not yet publicly announced plans to use SAF blends to reduce aviation-related GHG emissions. However, it is likely that SJC management is studying this potential, including possible synergy with SFO and/or OAK to support customer airlines in procuring SAF blends.

[107] Oakland International Airport, "About Oakland International Airport," https://www.oaklandairport.com/oakland-international-airport-goes-green-blue-natural-gas-buses/.
[108] Ibid.
[109] Red Rock Biofuels, presentation at ABLC Next by founder / CFO Jeff Manternach, October 2019, https://www.biofuelsdigest.com/bdigest/2020/01/12/from-woody-biomass-to-renewable-fuels-the-digests-2020-multi-slide-guide-to-red-rock-biofuels-lakeview-project/.
[110] Personal communication from CAAFI to GNA, September 2020.
[111] San Jose International Airport, "2019 Facts and Figures," https://www.flysanjose.com/sites/default/files/financial/activity_reports/2019%20Facts%20%26%20Figures.pdf.

7. High-Level Estimate of SAF-Related Emissions Benefits at Top Bay Area Airports

7.1. Greenhouse Gases

The BAAQMD maintains a district-wide GHG emissions inventory for a wide range of stationary and mobile sources, including aircraft. GHG emissions from aircraft are differentiated within the inventory by county and type of aviation (commercial, general, and military). Table 8 summarizes the direct GHG emissions (in metric tons CO2-equivalent) for the three major Bay Area airports for calendar year 2019, based on the emissions inventory.[112] These data represent estimated emissions occurring during the landing and takeoff (LTO) cycle, including flight from an altitude of approximately 2,300 feet[113] to ground level, on-ground taxi and idling, and take-off from ground level to 2,300 feet for commercial jet aircraft. The direct GHG emissions reported for each airport are translated into implied fuel consumption volumes using an emissions factor of 9.61 kgCO2e per gallon of CJF, derived from CARB's CA-GREET 3.0 model. This emissions factor is consistent with the emissions factors used in the BAAQMD GHG emissions inventory.

Table 8. Top BAAQMD airports: GHG emissions inventory from LTO events, and implied fuel consumption

Airport	Airport Type	Fuel/Engine Type	Direct GHG Emissions ($mtCO_2eq$ / year)	Implied Fuel Consumption During LTO Events (gal/year)
San Francisco International (SFO)	Commercial	Jet	1,332,084	138,650,209
Oakland International (OAK)			334,029	34,767,451
San José International (SJC)			188,270	19,596,156
[redacted]			**Total**	**193,013,816**

Note: GHG emissions (and therefore implied CJF consumption) may not fully include business aviation or general aviation flights, which can entail a significant portion of total emissions and fuel demand. For example, business aviation reportedly accounts for 5 to 6 percent of total CJF consumption in the U.S.

Full fuel cycle emissions (often called well-to-wheels or WTW emissions) -- and any GHG benefits that can be expected from using SAF blends -- are estimated using CARB's LCFS program methodology and CI data. As previously noted, the LCFS program assumes a baseline CI for CJF of 89.37 gCO2e/MJ. The CI for SAF used in the calculations for this study is determined using LCFS program quarterly data for credit generation, and volumes of SAF from Q2 2019 through Q1 2020. Table 9 summarizes these data and the implied average CI in each quarter. Note that the implied CI for Q2 2019 is 50.00 gCO2e/MJ, which is the temporary CI for Alternative Jet Fuel in the LCFS program and indicates that volumes claimed in Q2 2019 were produced under a temporary pathway rather than the actual, certified pathway. Consequently, data for Q2 2019 are not included in estimates of the volume weighted average CI for SAF of 36.06 gCO2e/MJ.

[112] GHG emissions data provided by BAAQMD staff for CY2019. Implied fuel consumption calculated by authors.
[113] 2300 feet is the approximate elevation at which atmospheric conditions change the dynamics of GHG impacts on warming, particularly when taking into account contrails.

Table 9. CARB LCFS program data for SAF

Quarter	Q2 2019	Q3 2019	Q4 2019	Q1 2020
Credits	3,600	4,579	2,924	2,082
Volume (gal)	723,542	693,621	445,027	284,190
Energy Density (MJ/gal)	126.37	126.37	126.37	126.37
Volume (MJ)	91,434,003	87,652,886	56,238,062	35,913,090
Base CI (gCO2e/MJ)	89.37	89.37	89.37	89.37
GHG Reductions (gCO2e/MJ)	39.37	52.24	51.99	57.97
Implied Avg CI of SAF (gCO2e/MJ)	50.00	37.13	37.38	31.40
Volume Weighted Avg CI gC02e/MJ (Q3 2019 – Q1 2020)				**36.06**

As noted, SFO staff report that approximately 1 billion gallons of CJF are loaded onto aircraft at the airport each year (pre-pandemic). The BAAQMD GHG inventory implies that approximately 139 million gallons of CJF for SFO-serving flights are consumed within the District boundaries (i.e., during LTO events), or approximately 14 percent of the total CJF volume loaded at SFO. This ratio is assumed to apply to the two other major airports in the region for purposes of estimating the total CJF volumes loaded at each airport.[114] As shown in Table 10, the combined fuel volumes loaded onto aircraft at the three major airports is approximately 1.4 billion gallons per year. CJF use results in full-fuel-cycle GHG emissions of 15.7 million metric tons per year.

Table 10. Estimated full fuel cycle GHG (CO2e) emissions and projected reduction potential

Airport	Implied Fuel Consumption (gal/year)	Estimated Fuel Loaded (gal/year)	WTW GHG Emissions (MT/year) Baseline CJF	Projected Reductions (MT/year) Full adoption of SAF5	Projected Reductions (MT/year) Full adoption of SAF25	Projected Reductions (MT/year) Full adoption of SAF50
SFO	138,650,209	1,000,000,000	11,293,687	336,827	1,684,134	3,368,268
OAK	34,767,451	250,756,572	2,831,966	84,462	422,308	844,615
SJC	19,596,156	141,335,207	1,596,196	47,605	238,027	476,055
Total	**193,013,816**	**1,392,091,779**	**15,721,849**	**468,894**	**2,344,469**	**4,688,938**

As previously described, current HEFA-pathway neat SAF reduces GHG emissions by approximately 60 percent compared to CJF. However, SAF is required to be blended with CJF at no more than 50 percent by volume, and much lower-level blends can be used to extend volume and/or improve affordability. Therefore, annual GHG reductions from SAF blends are dependent on the average fraction of CJF replaced by SAF. As shown in Table 10 and summarized in Table 11, GHG reductions from SAF blends at five percent to fifty percent would produce GHG reductions of approximately 0.47 to 4.7 million metric tons per year based on 2019 emissions estimates. The "Total" GHG reductions reported in Table 11 reflect emissions

[114] It is recognized that a larger percentage of flights operating out of SFO are international flights and that OAK and SJC host a larger percentage of domestic/regional flights. These differences could impact the ratio of fuel loaded versus fuel consumed within the BAAQMD, making the estimate of 14 percent for all airports a rough approximation only.

from all fuel loaded at the region's airports. The reductions are not constrained to only the reductions that occur within the BAAQMD boundaries. Emissions reductions within BAAQMD boundaries are calculated assuming that 14 percent of fuel loaded in the BAAQMD is consumed in the BAAQMD, as previously discussed. These differences in regional and total emissions highlight the additional GHG reductions that can be achieved by leveraging policies that support availability of SAF in the BAAQMD.

Table 11. Summary of GHG reduction potential from SAF using 2019 volumes (metric tons/year)

Blend	Total GHG Reductions (MT CO2e/year)	BAAQMD GHG Reductions (MT CO2e/year)
SAF5	468,894	65,012
SAF25	2,344,469	325,061
SAF50	4,688,938	650,122

7.2. Criteria and Hazardous Air Pollutants

SAF can produce significant reductions in CO, SOx, and PM emissions from jet aircraft, as discussed in Section 2.4 of this report. Such reductions increase with the percentage of SAF relative to CJF, as summarized in Table 12. While these reductions are significant on a percentage basis within the sector, an analysis of total mass emissions reductions based on the BAAQMD emissions inventory was conducted to place the emissions reductions in context to District-wide emissions.

Table 12. Emissions reduction factors for SAF blends (source: ACRP 02-80 study)

Blend	CO	SOx	PM10
SAF5	1%	4%	9%
SAF25	5%	19%	40%
SAF50	11%	37%	65%

Emissions inventory data (2011 calendar year) for commercial aviation in the counties hosting the three major commercial airports were extracted from BAAQMD's inventory and used to represent baseline emissions of criteria pollutants resulting from CJF combustion. These emissions rates are summarized in Table 13. The NOx emission rates are provided for context; as described, no NOx reduction benefit is assumed for SAF blends.

Table 13. Baseline criteria pollutant emission rates (CY 2011)

	2011 Base Inventory (tons/day)			
Airport	**NOx**	**CO**	**SOx**	**PM_{10}**
San Francisco International (SFO)	7.0	9.8	0.6	0.1
Oakland International (OAK)	1.8	3.6	0.2	0.0
San José International (SJC)	1.1	1.6	0.0	0.0
	9.9	**15.0**	**0.8**	**0.1**

Baseline emissions rates were then escalated to calendar year 2019 levels using the relative increase in direct GHG emissions for each airport, as reported by BAAQMD staff when compared to the 2011 baseline GHG emissions inventory. OAK and SJC emissions are estimated to have increased by 9 percent between 2011 and 2019; SFO increased an estimated 2 percent (Table 14).

Table 14. Projected criteria pollutant emissions rates (CY 2019)

	From GHG Inventory	2019 Projected Inventory (tons/day)			
Airport	**Implied Growth (2011-2019)**	**NOx**	**CO**	**Sox**	**PM_{10}**
San Francisco International (SFO)	2%	7.1	10.0	0.6	0.1
Oakland International (OAK)	9%	2.0	3.9	0.2	0.0
San José International (SJC)	9%	1.2	1.7	0.0	0.0
Totals	4%	10.3	15.7	0.8	0.1

Potential emissions reductions from SAF were determined by applying the emissions reduction factors from Table 12 to the emissions inventory data in Table 14 for blend levels of 5 percent, 25 percent, and 50 percent SAF. Table 15 summarizes these results and indicates that displacing all CJF with a SAF50 blend could provide reductions in CO emissions of 1.72 tons per day, SOx emissions of 0.31 tons per day, and PM10 emissions of 0.07 tons per day.

Table 15. Summary of criteria air pollutant reduction potential from SAF (CY2019 tons per day)

Blend	**NOx**	**CO**	**SOx**	**PM10**
SAF5	0.00	0.16	0.03	0.01
SAF25	0.00	0.78	0.16	0.04
SAF50	0.00	1.72	0.31	0.07

8. Cost, Price and Relative Value

The costs to produce SAF -- and the prices that end users pay for it (accounting for incentives) -- are key determinants for the pace at which SAF will be able to displace very large volumes of CJF in Bay Area commercial aviation operations. Purchasing fuel typically represents 20 to 30 percent of an airlines' total expenses (second only to labor costs). Consequently, paying significantly more for SAF will play a big factor in the financial position and stability of adopting airlines. Notably, one cost-related advantage of SAF is that CJF pricing can be very volatile, as it tracks crude oil pricing.[115]

8.1. Costs of Producing SAF as a Function of Product Yield

SAF costs more to produce than conventional petroleum-based jet fuel. This is generally the case with renewable transportation fuels that are produced on a relatively small scale. The actual incremental cost to produce SAF can vary as a function of many factors. These include feedstock type and location, capital and operational costs associated with the production process (e.g., the cost to purchase hydrogen for the HEFA process), the targeted relative "yields" of SAF and co-products, and how far the final product must be transported to reach end-use markets.

The International Coalition for Clean Transportation (ICCT) recently evaluated the costs of producing SAF for use in European aviation markets. ICCT estimated that the levelized cost to produce SAF (assuming a ~15% baseline yield for a HEFA process) is about $0.98 to $1.21 per liter ($3.71 to $4.58 per gallon). By comparison, CJF is produced at a cost of approximately $0.54 per liter ($2.03 per gallon). Based on the low case for SAF ($3.71 per gallon), it costs about 83 percent (1.8 X) more to produce SAF than CJF. ICCT attributes much of this to feedstock costs (tallow or other sources of triglycerides), which represents 50 to 75 percent of the total production cost. ICCT notes that the incremental cost of producing SAF may be lower for larger future facilities, due to economies of scale and/or technology improvements.[116]

Based on comments by various biofuel producers, the current incremental cost of making SAF is even higher than 1.8 X. In a 2018 interview, leading biofuels producer Neste indicated it pays "somewhere in the region of 3-4 [times] more" to produce SAF than fossil jet fuel. The actual multiplier varies largely as a function of volatile CJF pricing.[117] According to a May 2020 "Fact Sheet" prepared by the Air Transport Action Group, estimates for the incremental cost of producing SAF range from "2X for some waste-based sources" (e.g., the currently leading HEFA pathway), to "6-10X for synthetic fuels using carbon capture." Similar to the ICCT report, ATAG notes that the combination of new SAF-production facilities being built,

[115] Statista, "U.S. Airline Fuel Cost from 2004 to 2019," https://www.statista.com/statistics/197689/us-airline-fuel-cost-since-2004/.
[116] ICCT, "The costs of supporting alternative jet fuels in the European Union," 2019.
[117] Statement by Neste's Damian McLoughlin, reported during interview by Airport-Technology.com, "Renewable jet fuels : how to handle the heavy costs," August 21, 2018, https://www.airport-technology.com/features/renewable-jet-fuels-how-to-handle-the-heavy-costs/.

in tandem with major airlines now committing to large-volume offtake agreements with SAF producers -- "will help bring down the cost of SAF in the mid-to-long-term."[118]

As previously noted, biofuel refineries can be modified to produce a higher fraction of SAF in the co-product slate (up to about 50 percent). However, this entails greater incremental cost and may compromise the overall biofuel yield's market value, depending on the production process. The additional cost is attributed largely to reduced overall fuel production, as a fraction of the initially dominant co-product RD must be upgraded to SAF through additional refining that reduces yields by about 10 percent. ICCT estimates that producing SAF via the HEFA process at a 50 percent yield adds an additional $0.30 per gallon.[119] And, as previously noted according to one major SAF producer's comments, the overall yield of all co-products becomes less valuable.

These dynamics were alluded to by RD producer Renewable Energy Group, Inc. (REG) in comments to CARB about the need to treat SAF production differently than RD in the LCFS:

> *"The vast majority of renewable fuel producers capable of manufacturing (SAF) are currently producing renewable fuels for on-road transportation use. Due to historic incentives, these facilities were designed, built, and operated to produce on-road fuel rather than (SAF). While these facilities are capable of producing (SAF) with little modification to their process, generally the production of (SAF) leads to decreased yields and increased operating expenditures when compared to on-road renewable fuel production."*[120]

This cost / price disparity has reportedly resulted in SAF providers "struggling to find buyers in the industry" for SAF, "due to high production costs and limited supply."[121] Currently, airlines using SAF at SFO pay about $1.00 to $1.25 per gallon more for neat SAF compared to CJF[122] -- after taking into account government subsidies through the LCFS and RFS2 programs (see 8.2). Notably, this does not seem to diminish airline demand for SAF at SFO, at least in the current demonstration scale of deployment. They understand that, while SAF is a premium jet fuel that costs more, it delivers important hard-to-find in-sector GHG reductions that provide both societal and corporate benefits.

Still, fuel cost premiums have a big impact on airlines purchasing large volumes of jet fuel, so the higher price of SAF is a big barrier to scaled-up use. For example, Alaska Airlines consumes about 500 million gallons of CJF each year. According to company management, even the smallest incremental cost per

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[118] Air Transport Acton Group, "Aviation's Energy Transition, FACT SHEET #5," May 2020, http://www.caafi.org/resources/pdf/FACT_SHEET_5_Aviations_Energy_Transition.pdf.

[119] International Council on Clean Transportation, "Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities," Briefing paper, January 2019, https://theicct.org/sites/default/files/publications/Alternative_fuel_aviation_briefing_20190109.pdf.

[120] Renewable Energy Group, Inc., comments submitted to CARB regarding addition of AJF to the LCFS, May 2, 2017, https://ww3.arb.ca.gov/fuels/lcfs/workshops/05022017_reg.pdf

[121] Airport-Technology.com, "Renewable jet fuels : how to handle the heavy costs," August 21, 2018, https://www.airport-technology.com/features/renewable-jet-fuels-how-to-handle-the-heavy-costs/.

[122] Personal communication from Erin Cooke and John Galloway (Environmental Dept at SFO) to GNA, telephone interview, August 12, 2020.

gallon has "tremendous" negative impact on the airline's bottom line. To help lower future costs and prices, Alaska continues to search for alternative ways and feedstocks to produce SAF.[123]

SAF is especially expensive and cost-prohibitive for airlines operating outside of carbon markets like the low-carbon fuel programs in California and Oregon (if even available). This is similar to the case of ground transportation fleets outside these states trying to purchase RD. As to be expected, major airports in California – specifically SFO and LAX – are leading the way to demonstrate SAF blends in commercial aircraft, thanks to significant "market pull" that emerged when CARB modified its LCFS program to make alternative jet fuel a credit generator, effective in 2019. The federal Renewable Fuel Standard also helps buy down the costs of producing and purchasing SAF, albeit to a lesser degree. The following summarizes how California's LCFS program combines with the Federal RFS to help reduce SAF costs to end-user airlines.

8.2. Monetization of SAF Benefits by Key Government Programs

State Low Carbon Fuel Programs

California's LCFS and its counterpart, Oregon's "Clean Fuels Program," are the only two state programs that have (to date) monetized SAF's GHG-reduction benefits. Both programs have enabled alternative jet fuel to generate sellable credits when dispensed into aircraft within their state boundaries. SAF Producers pass some of these credit values on to their airline customers. This makes it possible for airlines servicing California and Oregon airports to purchase SAF at a lower cost, although not on price parity with CJF. Further information is provided below about how SAF is monetized under the California LCFS program. Oregon's Clean Fuels program uses a similar structure.

[123] Statement by Alaska Airlines executive, "Bridge to Biofuels: Renewable Biofuels and Biochemicals from Poplar Trees – Part 3 – Biojet Fuel, https://www.youtube.com/watch?v=pLye9duz1nU.

Effective in 2019, CARB added "alternative jet fuel" (AJF, used synonymously with SAF) as a credit-generating option in the LCFS. Figure 6 provides CARB's "benchmarks" for the CI values of fuels to be substituted for CJF under the LCFS, for years 2019 to 2030 (and beyond). To generate LCFS credits each year, an AJF's CI value must be below the corresponding benchmark. Overall, from 2019 to 2030 the CI benchmark curve declines by 10 percent.

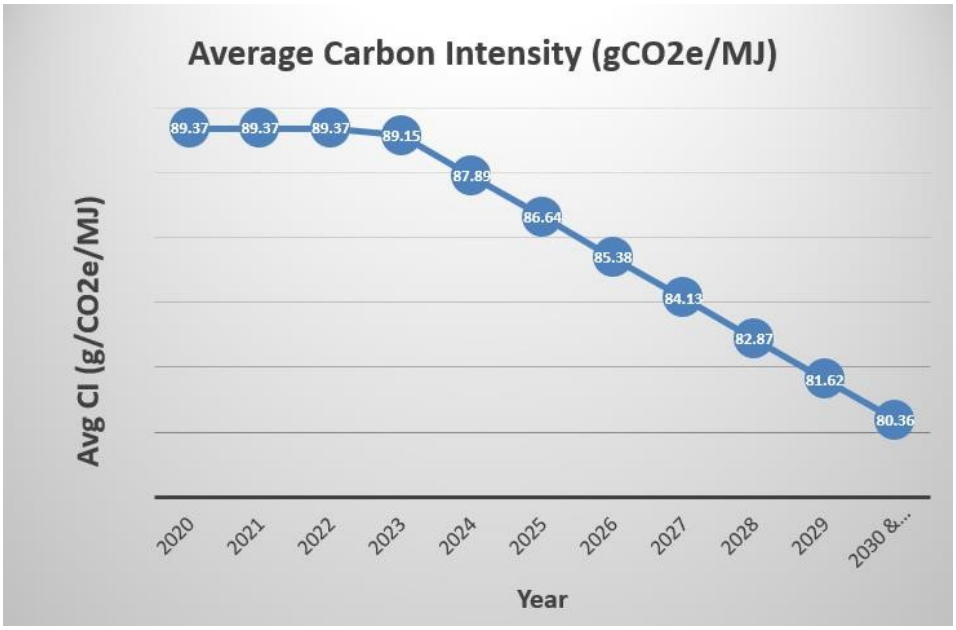

Figure 6. CARB's LCFS CI "benchmark" curve applicable to SAF credit generation

Upon this change, staff noted that SAF presents "major opportunity to generate LCFS credits." They estimated significant per-gallon values for SAF in the LCFS market as function of three feedstock types, all using a HEFA pathway. Table 16 provides CARB staff initial estimates[124] for the CI ratings and LCFS trading values of SAF made from animal tallow and two other feedstocks expected to become prominent for making SAF.

Table 16. CARB's assumptions for LCFS value of Alternative Jet Fuels by key feedstock

Feedstock	Assumed CI (gCO2e/MJ)	Reduction from 2020 Baseline (CI=89.37)	LCFS Value* ($/gallon)
Soybean	55.22	38%	$0.75
Tallow	37.61	58%	$1.14
Used Cooking Oil	22.40	75%	$1.47
Based on credit price of $190 / MT. (Prices currently range from about $188 to $210 / MT) *CARB assumes an energy density for AJFs of 126.37 MJ/gal* *CARB assumes an EER value of 1.0 for AJFs (i.e., same efficiency as conventional jet fuel)*			

[124] James Duffy, CARB, "Low Carbon Fuel Standard," Presentation at ACT Expo "Greening Aviation" session, April 26, 2019.

Notably, these were snapshots from early 2019; LCFS values are dynamic, depending on the value of LCFS credits, CI values of each pathway, and other factors. As further described below, the per-gallon LCFS credits for SAF can be significantly higher than shown in this table. However, the per-gallon LCFS value for SAF is not as high as RD used in ground transportation, even though they are currently co-produced using the same HEFA process and feedstocks. This important issue is discussed further in Section 8.3.

Federal Renewable Fuel Standard

At the federal level, EPA administers the Renewable Fuel Standard 2 program (RFS2), which also monetizes the societal benefits of renewable fuels, including SAF. Similar to California LCFS and Oregon Clean Fuels Program, jet fuel producers participate in RFS2 voluntarily – CJF producers are not subject to renewable "obligations." Producers (or importers) of "renewable jet fuel" (essentially SAF) can generate valuable "Renewable Identification Number" (RIN)[125] credits, provided their fuel meets applicable RFS2 definitions and EPA has approved a "D code" for it.

To date, EPA has approved multiple pathways that can be used to produce SAF and generate RINs. Notably, these pathways can also be used to produce RD and/or biodiesel for transportation use. Texmark-Neste's pathway (D-4 RIN), which EPA approved on September 23, 2019, appears to be the pathway for Neste's SAF now being provided to airlines at SFO. Under this pathway, Neste sells RD it produces in Finland (HEFA pathway) to Texmark Chemicals, Inc. Texmark fractionates this RD at its Texas facility, thereby producing SAF / RJF with entirely new D-code 4 RINs.[126]

As discussed below -- and similar to the case with LCFS credits -- under the current RFS structure the per-gallon value of HEFA-pathway SAF is worth about 6 percent less than RD used for ground transportation.

8.3. Current Market Value vs Renewable Diesel for Ground Transportation

Note: the discussion below provides an overview of key issues and implications associated with the relative market values of SAF versus RD. This topic has been extensively debated within aviation fuel stakeholders. For a comprehensive discussion that includes detailed perspectives from major biofuel producers – with CARB staff responses – see CARB's Final Statement of Reasons for the 2018 amendments to the LCFS that introduced alternative jet fuel into the program.[127]

Understanding the differential costs and values of SAF versus RD begins with the feedstock and refining biochemistry of these two co-products. The currently dominant HEFA production method co-produces a mixture of renewable long-chain paraffinic hydrocarbons in the boiling ranges of both jet and diesel fuel. RD is the dominant yield, with lighter chains like SAF being a subdominant coproduct. Based on limited

[125] RINs are tradeable commodities that represent gallons of renewable fuel produced and blended into U.S. gasoline and diesel fuels. One RIN is equivalent to one gallon of ethanol. Renewable fuels with more energy content per volumetric unit can generate more than 1.0 RIN per gallon. SAF is a D4 code RIN (defined to achieve least a 50 percent GHG reduction versus CJF) that generates 1.6 RINs per gallon.
[126] U.S. EPA, letter to Texmak Chemicals Inc., https://www.epa.gov/sites/production/files/2019-10/documents/texmark-chem-neste-us-deter-ltr-2019-09-23.pdf.
[127] CARB, https://ww3.arb.ca.gov/regact/2018/lcfs18/fsorlcfs.pdf.

public information, under current market conditions the SAF yield using a typical HEFA production pathway ranges from 10 to 15 percent of the total biofuel produced.[128] The refining process can be modified to increase SAF's relative yield, but there are tradeoffs with cost. Equally important, the total biofuel yield and/or its market value may be significantly reduced.

In addition to these production-related cost tradeoffs, a related disincentive to increasing the SAF yield is that a gallon of SAF has less value in today's market than a gallon of RD. Figure 7 compares the per-gallon market values of RD (left) and SAF (right) under current market dynamics, after taking into account combinable monies afforded under California's LCFS and Cap & Trade programs, plus the D4 RINs earned under the federal RFS2 program.

As can be seen from the stacked bar graph, SAF is currently worth roughly $0.42 per gallon (~8 percent) less than RD. This adds to the disadvantage that SAF is currently more expensive to produce than RD, due to additional production steps in the HEFA process. Finally, the renewable fuel produced in the jet fuel boiling range (i.e. upgradable to SAF) may be more valuable blending in with RD than it would be as SAF. The end result, according to an analysis by Stillwater Associates, is that "airlines would need to pay at least $0.42 more per gallon" for SAF compared to CJF "in order to pull the RD from the diesel pool into the jet fuel pool." Consequently, airlines that seek to reduce their carbon footprint using SAF blends "add about 25% to the cost of their fuel," which constitutes roughly 22 to 25 percent of each airline's operational expenses. Stillwater notes that under this current economic reality, "Any airline trying to

[128] International Council on Clean Transportation, "Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities," Briefing paper, January 2019, https://theicct.org/sites/default/files/publications/Alternative_fuel_aviation_briefing_20190109.pdf.

reduce its carbon footprint by using (SAF) would, therefore, be at a considerable competitive cost disadvantage to another airline that does not use (SAF)." [129]

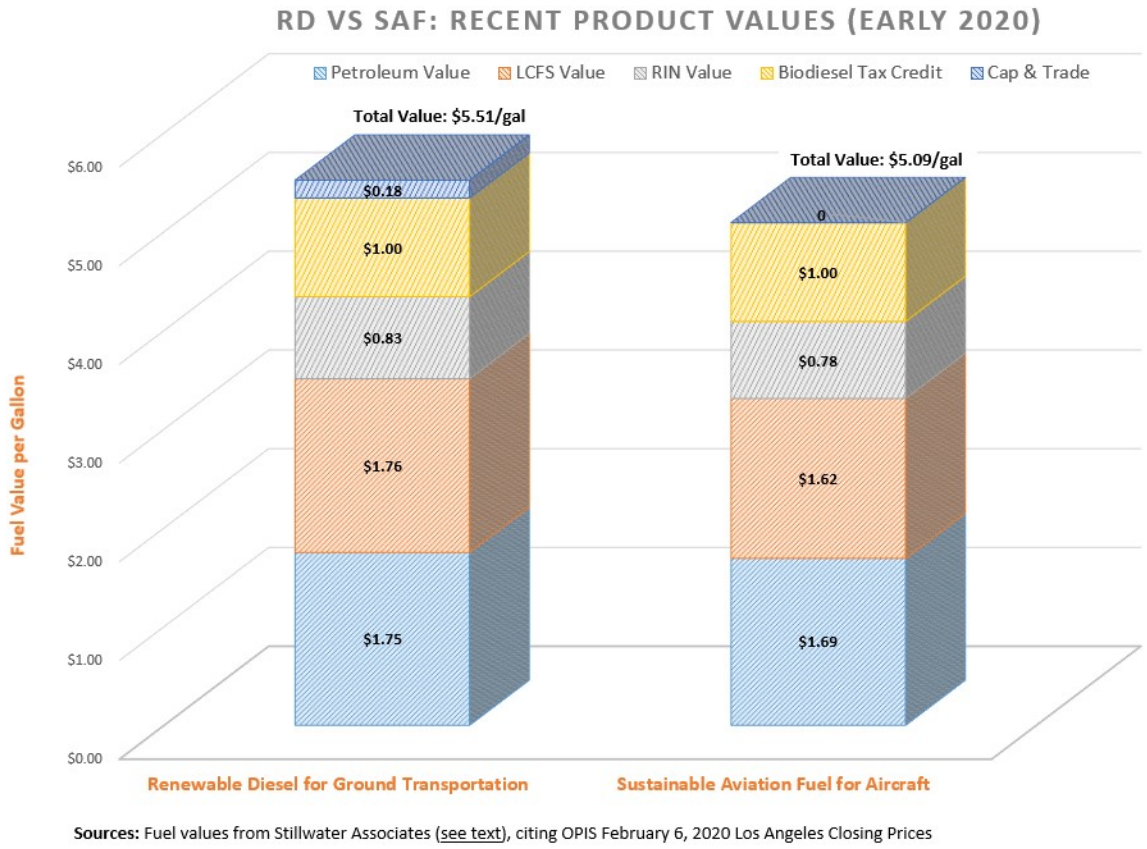

Figure 7. Recent Product Values for Renewable Diesel (left) vs SAF (right)

Stillwater Associates describes the economic dynamics of why SAF is less valuable, as follows:

> *". . . . RD is worth more than (SAF) because RD is assigned a higher energy density which is used to calculate RINs and LCFS credits per gallon of fuel. (RD generates 1.7 RINs per gallon and (SAF) earns 1.6 RINs per gallon. For calculating LCFS credit value, CARB assigns RD an energy density of 129.65 MJ/gal and (SAF) an energy density of 126.37 MJ/gal.) The cost to purchase allowances for California's Carbon Cap and Trade (C&T) Program is also much lower for RD than its petroleum-based diesel counterpart (ULSD), so RD has additional value relative to diesel in the market."* [130]

Notably, when asked about this Stillwater Associates analysis, the two leading RD / SAF producers both confirmed that Stillwater's figures are "directionally correct" or "essentially accurate."

[129] Stillwater Associates, "Airlines want Renewable Jet Fuel, but Renewable Diesel is Stealing their Thunder," February 6, 2020, https://stillwaterassociates.com/airlines-want-renewable-jet-fuel-but-renewable-diesel-is-stealing-their-thunder/?cn-reloaded=1.
[130] Ibid.

The disadvantage regarding how SAF is treated under California's Cap and Trade Program is further described and quantified by a representative for the SAF Producers Group – with an update from SFO's Director of Sustainability – as follows:

> *Under California's Cap-and-Trade program, on-road diesel fuel triggers an allowance obligation when the fuel is sold or transferred over the rack. The obligated party incurs a cost per gallon of diesel fuel received over the rack that is based on the price of the Cap-and-Trade allowances that must be purchased and retired for that fuel. This cost is estimated and reported by a petroleum market service (OPIS), and is typically referred to as the Cap at the Rack Cost. For 2020, the Cap at the Rack Cost has been estimated by OPIS and other sources as in the range of $0.25 per gallon.*[131]

A related barrier is summarized by the SAF Producer Group:

> *SAF is also disadvantaged from a blending and logistics standpoint in that conventional jet simply flows through the system to airports whereas SAF must be trucked or railed to a terminal for blending and certification.*[132]

There are other related issues that significantly contribute to SAF's less-compelling economic proposition for biofuel producers. CJF is currently allowed to contain up to 3,000 ppm of sulfur, although 550 to 750 ppm is typical.[133] Today's ultra-low diesel fuel (ULSD) for ground transportation is capped at just 15 ppm. The FAA described this additional cost barrier in a 2009 SAF "feasibility report" as follows:

> *Under current U.S. and European regulations for automotive fuels, the exceptionally low sulfur and aromatic content of these fuels yields a higher price premium for ground applications. So long as the specification for jet fuel allows sulfur content of the order of 100 ppm or higher, it is unlikely that aviation uses of (ultra-low-sulfur) alternative fuels will be cost competitive with automotive applications.*[134]

Additionally, all renewable transportation fuels – including SAF and RD-- are disadvantaged by the current low market price of conventional (petroleum) fuels, with crude oil prices that hover around $40 per barrel in Q4 of 2020. Prices were as low as $20 per barrel in Q1 of 2020.[135]

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[131] Personal communication to GNA from Erin Cooke of SFO, citing an updated version of a letter submitted to CARB by the SAF Producers Group, September 2020.

[132] Letter to CARB from Graham Noyes (Noyes Law Corporation), representing the "SAF Producer Group," September 21, 2020, provided to GNA from a leading SAF producer.

[133] Atmospheric Chemistry and Physics (multiple authors), "Impacts of aviation fuel sulfur content on climate and human health," 2016, https://acp.copernicus.org/articles/16/10521/2016/acp-16-10521-2016.pdf.

[134] Federal Aviation Administration Technical Report: Near Term Feasiblity of Alternative Jet Fuels, James I. Hileman, MIT, David S. Ortiz, RAND, James T. Bartis, RAND Hsin Min Wong, MIT, Pearl E. Donohoo, MIT, Malcolm A. Weiss, MIT, and Ian A. Waitz, MIT; 2009, https://ascent.aero/documents/2020/01/near-term-feasibility-of-alternative-jet-fuels.pdf/.

[135] U.S. Energy Information Administration, https://www.eia.gov/outlooks/steo/report/prices.php.

9. Future Landscape: Opportunities and Barriers for Wider SAF Use

9.1. Estimated SAF Volumes Needed for Market Viability and to Meet GHG Goals

Various stakeholders have assessed the volume of SAF that will be needed over the near- to long-term to achieve a commercially stable market that can meet various state, national and international goals to reduce GHG emissions in the aviation sector. Citing various aviation industry sources and stakeholders, analysis performed by NREL in 2016 indicated that "a viable market for biofuels can be maintained when as little as 1% of world jet fuel supply is substituted by a biofuel . . . with aggregation of higher blending ratio for future years, such as 25% by 2020, 30% by 2030, and 50% by 2040." The NREL report estimated that biofuel (SAF) could meet 35 to 100 percent of global jet fuel demand by 2050.[136]

CAAFI has played a key role in bringing together stakeholders to assess the future supply of SAF for U.S. commercial aviation, specifically to meet goals set under CORSIA and other initiatives to reduce GHG emissions. For example, at its General Meeting in December 2018, CAAFI assembled an expert panel to discuss "Potential Future Scenarios for Aviation Biofuel." The focus of the panel was on 1) the possibility of producing 1 billion gallons of SAF "in the near term," and displacing "30% of the jet fuel market (6 billion gallons) with biofuels" by the 2030 or 2040 timeframes.

Key conclusions reached by various government and academic experts include the following (**emphasis added**):

- "**100% of 2050 jet fuel demand could be satisfied by domestically produced aviation biofuels**. But there may be decreasing marginal climate benefits of large fuel volumes." [137]
- "Satisfying 100% of US jet fuel demand **requires a 45% expansion in cultivated crop area**." [138]
- "**200 million to 1 billion gallons per year** of alternative jet fuel production **are possible by 2030 given multiple incentives and a favorable investment climate**"[139]
- "**Reaching a billion gallons of (SAF)** using only (HEFA and two other promising production pathways) **by 2030 will require concerted policy support and incentives**."[140]
- "Analysis suggests **6 billion gallons of aviation biofuel by 2030 (are) possible with aggressive assumptions**."[141]

[136] National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy16osti/66291.pdf.
[137] Dr. Mark Staples, MIT, Long-term CO2 emissions reduction potential of aviation biofuels in the US," presentation at CAAFI General Meeting, December 5, 2018, http://www.caafi.org/resources/pdf/2.3_Future_Production.pdf.
[138] Ibid.
[139] Lewis, K., E. Newes, S. Peterson, M. Pearlson, E. Lawless, K. Brandt, D. Camenzind, et al. "U.S. Alternative Jet Fuel Deployment Scenario Analyses Identifying Key Drivers and Geospatial Patterns for the First Billion Gallons." Biofuels, Bioproducts and Biorefining, Accepted 2018.
[140] Kristin C. Lewis, Ph.D., Department of Transportation Volpe National Transportation Systems Center, presentation at the CAAFI Biennial General Meeting, "U.S. Alternative Jet Fuel Deployment Scenario Analyses Identifying Key Drivers and Geospatial Patterns for the First Billion Gallons," December 2018, http://www.caafi.org/resources/pdf/2.3_Future_Production.pdf.
[141] Newes, E., Jeongwoo H., and S. Peterson. "Potential Avenues for Significant Biofuels Penetration in the U.S. Aviation Market." Golden, CO: National Renewable Energy Laboratory, 2017. http://www.nrel.gov/docs/fy17osti/67482.

- "**Construction/build out capabilities and development of the feedstock market are key bottlenecks** in the initial years." [142]
- "**Displacement of jet fuel by 30% with biofuels by 2030 is possible**, but several factors related to **policy design**—in the absence of high oil prices or policy uncertainty— contribute to the timing and magnitude of aviation biofuels production." [143]
- "Although the feedstock price and availability and energy intensity of the process are significant barriers, **biomass-derived jet fuel has the potential to replace a significant portion of conventional jet fuel required to meet commercial and military demand**."[144]

A 2019 SAF briefing report by ICCT presented a less optimistic outlook for SAF, implying likelihood that the aviation sector will get lower priority for biofuel feedstock compared to RD for ground transportation. ICCT projected the percentages of the world's low-carbon biomass "that could be supplied" to produce renewable transportation fuels and other bioenergy by 2050. ICCT concluded that – due to SAF's relatively unfavorable economics (described above) – the aviation sector will "likely" draw only about nine percent of the total available bioenergy, compared to roughly 40 percent for non-electric road transportation (even under an "aggressive vehicle electrification" scenario). ICCT summarized that "realistically" these market and supply dynamics for SAF make it unlikely that the aviation industry will "significantly decarbonize aviation fuel until well beyond 2050."[145] This assessment does not necessarily account for addition of new incentives for SAF use and production, as might be justified by its full suite of societal benefits. For example, one major SAF producer points out SAF benefits such as reduced emissions of black carbon and total ultra-fine particles in contrails[146] -- which, if fully valued / monetized, could significantly increase market pull.[147]

9.2. Primary Impediments to Rapid Growth and Adoption at Bay Area Airports

As described throughout this report – and corroborated by leading SAF advocate CAAFI[148] – three related issues are the primary impediments to rapid scale-up of SAF production for widescale use in U.S. commercial aviation (i.e., 1 to 6 billion gallons per year) are:

- Incremental production cost / higher price than CJF

[142] Newes, E., Jeongwoo H., and S. Peterson. "Potential Avenues for Significant Biofuels Penetration in the U.S. Aviation Market." Golden, CO: National Renewable Energy Laboratory, 2017. http://www.nrel.gov/docs/fy17osti/67482.
[143] Ibid.
[144] Wei-Cheng Wang, Ling Tao, Jennifer Markham, Yanan Zhang, Eric Tan, Liaw Batan, Ethan Warner, and Mary Biddy, National Renewable Energy Laboratory, "Review of Biojet Fuel Conversion Technologies," July 2016, https://www.nrel.gov/docs/fy16osti/66291.pdf.
[145] International Council for Clean Transportation, "Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities," January 2019, https://theicct.org/sites/default/files/publications/Alternative_fuel_aviation_briefing_20190109.pdf.
[146] See for example 1) Nature.com, "Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions," October 2018, https://www.nature.com/articles/s41612-018-0046-4; and 2) ACS Publications, "Comparison of Particle Number Emissions from In-Flight Aircraft Fueled with Jet A1, JP-5 and an Alcohol-to-Jet Fuel Blend, https://pubs.acs.org/doi/abs/10.1021/acs.energyfuels.0c00260#.
[147] Personal communication to GNA from a major SAF producer, September 2020.
[148] Steve Csonka, Executive Director, Commercial Aviation Alternative Fuels Initiative, "Sustainable Aviation Fuel (SAF): Aviation needs SAF . . . SAF needs your technologies," key note speech, tcbiomass*plus*2019 conference, October 9, 2019, https://www.gti.energy/wp-content/uploads/2019/10/47-tcbiomass2019-Presentation-Steve-Csonka.pdf.

- Competition from renewable diesel for ground transportation
- Unfavorable policy environment to widely implement SAF blends as a GHG-reduction strategy

A fourth impediment to wide-scale use of SAF in commercial aviation is the current COVID-19 pandemic. This has dramatically reduced worldwide air travel and CJF consumption, including in the Bay Area, which is a major North American deployment site for SAF. Notably, this may not be a factor at current demonstration scale; many of the SAF offtake agreements summarized above were announced since breakout of the COVID-19 pandemic.

A fifth impediment is the potential for California to be "outcompeted" for limited available SAF supplies, because other nations (or even regions of the U.S.) now offer more favorable incentives and/or policies, or may offer them in the near-term future. While California currently has the big draw – its Low Carbon Fuel Standard -- other nations (such as those in the European Union) have already adopted policies that could "outpace" California as a market draw for SAF. This could make it increasingly difficult for airlines serving the Bay Area to procure large volumes of the fuel.

Further discussion is provided below for each of these four impediments, including actions that are being taken to address barriers and accelerate SAF adoption.

Incremental Production Cost / Higher Price Than CJF

As described in the previous section, the current higher cost to produce SAF (relative to CJF), in tandem with its low market value in the aviation sector (relative to RD's value for ground transportation), combine to present a formidable economic barrier to SAF becoming a major aviation fuel. This is the case even at California airports, where airlines can take advantage of low-carbon credits to reduce the price of neat SAF by more than $1 per gallon. As summarized in a 2016 report for the National Academy of Sciences, "commercial aviation is a highly competitive industry" that makes cost issues especially challenging.[149]

According to ICCT, in the currently dominant HEFA production process "approximately 65% of levelized HEFA costs are the feedstock . . . and these costs are unlikely to come down over time." Also, the HEFA process requires large volumes of hydrogen, which is the second-most-expensive cost when using this SAF production pathway. Moreover, hydrogen for the HEFA process is commonly made through steam methane reforming of pipeline natural gas; this process can be carbon intensive and lower the value of LCFS credits for SAF (i.e., it increases the SAF production pathway's CI value). ICCT notes that more-advanced production pathways of the future may hold the best promise for achieving significant cost

[149] National Academies of Sciences, Engineering, and Medicine 2016. "Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions." Washington, DC: The National Academies Press. https://doi.org/10.17226/23490.

reductions, but "the high and uncertain costs of first-of-a-kind plants for advanced technologies compared with HEFA are deterring investments." [150]

The Air Transport Action Group (ATAG) cites "growing policy progress" as being they key for significant SAF price reductions for end users. ATAG notes that the incremental cost of SAF is coming down due to the many emerging very large offtake purchase agreements, such as those United Airlines is executing:

> *"Global policy developments are making SAF a more important strategic consideration for aircraft operators and we have already seen some massive forward purchase agreements from airlines, with most able to negotiate SAF at only slightly higher cost than traditional jet fuel."*[151]

There also appears to be some uncertainty about how tightening environmental requirements that favor SAF use will affect future demand of SAF, and therefore its pricing. For example, FedEx has noted that CORSIA obligations to achieve offsets of aviation-related GHG emissions – which start in 2021 and can be reduced by SAF use – will cause prices to spike as respective settlement dates approach.[152] However, other stakeholders have noted that such a scenario is extremely unlikely, given the nature and limitations of CORSIA offsets.

Competition Between SAF for Aviation and RD for Ground Transportation

In the current situation of early commercial deployments, U.S. airlines have generally been able to procure sufficient supplies of SAF blends to launch new carbon-reduction programs and advance corporate sustainability goals. Although it appears that airlines currently purchase SAF as a premium fuel, it offers them a cost effective means to achieve valuable GHG reductions. Existing producers like Neste, World Energy -- and emerging producers like Fulcrum, Red Rock and others -- are building major new production capacity that will help reduce SAF costs.

Notwithstanding all this progress for SAF, it has been noted that scaling up SAF production to large volumes for widescale use in the aviation sector may be hindered by competition with RD's production and use as a ground transportation fuel. The emerging question pertains to how rising demand for SAF will impact already strong (and growing) use of RD for ground transportation uses, and vice versa. Because the same companies generally produce both types of biofuels – from the same feedstocks – it appears that important competition is emerging between these key end-use sectors to obtain as much RD or SAF as possible. The specific issue is that RD for ground transportation has key advantages, for both fuel production and end use.

[150] International Council for Clean Transportation, "Long-term aviation fuel decarbonization: Progress, roadblocks, and policy opportunities," January 2019, https://theicct.org/sites/default/files/publications/Alternative_fuel_aviation_briefing_20190109.pdf.
[151] Air Transport Action Group (ATAG), "Beginner's Guide to Sustainable Aviation Fuel," Edition 3, November 2017, https://aviationbenefits.org/media/166152/beginners-guide-to-saf_web.pdf.
[152] Allison Bird, FedEx, "Championing Sustainability in Air Freight," Presentation at ACT Expo "Greening Aviation" session, April 26, 2019.

The Atlantic Council recently evaluated "a menu of policy options for establishing a viable SAF sector in the United States." The report summarized why SAF does not yet compete on a level playing field with RD (and other on-road biofuels), as follows:

> *Currently, SAF is largely included as an add-on to existing renewable fuels policies that focus on addressing emissions from ground transportation. In this context, SAF is challenged to compete with other renewable fuels. This is partly due to its relatively recent emergence compared with other renewable fuels, the fact that it sells into a voluntary (rather than obligated) aviation fuel market, and that it receives fewer incentives.*[153]

In 2019 testimony to Congress, Neste's vice president used the "relative value" explanation to put "SAF versus RD competition" into the fuel producer's perspective:

> *"Unfortunately, the existing policy landscape does not adequately incentivize SAF deployment. In fact, there are both structural and policy disincentives to the production of SAF versus on-road renewable fuels. Policies like the Renewable Fuel Standard (RFS) were designed for ground transportation fuels, and while SAF qualifies under many of these policies, SAF generally generates fewer credits. For example, under the RFS, SAF receives 1.6 RINs per gallon while similar renewable diesel receives 1.7. And while states like California and Oregon have also sought to allow SAF to participate on an opt-in, credit-generating basis in low carbon fuel standards, SAF also generates fewer credits under these programs. Diesel historically commands a higher spot price than jet, further disincentivizing jet replacements as compared to diesel replacements. In sum, the significant opportunity costs for renewable fuel producers to produce SAF versus similar ground transportation fuel applications has been a headwind for the SAF industry."* [154]

Renewable Energy Group, Inc. (REG) – a major domestic producer of RD that seems likely to also enter the SAF market – noted the following to CARB in 2017:

> *"If producers are not equally incentivized to produce on road transportation fuel and (SAF), they will opt for the fuel which requires less operating expenses and inherently has greater credit generation potential. Furthermore, we believe that aircraft fuel emissions weigh more than on- road transportation fuel emissions (~2x) per a recent Biofuels Digest article and believe CARB should weigh the credit impact accordingly."*[155]

Reportedly, this has become a key concern for CARB, now that SAF has been added into the LCFS. Several interviewed stakeholders indicated that CARB is exploring ways to give greater prioritization for SAF, given the relatively few decarbonization options that exist for the aviation sector. CARB has convened high-level

[153] Atlantic Council Global Energy Center, "Sustainable Aviation Fuel Policy in the United States: A Pragmatic Way Forward," by Fred Ghatala, April 2020, downloaded at https://www.atlanticcouncil.org/in-depth-research-reports/report/sustainable-aviation-fuel-policy-united-states/.
[154] Neste Corporation, Statement of Jeremy Baines, President Neste US, testimony to U.S. Congress, October 23, 2019, https://www.congress.gov/116/meeting/house/110124/witnesses/HHRG-116-IF18-Wstate-BainesJ-20191023.pdf.
[155] REG, comments submitted to CARB, May 2017, https://ww3.arb.ca.gov/fuels/lcfs/workshops/05022017_reg.pdf.

government-industry meetings to work through optimal ways that can ensure that both aviation and ground transportation markets get sufficient access to feedstocks and the low-carbon liquid fuels ultimately produced, to maximize GHG-reduction benefits.[156]

In mid-2020 interviews with several top biofuel producers, they readily recognized this disparity in value, but tended to downplay "competition" between RD and SAF. They indicate there is enough production capacity and resources for both fuels, and they intend to meet demand of their customers in both the aviation and ground transportation sectors. They cite production synergy between SAF and RD, and that they do not intend to "cannibalize" production of either fuel over the other. Moreover, many government and/or industrial studies exist that support these basic findings.[157]

They do acknowledge, however, that producers will choose to maximize the yield of one biofuel over the other depending on complex market dynamics. These entail many factors beyond cost and price, including their desire to establish and maintain strong long-term relationships with key customers in both sectors. They also note that "the relative urgency of reducing GHG emissions for the respective transportation sectors will come into play."[158] This factor seems to increasingly favor greater production yield for the SAF co-product.

Still, these dynamics are important factors in their current market decisions. For example, it appears to be the key reason why major existing and expected RD and SAF producers stress their "capacity" to produce SAF, rather than actual existing (or definitively planned) SAF production. This situation is fluid, and can change with improved SAF policies. As one of the major producers explained to GNA,

> *"We often note in our SAF policy advocacy that our announcements are related to capacity, and that ultimate SAF volumes will rely on eliminating the existing policy disincentives to SAF production vs. on-road production."*

As the world's largest producer of biomass-based biofuels (primarily RD, to date), Neste appears to be stepping up plans to commit emerging new production capacity to favor greater production of SAF (co-produce a higher relative yield). Neste is increasingly echoing aviation stakeholders by noting that there is greater need to use liquid renewable fuels for jets than ground vehicles, and demand is likely to last farther into the future for aviation. Noting that aviation-related GHG emissions "could triple by 2050," Neste U.S.'s president told Congress that

> *. . . .climate policy for aviation must be built around technologically feasible developments in the industry, and there is widespread consensus that while aircraft can continue to improve efficiency through use of advanced materials and more efficient engines, the vast majority of use cases (i.e.*

[156] Personal communications to GNA during interviews with representatives from the California Energy Commission and various SAF producers, mid-2020.
[157] Personal communication to GNA from Erin Cooke of SFO, September 2020.
[158] Based on a mix of personal communications to GNA from Neste, World Energy, and REG, August 2020.

medium- and long-haul and larger short-haul jets) will require liquid hydrocarbon fuels through at least 2050."[159]

The airline industry has taken notice of this competition between RD for ground use versus SAF for jets. For example, the National Air Transportation Association (representing more than 2,600 U.S. aviation-related businesses). In mid-2019, NATA's Chief Operating Officer publicly stated that the U.S. aviation industry seeks to become North America's dominant end user of renewable hydrocarbon diesel fuels (i.e., inclusive of both RD and RJF). Essentially, he stated that U.S. commercial and passenger airlines intend to outcompete ground transportation markets (goods movement trucking, in particular) to "soak up all available" renewable diesel fuels.[160] Notably, in the current policy environment and given the relative market values – plus the major drop off in air travel due to COVID-19 (see below) – market dynamics do not favor this happening.

At SFO, which is serving as a major North American testing grounds for SAF, officials consider this competition with RD to be a "primary barrier" for expanded SAF use in commercial aviation. They note that California's leadership in low-carbon fuels for ground transportation has been important and commendable, but the aviation sector has higher need for liquid fuels to decarbonize, and the "nascent" SAF industry is in a delicate stage that needs strong government support. They note it is time to "pivot" the competitive advantage towards SAF. Fortunately, there is promising movement, at various government levels, to get greater policy and monetary support (see below).[161]

Lack of Favorable Policies

The above two related problems – SAF's high incremental production cost and the potential for it to be "outcompeted" by RD (ground transportation) for favored production and use – have led SAF stakeholders to call for improved policies in the U.S. In effect, they argue that policy changes are needed to put greater value on rapidly decarbonizing the commercial aviation sector, because of the greater challenges and fewer options compared to ground transportation. In testimony to Congress, Neste further summarized this need for changes to SAF-related policies:

"Because of these significant structural and policy disincentives surrounding the production of SAF, the industry is unlikely to sufficiently scale and reach its full potential absent policy and price parity with ground transportation fuels. Given aviation's dearth of other options to decarbonize, the relative immaturity of the SAF industry, and the need to rapidly scale production, there is a

[159] Neste Corporation, Statement of Jeremy Baines, President, Neste US, to the House Energy and Commerce Committee, Subcommittee on the Environment and Climate Change Hearing on "Building a 100 Percent Clean Economy: Solutions for Planes, Trains and Everything Beyond Automobiles," October 23, 2019, https://docs.house.gov/meetings/IF/IF18/20191023/110124/HHRG-116-IF18-Wstate-BainesJ-20191023.pdf.
[160] Timothy Obitts, COO & General Counsel, National Air Transportation Association, "Green Aviation: Funding and Regulatory Drivers," Presentation at ACT Expo "Greening Aviation" session, April 26, 2019.
[161] Personal communication from Erin Cooke and John Galloway (Sustainability & Environmental Policy at SFO) to GNA, telephone interview, August 12, 2020.

compelling policy justification for additional, SAF-specific policies. Congress is uniquely positioned to develop these policies given its primacy over aviation."[162]

To expand SAF production and end use, Neste recommends that Congress adopt new polices that include "an economy wide price on carbon," improved support for "low-carbon liquid fuels," a long-term extension (20+ years) of the federal Renewable Fuel Standard, a higher RIN value for SAF, and more-favorable tax policies applicable to SAF. Some of these recommendations are now playing out at federal, state and local levels. For example, H.R. 6800: The Heroes Act is now under consideration by the House of Representatives. This bill includes COVID-19 relief payments for biofuel plants.[163] Additionally, the Moving Forward Act (H.R. 2) has significant grant and R&D provisions for SAF, although it lacks a long-term demand mechanism needed to scale the SAF industry (e.g., a tax credit).[164]

Airline industry supporter ATAG identifies a number of "positive policy options" that government agencies should pursue to "enable" wide-scale transition from CJF to SAF. These include[165]:

- Reduce commercial risk for SAF producers and users
- Ensure that aviation has access to the same alternative fuel policies as other transport modes
- Prioritize "aviation as a user of liquid alternative fuels" because "other transport modes have better options"
- Support research into / technology advancement for new SAF production processes and feedstocks
- Help alleviate costs and risks associated with constructing new production facilities
- Support ASTM's technical fuels approvals process
- Divert economic support from fossil jet fuel (CJF) towards SAF

As noted, SFO is taking a leading role in the Bay Area to identify and adopt new policies to help bring large SAF volumes to commercial aviation. This was codified first with SFO's 2017 adoption of an "Airport Policy on the Advancement of Sustainable Aviation Fuels." SFO's 2019 "feasibility" study on SAF identified a goal to obtain as much as 300 million neat gallons of SAF for its airline MOU partners, within about 10 years. The study prefaced the need for improved SAF policies by stating that "California's current policy environment favors the production of renewable diesel over SAF." Consequently, the SFO study identified the need for policy advocacy to correct "discrepancies" in the LCFS, i.e., the higher LCFS credit value afforded to RD compared to SAF. To that end, SFO has led a coalition of airlines, producers, NGOs and others in recommending higher ambitions for SAF through meetings with key California regulators and legislators, and is part of a coalition encouraging the same at the federal level in Washington, DC. Another key SFO focus that emerged was how to identify and implement various types of policies that support new

[162] Neste Corporation, Statement of Jeremy Baines, President Neste US, testimony to U.S. Congress, October 23, 2019, https://www.congress.gov/116/meeting/house/110124/witnesses/HHRG-116-IF18-Wstate-BainesJ-20191023.pdf.
[163] The HEROES Act (H.R. 6800) seeks a 45 cents per gallon payment for SAF and other qualified RFS-approved biofuels). However, it appears that RD will get the same subsidy, which would not necessarily improve SAF's ability to compete.
[164] See https://www.congress.gov/bill/116th-congress/house-bill/2/text.
[165] Air Transport Acton Group, "Aviation's Energy Transition, FACT SHEET #5," May 2020, http://www.caafi.org/resources/pdf/FACT_SHEET_5_Aviations_Energy_Transition.pdf.

funding mechanisms and sources.[166] SFO staff recently corroborated that improved or entirely new incentives for production and use will be important enablers to attain SFO's ambitious goals to deploy large SAF volumes over the next decade.

Other airports and their stakeholder airlines are taking similar actions. At Washington's SeaTac Airport, Alaska Airlines has joined with airport officials to identify "creative funding mechanisms" to address significant economic barriers associated with making SAF at scale. They note that developing new SAF production facilities can cost "hundreds of millions of dollars." [167] A study prepared by the Rocky Mountain Institute focused on SeaTac to further explore "innovative funding for SAF at U.S. airports." According to RMI, a variety of promising mechanisms are under development to make SAF more affordable; most of these involve fees and taxes on airlines and the general public when using aviation and peripheral services.[168]

COVID-19 Pandemic

The 2Out020 onslaught of the global COVID-19 pandemic has caused a major downturn in worldwide air travel. This has led to precipitous drops in the volume of CJF dispensed at airports in the U.S. and around the world. Even if the pandemic proves to be a temporary phenomenon, as long as it decreases air travel COVID-19 disincentivizes supply of / demand for low-carbon jet fuel. Thus, the pandemic could potentially deal a substantial blow to SAF progress at SFO, in its role as a major testing ground. While it is not possible to make meaningful estimates about how SAF growth in the Bay Area will ultimately be affected, the following discussion helps understand the directional impacts and challenges ahead.

Average CJF consumption in the U.S. for commercial aviation dropped from 4.3 million barrels per day in pre-pandemic 2020, down to just 1.0 million barrels per day by the start of Q2 2020 -- nearly an 80 percent reduction. Year-over-year drops were as high as 67 percent. The U.S. EIA notes that CJF consumption recovered somewhat during late spring and early summer of 2020, but it remains significantly reduced as of mid-summer 2020. In an August 2020 report about the impact of COVID-19 on air travel and energy consumption, EIA made the following distinction: "interior airports that cater primarily to domestic air travel have generally recovered faster than their typically coastal, more internationally oriented peers.[169]

[166] San Francisco International Airport, "Sustainable Aviation Fuel Feasibility Study," Final Report, September 2019, provided to GNA by SFO staff, July 2020. Additional inputs from this paragraph were communicated to GNA by Erin Cooke of SFO, September 2020.
[167] Statement by Alaska Airlines executive, "Bridge to Biofuels: Renewable Biofuels and Biochemicals from Poplar Trees – Part 3 – Biojet Fuel, https://www.youtube.com/watch?v=pLye9duz1nU.
[168] Craig Schiller, Rocky Mountain Institute, "Greening Aviation: Sustainability Takes Flight with Leading Airlines," Presentation at ACT Expo "Greening Aviation" session, April 26, 2019.
[169] U.S. Energy Information Administration, "COVID-19's impact on commercial jet fuel demand has been significant and uneven," August 7, 2020, https://www.eia.gov/todayinenergy/detail.php?id=44676.

In line with this point, California's three large "coastal, more internationally oriented" airports – SFO, LAX and San Diego -- have experienced prolonged, deep drops in commercial jet departures, which correlate directly with major reductions in dispensing of CJF at these airports. As shown in Figure 8, during the period of March 3 to April 21, 2020, jet aircraft departures declined by 67 percent at SFO, 56 percent at LAX, and 60 percent at San Diego. [170]

One official at LAX stated that the drop-off in flight departures and passenger throughput at major U.S. airports like LAX constitutes "the most steep and potentially sustained decline in air travel history." At SFO, it was noted that "United Airlines was hardest hit . . . in terms of raw decrease in flights," experiencing an overall departure decline of 87 percent."[171] At peak loss in April 2020, United – the largest airline serving SFO – reduced daily flights by six-fold, although this improved markedly by late summer. In

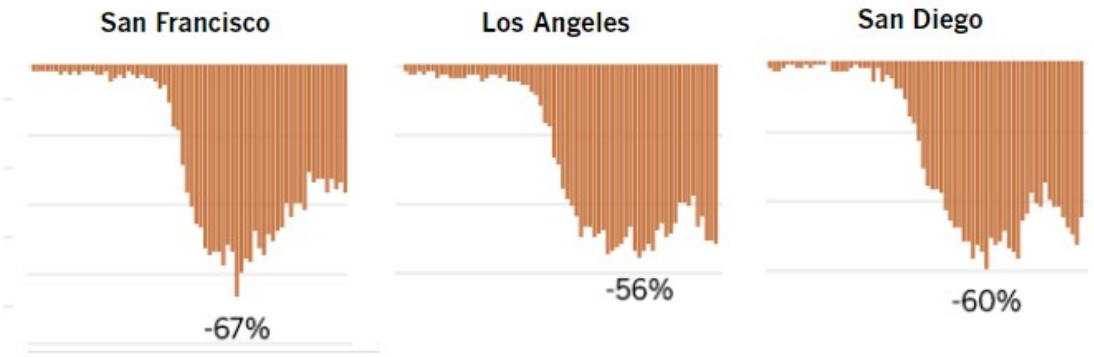

Figure 8 COVID-19-related reductions in commercial jet departures from March 3 to April 21, 2020

September 2020, United announced it will lay off more than 3,200 workers in the Bay Area, due to this pandemic-related collapse of air travel at SFO and other local airports.[172]

Commercial aviation industry association ATAG has acknowledged that COVID-19's impact on the world's aviation sector "is unprecedented in its severity" and scale. Effectively, ATAG noted that "it is much too early" to further define or quantify COVID-19's impact on longer-term GHG-reduction solutions like SAF under CORSIA.[173]

A spokesperson for the Low Carbon Fuels Coalition (representing most SAF producers) recently confirmed that the pandemic-caused downturn in commercial aviation "changes what the (SAF) growth curve looks

[170] Los Angeles Times, "California air travel plunged after the coronavirus. But by how much?", April 28, 2020, https://www.latimes.com/projects/california-coronavirus-travel-tracking-decline/.
[171] Ibid.
[172] SFGATE.com, "United to lay off 3,200 employees in the Bay Area, September 2, 2020, https://www.sfgate.com/travel/article/United-layoffs-SFO-15537360.php.
[173] ATAG, "Aviation Industry Welcomes Progress on CORSIA, Despite Global Emergency," press release, March 16, 2020, https://www.atag.org/component/news/?tmpl=pressrelease&view=pressrelease&id=119.

like, at least in the short term." But he emphasized that COVID-19 does not change the underlying fundamentals: people will continue to fly, and jets "will require liquid fuels for the foreseeable future." (Similar comments were recent made by the International Civil Aviation Organization, ICAO.) Emphasizing what has already been accomplished with SAF – multiple ASTM-approved production pathways for a drop-in CJF replacement fuel that is "truly sustainable" – the industry spokesman predicted that SAF will continue to generate "tremendous interest" with the commercial aviation sector. However, he implied there may be a temporary focal "shift" for SAF use towards the "business jet community" rather than "mainstream commercial aviation." He cited "more mobility" in this sector to regain pre-pandemic momentum of SAF deployments.[174] This appears to refer to private jet use operated by corporations, which may have less loss of jet travel demand and can better afford the price premium of SAF, especially in a period of relatively low demand. A good example of progress here is the recent announcements between Signature Flight Support and Neste for expanded SAF use by private aviation operators at SFO.[175]

Prior to the pandemic, the volume of CJF dispensed at SFO was expected to grow 20 to 40 percent over the next several years, reaching 1.2 to 1.4 billion gallons per year. Within about a decade, jet fuel use at SFO was expected to reach as high as 1.8 billion gallons per year. Pre-pandemic goals for neat SAF usage at SFO were set at 30 million gallons per year within 3 to 5 years (~2 percent of CJF use), and up to 300 million neat gallons per year within 5 to 10 years (~17 percent of CJF use).

Officials at SFO confirm that CJF usage at SFO is "way down" from this trajectory, due to COVID-19. As noted, United Airlines is the largest passenger airline at SFO -- and one of SFO's major SAF users. Notably, in this early phase of SAF adoption and usage, this does not appear to have reduced dispensing of SAF during the pandemic (e.g., at SFO). Of course, it remains to be determined how long COVID-19 will continue to dramatically reduce air travel at SFO (and other Bay Area airports). Given all these factors, it is not possible to predict how it will impact SFO's goal to obtain and dispense 300+ million gallons per year within about a decade.

Outlook on Progress to Overcome SAF Impediments

Notwithstanding these four related impediments and other market barriers for SAF, CAAFI notes that progress continues to accelerate. CAAFI's Executive Director notes that key collaborative efforts are being spearheaded by stakeholders that include "academia, national labs, entrepreneurs, big oil, fuel suppliers, pipeline companies, farmers and foresters, facilitators, aviation partners." Just prior to the pandemic

[174] Argus Media.com, "Q&A: LCFS key in post-COVID world," interview with Graham Noyes, Executive Director, Low Carbon Fuels Coalition, May 18, 2020, https://www.argusmedia.com/en/news/2106357-qa-lcfs-key-in-postcovid-world.
[175] See https://www.signatureflight.com/about/newsroom/details/2020/09/14/signature-flight-support-neste-and-netjets-establish-strategic-partnership-to-accelerate-the-adoption-of-sustainable-aviation-fuel-within-business-aviation

outbreak, he stated the following: "Given a policy framework that addresses the above, SAF is perhaps on the cusp of rapid expansion and replication."[176]

SAF producers intend to push forward on policy and technological fronts to help ensure both supply and demand for SAF continue to grow. They note that low-carbon SAF is a "must have" for commercial aviation to continue systematic decarbonization. SAF production has strong synergy with America's overall push for affordable, low-carbon biofuels across all energy sectors. Their message to stakeholder airports like SFO and agencies like BAAQMD is "SAF is here; stay the course and continue to lead."

[176] Steve Csonka, Executive Director, Commercial Aviation Alternative Fuels Initiative, "Sustainable Aviation Fuel (SAF): Aviation needs SAF . . . SAF needs your technologies," key note speech, tcbiomass*plus*2019 conference, October 9, 2019, https://www.gti.energy/wp-content/uploads/2019/10/47-tcbiomass2019-Presentation-Steve-Csonka.pdf.

10. Conclusions and Recommendations

10.1. Conclusions

Sustainable aviation fuel (SAF) is a drop-in replacement for conventional jet fuel (CJF) that can significantly reduce full-fuel-cycle GHG emissions from commercial aircraft. Neat SAF produced using the currently dominant "HEFA" process has a carbon intensity approximately 60 percent lower than baseline CJF, and future types of SAF will likely provide even greater GHG reduction benefits. SAF offers a cost-effective strategy to help decarbonize the world's commercial aviation sector, which currently contributes roughly two percent of combustion-related GHG emissions. Importantly, aviation presents greater challenges to decarbonize compared to surface (ground and water) transportation modes. Globally, SAF is emerging as the leading approach to further reduce in-sector GHG ("CO2e") emissions from commercial aviation.

Several million gallons of neat SAF are being used in the U.S. today (pre-COVID-19). The majority of this is being dispensed at two California airports -- Los Angeles International Airport (LAX) and San Francisco International Airport (SFO) -- which have become proving grounds for SAF use in North America. This is largely due to CARB's addition of SAF as a credit generator under the landmark LCFS program, beginning in 2019.

As described in this report, the GHG-reduction benefits of SAF are compelling, and it can also help improve local ambient air quality in the Bay Area. However, SAF is a premium jet fuel that is not yet available and affordable for wide-scale use. It currently costs at least two times as much to produce SAF compared to CJF, using the leading HEFA pathway and assuming a typical SAF yield of less than 15 percent, with RD being the dominant co-product. While the SAF yield can be increased up to 50 percent, this entails greater incremental cost and appears to compromise the market value of the overall biofuel products. Once produced, an equally important market barrier is that a gallon of neat SAF's current market value in California (the best-case scenario for SAF, due to the LCFS) is about eight percent lower than a gallon of RD, even though they are co-produced in the same HEFA process. Consequently, SAF producers are likely to continue gearing their biofuel production to maximize the yield of RD – the more valuable co-product – unless and until SAF becomes a more highly valued biofuel (monetarily, environmentally, or both).

While "offtake" agreements for SAF are confidential, it appears that this combination of higher cost / lower market value gets passed on to airlines that purchase SAF. Airlines using SAF at San Francisco International Airport (SFO) reportedly pay a premium of about $1.25 per gallon, under a best-case scenario that includes buydown of SAF costs using LCFS credits and RFS2 RIN values. Nonetheless, SAF has been in fairly strong demand in California -- specifically at SFO and LAX, the other North American test center for SAF. Roughly five million gallons of SAF blends were dispensed at these two airports in 2019 (just prior to the COVID-19 pandemic).

CAAFI and SAF producers indicate that at least 350 million gpy of neat SAF will be produced and available for dispensing at U.S. airports by the 2023 timeframe, with most of that likely to be dispended into aircraft serving SFO and LAX.

SAF Potential for Reducing GHG Emissions at Bay Area Airports

SFO in particular is a world leader in its commitments and actions to foster replacement of very large CJF volumes with SAF blends. The airport has been working with its airline partners for several years to test SAF blends and develop innovative ways to increase supply, while lowering costs. Under an MOU with airlines as well as SAF providers like Neste and World Energy, SFO has established the goal to procure and dispense enough neat SAF within three to five years to displace about two percent of its CJF use (30 million gallons per year), and 17 percent (300 million gallons per year) within about a decade. While this near-term goal may have been significantly set-back by the unprecedented COVID-19 pandemic, it is too soon to know the impact on meeting the longer term goal (a decade out).

Oakland International Airport (OAK) is the other Bay Area airport that has made progress to pilot test the benefits of SAF blends in commercial aviation. At least six million gallons per year of neat (100 percent) SAF have been committed to FedEx and Southwest Airlines for dispensing out of the OAK fuel farm facility. There appears to be significant synergy between SFO, OAK and SJC to share delivery and storage logistics for large-scale SAF usage in the Bay Area, as SFO has invited both airports to join its MOU and interdisciplinary Stakeholder Working Group (SWG) that meets each quarter to deliver work defined within its own Feasibility Study.

Over the longer term (about a decade), pre-pandemic estimates indicate that one to six billion gallons of neat SAF may be available for the U.S. commercial aviation sector. This will be supplied by a combination of key current SAF producers (primarily World Energy and Neste) as well as newcomers to SAF production such as Fulcrum BioEnergy, Red Rock Biofuels, Phillips 66 and others. The vast majority of this appears likely to be targeted for consumption in California, due to monetary incentives offered under the LCFS. A significant portion – perhaps half or more – may be used in the Bay Area at SFO and OAK, with potential synergy for use at SJC.

A high-level estimate was performed to roughly calculate the full-fuel-cycle GHG reductions that could be realized by widely using SAF blends at the three largest Bay Area airports. The assumptions were that pre-pandemic demand will return for jet fuel at SFO, OAK and SJC; and that 100 percent of the flights at all three airports will use SAF blends instead of neat CJF. A range of blends – SAF5, SAF25, and SAF50 – were evaluated. It is estimated that GHG reductions from SAF blends would range from 0.47 million metric tons per year (SAF5) up to 4.7 million metric tons per year (SAF50), based on 2019 emissions estimates. Notably, these combined GHG reductions reflect emissions from all fuel loaded at these three Bay Area airports, i.e., they are not constrained to reductions that would occur within BAAQMD boundaries.

A similar analysis was performed to estimate criteria pollutant emission reductions that could be realized within BAAQMD boundaries under the same SAF blend deployment scenarios. For the best-case scenario, it is estimated that displacing all CJF use at the three major airports with a SAF50 blend could provide reductions in CO emissions of 2.27 tons per day, SOx emissions of 0.39 tons per day, and PM10 emissions of 0.28 tons per day.

A number of challenges and barriers exist that currently hinder SAF producers from providing commercial aviation operations at SFO and other California airports with the large volumes they ultimately seek. The three key (related) impediments under current dynamics are 1) higher cost/price of SAF relative to CJF; 2) reduced value of SAF on a per-gallon basis compared to its more-dominant co-product RD (which disfavors gearing the production process for a higher SAF yield versus RD); and 3) federal and state policies that generally favor using limited biofuel resources to decarbonize surface transportation more than the aviation sector.

A fourth impediment has been the global COVID-19 pandemic, which has dramatically decreased aircraft departures at large coastal airports (nearly 70 percent at SFO at its peak), thereby greatly reducing demand for CJF and lessoning the need for airlines to continue switching to SAF blends.

A fifth impediment is the potential for California to be "outcompeted" for limited available SAF supplies, because other nations (or even regions of the U.S.) now offer – or may offer in the near future -- more favorable incentives and/or policies, which could make it increasingly difficult for airlines serving the Bay Area to procure large volumes of the fuel.

10.2. Recommendations

The following provides actions that BAAQMD may wish to explore and implement – in conjunction with various stakeholders – to address barriers currently impeding wider-scale use of SAF at Bay area airports and achieve GHG-reduction objectives for the commercial aviation sector.

- Engage with CARB and other relevant state or federal agencies about how to 1) improve the relative value of SAF through changes in the monetization metrics of key programs (LCFS, Cap and Trade, RFS2, etc.), and 2) generally modify California's GHG-reduction policies to more favorably treat SAF production and/or end use.

- Further evaluate the pros and cons of channeling more types of support (policy, incentive funding, permitting requirements, etc.) towards SAF as the leading available strategy to further decarbonize the Bay Area's aviation sector. This may or may not entail reducing emphasis on RD as a strategy to decarbonize ground transportation, which has growing near-term access to deploying electric drivetrain technology (battery-electric and hydrogen fuel cell architectures) as the key decarbonization strategy.

- Consider exploring new pilot program incentives for SAF production and end use, based on air qualify benefits associated with reducing criteria pollutants and air toxics in DAC / EJ areas near Bay Area airports.

- Consider creative methods to incentive larger-scale production and use of SAF, such as fast-track permitting and/or CEQA approval for new biofuel production facilities or conversion of conventional refineries to biorefineries.

- Commission a study (e.g., using the UC system) that corroborates and further quantifies SAF's effects on criteria and toxic air pollutants from commercial aircraft, which can help ensure that grant funding achieves its intended use (i.e., to reduce surplus, quantifiable emissions.

- Establish (or join existing) regular working groups with SFO and other major Bay Area Airports (OAK, SJC) to monitor SAF-related progress, developments and status of key impediments (including Covid-19 impacts).

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