PROPOSED TRIENNIAL STRATEGIC RESEARCH PLAN FISCAL YEARS 2018-2021

April 23, 2018

CALIFORNIA
AIR RESOURCES BOARD

The statements and conclusions in this report are not necessarily those of the California Air Resources Board (CARB). The mention of commercial products, their source, or their use in connection with material reported is not to be construed as either actual or implied endorsement of such products. To obtain this document in an alternative format, please contact the Air Resources Board Disability Coordinator at (916) 323-4916 or 7-1-1 for the California Relay Service. This report is available for viewing or downloading from the Air Resources Board's Internet site at https://ww2.arb.ca.gov/our-work/programs/research-planning.

TABLE OF CONTENTS

INTRODUCTION

As required by State law (Health and Safety Code Section 39700), the California Air Resources Board (CARB or Board) sponsors a research program that is guided by the mission of providing sound and timely scientific results to support CARB's policies and programs. The Board's research program was established by the Legislature in 1971 and has formed the basis of CARB's regulatory programs since its inception. Over the past 47 years, CARB's research goals of informing health-based air quality standards, reducing air pollution exposures, and protecting California from the potential impacts of climate change have been met through a diverse portfolio of projects. CARB's annual research plans outline past and current research and describe new research initiatives.

This report, *The Proposed Triennial Strategic Research Plan for Fiscal Years 2018-2021* (Plan), reflects a concerted effort to identify the areas of CARB's highest priority research needs for the next three years. The research initiatives outlined in this Plan describe the research questions that CARB aims to address through in-house and externally contracted research projects. These research initiatives build on past research and will provide continued support for the development of new policies and regulations, track the implementation of existing programs, and ensure that the benefits of longer-term strategies are realized in all communities. This work will provide the scientific foundation for California to meets its air quality, air toxics, and climate goals, including federal deadlines for national air ambient air quality standards (NAAQS), and greenhouse gas (GHG) reduction goals in 2020, 2030, and beyond (Figure 1).

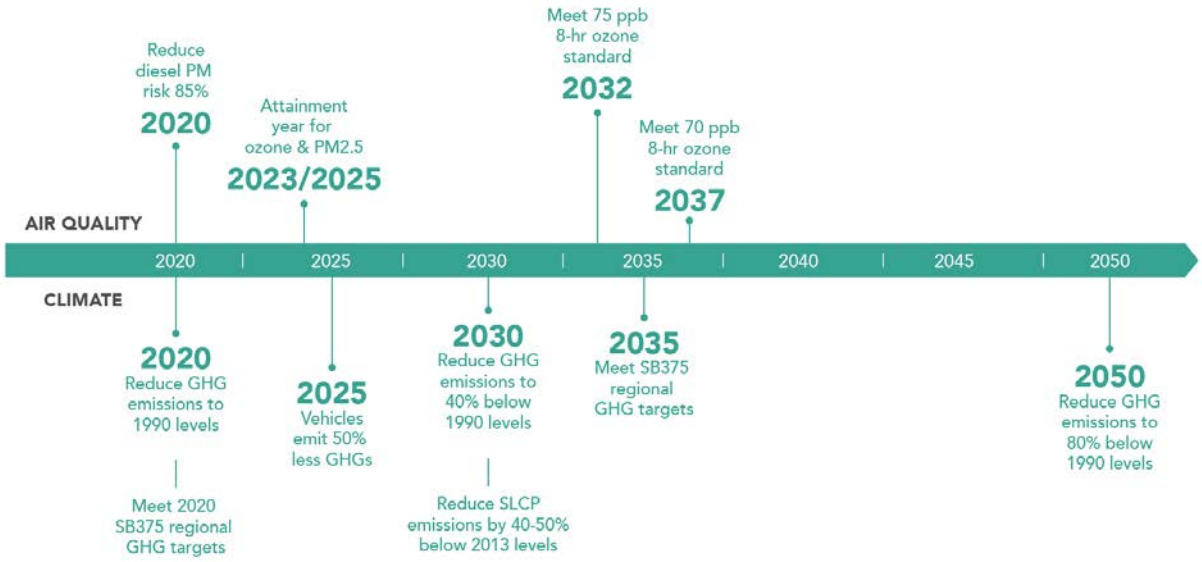


Figure 1: California's key air quality and climate change goals through 2050.

The research initiatives in this Plan may be fulfilled through in-house research or funded through external contracts. Since these research initiatives represent a body of research greater than what CARB can fund alone, CARB will continue to leverage complementary research supported by other funding organizations to focus on issues that are unique to California, or specific to its vulnerable populations and regions.

PROGRAM HISTORY

For the past 47 years, CARB and key public and private partners have collaborated to make California a center for pioneering air pollution research. The results of CARB's forward-thinking research have inspired legislative actions and regulatory solutions in California, often leading to national and global solutions. Below are highlights of major research efforts throughout the past five decades. These efforts filled gaps in the scientific literature to inform the development and successful implementation of CARB programs.

1970s and 1980s – Science-based Strategies to Control Smog Formation

Ozone concentrations in the smog-clogged Los Angeles Air Basin of the 1960s and 1970s signaled the need to reduce ozone precursors, such as volatile organic compounds (VOC) and nitrous oxide (NO_X). The U.S. Environmental Protection Agency's strategy to attain ozone standards was to reduce VOC emissions. CARB, meanwhile, working with the South Coast Air Quality Management District, (SCAQMD), and other partners, performed modeling, monitoring, and field studies to identify the most effective strategy for reducing ozone concentrations in Los Angeles. This research collaboration produced more accurate estimates of VOC and NO_X emissions and advanced scientific understanding of their relative importance in smog formation. Discovery of the critical role of mobile-source NO_X emissions in ozone formation prioritized NO_X control in State ozone and particulate matter reduction programs. CARB's ozone precursor findings also guided the 1990 Amendments to the federal Clean Air Act, increasing its reliance on NO_X controls to reduce ozone emissions. The National Academy of Sciences also recognized the importance of CARB's ozone research in its 1991 report "Rethinking the Ozone Problem in Urban and Regional Air Pollution," stressing the need for NO_X control in addition to VOC control. NO_X controls are now a globally recognized tool for improving air quality.

1980s – Acid Deposition Impacts

Airborne emissions of sulfur and nitrogen compounds, (SO_2 and NO_X) react with water, oxygen and other chemicals to form harmful acids that fall to earth as acid rain or dust. When the federal government established programs in the 1980s to study the impacts of sulfur dioxide (SO_2)-based acids from coal combustion, California's legislature had already taken steps to reduce SO_2 emissions from power plants and to study acid deposition impacts of mobile-source emissions of NO_X. CARB research into the causes and effects of acid deposition in California supported these actions by monitoring the impacts of NO_X-derived acids on human health and ecosystems. CARB-funded research evaluated the human health risks of long-term exposure to acidity, as well as its adverse impacts on California's aquatic and forest ecosystems. In the fall of 2000, CARB-funded research found that there was no longer a need for an acidic air pollutant standard because atmospheric acidity levels had declined in response to control measures adopted to reduce ambient ozone and particulate matter.

1990s – Protecting Children's Health

The 10-year Children's Health Study (CHS), initiated in 1993, was the first major study to assess the impacts of long-term air pollution exposure on the respiratory health of California's children. Following 5,500 students in 12 southern California communities from fourth grade through high school, this CARB-funded study found that children exposed higher levels of air pollution from traffic and other sources:

- Had reduced lung growth that persisted into early adulthood.
- Had increased asthma prevalence, symptoms, and medication use.
- Developed asthma more frequently if active in outdoor sports.
- Had more frequent school absences.

The CHS supported legislation, such as The Children's Environmental Health Protection Act (SB 25, 1999), which required California to reassess its air quality standards to ensure the health of children. It also spurred other researchers to investigate the links between air pollution and other adverse health effects among children, such as autism and birth defects. CARB research continues to investigate children's health and exposure, assessing the impacts of exposure to air pollutants near roadways, in school buses, and in proximity to stationary sources including rail yards, ports, and refineries. Findings from this ongoing work have helped develop California air quality standards, as well as voluntary planning guidelines for proximity of "sensitive" land uses such as daycare centers, schools, and playgrounds to nearby emission sources. More recent CARB research measured air pollution exposure near freeways and identified new mitigation strategies, such as sound wall and vegetation barriers, to help protect the health of children living in near-roadway environments.

2000s – Ensuring Clean Air for All Communities

CARB's environmental justice research program focuses on vulnerable populations, including children, the elderly, low-income, and minority communities that exposed to higher levels of air pollution. Due in part to proximity to hazardous waste sites, industrial facilities, freight hubs, ports, freeways and rail yards, these populations disproportionately suffer the adverse health effects of exposure to PM2.5, NO_X, and CO. Focusing initially on the impacts of mobile sources on exposures in disadvantaged communities, CARB-funded studies leveraged population health studies to assess the causes of the asthma burden disparity among vulnerable populations. Researchers found higher concentrations of air pollutants at schools and communities downwind of freeways, and higher prevalence of asthma attacks, medication use, and emergency room visits among the residents of those communities. These studies contributed to a growing literature highlighting the greater vulnerability of people in poor and minority communities to the effects of exposure to traffic-related air pollution. CARB's research findings helped inform policy decisions on motor vehicle emissions control, and asthma prevention and education among low-income populations. California's School Siting Bill (SB 352, 2003) drew on these results to prohibit public school siting within 500 feet of freeways. CARB-funded researchers also combined geospatial data on disparities in hazard proximity, air pollution

exposure, and socioeconomic status to develop the Environmental Justice Screening Method (EJSM). CARB's EJSM laid the technical foundation for CalEnviroScreen, the mapping tool that guides allocation of Cap-and-Trade auction proceeds to environmental justice communities. Current CARB-funded research continues to ensure that clean air programs benefit all communities by investigating potential displacement of low-income residents by transit oriented development and by exploring the health impacts of noise and walkability in the built environment.

2000s – Creating Safe Environments Indoors

CARB's indoor air quality research improves Californians' health by identifying and reducing exposure to indoor air pollutants. A 2005 air-cleaning device survey, for example, found that while most purchased air cleaners to help alleviate asthma and allergy symptoms, many devices emitted high ozone levels – some as high as a Stage-One smog alert. This finding led to State legislation authorizing CARB to regulate ozone emissions from indoor air cleaning devices. CARB's Indoor Air Cleaning Devices regulation, the first of its kind, went into effect in 2010. More recent CARB research again found high ozone emissions from in-duct air cleaning devices, and identified other new air cleaning products claiming to remove VOCs that emit more VOCs than they remove. CARB-funded studies also spurred regulation of other toxic indoor emissions, such as formaldehyde emissions from plywood. CARB's regulation limiting formaldehyde emissions from compressed wood products was followed by federal legislation requiring national regulation of formaldehyde emissions from building materials. CARB's building products research also contributed to both State and national green building standards and certification criteria. More recently, CARB's indoor research program has evaluated the mitigation of toxic indoor exposures through high-efficiency filtration, which was found to remove up to 98 percent of all particles from the airstream in vehicles and homes. These findings have already influenced California building codes for commercial building air filtration, and they are driving requirements for higher-efficiency filtration ventilation in 2019 building codes.

2010s – Tracking and Reducing Emissions of Short-lived Climate Pollutants

The CARB's Short-Lived Climate Pollutant (SLCP) research program monitors and characterizes sources of fluorinated gases (F-gas), methane (CH_4) and black carbon (BC) emissions, and evaluates strategies for mitigation of these potent climate forcers. State and federal partners, including the California Energy Commission, NASA's Jet Propulsion Laboratory, and the National Oceanic and Atmospheric Administration (NOAA) have been key contributors to CARB's research program. CARB research showed that F-gas emissions, while growing rapidly in California, could be cost-effectively controlled by reducing emissions from commercial refrigeration systems. These findings supported the adoption of CARB rules to reduce F-gases from commercial refrigeration. In 2010, CARB research established the world's first ambient monitoring network to identify and monitor CH_4 emissions from Central Valley agriculture, livestock, and oil and gas operations. CARB's BC research contributed to the body of research that revealed BC's climate-forcing role and the effectiveness of California's diesel emission

controls in reducing ambient BC emissions by 50 percent over 20 years. CARB's comprehensive SLCP research enabled the Board to respond effectively to legislation (SB 605, 2014) requiring a comprehensive strategy to reduce the emissions of SLCPs in California. CARB-supported satellite studies of methane hot spots in the Central Valley spurred legislation, (AB 1496, 2015 and SB 1383, 2016), calling for monitoring and reduction of CH_4 emissions from livestock and dairies, landfills, and natural gas production and distribution operations. CARB's extensive CH_4 monitoring research was also crucial in meeting the need for timely emissions information during the Aliso Canyon natural gas leak. Looking ahead, CARB researchers will continue to study SLCP emissions and their impacts on California communities in support of the State's efforts to achieve its climate goals.

Research Going Forward

Despite dramatic improvements in air quality, and the establishment of effective GHG emission reduction programs, California must continue to achieve significant new reductions to meet ambitious future air quality and climate goals. CARB will continue to support the State's efforts to act as a living laboratory for applying science to policy, and thereby lead the world by example. California's diverse industries, topography, ecosystems, and cultures, provide a microcosm for current and future health, environmental, and economic challenges. These challenges often disproportionally impact underserved populations in California. Research will continue to focus on identifying how CARB programs can benefit all communities. The continued development of partnerships with other research entities and stakeholders will be essential to support effective program implementation by providing information on emission inventories, tracking progress, modeling projections, and ensuring the successful implementation of CARB programs. The projects included in this Plan will increase the understanding of the health impacts of air pollution and California's progress on air quality, answer near-term questions important for program implementation, and explore benefits of longer-term strategies.

TRENDS IN RESEARCH QUALITY AND SCIENTIFIC IMPACT

CARB-Funded Research in World Class Publications

Over the past two decades, CARB has funded more than 460 research contracts which have resulted in a similar number of peer-reviewed, highly-cited publications in high-impact journals. On average, these CARB-funded publications are cited about 82 times each by other articles, and approximately 80 percent are published in the top quartile of journals in terms of scientific impact, which compares favorably to other funding organizations such as the U. S. Environmental Protection Agency and the Health Effects Institute. Health and exposure, atmospheric science, and emissions monitoring and control publications have received the most citations, and reflect CARB's long-standing research strengths. CARB research also has been cited in reviews of the National Ambient Air Quality Standards and in dozens of CARB regulatory documents. Publications resulting from CARB research contracts have won multiple Haagen-Smit Prizes for outstanding papers published in the journal *Atmospheric Environment*, the John Johnson award for outstanding research in diesel engines from the *SAE International Journal of Engines*, and the Arthur C. Stern Distinguished Paper award from the *Journal of the Air and Waste Management Association*.

CARB's Research Staff Produce High-Impact Publications

During the past 15 years, Research Division staff has authored or co-authored 121 peer-reviewed scientific articles published in widely-read, prestigious journals. These articles were cited 2,640 times in subsequent journal articles by other researchers in the field.

RESEARCH PLANNING

To implement the initiatives that will be laid out in the Triennial Plan, the annual process to select individual research projects begins with the collection of research concepts from an open, public solicitation (Figure 2). Research concepts are then mapped to the Initiatives and prioritized through internal and external coordination meetings. CARB coordinates with State and federal agencies, local air districts, and research institutions, in order to avoid duplication of effort, leverage funding, and identify opportunities for collaborative efforts. CARB has also begun the process of identifying environmental justice community representatives to include in this coordination process, in order to better address the needs of these communities. Projects approved by the Board are developed into contracts through a solicitation process. CARB receives input from external collaborators in the review process to select winning proposals, which are then reviewed by the statutorily mandated Research Screening Committee (RSC). Once a project is approved by the Board, work can begin. CARB staff manage projects and solicit input on a quarterly basis. Large or complex projects are assigned technical advisory panels for oversight. Final reports are released to the public, and available on our website, after approval from the RSC.

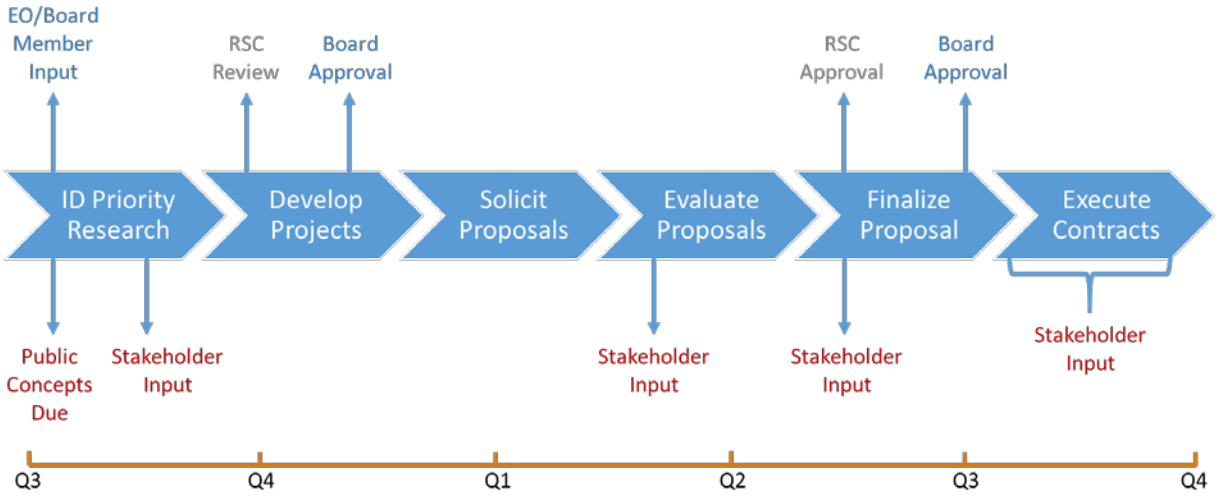


Figure 2: Research plan development timeline.

RESEARCH COORDINATION AND DISSEMINATION

Coordinating our research with other State agencies, federal agencies, local air districts, and research institutions ensures that CARB research avoids duplication of effort, leverages funding, identifies opportunities for collaborative efforts, and maximizes the utility and applicability of research results.

To promote coordination, research results are disseminated at all stages of the research process, from project development to updates on research progress and final reports. Additional coordination with other State agencies is done through participation in interagency working groups, such as the Climate Action Team Research Working Group, and the Transportation Research Roundup. These groups provide a forum for CARB staff to present research results and proposed research activities. CARB staff also make efforts to reach out through individual meetings to facilitate coordination with external groups, including academia, federal agencies, the international community, and private entities.

Research Communication Tools

- CARB Research Website
- CARB Research Listserv
- Press Releases
- Factsheets
- Research Briefs
- Public Seminars
- Peer-reviewed Journal Articles
- Final Reports
- Research Updates to the Board

These items, and more information on how to get involved in our research planning process, can be found on CARB's research website (http://www.arb.ca.gov/research/research.htm)

Providing sponsorship for other research entities is another way that CARB's research program coordinates and leverages expertise in the research community. Sponsorship opportunities also provide an opportunity for CARB to collaborate on research initiatives at other institutions and ensure that CARB's research results are elevated to national and international platforms. Examples of entities that CARB partners with include the National Center for Sustainable Transportation (NCST) and the Sustainable Transportation Energy Pathways (STEPS) Center at the University of California, Davis. CARB also coordinates with the Coordinating Research Council (CRC), the Health Effects Institute, the Transportation Research Board, and several federal agencies.

Leveraging Research Dollars

CARB staff seeks to maximize the use of research funding by collaborating with other research entities. One example of leveraging funds in this Plan is a project that will evaluate an existing zero net energy (ZNE) community project in Richmond that has been awarded $2.6M from the California Energy Commission (CEC) challenge for disadvantaged communities. The CEC funds will allow for the planning, permitting, and design of low-income ZNE housing. CARB funds will develop a benchmarking framework for zero net carbon (ZNC) communities that include the evaluation of building and community-level greenhouse gas emission reduction strategies associated with waste, water, and other factors that aren't accounted for in a ZNE framework.

Research Partners

- Federal Agencies
- State Agencies
- Non-Governmental Organizations
- Air Districts
- University of California
- California State Universities
- Land Grant Institutions
- National Labs

Communicating Results

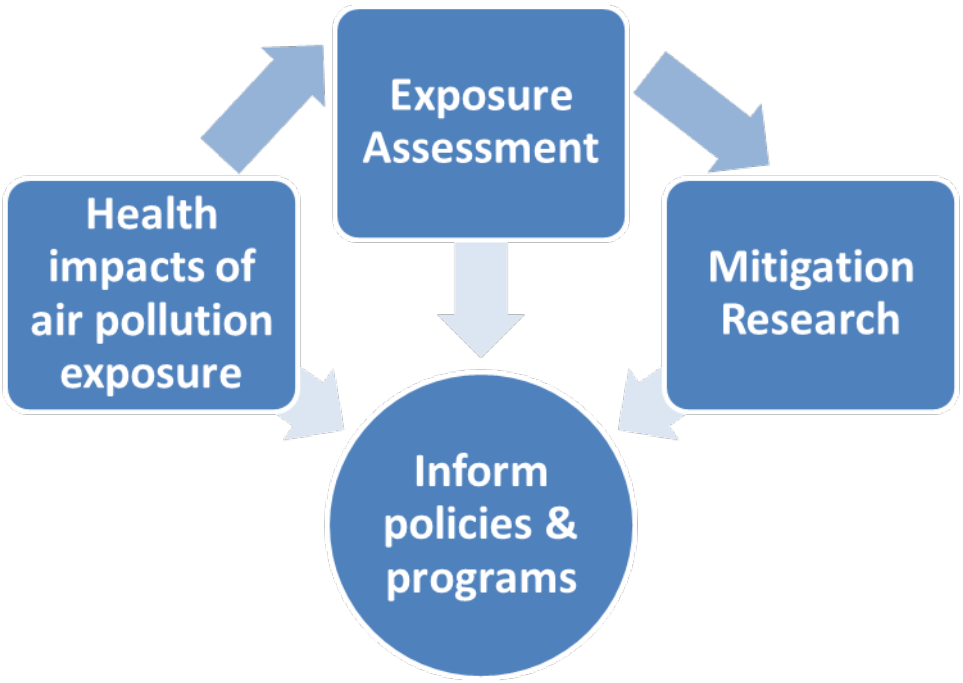
CARB staff disseminates new research results to the public through seminars, press releases, newsletters, final reports, and updates at Board Meetings. CARB also co-sponsors workshops with other State agencies on a variety of research topics. The workshops provide a public setting for researchers funded by multiple State agencies to showcase their efforts, provide an opportunity for an in-depth discussion of the implications of their results, and identify remaining research gaps.

RESEARCH TO SUPPORT CARB'S PROGRAMS

HEALTH & ENVIRONMENTAL JUSTICE

HEALTH & EXPOSURE

CARB's research on the health effects of air pollution has helped to set national air quality standards, and focuses on emerging issues of importance to protect California's communities. Improving the understanding of air pollution exposures, and developing exposure mitigation strategies, continue to be high priorities. CARB's in-house health assessments are guided by the latest science and inform all CARB programs, plans, strategies, and regulations about the potential impacts on human health. The health program also funds external research to fill research gaps in the literature on topics ranging from the health effects from air pollution exposure and assessments of real-world exposures to pollutants, particularly among California's vulnerable populations to the identification of exposure mitigation strategies.



Sustainable Community Research Highlight - Research Informing Policy: Reducing Exposure to Traffic-Related Air Pollution

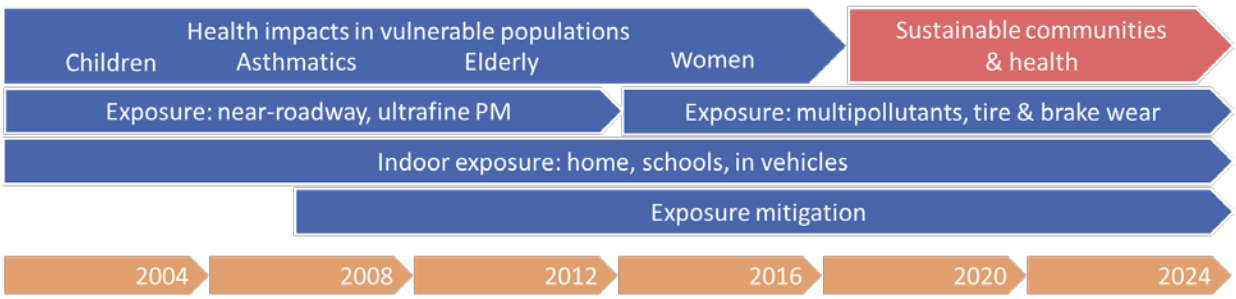
Since the passage of SB 375 in 2008, there has been growing concern that by increasing infill development, to reduce GHG emissions, more people may be exposed to higher concentrations of traffic-related air pollution. Existing scientific literature, and past CARB-funded studies have revealed a suite of possible exposure reduction strategies. For example, high efficiency air filters have been shown to remove 50-99 percent of particles in indoor environments. Also, pollution dispersion models were shown to predict pollution hotspots in city streetscapes to inform future urban design decisions.

To translate research into a form that planners and other stakeholders can use readily, staff developed a "Technical Advisory" to supplement the 2005 Land Use Handbook. This Technical Advisory includes strategies that CARB staff has determined—based on scientific literature and CARB studies—can effectively reduce air pollution exposure near high-volume roadways. The strategies also emerged from discussions with various State and federal agencies, academic experts, and other stakeholders. The Technical Advisory's key strategies appear in the 2017 update of the General Plan Guidelines, and include direct links to CARB's Technical Advisory for planners and stakeholders seeking more information.

Health & Exposure Research Initiatives for FY 2018-21

For decades, CARB has funded health research on the impact of exposure to air pollution in vulnerable populations which has included the Children's Health Study, as well as studies on asthmatics, the elderly, and women. This line of research has evolved to include the health co-benefits of sustainable communities. CARB's health research on exposures indoors and in-vehicles, and to multiple pollutants in outdoor environments will continue, as will our research on exposure mitigation, which recently has focused on high efficiency filtration.

The timeline below depicts high-level research initiatives (groups of projects on a given topic) that have led to the development of our current research priorities. The timeline extends to 2024 to account for the time that research projects initiated by the Triennial Plan would be completed. Bars in shades of red represent new research initiatives, while bars in shades of blue represent research initiatives that have either concluded or are currently in progress and will continue to be a priority in the future.



SUSTAINABLE COMMUNITIES & HEALTH

This Plan will address these research questions related to sustainable communities and health:

- To what extent are vulnerable groups (e.g., children, the elderly) more sensitive to air pollution impacts, and how will these groups' exposure to pollutants change in future (e.g., as tailpipe emissions decline, and communities reduce vehicle miles traveled)?
- What are the net health benefits/impacts associated with smart growth, active transportation, and other strategies to reduce vehicle miles traveled, and what strategies can communities employ to maximize health benefits and reduce near-roadway air pollution exposure?

Over the years, CARB has sponsored landmark research on the health impacts from air pollution on vulnerable populations, including children, asthmatics, the elderly, and women. One such study is the Children's Health Study, which revealed the extent to which ozone, nitrogen dioxide, acid vapors consisting of nitric acid and hydrogen chloride, and particulate matter affect children's lung development. The results of this study are evidence for classifying children as sensitive receptors to air pollution and have influenced research since and shaped California legislation addressing children's microenvironments. CARB also funded a study of families in different neighborhoods in Los Angeles County. The researchers found that children more highly exposed to traffic pollution were 30-40 percent more likely to report wheeze symptoms. Additional work on elderly subjects with cardiovascular disease in Los Angeles explored new ways to study vulnerability, such as examining the impact of genetic variability on health in populations exposed to different sources of air pollution, and provided information on the effects of air pollution exposures from different sources, including traffic.

CARB's most recent research has focused on the increased sensitivity to PM2.5 in women, which has prompted additional research to shed light on the basis for the increased sensitivity using a toxicological approach. In addition, the health effects of ultrafine particulate matter (UFPM) exposure in women is being investigated using an epidemiological approach. Another study is examining whether changes in immune function induced by air pollution exposure can be passed on from mother to offspring. The research program will continue to quantify the degree to which vulnerable groups are more sensitive to air pollution exposure and how their exposure may change as communities develop strategies to reduce vehicle miles traveled.

California planners and policy makers face increasing demands for information on the health impacts of strategies to reduce GHG emissions from transportation. SB 375 requires metropolitan planning organizations to reduce GHG emissions through land use and other strategies. Studies world-wide including several in California have identified the potential for health co-benefits of active travel (walking, cycling, and transit) in significantly reducing the existing burden of chronic disease. Current in-house and funded work is focused on how to accurately quantify active transport in communities and provide tools for policy makers and planners to calculate the health impacts of transportation strategies which are designed to reduce GHG and incorporate active-transportation.

Several Metropolitan Planning Organizations (MPOs) have set voluntary health targets in their Sustainable Communities Strategies (SCS), and have used a spreadsheet version of the Integrated Transport and Health Impact Model (ITHIM) to estimate the health impacts of their preferred scenarios. To complement this work, a project funded in fiscal year 2017-18 will create an easy to use, open source, updated version of the Integrated Transport and Health Impact Model (ITHIM) to help MPOs set voluntary health targets in their Sustainable Communities Strategies, and calculate the health impacts of transportation strategies to reduce GHG that incorporate active-transportation. When coupled with land-use models, it may have additional applications to assess the health impacts of general plans. The insights gained from this research may lead to more sophisticated ITHIM versions that could be applied to project level and sub-county geographic scales.

Going forward, CARB will continue to support research that will help organizations engage in better informed decision making on issues related to transportation and health. Examples of other research priorities include an evaluation of the impact of living in a smart growth designed neighborhood on the health of residents relative to a nearby conventional community in order to assess the benefits of smart growth design. This work will help inform the implementation of SB 375 initiatives, and regulations that aim to reduce exposure to harmful traffic-related emissions.

Studies indicate that air pollution is not the only factor that can impact health. Noise may also be a significant contributor to health impacts associated with proximity to traffic. CARB currently has plans to use noise monitors and personal air pollution monitoring devices to collect data on commuters' exposure to noise and air pollution. This represents an important first step in improving our understanding of noise-related health effects and considerations of noise in the development of future compact, infill communities.

Additional research is needed to evaluate the overall net health effect of SB 375 implementation. While it is possible that more people will face increased exposure to traffic related air pollution near their homes in compact, infill neighborhoods, it is also possible that reduced in-vehicle exposure resulting from shorter commutes will offset these increases in near-home exposure. Also, it is possible that regional reductions in VMT will reduce regional pollution levels, and this could lower the background concentrations that would be experienced by near-roadway receptors.

Finally, there is a growing body of literature examining the health benefits of walkable communities and neighborhoods that facilitate active transportation and increased physical activity. It may be possible in the future to quantify these health benefits and incorporate them into the equation for estimating the net health effects of SB 375.

EXPOSURE: MULTIPOLLUTANTS, TIRE & BRAKE WEAR

This Plan will address these research questions related to multipollutant exposures and tire and brake wear emissions:

- Are health effects that result from multipollutant exposures distinct from exposure to individual pollutants?
- What are the health effects that result from exposure to non-tailpipe emissions near busy roadways?

CARB regulations have reduced air toxics from vehicle tailpipe emissions and evaporative emissions from fuels, as well as from stationary sources and from consumer products since the mid-1980s. In response to public concern, the California Legislature passed the Toxic Air Contaminant Identification and Control Act in 1984. Since then, CARB has adopted and implemented several regulations to limit toxic air contaminant emissions. In 1987, the California Legislature passed the Air Toxics "Hot Spots" Information and Assessment Act, which requires businesses to reduce risks from exposure to emitted toxic air contaminants.

CARB has performed in-house research on the historical trends of toxic air contaminants, which was published in 2015. The study found that the cancer risk from exposure to the State's most significant air toxics declined 76 percent over a 23-year period in California. The decline is a direct result of regulations targeting unhealthful emissions of these air toxic pollutants. The study quantified emission trends for the period from 1990 through 2012 for seven toxic air contaminants that are responsible for most of the known cancer risk associated with airborne exposure in California. This reduction was particularly striking given the steady growth in California's population and number of vehicles on the road. These reductions highlighted the strength of California's program to reduce public exposure to toxic air pollution.

A project initiated in fiscal year 2017-18 will examine the efficacy of various low-cost portable technologies to measure ambient concentrations of toxic metals in real time. The results of this project will identify the most cost effective and efficient technologies to support CARB's Air Toxics Program in its efforts to detect ambient concentrations of a broad range of metals. This work will help to identify potential sources of toxic metals, and help prioritize subsequent efforts to further evaluate the emissions from these sources.

CARB has funded research to improve our understanding of the near-roadway health impacts of exposure to PM2.5 and (UFPM) and mixtures of air pollutants, particularly in vulnerable populations. While studies on single pollutant studies have been essential to the process of

establishing health protective levels for NAAQS, in the past few year, CARB has expanded its research portfolio to look at how concurrent exposure to ozone and PM2.5 may affect public health, which is the focus of a research project initiated in fiscal year 2017-18.

CARB is also working to assess the microenvironments that contribute to multipollutant exposures of Californians, including ozone, PM, UFPM, and toxics. In one in-house pilot-level study, 12 volunteers were followed for 24-hour periods using small, portable monitors. The results showed that some of the highest UFPM exposures resulted from cooking activities, gardening, and certain forms of transportation. This information can be used to help design strategies to mitigate pollutant exposure. In another in-house study, CARB staff measured personal exposures of commercial gardeners to the emissions from gasoline-powered lawn and garden equipment in California. The study results will be used to estimate the health benefits of zero-emission technologies for lawn and garden equipment, and support the anticipated regulation for small off-road engines. Continued research in this area will focus on evaluating pollutants that Californians, particularly in disadvantaged communities, are exposed to during their typical daily activities, and contributing sources and potential mitigation measures.

Although regulations have resulted in meaningful decreases in combustion-related emissions from on-road vehicles, emissions from brake and tire wear have remained relatively constant, and are projected to become an increasingly larger portion of the on-road PM2.5 inventory in the future (Figure 3). Understanding the health impact of exposure to these emissions is essential, especially since transportation plans project a larger percentage of the population living closer to major roads, thereby increasing exposure to tire and brake wear particles, as well as road dust re-suspended particles.

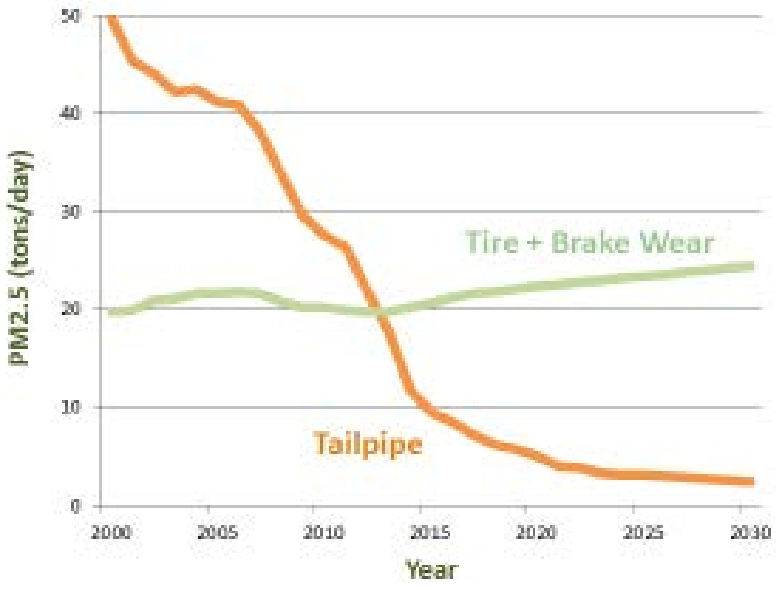


Figure 3: PM2.5 emission sources from on-road vehicles since 2000.

A project initiated in fiscal year 2017-18 on the health impacts of emissions from tire and brake wear will examine the health impacts of different types of particles emitted from tire and brake wear in various Los Angeles locations. This work will inform the implementation of SB 375 initiatives and regulations that aim to reduce exposure to harmful traffic-related emissions. However, additional research is needed to identify other non-tailpipe emission sources, particularly from new vehicle technologies (e.g. new formulations for tire or brake pad material) and their impact on health, particularly in communities with the greatest exposure. This work will help inform regulations that aim to reduce exposure to harmful traffic-related emissions.

INDOOR EXPOSURE: HOME, SCHOOLS, IN VEHICLES

This Plan will address this research question related to indoor exposure:

- Which activities and microenvironments result in the largest air pollution exposures?

The indoor microenvironment has been a continually impactful area of research for CARB over the past few decades. CARB's indoor air quality research improves Californians' health by identifying effective exposure reduction approaches for indoor air pollutants. A 2005 air-cleaning device survey, for example, found that while most people purchased air cleaners to help alleviate asthma and allergy symptoms, many devices emitted high ozone levels – some as high as a Stage-One smog alert. This finding led to State legislation authorizing the CARB to regulate ozone emissions from indoor air cleaning devices. CARB's Indoor Air Cleaning Devices regulation, the only one of its kind, went into effect in 2010. More recent CARB research found high ozone emissions from in-duct air cleaning devices and some home appliances such as ozone-emitting laundry devices, and identified other new air cleaning products claiming to remove VOCs that emit more VOCs than they remove. CARB-funded studies also spurred regulation of other indoor toxics, such as formaldehyde emissions from composite wood products. CARB's regulation limiting formaldehyde emissions from composite wood products was followed by federal legislation requiring national regulation of formaldehyde emissions from building materials. CARB's building products research also contributed to both State and national green building standards and certification criteria.

New technologies and building materials present the potential for new exposures to harmful air contaminants. Evaluating new exposures and quantifying total personal exposures of residents of disadvantaged communities, including indoor and in-vehicle exposures, and identifying the sources that contribute most to their exposures, will be a research priority. Studies in this line of research will likely include measuring indoor source emissions of formaldehyde and acrolein, and obtaining total personal exposure data on TACs, criteria pollutants and semi-volatiles for children and those living in low socio-economic status communities. Other priority areas of research include assessing the impacts of climate change and associated factors on indoor air quality; measuring emissions of ozone from air cleaners used in vehicles and confirming the long-term effectiveness of high efficiency passenger cabin air filters; and investigating the

health impacts of exposure to elevated levels of CO_2 (recently shown to impair thinking and decision-making functions at levels commonly found in schools, cars and other enclosed environments).

EXPOSURE MITIGATION

This Plan will address this research question related to exposure mitigation:

- What are the most effective strategies (e.g., for buildings, vehicles, or land use planning) that reduce air pollution exposure for high-exposure microenvironments and activities?

CARB's exposure mitigation research is primarily focused on source control, but recently has also included a focus on high efficiency filtration. In vehicles, CARB-funded research found that high-efficiency cabin air filters for passenger vehicles and school buses can reduce particle concentrations by 55 to 90 percent inside vehicle cabins, about twice the reduction achieved by the filters typically found in cars and buses.

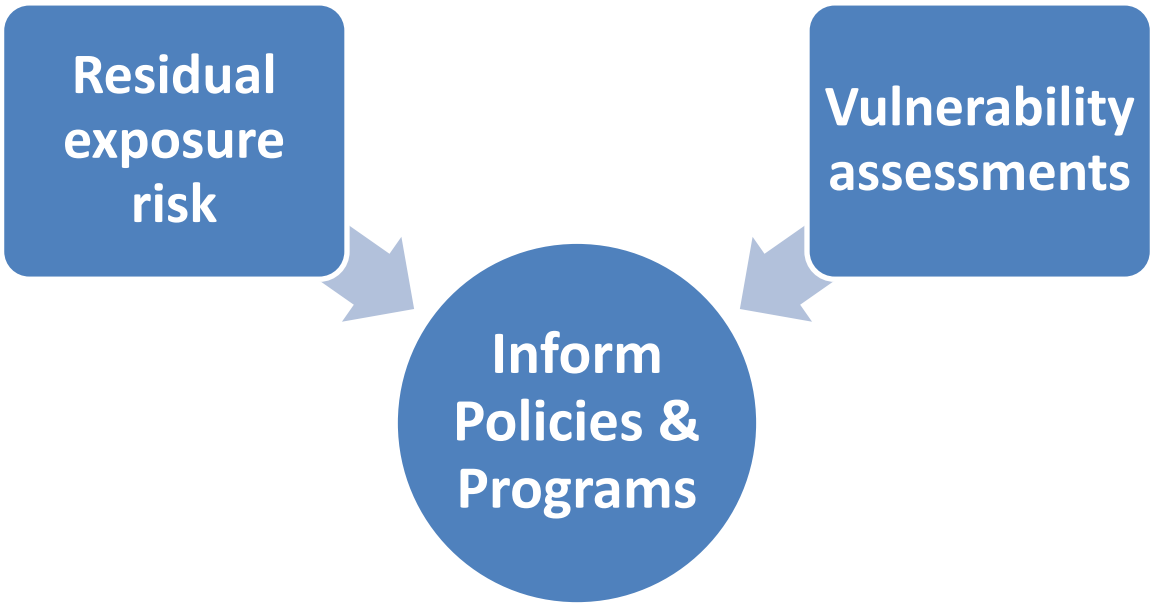
Recent CARB-funded research in buildings found that high-efficiency filtration (i.e., filtration that can remove much smaller particles than standard filters) in homes can remove over 90 percent of the particles from incoming outdoor air, with relatively low energy consumption. A study of high efficiency filtration in homes of children with asthma found that high efficiency portable air cleaners can be effective in reducing particle levels, and that particle reduction may help reduce the children's need for doctor's visits. Another study examined formaldehyde emissions from residential fiberglass air filters compared to central system air filters manufactured with other materials, because prior research showed elevated formaldehyde emissions from commercial fiberglass filters. Research from these studies can help guide State and local agencies seeking air pollution mitigation options to protect communities already living near freeways and other major sources of PM. For example, current building codes only require ventilation in new homes to reduce air pollution generated indoors, but not pollution from outdoor sources. Results from CARB's filtration studies will help to improve California's building ventilation codes, and thus improving overall indoor air quality. Continued research on the effectiveness of different ventilation and filtration technologies will be needed to advance policies, such as the Building Code, as filtration technology advances and new sources of pollutants are found.

CARB exposure mitigation research is also focused on reducing exposure outside by altering the built environment. For example, previous CARB-funded research found that street designs that have more open space and varied building heights can decrease near-street traffic pollution by up to 67 percent. It was also found that moving bus stops farther from intersections can reduce exposures to traffic pollution by up to about 50 percent if moving from 65 feet to 130 feet from an intersection. Sound walls and dense vegetation together can also reduce traffic pollution downwind of freeways, but the magnitude of reduction varies greatly, largely depending on wind speed and direction. CARB staff are also doing in-house work investigating commuters'

exposures to traffic pollution for different transportation modes and analyzing the impacts that SB 375 and other policies to reduce vehicle emissions are likely to have on exposures to traffic pollution. Although ongoing efforts to reduce emissions from cars and trucks and to move all vehicles towards zero emission alternatives will continue to drive down traffic pollution, CARB will continue to evaluate existing, and develop new strategies to reduce exposure to pollutants in urban areas.

ENVIRONMENTAL JUSTICE

Environmental justice is one of the most important objectives of air quality management, and CARB has continued its commitment to reducing the disproportionate exposure to air pollutants in disadvantaged communities. CARB has partnered with local and community organizations, carried out research projects and air monitoring studies to identify residual exposure risks, conducted vulnerability assessments of communities near ports and rail yards, adopted regulations, and refocused enforcement efforts and incentive programs, all in support of environmental justice goals. These actions have resulted in large improvements in air quality, especially in those communities where air pollution impacts have historically been the greatest.

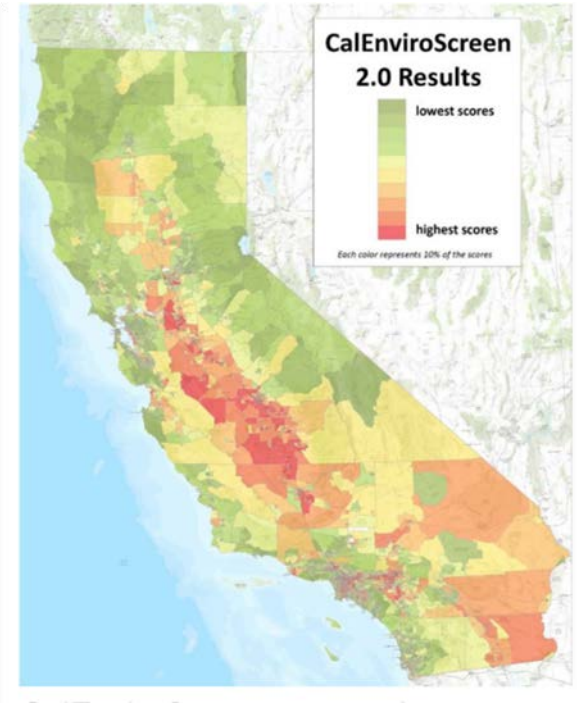


Environmental Justice Research Highlights

Ensuring Clean Air for All Communities

Low income and minority communities are exposed to higher levels of air pollution due, in part, to their proximity to hazards like Toxic Release Inventory facilities, hazardous waste sites, busy roadways, ports, and railyards. To understand air pollution exposure in disadvantaged communities, the program leveraged population health studies such as the Los Angeles Family and Neighborhood Survey (LAFANS), the East Bay Kids Study, and the California Health Interview Survey (CHIS). These studies sought to determine impacts of pollution levels and greater sensitivity in low income neighborhoods on asthma, including in the CHIS study, on whether the asthma burden disparity is due to exposure to higher levels of air pollutants, greater vulnerability, or both. Findings from these studies have helped to inform policy

decisions on motor vehicle emissions control and enforcement, and asthma prevention, control, and education in low socioeconomic status populations. For example, these results helped to confirm the importance of the SB 352, which prohibits school siting within 500 feet of a freeway



To support CARB's environmental justice initiatives for all its programs, CARB funded the development of the Environmental Justice Screening Method (EJSM). CARB's EJSM research laid the foundation for CalEnviroScreen, which is used to guide decision-making regarding Cap-and-Trade Auction proceed investments, enforcement priorities, and to understand how CARB's regulatory strategies have impacted disadvantaged communities (Figure 4).

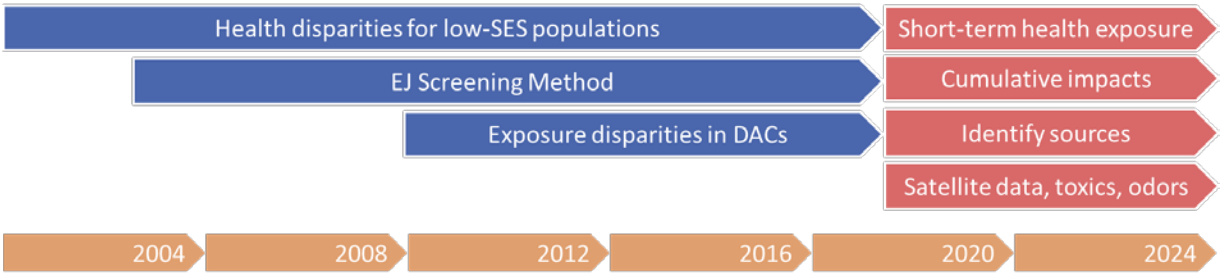
Figure 4: Spatial distribution of CalEnviroScreen 2.0 scores in California.

Environmental Justice Research Initiatives for FY 2018-21

In order to ensure that all communities benefits from CARB's regulations, CARB has partnered with local and community organizations, and has carried out research on a number of monitoring and assessment projects in support of environmental justice goals. CARB's research on the Environmental Justice Screening Method, led to the development of CalEnviroScreen and further research on climate disparities. This line of research will expand to focus on cumulative impacts of exposure to multiple stressors, in addition to exposure to air pollution. Our in-house work on exposure disparities in DACs has highlighted the need to focus on identifying the sources of these disparities. CARB's environmental justice research is expanding to include innovative methods to detect and monitor odors and toxics, including metals and PAHs.

The timeline below depicts high-level research initiatives (groups of projects on a given topic) that have led to the development of our current research priorities. The timeline extends to 2024 to account for the time that research projects initiated by the Triennial Plan would be completed. Bars in shades of red represent new research initiatives, while bars in shades of

blue represent research initiatives that have either concluded, or are currently in progress and will continue to be a priority in the future.



SHORT-TERM HEALTH EXPOSURE

This Plan will address these research questions related to the health impacts of short-term air pollution exposure:

- What are the health impacts of short-term exposures to air toxics and criteria air pollutants?
- What are the most effective methods of communicating the health impacts of short-term exposures in combination with real-time air quality data?

Research on health disparities for low socioeconomic status populations has provided results on increased vulnerabilities within these communities, including elevated exposures and greater sensitivity in specific groups. Low income and minority communities are exposed to higher levels of air pollution due, in part, to their proximity to hazards like Toxic Release Inventory facilities, hazardous waste sites, busy roadways, ports, and railyards. In particular, CARB has a long history of examining the impacts of traffic and particulate matter pollution on children. Most children who have exposure to higher traffic and other pollutants living in lower income areas, which is also an environmental justice issue. This work has leveraged population health studies such as the Los Angeles Family and Neighborhood Survey (LAFANS), the East Bay Kids Study, and the California Health Interview Survey (CHIS). These studies sought to determine whether the asthma burden disparity is due to exposure to higher levels of air pollutants, greater vulnerability, or both.

Results from this work found that asthmatic children in lower income families had both higher exposures to pollution, particularly traffic pollution and were disproportionally affected by this pollution and had increased exacerbation of their asthma. In the CHIS, asthmatics from lower income and minority groups were found to be more vulnerable to the effects of air pollution exposures than other asthmatic groups at the same levels of exposure. Studies of asthmatic Hispanic children in Huntington Park, children attending schools in lower income neighborhoods in the Bay Area, and asthmatic children in Orange County all confirmed that different ethnic and lower socioeconomic groups are more vulnerable to the effects of traffic-related pollution and suffer from increased exacerbation of their asthma. Findings from these

studies have helped to inform policy decisions on motor vehicle emissions control and enforcement, and asthma prevention, control, and education in low socioeconomic status populations. For example, these results helped to confirm the importance of SB 352, which prohibits school siting within 500 feet of a freeway.

CARB is currently providing technical support for monitoring studies in the Imperial Valley and San Ysidro, and CARB lent Ogawa samplers for a study led by Michael Jerrett, Beate Ritz and Jason Su to establish a network of 60 passive air sampling sites around Sacramento. The latter study focuses on the association of cognitive decline and dementia in the elderly in a population of Mexican Americans that are enrolled in the "Sacramento Area Latino Study on Aging" (SALSA) cohort study. CARB will build on this work to focus on the health impacts of short-term exposures to toxics and criteria pollutants and improve methods of communicating the health impacts of real-time air quality data. CARB will continue to leverage existing monitoring efforts and work with research partners such as the Office of Environmental Health Hazard Assessment and the Health Effects Institute to avoid duplication of effort and build on existing work.

CUMULATIVE IMPACTS

This Plan will address this research question related to the cumulative impacts:

- What risk factors, individually or in combination, are most strongly associated with enhanced vulnerability to health effects associated with air pollution (e.g., asthma), particularly for sensitive populations?
- How can information on the cumulative health burden in low-socioeconomic communities be used to develop criteria for the prioritization of sources for monitoring and mitigation strategies?

To support CARB's environmental justice initiatives for all CARB programs, CARB funded the development of the Environmental Justice Screening Method (EJSM). For the first time, EJSM demonstrated that disparities in proximity to hazards, air pollution exposure, and socioeconomic status can be combined in a map. These layers of vulnerability are combined into a spatial screening tool to identify communities burdened by the greatest cumulative impacts. CARB's EJSM research laid the foundation for CalEnviroScreen, which is used to guide decision-making regarding Cap-and-Trade Auction proceed investments, enforcement priorities, and to understand how CARB's regulatory strategies have impacted disadvantaged communities.

On-going CARB research continues to support research to improve CalEnviroScreen to better capture patterns of cumulative exposure impacts and social and health vulnerability of importance to environmental justice communities statewide. To estimate exposure, CalEnviroScreen includes the location of potential air pollution sources to estimate a census tracts' proximity to a given hazard. This information is lacking on the Mexico side of the US-

Mexico border, leading to the misrepresentation that there is very little pollution in border communities. A project initiated in fiscal year 2016-17 is creating a geospatial database of stationary, area, and mobile sources on the Mexico side of the US-Mexico Border as inputs to CalEnviroScreen. The investigators will use Mexico's version of the Toxic Release Inventory, and Google Earth, to verify locations and geocode stationary and area sources. The results will be used to improve the CalEnviroScreen analysis at the U.S.-Mexico border and will complement on-going monitoring at the border in California and in Mexico through collaboration with the Mexican Government, as well as monitoring studies in the Imperial Valley and San Ysidro, which are community-led monitoring efforts by Comite Civico and Casa Familiar.

Given that past research efforts have established that environmental justice communities suffer disproportionately from asthma or asthma-like symptoms, additional research is needed to identify factors that increase vulnerability to pollutant effects in these sensitive populations, particularly those due to multiple stressors. Examples of additional stressors that should be included are access to healthy foods, water quality, and psycho-social stress biomarkers. Exposure should be evaluated in all of the environments in which community members spend their time, including in homes, retail, transit, and work environments. For example, in agricultural communities, exposure to pesticides, heat, and dust in the work environment should be considered in combination with exposures indoors and in transit. CARB will also focus future research on improving user-friendly access to data on real-time exposure and their cumulative impacts on public health.

IDENTIFYING SOURCES

This Plan will address this research question related to identifying pollution sources:

- What pollution sources contribute to the elevated pollution levels in disadvantaged communities?

To address the issue of vulnerability of low-income and minority populations to exposure to air pollution and the resulting air pollution-related illnesses, CARB has supported a variety of in-house and external research efforts. Current in-house research is focused on comparing the trends in pollutant concentrations in high and low socioeconomic status communities. This work allows CARB to track the effectiveness of current rules and regulations to reduce traffic-related pollutants, as well as to quantify their impact on specific vulnerable communities to ensure that California's disadvantaged communities benefit equitably from California's air pollution control programs.

CARB's work on exposure disparities in disadvantaged communities has focused on long-term monitoring of multiple criteria pollutants and air toxics in communities across the State. This work has been implemented in collaboration with Manuel Pastor, Rachel Morello-Frosch, and James Sadd. Results from this work indicates that pollutants with controls that impact near-source concentrations, diesel particulate matter (DPM), NO_2, and CO, have the greatest decreases at monitors located in EJ census tracts. The regional pollutants, PM2.5 and ozone, are

formed in the atmosphere far from sources, and show similar declines at monitors located in both EJ and non-EJ communities (Figure 5**)**. This information will help guide continued efforts to reduce local exposures of these regional pollutants and has highlighted the need to identify the sources of these disparities in EJ communities.

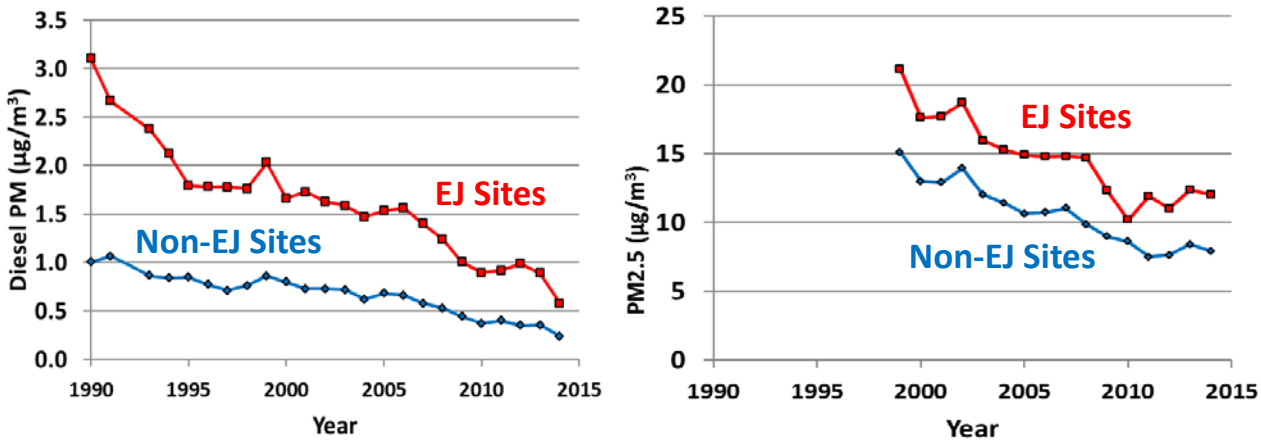


Figure 5: Diesel particulate matter (DPM) and PM2.5 disparities between environmental justice (EJ) and non-EJ sites.

To further explore PM2.5 hotspots, we are using satellite data to identify high PM2.5 areas. A study initiated in fiscal year 2017-18 will examine sources contributing to higher levels of PM2.5 in disadvantaged communities. This project will develop a methodology to more accurately characterize exposure to PM2.5 sources in CA and help to prioritize sources contributing to higher concentrations in EJ communities. Another study that was also initiated in fiscal year 2017-18 will identify sources contributing to higher levels of benzene and other air toxics in disadvantaged communities by conducting a statewide survey of air toxics concentrations in disadvantaged communities with the highest CalEnviroScreen scores. These studies will be useful in the identification of emission sources that need further control in EJ communities, with the goal of minimizing exposure disparities in California.

A pilot study that began in fiscal year 2016-17 characterized the potential health and equity impacts of oil and gas extraction activities in California. The proliferation of oil and gas exploration activities in California and nationally has raised concerns about the potential health and equity impacts on local communities due to increases in air pollution and water contamination. Residential proximity to production may increase exposures to air pollutant emissions. This study looked at the relationship between health risks and distance from oil and gas development sites in California, with the aim of more fully characterizing the health and environmental equity impacts of oil and gas development. This work will inform new research to expand the scope of this line of study to leverage existing collaborations with FluxSense INC to measure the co-emissions of gaseous toxics and other volatile organic compounds (VOCs) from these methane super-emitters. This data will allow for a more detailed analyses of the relationship between health risks, equity impacts, methane super-emitters, and their associated co-emissions from gaseous toxics and other VOCs from oil and gas development and

activities in the State. Results from this work will also help to better characterize the potential health and equity impacts on local communities and help provide a better understanding for policy and strategies for conducting targeted research and monitoring in areas of concern. In addition to expanding monitoring efforts to identify air toxics of concern and their sources in EJ communities, future research should also assess the effectiveness of CARB's regulatory programs in EJ communities by building databases to track GHG and co-pollutant reductions from CARB programs. In this way, a basis for testing patterns of disparity in these communities can be developed.

SATELLITE DATA, TOXICS, AND ODORS

This Plan will address this research question related to satellite data, toxics, and odors:

- What can new measurement and data analysis methods reveal about previously hard-to-detect sources of air pollution, particularly in disadvantaged communities?
- How can advanced screening tools that integrates all of the real-time air quality monitoring data be used to identify air pollution hotspots for mitigation purposes

CARB's environmental justice research has recently expanding to include innovative methods to detect and monitor air toxics, such as benzene, toluene, ethylbenzene and xylene (BTEX). A project initiated in fiscal year 2017-18 will conduct a statewide survey of sources contributing to higher levels of benzene and other air toxics concentrations in disadvantaged communities with the highest CalEnviroScreen scores. The results from this study will be useful to identify high-risk communities for prioritizing air pollution mitigation efforts, support enforcement efforts to address high BTEX sources, and conduct real-world verification of the impact of the oil and gas regulation (effective Jan 1, 2018) on methane and BTEX emissions. This project compliments planned community monitoring efforts by CARB that will measure speciated VOCs and other toxics of concern around oil and gas infrastructure.

Although technologies to monitor for criteria pollutants are currently available, commercial technologies are not available for monitoring toxic metals in real time. A project initiated in fiscal year 2017-18 will address this by examining the efficacy of various portable technologies to measure ambient concentrations of toxic metals in real time. The results of this project will identify the most cost effective and efficient monitoring technologies to support CARB's Air Toxics Program in its efforts to detect ambient concentrations of a broad range of metals. This project will also help to identify potential sources of toxic metals, and help prioritize subsequent efforts to further evaluate the emissions from these sources. This work overlaps with the interests of the air districts and other research entities. CARB staff is collaborating with these organizations to ensure that concurrent efforts are not duplicated.

CARB staff are also developing novel applications of satellite remote sensing data for estimating spatially resolved PM2.5 concentrations. This effort will generate concentration estimates at a 1 km resolution scale (Figure 6). The availability of a PM2.5 concentration pattern gradient

presents tremendous opportunity to examine air pollution “hot spots” across California. This data is particularly valuable for finding high PM2.5 areas where monitors do not exist. Such hot spot identification will allow more robust health effect studies in California. Furthermore, this data has the potential to advance efforts for reducing disparities among disadvantaged communities identified under AB 617 initiatives.

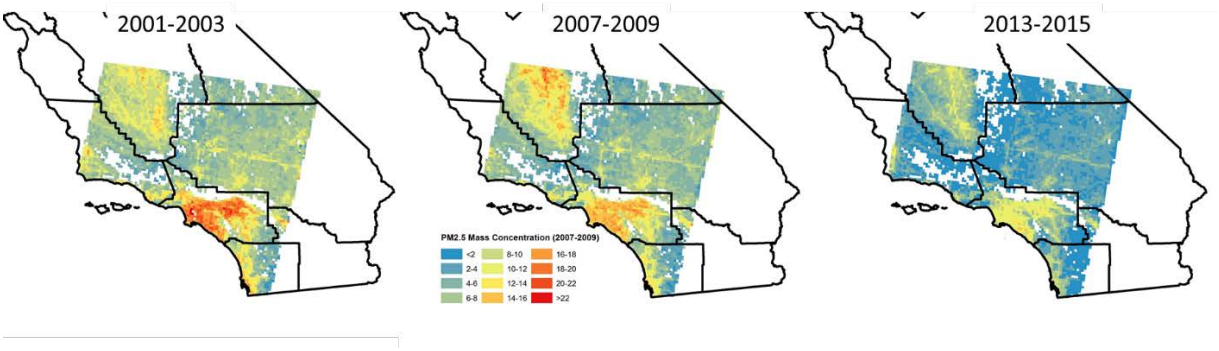


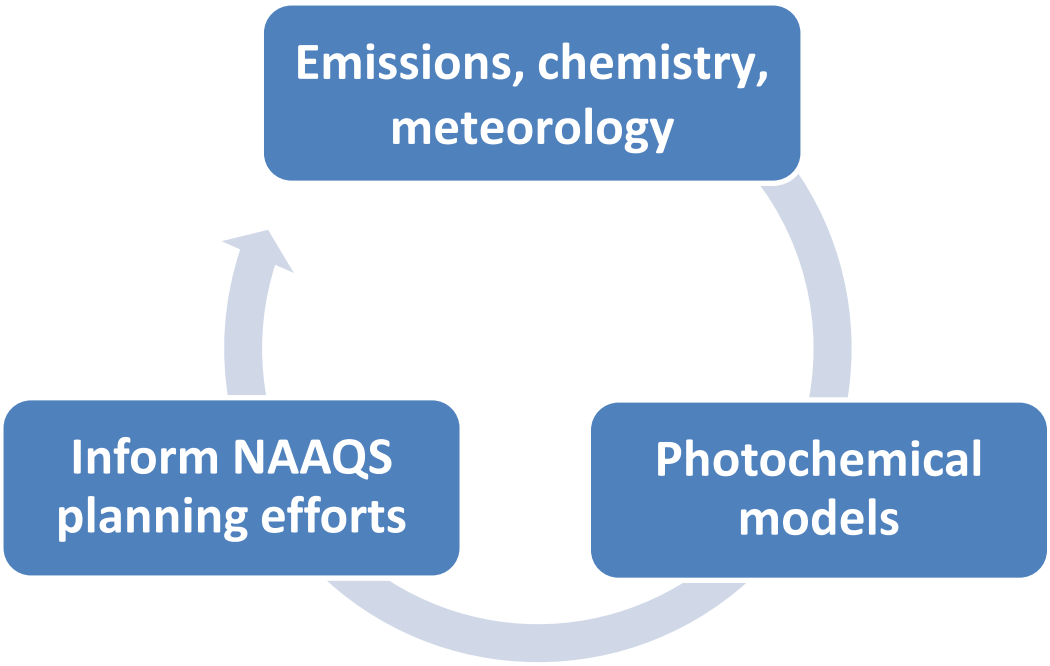
Figure 6: The spatial distribution of PM2.5 mass concentration in Southern California 2001-2015

These projects are a first step to developing community monitoring systems and identifying hotspots. Additional research to support the development of programs that provide accurate, real-time monitoring of toxic air contaminants, and identify remaining health risks, is critical to protect vulnerable populations. Long-term community monitoring systems for a broad suite of toxic air contaminants need to be established, especially in disadvantaged communities. This research should leverage existing monitoring equipment already available and establish methods to ensure the accuracy of the data collected from existing and future monitoring equipment. Some of the highest priority toxic air contaminants include particulate emissions from diesel exhaust, aromatic hydrocarbon toxics like benzene, toluene, ethyl benzene and xylene from light and heavy duty vehicles, polycyclic aromatic hydrocarbons (PAHs) from light-duty, heavy-duty, and off-road mobile equipment, and improved speciation profiles for hexavalent chromium in total chromium concentrations. Additional work to determine the necessity for the development of a short-term (1-hour) PM2.5 standard is also a priority, since recent studies have shown that traffic related air pollutants (of which PM2.5 is a major component) may produce health effects with exposure times as short as one hour.

Future research will aim to identify pollutants that may be responsible for odor complaints from a variety of air pollution sources, such as foundries, diaries, industrial facilities, and fuel storage facilities. This work will evaluate the potential health impacts of odors from these sources, and monitoring methods for identified pollutants. Noise is also a variable that should be monitored and evaluated for its impact on health on vulnerable populations in California. This issue is particularly true near high-speed roads where most of the sound is generated by tire contact with pavement, not engines.

STATE IMPLEMENTATION PLANS (SIP)

CARB's research continues to improve the scientific foundation that supports the development of State Implementation Plans (SIPs) in compliance with the Clean Air Act requirements for meeting the National Ambient Air Quality Standards (NAAQS). CARB's air quality research has improved emissions inventories, chemical mechanisms, and air quality models that provide the technical foundation for California's SIPs. To support these efforts, numerous laboratory, field, and modeling studies have been conducted to improve our understanding of the nature of the air pollution problems in the South Coast Air Basin, San Joaquin Valley, and other areas of the State.



SIP Research Highlights – Science-based Strategies to Improve Air Quality

CARB's air quality research program has collaborated with various partners on multiple large-scale field studies. These field studies brought instrumented aircrafts, research vessels, ground-based laser systems, and other state-of-the-science instruments to study the influence of emissions, meteorology, atmospheric processes, and long-range transport on surface ozone and PM2.5, all while establishing the nexus between air quality and climate change in California. Major results from these studies include top-down assessments of emission inventories for ozone precursors, PM2.5 precursors, and greenhouse gases; the quantification of long-term trends in ozone precursor emissions; an improved understanding of the important role of nitrogen oxide (NO_X) emission control for simultaneous reductions in both ozone and PM2.5, and identification of the potential climate change impact that could affect ozone standard attainment. There are clear interactions between climate and criteria pollutants within the atmosphere. These interactions often worsen the impacts from greenhouse gases and increase background levels of criteria pollutants. The findings from these field studies informed the development of the SIPs and helped track and model progress towards attaining California's air quality and climate goals.

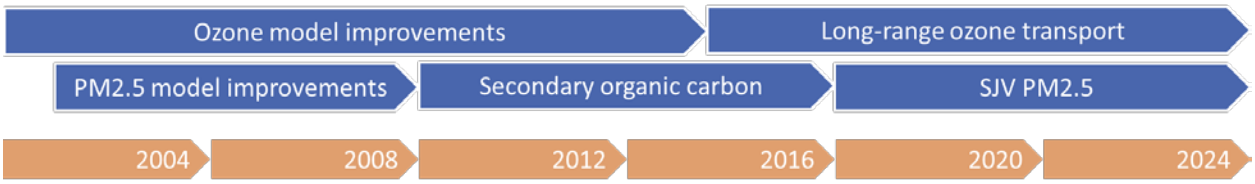
In order to disseminate research results, increase collaboration, and leverage concurrent research activities, CARB coordinates with researchers, and other entities interested in improving air quality, through sponsorship of three major series of scientific conferences biennially at the University of California at Davis; the International Conference on Atmospheric Chemical Mechanisms (ACM), which mainly focuses on gas-phase chemistry that leads to ozone formation, the International Aerosol Modeling Algorithms (IAMA) conference, which focuses on the PM formation mechanisms, and the Meteorology And Climate – Modeling for Air Quality (MAC-MAQ) conference which focuses on the modeling and prediction of regional climate and meteorology as it relates to air quality. In addition, CARB sponsors the annual Symposium on Kinetics and Photochemical Processes in the Atmosphere (ISKPPA) with focus on preliminary results derived from ongoing air quality research projects, including those funded by CARB.

FY 2018-21 Research Initiatives for State Implementation Plans

CARB's air quality research portfolio will continue to improve the scientific foundation that supports the development of SIPs for meeting the NAAQS. Results from research in this program area have refined emissions inventories and improved our understanding of chemical reactions in the atmosphere, and has led to the development of improved air quality models

that provide the technical foundation for California's SIPs. There will be a continued focus on long-range transport of ozone and sources of PM2.5 in the San Joaquin Valley.

The timeline below depicts high-level research initiatives (groups of projects on a given topic) that have led to the development of our current research priorities. The timeline extends to 2024 to account for the time that research projects initiated by the Triennial Plan would be completed. Bars in shades of red represent new research initiatives, while bars in shades of blue represent research initiatives that have either concluded, or are currently in progress and will continue to be a priority in the future.



LONG-RANGE OZONE TRANSPORT

This Plan will address these research questions related to long-range ozone transport:

- As local emissions are reduced, what is the impact of baseline ozone on regional air quality?

Health effects research has consistently led to more stringent ambient air quality standards for ozone, therefore California must continue to achieve significant new reductions in ozone precursor emissions. As regional ozone concentrations decrease, due to emission controls, background ozone is becoming a larger fraction of ozone in the ambient air, making attainment of the more stringent ozone standards increasingly difficult. Understanding the variability and concentrations of baseline ozone is critical for attainment of future ozone standards.

A large number of observations around the world have documented the presence of elevated ozone concentrations aloft that could potentially contribute to ground level exceedances. While some field studies have collected measurements of aloft ozone near and over California, these relatively short-term efforts do not provide sufficient information to fully explain the spatial and temporal variations in baseline ozone concentrations entering California and the processes by which baseline ozone aloft may mix down and contribute to surface ozone standard exceedances.

The California Baseline Ozone Transport Study (CABOTS) was designed to investigate policy relevant questions about the content and daily variability of ozone vertical profiles as they enter the State from the Pacific Ocean, and the extent to which trans-Pacific long-range transported ozone mixes down to surface sites in the San Joaquin Valley (SJV). CABOTS is a coordinated effort with San Jose State University and NOAA. Aircrafts flown by two NASA

programs, two CARB-funded contracts, and a surface ozone monitoring site in the Coastal Range supported by the San Joaquin Valley Air Pollution Control District became the foundation of this study. The field measurements have provided a detailed observation-based analysis of ozone over California and highlight the importance of considering both surface ozone and ozone aloft in the context of increasing baseline ozone and more stringent air quality standards. Given the challenges of modeling ozone in the mountainous terrain of the western U.S., this study provides useful insight into the sources of elevated surface ozone observed in the rural western U.S.

CARB is also funding a project that began in fiscal year 2017-18 that will analyze aerial ozone measurements collected by NASA during CABOTS to better understand vertical ozone distributions over California. In addition, a CARB-BAAQMD modeling collaboration is ongoing to evaluate the performance of chemical transport models through sensitivity analysis of atmospheric boundary conditions. Additional work on this topic is needed to fully understand the impact of baseline ozone on regional air quality to effectively develop regulatory policies addressing ozone attainment in California, especially as local emissions are reduced.

SAN JOAQUIN VALLEY PM2.5

This Plan will address these research questions related to new sources of PM2.5 in the San Joaquin Valley:

- What are the remaining sources of ammonia, PM2.5, and PM2.5 precursors in the San Joaquin Valley (SJV) and what are the air quality impacts in downwind communities?
- What opportunities are there for controlling sources of ammonia, PM2.5, and PM2.5 precursors?

CARB has funded several projects to improve the PM modeling for the SJV, which is needed to address the more stringent annual-average PM2.5 standard adopted by the U. S. EPA in 2012. These projects have incorporated field observations into improved models for the stagnation events leading to PM2.5 exceedances. The identification and removal of biases in model inputs and the further development of new processes for PM2.5, in particular nitrate, formation will allow regional chemical transport models to predict the effects of future emissions control strategies at lower PM2.5 concentrations which are expected in the coming decades.

CARB research has specifically addressed the complex problem of modeling secondary organic aerosol (SOA) formation. Organic aerosols are a significant component of PM2.5 in California. As emissions from more dominant air pollution sources continue to decrease, less prominent SOA precursor sources become more important for future SOA reduction and attainment of the PM2.5 standard. Hence, the sources, impacts of existing controls, precursors, and processes that form SOA are the focus of several research projects. Increasing our knowledge of the processes associated with SOA formation will improve PM2.5 modeling used in SIPs. CARB also funded projects to address questions concerning organic compounds used in consumer

products. These projects answered questions about the environmental fate of currently exempt low vapor pressure volatile organic compounds (LVP-VOCs) and the actual impact of these compounds on ozone and SOA formation. While the results of these experiments are useful to calibrate models and provide SOA formation relative to chemical structure of the compounds, it is noted that real atmospheric conditions vary widely and the results of this work only represent SOA formation in certain environmental conditions. Hence, further detailed studies are required to determine functional relationships of other LVP-VOC compounds to improve future PM2.5 modeling.

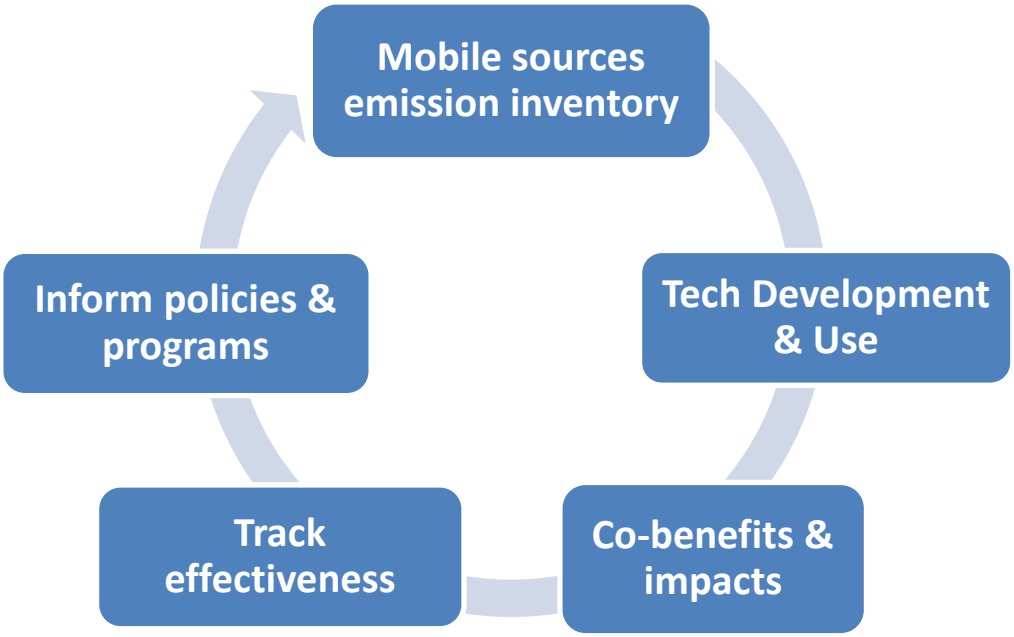
Although air quality in the SJV has improved in recent years, the area still exceeds the federal standards. Conditions that have led to recent PM2.5 exceedance events need to be better understood to attain future PM2.5 standards. A project that began in fiscal year 2017-18 will acquire and deploy an advanced air quality analyzer in the SJV to collect measurements that will allow researchers to identify sources and chemical pathways that lead to PM2.5 formation. This project will measure concentrations of PM2.5 species with sub-hourly time resolution, thus bridging the gap between the long-term measurements and detailed observations from short-duration field campaigns. The results from this study will contribute to the development of effective and appropriate future PM2.5 control strategies for the SJV.

Dairy operations are an important source of greenhouses gases (GHGs), volatile organic compounds, and nitrogenous compounds. CARB funded a project that aims to utilize ambient measurements and chemical transport modeling to evaluate the GHG emissions and the AQ impacts of California dairies after the implementation of alternative manure management practices (AMMPs). The results from this project will help determine whether the implementation of AMMPs in California’s agricultural sector is an effective air pollution mitigation strategy for existing dairies, and will help construct regulatory policies for the development of SIP and Short-Lived Climate Pollutant reduction strategies.

Although there is a significant amount of current in-house, sponsored, and leveraged research activity to support SIP development, additional research is needed to further understand the important atmospheric processes that affect air quality under California's future emissions scenarios and in a changing climate. Continued research on unsolved and emerging sources of PM2.5 will help to support the development of control strategies for achieving stringent air quality standards as well as California's greenhouse gas targets. For example, modeling of ammonium nitrate in the SJV, the single largest component of PM2.5, could be improved through targeted collection of ambient ammonia data and improved chemical mechanisms.

MOBILE SOURCES

CARB's mobile source emissions research program supports California's effort to meet NAAQS, reduce health risk from toxic air contaminants, and meet GHG reduction goals. The results of these research efforts support the development and implementation of regulations and incentive programs that reduce transportation related emissions. The research in this area often evaluates advanced emission reduction technologies and monitors the effectiveness of emission reduction strategies to ensure that the expected air quality and public health benefits are achieved. The results from this suite of projects are also used to ensure that emission reduction programs don't have any unintended impacts, and provide information for future policy development.



Light Duty Research

Light Duty Research Highlights - Tracking Real-World Passenger Car Emissions

In order to address the question of how decades of evolving emissions standards affected real-world emissions from California's light-duty vehicle fleet, CARB initiated a project in fiscal year 2012-13 with University of Denver researchers to sample passenger vehicle emissions at a West Los Angeles freeway on-ramp where the researchers had sampled vehicles in several previous campaigns since 1999. The researchers found that California's emissions control programs have reduced real-world emissions of carbon monoxide, hydrocarbons (HC), and oxides of nitrogen from light-duty vehicles by 70-80 percent between 1999 and 2015. The researchers also found an abrupt increase in average vehicle age – from 7.4 years in 2005 to 9.1 years in 2015 – reversing the prevailing trend. The explanation for this trend reversal was a 45 percent drop in

California new car sales from 2007 to 2009 due to the economic recession. This downturn in the economy resulted in a larger number of 10-to-20-year old vehicles remaining in circulation longer, meaning that 2013 passenger cars' emissions were as much as 28 percent higher than they would have been without the recession. Since 2009, new light-duty vehicle sales have rebounded to pre-recession levels, but even at this rate it will take more than 20 years to return to the 2008 average vehicle age of 7.4 years. Meanwhile, the share of emissions from the dirtiest 1 percent of passenger cars increased between 1999 and 2015. The highest-emitters' share of fleet HC emissions, for example, grew from 17 percent in 1999 to 46 percent in 2015 (Figure 7). This research verifies that CARB's mobile source emission control programs are performing as expected, and underscores the value of vehicle scrappage programs that get the highest-emitting vehicles off the road (such as CARB's Enhanced Fleet Modernization Program).

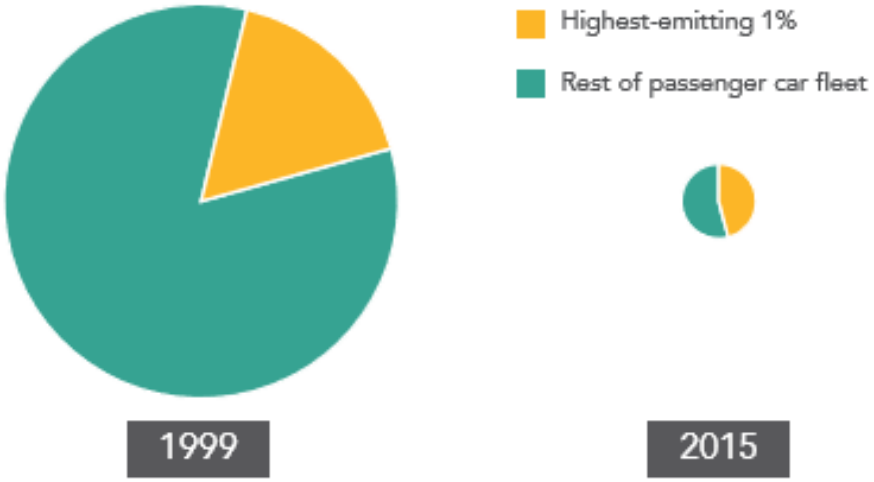


Figure 7: The share of hydrocarbon emissions from the highest-emitting passenger vehicles in 1999 and 2015. (Circles are scaled to fleet average emission factors)

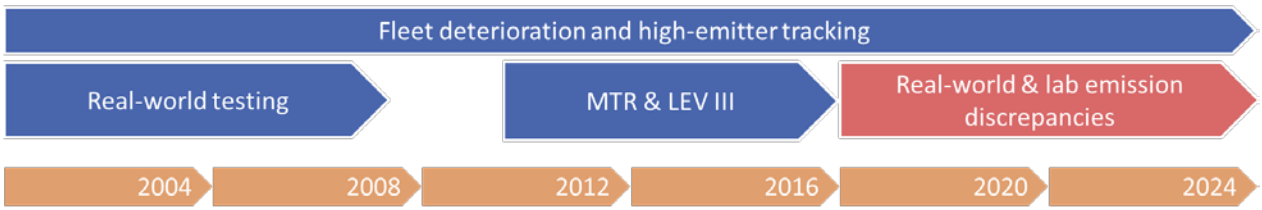
Based on in-house work using the same dataset, it was found that passenger vehicle emissions are highly correlated with community socioeconomic status (SES). Although emissions from passenger vehicles had been reduced substantially across the communities over the sampling periods, emission factors for the highest SES value communities (e.g., disadvantage communities) were three to ten times higher than the lowest SES value communities, depending on pollutants. Potentially, this result could be involved with that the vehicles in disadvantage communities operate with higher accumulated vehicle miles, less preventative maintenance, higher LEV proportion and lower ULEV proportion in LEV I technology group. This finding calls for enhanced ZEV incentive programs for disadvantaged communities.

Light Duty Research Initiatives for FY 2018-21

For light-duty vehicles, research on criteria pollutant reductions has focused on the long-term trend in real world emissions, which is providing an understanding of how well the emission controls continue to perform in vehicles subject to LEV I and II. In response to the adoption of the Advanced Clean Cars program, CARB's research expanded to include a portfolio of projects

that address market forces, consumer acceptance, and driving and fueling behavior associated with new vehicle technologies. Results from these projects informed the "Midterm Review" of the Advanced Clean Cars program. This research will now focus on the discrepancies between real-world and laboratory emissions and will inform the Advanced Clean Car II program.

The timeline below depicts high-level research initiatives (groups of projects on a given topic) that have led to the development of our current research priorities. The timeline extends to 2024 to account for the time that research projects initiated by the Triennial Plan would be completed. Bars in shades of red represent new research initiatives, while bars in shades of blue represent research initiatives that have either concluded, or are currently in progress and will continue to be a priority in the future.



FLEET DETERIORATION AND HIGH EMITTER TRACKING

This Plan will address these research questions related to fleet deterioration and high emitter tracking:

- What makes and models of light-duty vehicles are high emitters?
- How should current monitoring efforts adapt to detect the existence of new defeat technologies?

CARB has invested in research efforts to monitor fleet emissions to identify high-emitting vehicles and evaluate the effectiveness of emission reduction technologies. This work has employed a variety of methods, including remote sensing and on-road portable emission measurement systems. Recently, this work allowed for the discovery that certain makes and models of vehicles had employed a "defeat device" enabling certain models of their vehicle to pass the certification testing, but emit at much higher levels in actual real-world use. The question arises whether there are other vehicle makes and models exhibiting similar behavior, and whether or not this is a widespread problem.

In order to identify high emitting light-duty vehicle (LDV) makes and models, a project initiated in fiscal year 2017-18 will leverage an existing dataset of over 50 million remote sensing emission measurements to identify specific vehicle makes and models that have higher than expected on-road emission rates. A second project will evaluate LDV emission trends by continuing a series of criteria pollutant measurement campaigns in West Los Angeles using remote sensing devices. Together, these projects will improve the emission inventory, identify

issues important to SIP compliance, track program effectiveness, assess disproportionate exposure in disadvantaged communities, and guide future regulation development.

Going forward, it will be necessary for CARB to continue monitoring efforts to identify anomalously high emitting makes and models to alert regulators of the potential existence of new defeat technologies. This line of research will continue to inform inventory estimates and guide future regulation development and enforcement. Identification of the specific makes and models could be used as the basis to initiate targeted investigations into manufacturer's practices and to support regulatory compliance actions.

REAL-WORLD & LAB EMISSION DISCREPANCIES

This Plan will address these research questions related to real-world and laboratory emission discrepancies:

- How can on-board diagnostic data be effectively collected and used to easily evaluate activity and engine performance to assess real-world emissions, energy use, and operating patterns of light-duty vehicles to inform certification cycles?
- What most effective monitoring technologies are available to measure real-world tailpipe emissions (e.g., smaller PEMS) and verify on-board diagnostic tools?
- How will advanced technology vehicles change emissions from the light-duty fleet (e.g. impacts from cold start emissions in hybrids and PM from regenerative braking)?

CARB's LDV research also monitors the effectiveness of emission reduction strategies to ensure that the expected air quality and public health benefits are achieved. This research has informed the State on how well the emission controls continue to perform in vehicles subject to LEV I and LEV II, and the transition to SULEVs. In 2012, CARB adopted the Advanced Clean Cars program to reduce emissions from passenger vehicles in accordance with California's long-term air quality and climate goals. As a result, CARB-funded research on light-duty vehicles expanded beyond emissions measurements, and now includes a portfolio of projects that address market forces, consumer acceptance, and driving and fueling behavior associated with new vehicle technologies. Results from these projects informed the "Midterm Review" of the Advanced Clean Cars program, and continue to support the State's efforts to attain zero-emission vehicle targets and greenhouse gas and PM standards.

Future research will aim to address remaining challenges associated with regulation compliance, and improving emission inventory data. These challenges include the disparity between real-world emissions and those measured during certification, and the insufficiency of data to track the long-term effect of the Low Emission Vehicle regulation in reducing exhaust emissions. Testing has also confirmed that cold-start emissions during plug-in hybrid drive cycles can be significantly higher than emissions from traditional engine cold starts. In order to address these issues, a project that was initiated in fiscal year 2017-18 will characterize the activity profiles of cold start emissions produced by blended plug-in hybrid vehicles in order to

understand the real-world scale of the increased emission profiles previously measured in the lab.

Although regulations have resulted in meaningful decreases in combustion-related emissions from on-road vehicles, emissions from non-tailpipe sources, such as airborne dust from brake and tire wear have remained relatively constant, and are projected to become an increasingly larger portion of the on-road PM2.5 inventory in the future. Research began in fiscal year 2017-18 to refine emission estimates for brake wear by measuring PM emissions from this source under controlled laboratory conditions. CARB hopes to compliment this project with future work to measure emissions from tire and brake wear near roadways. Results of this study will be useful in refining the fractional contribution of non-exhaust PM in emissions inventories and provide a better understanding of the impact of this increasingly important source has on air quality.

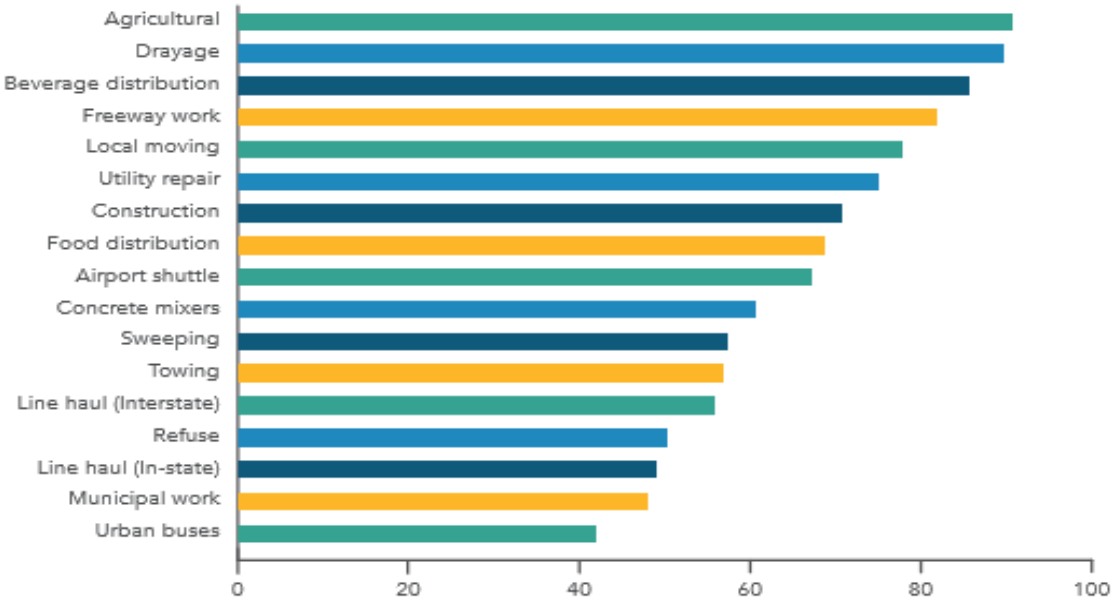
CARB has also started addressing the disparity between real world and laboratory emissions by initiating in-house research to collect activity data from internal combustion engines and advanced propulsion technologies using on-board diagnostic (OBD) wireless transmitters with smartphone applications and OBD dataloggers. The data will be used to evaluate real-world energy use, and determine how this energy use is influenced by operation conditions and vehicle characteristics. Findings from this study will advance understanding of real-world vehicle activity and energy use patterns and examine the cost effectiveness of operating advanced technology vehicles compared to internal combustion vehicles. Going forward, additional research will build on this work to provide essential information on activity and engine performance that will be used to make accurate assessments of the real-world emissions, energy use, and operating patterns of LDVs, as well as comparison of real-world duty cycles with certification cycles.

Heavy-Duty, Off-road, and Freight Research

Heavy-Duty, Off-road, and Freight Research Highlight - One for the Road: Big Trucks, Big Data, Big Difference

CARB's Mobile Sources research includes forward-thinking projects that address the agency's long-term needs related to updating emission inventories and track the progress of regulations aimed at reducing transportation-related emissions. California's efforts to reduce particle pollution from heavy-duty diesel vehicles have been very effective but more recent health science emphasizes the need to do more to protect children and other vulnerable residents living near large concentrations of diesel sources. Heavy-duty vehicles remain California's largest source of diesel particulate matter (DPM) and oxides of nitrogen (NO_X). Modern exhaust treatment systems work best for NO_X when the exhaust is very hot, above 250 degrees Celsius (250˚C). When the exhaust is cooler, such as just after engine ignition, or when idling or crawling through traffic, the exhaust treatment is less effective, and the trucks therefore emit more NO_X. Researchers from the University of California, Riverside found that the exhaust of many types of large trucks and buses is below 250˚C for at least half of their working hours

(Figure 8). Data was collected for both location and exhaust temperature from 90 heavy-diesel vehicles representing 19 vocations. CARB will use this data to estimate where and when each type of



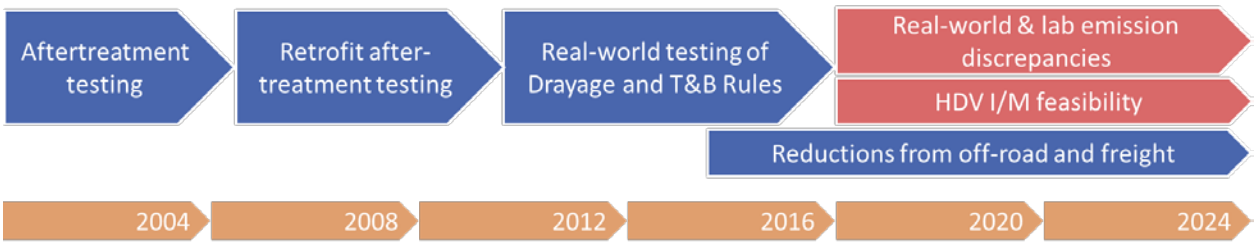
vehicle emits the most pollution. These results, and additional analysis of collected data, will enable CARB to improve vehicle emission control programs, and help achieve emissions reductions vital to reaching long-term air quality goals outlined in California's Mobile Source Strategy.

Figure 8. Fraction (%) of operating time with exhaust temperature < 250˚C

Heavy-Duty, Off-road and Freight Research Initiatives for FY 2018-21

In the heavy-duty sector, research to reduce criteria pollutants has focused on the durability of emission control technologies, and tracking the results of regulatory efforts. New research will provide information on the feasibility of the heavy-duty vehicle inspection and maintenance (HDV I/M) program. Another priority for heavy-duty research will focus on reducing emissions from off-road equipment and identifying strategies to improve efficiencies in the freight sector.

The timeline below depicts high-level research initiatives (groups of projects on a given topic) that have led to the development of our current research priorities. The timeline extends to 2024 to account for the time that research projects initiated by the Triennial Plan would be completed. Bars in shades of red represent new research initiatives, while bars in shades of blue represent research initiatives that have either concluded, or are currently in progress and will continue to be a priority in the future.



REAL-WORLD & LAB EMISSION DISCREPANCIES

This Plan will address these research questions related to real-world and laboratory emission discrepancies:

- Which on-road heavy-duty vehicles have high emissions and community exposure impacts, including high rates of deterioration and malfunction?
- How can the operating conditions of heavy-duty vehicles with higher than expected criteria pollutant emission rates be identified?

CARB's research has focused on monitoring emissions from the heavy-duty sector in order to improve our understanding of trends in on-road emissions. This research has tracked the effectiveness of current regulations (i.e., Drayage and Truck and Bus Rules), and programs to reduce DPM emissions by 85 percent from 2000 levels, by 2020. In order to estimate the effectiveness of in-use rules, diesel emissions research has examined the durability, degradation, and failure rates of aftertreatment that reduces NO_X and DPM, and the real-world efficacy of NO_X controls. This has been accomplished by measuring emissions from the in-use fleet on laboratory dynamometers, in tunnels, at ports, and at weigh-in-motion stations in California.

Current research on heavy-duty diesel vehicles is underway to adapt diesel particulate filter use to a wider variety of engines, how to achieve significant additional NOx emission reductions, and develop and deploy zero-emission technology and infrastructure. To support and inform the California Sustainable Freight Action Plan (CSFAP), the 2016 SIPs, and other CARB emission reduction planning efforts, CARB and the South Coast Air Quality Management District have been conducting technology and fuels assessments for a variety of source categories. Work that began in fiscal year 2016-17 expanded this effort to assess emissions of in-use NO_X from vocational trucks with multiple engine types and alternative fuels. Results from this research will improve emission inventories used for air quality planning, explore the effective applicability of engine and fuel technologies to specific vocation types, and develop effective strategies for achieving the federal ambient air quality standards. These assessments will provide essential information on the technologies and fuels that will provide the most benefit for California to meet its air quality and climate goals, including black carbon reductions. Research initiated in fiscal year 2017-18 will add to these efforts by modeling emission reductions we can expect from advanced technologies, such as connected and automated

fleets, and projecting criteria pollutant and greenhouse gas emissions from heavy-duty fleets out to 2050. Together, this work will inform policies and the use of incentive funds to help us achieve climate and air quality goals in the heavy-duty sector and avoid unintended impacts on disadvantaged communities.

HEAVY-DUTY INSPECTION AND MAINTENANCE FEASIBILITY

This Plan will address these research questions related to heavy-duty inspection and maintenance feasibility:

- How can advanced methods to analyze big data and behavioral science be harnessed to make "smarter" regulations and streamline enforcement?
- How can the identification of vehicles and manufacturers with high rates of deterioration, malfunction, and cheating be streamlined?

Remaining research needs include the evaluation of the evolving state of telematics technology and its potential as a useful tool in tracking fleet deterioration. This research would help inform a large-scale heavy-duty vehicle inspection and maintenance program. Establishing the reliability of on-board diagnostic technology to identify malfunctions and high emitters is also needed to ensure that this tool is having its intended effect. Additionally, it will be important to identify potential security weaknesses in order to minimize fraud and ensure that all transmitted data is secure. Non-traditional data sources, such as on-board diagnostic and engine control unit broadcasts will also be used to better understand real-world emissions and inform strategies for achieving reductions.

REDUCTIONS FROM OFF-ROAD

This Plan will address these research questions related to reductions from off-road vehicles and equipment:

- What small off-road vehicles and equipment have the highest emissions and community exposure impacts, and how can their emissions be mitigated?

Research on the tracking and reduction of off-road emissions began in fiscal year 2014-15 with a project evaluating the feasibility, cost-effectiveness, and necessity of equipping small (<37 kW) off-road diesel engines with advanced PM and NO_X aftertreatment. The results of this study will be used to determine whether or not small off-road engines should be subject to more stringent exhaust standards, identify reasonable levels of exhaust control based on costs, and support possible future amendments to the off-road diesel engine regulations. Additional research is looking at the impact of an alternative to current allowances for averaging fleet emissions. This project will help demonstrate compliance and determine the distribution of

engines with the best available controls and gain a better understanding of the emission impacts of current rules.

Current CARB research is also addressing remaining challenges associated with improving emission inventory data for off-road equipment and vehicles. A project that began in fiscal year 2017-18 will characterize the activity profiles for heavy-duty off-road diesel vehicles and engines used for construction. Research is also needed to refine emission estimates of NO_X as well as the activity profiles (e. g., duty cycle, load factor variation, and exhaust temperature) of equipment in the agricultural sector. Field measurements of off-highway recreational vehicles are also needed to support the emissions inventory.

Research that refines emissions estimates will help support the development of emission reduction strategies. Since the market of off-road diesel engines is expanding, and off-road emission are becoming a larger portion of the inventory due to better control of emissions from on-road vehicles, developing emission reduction strategies in the off-road sector will be essential for the State to achieve stringent air quality goals. CARB intends to focus fiscal year 2018-19 research on two projects that will examine potential strategies. One project will measure criteria and non-criteria pollutants from off-road diesel engines with different aftertreatment configurations. This work will help advance the development and deployment of low-emission off-road equipment. The second project will examine economic and technical feasibility of the electrification and hybridization of off-road equipment. Going forward, additional research will be needed to support the development and implementation of a suite of strategies to lower emissions from existing and new off-road equipment. This work will be essential to guide CARB's future incentive, regulatory and voucher programs aimed at reducing the climatic and air quality impacts of off-road equipment.

INCREASED FREIGHT EFFICIENCY

This Plan will address these research questions related increasing efficiencies in the freight system:

- What are the quantitative benefits of strategies to improve efficiencies in the freight system, individually and in combination?
- What mechanisms can support industry efforts to boost efficiency?

In July 2015, Executive Order B-32-15 directed multiple State agencies, including CARB, to work together to develop the CSFAP. The CSFAP, which was released in July 2016, establishes clear targets to improve freight efficiency, transition to zero-emission operations, and increase the competitiveness of the State's freight system. As part of the Plan, feedback was solicited from a broad range of stakeholders, including academics, industry, and government. As part of this engagement, the Freight Efficiency Strategies Development Group was formed to produce a series of white papers to identify promising strategies for increasing the efficiency of the freight system. These papers will help guide future research funded by CARB, in coordination with the

other agencies involved with the development of the CSFAP; the California Department of Transportation (Caltrans), the California Energy Commission (CEC), and the Governor's Office of Business and Economic Development (GO-Biz), California State Transportation Agency (CalSTA), the California Environmental Protection Agency (CalEPA), and the Natural Resources Agency (CNRA).

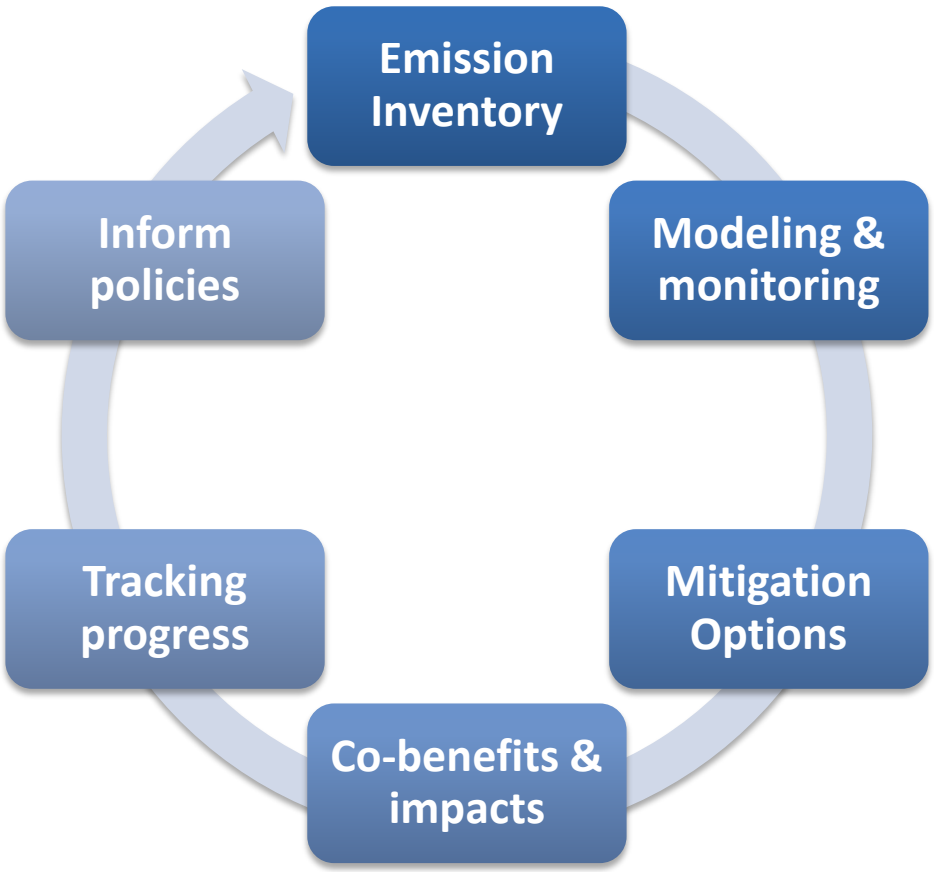
Going forward, CARB will continue to coordinate with academics, stakeholders, and State and Federal agencies to ensure that freight research efforts are efficiently leveraged and duplication of effort is avoided. Stakeholder engagement during the research development and execution process will also be essential to identify real-world needs and provide input on the feasibility of implementing potential efficiency strategies. California is a diverse geographic location for freight, with various requirements and constraints throughout the State. Research to improve efficiency should address the needs of the different sectors and layers of the economy. Case studies should be examined and regional strategies should be defined, since no single strategy will result in significant improvements on its own. The inherently complex and evolving system will require an equally complex and visionary set of solutions.

Current research priorities include identifying sources of inefficiencies in the on-road trucking and maritime sectors, where congestion often impedes maximizing asset utilization. Urban freight also faces many challenges due to lack of parking infrastructure, conflicting regulations, and higher costs of conducting business in many large dense areas. Strategies should focus on freight planning at all levels by fostering collaborative logistics practices and freight demand management, and identifying behaviors that need to be fostered, or mitigated. In many cases, lack of data is the greatest barrier to conducting assessments of these systems. Therefore, research efforts should also focus on efforts to estimate the magnitude of the potential effects of implementing each efficiency strategy (e.g. reduced congestion/delays, lower emissions, increased safety, economic impacts, and costs).

GREENHOUSE GAS INVENTORIES AND MITIGATION

California's seminal Global Warming Solutions Act, AB 32, charges CARB with developing a Scoping Plan that describes the approach California will take to reduce GHG emissions to achieve the goal of reducing emissions to 1990 levels by 2020. SB 32 recently codified a new 2030 GHG emissions target of 40 percent below 1990 levels by 2030.

SLCPs and nitrous oxide (N_2O) emissions reductions are critical to achieving California's GHG emissions reduction goals set by AB 32 and SB 32. SLCPs include methane (CH_4), F gases (including hydrofluorocarbons, or HFCs), black carbon (soot). These gases are powerful climate forcers that have an outsized impact on climate change in the near term compared to longer-lived GHGs such as carbon dioxide (CO_2). SB 1383 (Lara, 2016), also requires a 40 percent reduction in methane and HFC emissions and 50 percent reduction in black carbon emissions, all relative to 2013 baseline levels by 2030. CARB's research program has sponsored external research and developed in-house research initiatives to support the agency's efforts to inventory, monitor, and mitigate the emissions of these SLCPs in order to track progress toward achieving these mandates and inform future legislation.



Climate Research Highlight - Tracking and Reducing Emissions of Climate Pollutants

CARB's research continues to improve our understanding of emissions of important climate forcing pollutants, such as CO_2, N_2O, and SLCPs. The climate research program leverages wide ranging in-house research efforts including a variety of measurements and modeling studies, which are complemented by numerous collaborative research efforts that provide critical results from satellites, aircraft, towers, mobile units, field studies, and remote sensing devices, as well as laboratory and modeling analyses.

Analysis of long-term measurements demonstrated a 90 percent reduction in ambient black carbon levels throughout California over the past 45 years, which confirms the successful implementation of California's diesel emissions control program and agricultural burning management activities. Field measurements of CH_4 and N_2O emissions from soils growing California's most economically important crops supported the development of a model to estimate GHG emissions from the application of fertilizers. This model is currently being used in-house for the development of CARB's state-wide inventory. Satellite, aerial, and ground-based measurements of CH_4 are leading to emission inventory improvements for all important source categories. CARB's dense network of CH_4 measurement efforts was also crucial to the State's response during the Aliso Canyon natural gas leak in the Los Angeles Air Basin. F-gas research has led to the establishment of the State's inventory, and identified mitigation strategies that have resulted in the successful development and implementation of multiple regulations and programs to reduce F-gas emissions. These programs include the Refrigerant Management Program, Small Can Regulation, Cap-and-Trade Program Compliance Offset Protocol for Ozone-Depleting Substances, and a new regulation to prohibit the use of certain

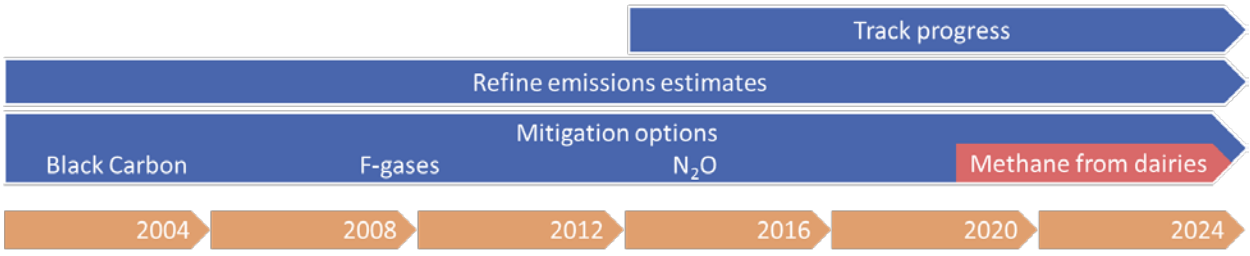
high-global-warming-potential HFCs in stationary refrigeration equipment and foams, which was approved by the Board in March 2018.

Collectively, these research efforts have helped to identify sources, evaluate the emissions from these sources, develop new emissions reduction strategies, and track progress in achieving GHG emission reduction goals across all sectors of the economy. These research efforts also allowed for a quick response when CARB was required to develop the SLCP Reduction Strategy (SB 605) and implement legislative mandates to reduce emissions of these powerful climate forcers (AB 1496 and SB 1383).

Greenhouse Gas Inventories and Mitigation Research Initiatives for FY 2018-21

Climate related research has focused on quantifying emission estimates, tracking progress of emissions reduction programs, and mitigating GHG emissions. Climate-related research projects respond to several key challenges, including SB 1383. A high priority going forward is to identify mitigation options for dairies, since they are a significant source of methane.

The timeline below depicts high-level research initiatives (groups of projects on a given topic) that have led to the development of our current research priorities. The timeline extends to 2024 to account for the time that research projects initiated by the Triennial Plan would be completed. Bars in shades of red represent new research initiatives, while bars in shades of blue represent research initiatives that have either concluded, or are currently in progress and will continue to be a priority in the future.



TRACKING PROGRESS & REFINING EMISSIONS ESTIMATES

This Plan will address these research questions related to tracking progress and refining emissions estimates:

- Are the State's regulations and programs to reduce the emissions of GHGs having their intended impact?
- Are there new or previously unknown sources of GHGs that are not captured in the State's inventory?

CARB is currently managing the operations of some key research efforts including the statewide GHG monitoring network, which measures a host of pollutants (e.g., CH_4, isotopic CH_4, CO_2,

N_2O, black carbon, and F-gases), a series of Mobile Platforms with research-grade GHG, air quality, and trace chemical measurement capabilities, as well as a series of research contracts which utilize innovative research tools. CARB staff is also involved in analyzing the complex set of data generated by the various tools to evaluate the emission behavior of important GHG sources from multiple sectors. CARB is further expanding GHG measurement and analysis efforts by initiating innovative and ground-breaking research efforts, such as high resolution VOC and toxics emissions and concentration measurements in environmental justice communities. An important goal of this research effort is to link ambient measurements to emission sources in California. In addition to the various in-house research efforts, CARB is also collaborating with others on a variety of ambient observations, including satellite, aerial, and ground-level measurements from fixed sites such as towers, mobile measurements, field campaigns, remote sensing studies that characterize sources, as well as laboratory studies. Collectively, these tools have helped us gain a better understanding of greenhouse gas sources and emissions in California.

Black Carbon

CARB research on black carbon began with the creation of a California inventory for black carbon. A CARB-funded study on black carbon observed a 50 percent reduction in black carbon measured at monitoring sites throughout California over the past twenty years, and a 90 percent reduction over the past 45 years. The 50 percent reduction in black carbon accounted for a 25 percent decrease in atmospheric heating in California. Through a collaborative research effort with NOAA, CARB was able to produce direct measurements of this forcing in the atmosphere. These results agree with the expected emission reductions associated with California's diesel emissions control program. Further reduction will likely be shown in the future due to CARB's Advanced Clean Car Program and district burning restrictions.

Black carbon, along with the co-emitted organic particles, is a major source of global dimming, which has been linked with a reduction in precipitation. The particle-cloud interactions due to black carbon, as well as the implied climate responses, were also examined. The results indicate that black carbon has more complex effects on precipitation that are dependent on vertical structure of the atmosphere and source region. Hence, considerable uncertainty surrounds the estimates of the net climate effects of black carbon. Furthermore, recent studies have suggested that certain fractions of organic carbon known as "brown carbon" could be stronger absorbers of solar radiation than previously understood. The warming effect of brown carbon may offset the cooling impact of other organic carbon particles, making the quantification of that absorption necessary for climate models to evaluate the net climate effect of organic carbon. To help characterize and differentiate sources of brown carbon from black carbon and understand their climate impact in California and globally, a current CARB-funded research project is applying advanced measurement methodology along with regional and global climate modeling simulations to characterize the extent to which brown carbon contributes to climate forcing in California. This work will improve our understanding of the fundamental processes

that dominate brown carbon formation, and help to determine the potential climate benefit of mitigating sources of brown carbon emissions in California.

CARB will continue efforts to refine the black carbon emission inventory. Wildfires represent a potentially large portion of the California black carbon inventory. Estimated black carbon emissions are very sensitive to the choice of source profile used to convert PM2.5 to black carbon. Additional measurements are needed to better characterize black carbon emissions by emission source, fuel type, and combustion conditions. These data are needed to improve black carbon emission factors and inventories, and to help reduce emissions and modeling uncertainties.

F-gases

CARB's research program on F-gases has inventoried California's sources of these high-GWP gases. Past CARB-funded research on HFCs and other high-GWP GHGs demonstrated that emissions of these gases are growing rapidly in California and are produced from a variety of sources. CARB's research program is currently funding research contracts to study the long-term ambient air concentration trends of F-gases in the South Coast Air Basin. The research program is also evaluating options to expand our F-gas air-monitoring capabilities to measure real-time regional concentrations across the State. These techniques will allow us to measure volatile organic compounds tracers in the ambient air, which will enhance our ability to study and understand the GHG emissions contributions of the various sources. Additional current research on F-gases is determining the technical feasibility, cost, and potential GHG reductions of low-GWP commercial refrigeration. CARB will continue to prioritize research to refine F-gas emission inventory estimates. Proposed research for fiscal year 2018-19 aims to improve an inventory of the current equipment in use in California that are using either HFCs or alternative refrigerants in small stationary refrigeration and air conditioning equipment. The results will be used to improve F-gas emissions estimates and will also be used to inform policy decisions to reduce GHG emissions from stationary refrigeration and air conditioning.

Carbon Dioxide

In-house and contracted projects to measure GHGs include measurements of CO_2 as a way to verify the inventory and track changes in GHG emissions as California follows its mandate to reduce emissions. This includes measurements from mobile and stationary monitors. A monitoring effort of CO_2 in the Los Angeles basin that began in 2009 also included isotopic analysis to allow the researchers to distinguish various types of fossil fuel combustion from natural CO_2 sources to better understand source contributions in the basin. This work complements the Megacities Carbon Project observing system for Los Angeles, coordinated with similar efforts in Paris and Rio de Janeiro, which utilizes multi-tiered measurements to understand GHG emissions and the impact of control policies, as a model for other cities. CO_2 monitoring will remain a research priority for CARB in order to track mitigation efforts, and understand the nature and the spatial and temporal distribution of its sources. In particular,

CARB will work to ensure that long-term monitoring efforts are maintained, especially since the longevity of federally funded programs working on this topic remains uncertain.

Nitrous Oxide

CARB's N_2O emission inventory research has focused on the development of a California-specific model, DeNitrification DeComposition (DNDC), that predicts GHG emissions from agricultural soils, the largest source of N_2O emissions in the State, based on California-specific soil, weather, and crop management practices. Field projects were carried out that measured N_2O emissions from major California cropping systems and provided the necessary data for DNDC calibration and validation. The model also allows for the identification of mitigation strategies that cut N_2O emissions from agricultural soils while maintaining the productivity and sustainability of California's cropping systems. Together, this work has improved estimates for N_2O emissions in California and quantified the potential of alternative management practices to mitigate N_2O emissions from agricultural soils. The model is currently being used by CARB staff to provide N_2O emissions for the State inventory.

A current CARB-funded project is focusing on CH_4 and N_2O emissions from California dairy operations. California dairy operations are a major source of GHGs, including both CH_4 and N_2O. The project will collect real world data on manure management systems and associated manure properties in selected California dairies and provide California-specific data for calculating manure emissions of CH_4 and N_2O from California dairies. The results of this project will be used to develop California-specific inputs to refine the California GHG inventory for dairies.

CARB research has also estimated N_2O emissions from motor vehicles and the effects of catalyst composition and aging on N_2O emission. The study confirmed that the current trend of decreasing N_2O emissions from light-duty vehicles is expected to continue as the result of increasingly stringent emission standards for NO_X. Long lifetime catalysts and reduced traffic congestion will also result in decreased N_2O emissions.

Updating the N_2O inventory will continue to be a priority research initiative for CARB. In particular, characterizing additional and uncertain sources will be necessary since several N_2O emission studies involving atmospheric monitoring and inverse modeling indicate that the current California N_2O inventory, based in international greenhouse gas emission protocols, may be underestimated, perhaps up to three-fold. Identifying these missing or underestimated sources of N_2O will require additional field data and modeling to allow for accurate emission estimates. These sources may include landfills, sewage systems, ocean upwelling, nurseries, golf courses, and other natural and urban sources. This research will help to resolve the discrepancy of N_2O emission estimates and will inform future efforts to reduce N_2O emissions in California.

Methane

California has made significant progress on understanding methane emissions in the State, and the results provide crucial information to inform California's climate change mitigation program under the requirements of AB32 and SB32, among other pieces of legislation. The Methane Research Program at CARB utilizes a variety of scientific approaches to understand source profiles and characteristics of methane emissions at regional and local scales as well as for different source sectors. Major research efforts include CARB in-house studies, CARB-funded research contracts, collaboration with local, State and federal organizations, and national labs and leveraged research outcome from other State agencies, such as California Energy Commission (CEC), California Department of Food and Agriculture (CDFA) and California Department of Resources Recycling and Recovery (CalRecycle).

At regional scales, CARB has supported both extramural and in-house research to perform top-down estimates of California methane emissions using inverse modeling approaches with data from the statewide GHG monitoring network. Model results suggest that statewide methane emissions may be 30 percent greater than current inventory estimates, with major additional emissions from the Central Valley, South Coast Air Basin and San Francisco Bay Area. Funded by CARB and CEC, a statewide aerial methane survey was conducted to map methane super-emitters throughout the State. The first phase of the survey identified 329 super-emitters spread across all sectors. These super-emitters are a relatively small fraction (<0.2 percent) of California's infrastructure, but could contribute significantly to statewide methane emissions. CARB also keeps a long-standing research collaboration with the Megacities Carbon Project in Southern California to study regional methane emissions in the Los Angeles area and will maintain the efforts due to the future uncertainty of federal funding on the program.

At local scales, CARB is further expanding methane measurement and analysis efforts by initiating facility-level emission flux quantification for all sources sectors with airborne flux estimation, ground-based mobile monitoring, and in-house flux tower and flux chamber measurements. The airborne technique has been successfully applied to quantify methane emissions during the Aliso Canyon leak incident and for all natural gas storage facilities in the State. The ongoing project extends these measurements to all major source sectors.

CARB is also supporting research to characterize source profiles for individual emission sectors, and to evaluate the effectiveness of mitigation measures. In the agriculture sector, CARB has several projects to characterize California-specific methane emissions from enteric fermentation and manure management, and evaluate methane emissions reductions from multiple mitigation strategies. In the energy sector, CARB has funded projects to estimate fugitive emissions from natural gas well heads, distribution pipelines, and customer gas meters. In the waste management sector, CARB is collaborating with CalRecycle to estimate landfill methane emissions and gas collection system efficiencies. CARB is also leveraging findings from research projects funded by CDFA, CEC, and CalRecycle for a comprehensive and integrated understanding on California methane emissions and mitigation measures.

While CARB has made progress in understanding methane emissions, there are still knowledge gaps that need to be addressed. Future research on methane emissions will need to translate facility-level emissions snapshots to relevant emission factors with the consideration of temporal and spatial variations. A more systematic understanding is needed for both source-specific activity patterns and emission rates to improve the current statewide inventory estimation. Future approaches for persistent monitoring of priority emissions sources could utilize a small hyperspectral satellite capable of detection and quantification of methane point sources throughout California at fine spatial resolution. Future research should also assess the community-level air quality impact from major methane emissions sources.

MITIGATION OPTIONS

This Plan will address these research questions related to mitigating GHG emissions:

- What new technologies or management strategies can be employed to mitigate the emissions of GHGs, particularly in the dairy sector?
- How can efforts to identify and mitigate emissions from the highest emitters be improved?
- How can the adoption of low-GWP and reduced-GWP technologies be accelerated?

California is working to reduce GHG emissions across all sectors of the economy under the framework of AB 32, SB 32, and SB 1383. Although CO_2 emissions constitute the largest share of California's inventory, nitrous oxide, and SLCPs are significant contributors to California's GHG inventory. As a result, new strategies to monitor and reduce emissions of SLCPs and nitrous oxide offer tremendous potential for climate benefits, and have therefore been a research priority for CARB. CARB's GHG emissions measurement efforts help to identify sources, evaluate the emissions from these sources, identify new emissions reduction strategies, and track progress in reducing emissions. CARB compliments this research with studies to examine the effectiveness of GHG mitigation strategies.

Black Carbon

California has made extraordinary progress to reduce PM and black carbon emissions, especially from on-road mobile sources. This record of success makes California an international leader in reducing harmful PM2.5 pollution, including black carbon and other constituents, to protect health, the environment, and climate. The strategies and technologies developed in California can also be applied to other regions to yield additional emission reductions. According to CARB's research study, if California's efforts in reducing black carbon can be replicated globally, we can slow down global warming in the coming decades by about 15 percent, in addition to protecting people's lives. CARB will continue to develop mitigation strategies from mobile sources, as well as through strategies to reduce the biomass burning. These research priorities are described in more detail in the Mobile Sources and Agriculture and Natural and Working Lands portion of this Plan.

F-gases

Reducing emissions of F-gases from refrigeration and air conditioning is one of the most impactful near-term actions for reducing climate change in California and the globe. CARB's F-gas research has identified mitigation strategies that have resulted in the successful development and implementation of multiple regulations and programs to reduce F-gas emissions. These programs have led directly to the adoption of national rules to reduce HFCs from commercial refrigeration, motor vehicle air conditioning systems, and other sources. In addition, based on this research, CARB adopted a protocol to provide incentives to recover and destroy ozone-depleting substances such as HFCs as part of the Cap-and-Trade Program. A new regulation to prohibit the use of certain high global warming HFCs in stationary refrigeration equipment and foams was approved by the Board in March 2018.

Continued research on this topic will be necessary to guide and inform HFC reduction measures laid out by SB 1383, which requires a 40 percent reduction in HFC emissions below 2013 baseline levels by 2030. Remaining research gaps include modeling and field testing to assess risk and potential emissions mitigation from low GWP refrigerant systems. This work is necessary to reduce potential health and environmental risks and inform the next round of building codes. Research also needs to examine the efficiencies in new heating and air conditioning technologies for residential and commercial buildings. This work should focus on supporting technology advancement, as well as testing the efficiencies of commercial-ready systems to improve energy efficiency and reduce refrigerant use in California buildings.

Research is also needed to guide the use of the Greenhouse Gas Reduction fund (GGRF), which is funded by Cap-and-Trade auction proceeds and are used to reduce GHG emissions within the State. These include programs for black carbon residential wood-smoke reductions, waste diversion, forestry related activities, healthy soils, and dairy CH_4 reduction projects. Continuing to support research related to F-gas mitigation is essential to guide future investments and ensure that SLCP mitigation strategies are successful and cost-effective.

Carbon Dioxide

CARB's past and current research, and future research priorities for the development of CO_2 mitigation strategies are described in the Mobile Sources, Sustainable Communities, Natural and Working Lands, and Transportation sections of this Plan.

Nitrous Oxide

CARB has funded several projects to calibrate a geochemical model called DNDC and use it to quantify the emission mitigation potential of specific management practices. This research has been well coordinated with external stakeholders, the California Energy Commission, and the California Department of Food and Agriculture. Recent improvements to the model expanded its capabilities to include more California cropping systems and refined parameters related to

manure management and irrigation methods, which has helped to identify best management practices with the potential reductions from mitigation strategies. For example, modeled emission scenarios indicate that the use of nitrification inhibitors, subsurface drip irrigation, and increasing the spatial frequency of fertilizer application consistently reduced emissions of N_2O. Modeling analyses depicting the spatial distribution of soil GHG emissions has also allowed CARB staff to identify potential hot spots that could help guide mitigation efforts. CARB will continue to fund research that will help to identify high-emitting sources of N_2O and develop strategies to mitigate emissions from these sources.

Methane

California has already started to implement methane reduction strategies in all anthropogenic source sectors, as required by SB 1383. CARB will continue to support future research to evaluate the opportunities and effectiveness of the reduction strategies. Efforts will focus on further understanding the fundamentals of source characteristics, identifying process-level emission profiles, investigating the contribution from super-emitters, evaluating the best management practices and tracking methane emission trends due to mitigation measures.

CDFA has created two incentive programs for dairy farmers to reduce air emissions from manure management practices. One program focuses on installing digesters on dairies to capture CH_4 and put it to beneficial uses. The other focuses on applying alternative manure management practices (AMMP) at a dairy to reduce existing CH_4 emissions. One CARB research project that began in fiscal year 2017-18 is attempting to characterize the impacts of implementing AMMPs at California dairies with respect to GHG emissions and local and regional air quality. Another research project initiated in fiscal year 2017-18 is examining the economic and logistical feasibility of strategies to inhibit CH_4 production from enteric fermentation and anaerobic manure storage lagoon sources at California dairy operations. SB 1383 allows only voluntary CH_4 reductions from enteric fermentation until specific findings outlined in the bill are reached. Other CARB--supported research projects will quantify and compare methane emissions from dairy farms before and after a dairy digester project and investigate the fugitive emissions from dairy digesters.

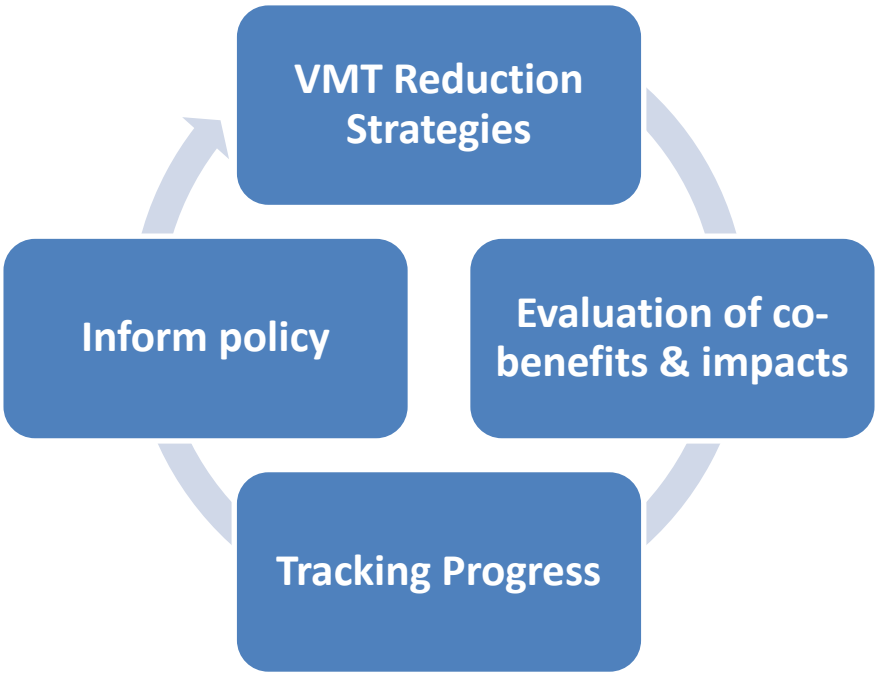
SB 1383 requires CARB and CDFA to work with a broad range of stakeholders to identify and address technical, market, regulatory, and other challenges and barriers to the development of dairy methane emission reduction projects. In keeping with this requirement, CARB, CDFA, the California Energy Commission, and the California Public Utilities Commission convened a Dairy and Livestock Working Group in May 2017 along with three subgroups that focus on the development of policy recommendations in specific areas (fostering markets for digester projects, fostering markets for non-digester projects, and research needs, including enteric fermentation). The goal of the research subcommittee is to develop a comprehensive Dairy Air Research Prospectus (Prospectus), by the end of 2018, that outlines various research concepts addressing the knowledge gaps in dairy air research for both manure management practices and enteric fermentation, including: assessing localized air pollution issues associated with dairies especially in environmental justice communities; developing a long-term dairy GHG and

air monitoring program to track progress on reducing CH_4 emissions from dairies; improving dairy emission inventories using California-specific data; and evaluating short and long-term benefits of air pollution mitigation strategies using regional GHG and air quality modeling. The Prospectus will help guide California's funding agencies and prioritize future research projects.

On January 1, 2018, CARB adopted the regulation to reduce methane emission from oil and gas production, processing and storage in California. In addition, the California Public Utilities Commission (CPUC) adopted a series of Best Practices for Methane Leakage Abatement and Emissions Reductions in 2017, which will lead to methane emission reductions from the natural gas transmission and distribution sectors. CARB's ongoing and future research effort will continuously monitor and quantify methane emissions from oil and gas facilities including oil/gas fields, gas storage facilities and refineries as the regulations take into place.

SUSTAINABLE COMMUNITIES PROGRAM SUPPORT

Sustainable communities are neighborhoods with safe, reliable, and affordable transportation choices, equitable and affordable resource- and location-efficient housing options, and access to quality employment, education, and other services. CARB's sustainable communities research program supports implementation of SB 375, the Sustainable Communities and Climate Protection Act of 2008, and helps pave the way for the 2050 climate goal. SB 375 encourages California transportation and land use agencies to consider the greenhouse gas impacts of their planning processes and requires them to create "sustainable communities strategies" (SCS) that describe how vehicle miles traveled (VMT) and associated GHG emissions will be reduced to meet State climate goals. In addition to SB 375, other State policies also support the development of more sustainable communities throughout California. The Green Building Standards (CALGreen) Code establishes requirements to improve the environmental and health impacts of residential and commercial new construction in California. Research themes include investigating strategies that reduce VMT and GHG emissions from the built environment, evaluating the co-benefits and potential impacts of those strategies, and tracking progress toward SB 375 goals. These projects have resulted in the identification of strategies to maximize the benefits of sustainable planning (including reduced air pollution, greater energy efficiency, and cost savings), and the development of tools to monitor and quantify these benefits. Results from these projects are designed to assist policy makers and local governments in their efforts to reduce GHG emissions while minimizing unintended impacts on health and social equity, and to guide future policies.



Sustainable Community Research Highlight - Research suggests LA housing is being built in transit-accessible neighborhoods but lacks easy access to jobs and shopping; underscores need for affordable housing near transit

With a nudge from SB 375, urban and transportation planners in California have been improving transit access for more Californians to help reduce climate-changing emissions from private vehicle travel. But ensuring that California remains on track to meet our climate goals requires a comprehensive effort to track whether "on the ground" changes in land use and transportation are aligned with SB 375. Recent legislation (SB 150) now requires CARB to produce a report for the legislature every four years on progress made by each of California's 18 metropolitan planning organizations in meeting their regional greenhouse gas emission reduction targets. CARB has funded several research projects which will inform the SB 150 report, including research to construct indicators of land use changes over time, and to examine the equity implications of the shift toward more transit-oriented neighborhoods.

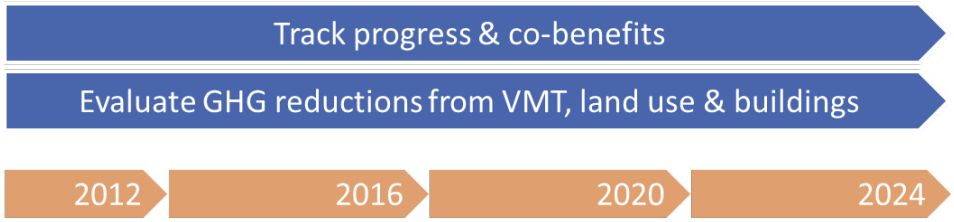
Researchers from the University of California at Los Angeles (UCLA) constructed metrics to track changes in housing density, access to jobs, access to retail, and access to transit over time. They focused first on Los Angeles (LA) County, and Caltrans is now funding the statewide scale-up of these metrics. Their findings for LA suggest that, since 2010, housing has been added primarily in low-density neighborhoods that have somewhat limited access to jobs and retail, but good access to public transit. Overall, these findings suggest that housing developments are not exactly sprawling into the suburbs and beyond, but there is room for improvement to better align with SB 375 goals. However, it is unclear that these newer transit-oriented developments are equally accessible to all Californians. Researchers from the University of California at Berkeley and UCLA found more people moved to and from transit-accessible neighborhoods (in LA and the Bay Area), and those moving in were more likely to be higher-income, college-educated, and white: a process called 'gentrification.' In contrast, the displaced households tend to be lower-income, less educated, and nonwhite. Displacement is occurring in many neighborhoods near rail stations in California's major metropolitan areas, especially older neighborhoods near downtowns. This research underscores the need for more affordable housing near transit to ensure that California's housing equity and greenhouse gas reduction goals can both be met, and highlights the value of tracking progress toward long-term goals over time to identify where course corrections are needed.

Sustainable Community Research Initiatives for FY 2018-21

Going forward, CARB will continue research to support the implementation of SB 375 while ensuring that there are co-benefits in all communities, and evaluating GHG reductions associated with vehicle miles traveled (VMT), land use, and buildings.

The timeline below depicts high-level research initiatives (groups of projects on a given topic) that have led to the development of our current research priorities. The timeline extends to 2024 to account for the time that research projects initiated by the Triennial Plan would be completed. Bars in shades of red represent new research initiatives, while bars in shades of

blue represent research initiatives that have either concluded, or are currently in progress and will continue to be a priority in the future.



TRACKING PROGRESS & CO-BENEFITS

This triennial plan will address these research questions related to tracking SB 375 progress and co-benefits:

- Are "on the ground" changes, and planned land use and transportation investments, in alignment with regional Sustainable Communities Strategies and State climate goals?
- Is SB 375 yielding anticipated co-benefits for health and equity, and are these co-benefits distributed equitably?

Tracking progress toward meeting the goals of SB 375 is important for ensuring that adopted sustainable community strategies (SCS) help the State achieve its climate change goals. CARB has funded research, in collaboration with Caltrans, to lay the foundation for a future statewide monitoring system that will evaluate whether built environment changes are consistent with SB 375 goals (refer to highlight). Results from LA County suggest that new housing is not exactly sprawling into the suburbs, but there is room for improvement to better align with SB 375 goals. Future research will continue to evaluate whether "on the ground" changes, and planned land use and transportation investments, align with regional SCSs and State climate goals.

CARB continues to conduct research that evaluates the potential co-benefits of SB 375 implementation, and evaluates whether all communities are benefiting equitably from the transition toward more sustainable communities. Recently completed case studies indicate that re-zoning for higher density development, reducing parking requirements, and requiring pedestrian-friendly design can result in up to $1 million in benefits to cities and over $100 million in benefits to the region. Another recent study showed that "complete streets" – designed for walking, biking, and transit, as well as cars – are sometimes associated with lower vehicle traffic volumes, less traffic pollution exposure, and more use by pedestrians and cyclists, but complete streets are much more successful in downtown business districts than in other types of neighborhoods. Research also illustrates the challenges of ensuring that transit-oriented developments remain equally accessible to all Californians. Displacement is occurring in many neighborhoods near rail stations in California's major metropolitan areas, especially older neighborhoods near downtowns, and CARB research developed tools to help communities identify neighborhoods that are at risk for gentrification and displacement, and

identified policies that local governments can adopt to help prevent it. Ongoing research is assessing both the VMT implications and co-benefits of affordable transit oriented developments to inform future State investments in affordable housing and quantification of both GHGs and co-benefits of those investments. CARB research has also begun focusing on the potential health impacts of active travel, including updating the Integrated Transport and Health Impact Model (ITHIM). The updated model will help policy makers and planners calculate the health impacts of transportation-related GHG reduction strategies that incorporate active-transportation, such as walking and biking. Future research will continue to assess and quantify the co-benefits of SB 375 implementation, and evaluate whether disadvantaged communities and low-income Californians are benefiting equitably.

EVALUATING REDUCTIONS IN GHGS FROM VMT, LAND-USE & BUILDINGS

This triennial plan will address these research questions related to evaluating reductions in GHGs from VMT, land use, and buildings:

- What is the potential of built environment changes to reduce VMT and GHGs, and to improve air quality and reduce air pollution exposure?
- What is the net emission reduction potential of the existing building stock (including fuel switching, advanced energy efficiency technologies such as low-GWP appliances, and combinations of strategies such as renewables, energy storage, and electric vehicle charging, etc.), and what are the associated GHG and air quality co-benefits?

Sustainable communities can yield GHG reductions as a result of declining VMT, but also from more sustainable land-use patterns and from buildings themselves. CARB funded a series of white papers on the VMT impacts associated with various transportation and land use strategies (Table 1), and has funded other studies to verify VMT benefits in the real world. A recent study assessed the travel behavior of residents living near the LA Expo Line before and after it opened. Those residents living close to stations drove less than people that lived farther away, and they still drove less 18 months after the opening. Another study analyzed travel survey data to quantify how much Californians will change the amount that they drive in response to changes in land use and transport system variables. The results of this research are embedded in the VMT Impact spreadsheet tool, which allows users to easily see the implications of this work for any census tract, city, or region in California. Ongoing research is assessing both the VMT implications and co-benefits of affordable transit oriented developments to inform future State investments in affordable housing and quantification of both GHGs and co-benefits of those investments.

Table 1: VMT impacts associated with various transportation and land use strategies

Type of Policy or Strategy	Strategy & Effect
Land Use: e.g., residential density, land use mix, street connectivity, etc.	For a 10% increase or improvement, up to 4% reduction in VMT.
Infrastructure and Services: e.g., distance to transit, quality of transit service, bike/pedestrian infrastructure.	For a 10% increase or improvement, up to 60% reduction in VMT.
Operations: e.g., eco-driving, transportation system management, traffic incident clearance.	Where implemented, can result in an 8% reduction in fuel consumption/GHG emissions.
Demand Management: e.g., telecommuting, employer-based trip reduction programs.	Each individual program participant can reduce VMT up to 90%.
Pricing: e.g., gas price or parking price increase, road user pricing.	For a 10% increase in pricing, up to 30% reduction in VMT.

Sustainable land use encompasses a variety of built environment strategies that reduce GHGs and improve air quality. CARB has funded research exploring the climate and air quality implications of cool roofs and cool pavements, which confirm that these strategies offer the potential to reduce urban heat islands and in some climate zones reduce the need for energy to cool buildings. CARB research has also illustrated that more compact housing development results in energy savings, and that local governments can facilitate VMT reductions through a variety of land use and transportation decisions (including zoning for higher density and mixed-use development, increasing transit service frequency, and requiring pedestrian-friendly design) many of which have been shown to result in financial savings as well. An ongoing study is investigating the potential to zero out GHG emissions from energy, transportation, waste, and water is leveraging an existing zero net energy community project in a disadvantaged community. The investigators will leverage the City of Richmond Advanced Energy Community Project (Richmond AEC Project) that has been awarded $2.6 M from the California Energy Commission EPIC challenge for disadvantaged communities. The results of this study will be useful in the development of a GHG baseline to quantify additional non-energy GHG reductions of California ZNE communities that are needed to achieve the 2050 target. Future research will continue to investigate the potential of built environment changes to reduce VMT and GHGs, and to improve air quality and reduce air pollution exposure.

Buildings also play a key role in creating more sustainable communities. Past CARB-funded research shows that certified green office buildings have significantly lower GHG emissions than their conventional counterparts, and other studies have highlighted large potential to reduce building energy use. Accounting for emission reductions associated with zero carbon buildings (encompassing waste, water and transportation, in addition to energy savings)will be essential as we continue to pursue an integrated approach to reduce the GHG impact of new and existing buildings while improving indoor air quality. An ongoing research project is evaluating the

technical feasibility of achieving zero or near-zero carbon buildings for both residential and commercial buildings, focused on transportation, water, and waste strategies that can be implemented at the building level by owners, property managers, and occupants. The results of this study will be used to assess the practicality and appropriate timeframe for a zero or near-zero carbon building State policy or program, and help keep California on track to achieve mid-term and long-term climate goals. Future research will shed light on the GHG, criteria pollutant, and toxic air contaminant co-benefits of retrofitting, operating, and maintaining existing homes as certified green homes. New research should also evaluate the net emission reduction potential of fuel switching and combinations of building-level strategies (e.g., cool roofs, solar photovoltaic, EV charging, and energy storage), and consider life cycle performance of energy efficiency technologies (e.g., low-GWP refrigeration equipment).

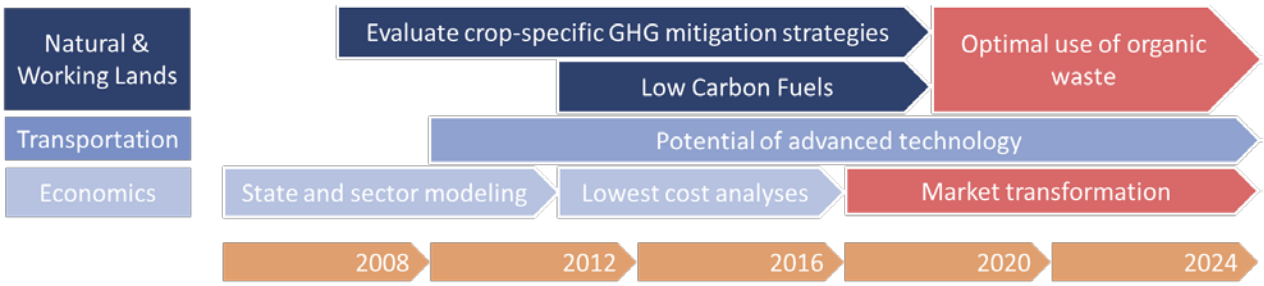
CROSS-CUTTING TOPICS

These cross-cutting topics represent areas of research where we have historically funded projects that exclusively looked at strategies to either reduce GHG or criteria pollutant emissions. Going forward, more of our research will aim to identify and prioritize GHG reduction strategies that simultaneously reduce criteria pollutant and toxics emissions.

Research initiatives for Cross-Cutting Topics for FY 2018-21

For agriculture and natural and working lands (NWL), CARB's future research will help ensure that GHG mitigation strategies, especially those outlined in the Short-Lived Climate Pollutant Reduction Strategy, do not lead to unintended consequences of increasing criteria pollutant or toxics emissions. Since the adoption of AB 32, CARB's research has evolved to focus on the reduction of both criteria pollutants, and GHG emissions. Going forward, transportation research will focus on ensuring that the use of advanced technologies, such as electrification, automation, and vehicle sharing, results in GHG, criteria pollutant, and toxics emission reductions. In the area of economics, CARB will work toward minimizing the economic impacts of programs and regulations while optimizing the use of incentive funds.

The timeline below depicts high-level research initiatives (groups of projects on a given topic) that have led to the development of our current research priorities. The timeline extends to 2024 to account for the time that research projects initiated by the Triennial Plan would be completed. Bars in shades of red represent new research initiatives, while bars in shades of blue represent research initiatives that have either concluded, or are currently in progress and will continue to be a priority in the future.



NATURAL AND WORKING LANDS (NWL)

NWL Research Highlight - Cutting Nitrous Oxide Emissions from California Farmland

Agricultural soil management is the largest source of the potent greenhouse gas nitrous oxide (N_2O) in California, contributing to roughly half of statewide N_2O emissions annually. California has the most diverse cropping systems, crop management practices, and environmental conditions in the nation, making it challenging to quantify N_2O emissions from California cropland. CARB has funded several projects to calibrate and validate a process-based biogeochemical model called DNDC as a quantitative tool for estimating both baseline N_2O emissions and N_2O mitigation potentials of alternative management practices. This research has been well coordinated with external stakeholders including the California Energy Commission and the California Department of Food and Agriculture. Recent improvements to the DNDC model allowed inclusion of more California cropping systems and refined parameters related to manure management and irrigation methods. Modeling of business-as-usual (BAU) scenarios using the California-specific model resulted in emission maps of soil GHGs from California cropland, which could help guide mitigation efforts (Figure 9). Modeling analyses of alternative management scenarios further provided estimates of mitigation potentials, which indicated the use of nitrification inhibitors, subsurface drip irrigation, and plant of cover crops may effectively reduce N_2O emissions from California cropland. The model is currently used in-house by CARB staff to develop California's N_2O emission inventory for agricultural soils, CH_4 emission inventory for rice cultivation, and other scientific and regulatory applications. For instance, staff is evaluating the use of this model to assess NO_X emissions from agricultural soils to inform California's SIP strategies.

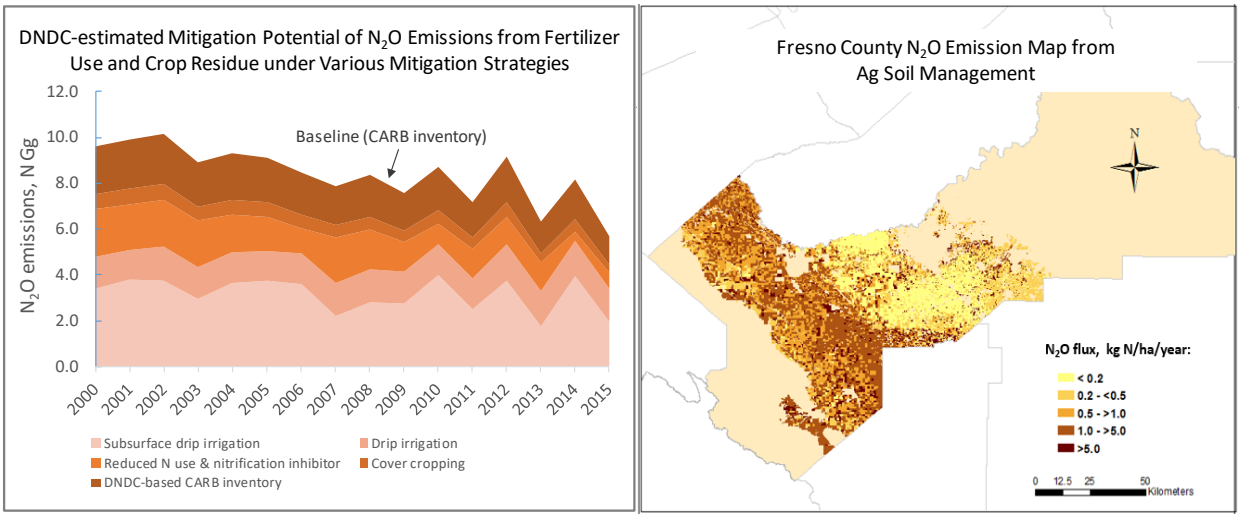


Figure 9: The DNDC model estimates the N_2O emission mitigation potential for various mitigation strategies (left). The map of N_2O emissions in Fresno County pinpoints hot spots that could guide mitigation efforts (right).

NWL Research Initiative for FY 2018-21

OPTIMAL USE OF ORGANIC WASTE

This Plan will address these research questions related to optimizing the use of organic waste streams:

- What are the immediate and long-term air quality and climate impacts of the creation and application of organic soil amendments (e.g. compost, biochar, chipped woody material, manure) intended for use in California agricultural?
- How does the best end use (e.g. bioenergy, biofuel, organic soil amendment) of organic waste streams vary by region in California? What policies and programs are needed to promote regional uses with the lowest criteria pollutant and GHG emissions?

Past research on low-carbon fuels supported the implementation of CARB's Low Carbon Fuel Standard (LCFS) and the development of the Short-Lived Climate Pollutant Reduction Strategy. Projects that were completed in 2016 and 2017 provided costs, feedstock availability, and the emission impacts of producing renewable natural gas (RNG) and renewable diesel and gasoline at the commercial scale in California. The study on RNG found that if current carbon credit prices persist into the future for programs like the LCFS, a substantial portion of natural gas consumption in the transportation sector can be satisfied by RNG. The study on renewable diesel assessed the distribution of solid biomass resources in the State (Figure 10) and found that California's waste biomass (woody leftovers from forests, mills, landfills, and farms) could replace up to 58 percent of diesel fuel and 8 percent of gasoline sold in the State while reducing

both carbon and criteria pollutant emissions. Renewable electricity generated as a by-product of the biomass-to-fuel conversion process would enable drop-in fuel refineries to achieve negative net carbon emissions. Drop-in diesel for heavy-duty trucks was found to be the optimal supply opportunity due to the near-term challenges of electrifying heavy-duty trucks. Another project completed in 2017 developed lifecycle assessments for production pathways of renewable hydrogen fuel that informed the development of new LCFS pathways. Future work to support the LCFS should improve techniques for inventorying changes in land use as a result of alternative fuel production in order to assess the policies and programs designed to protect these natural and working land systems.

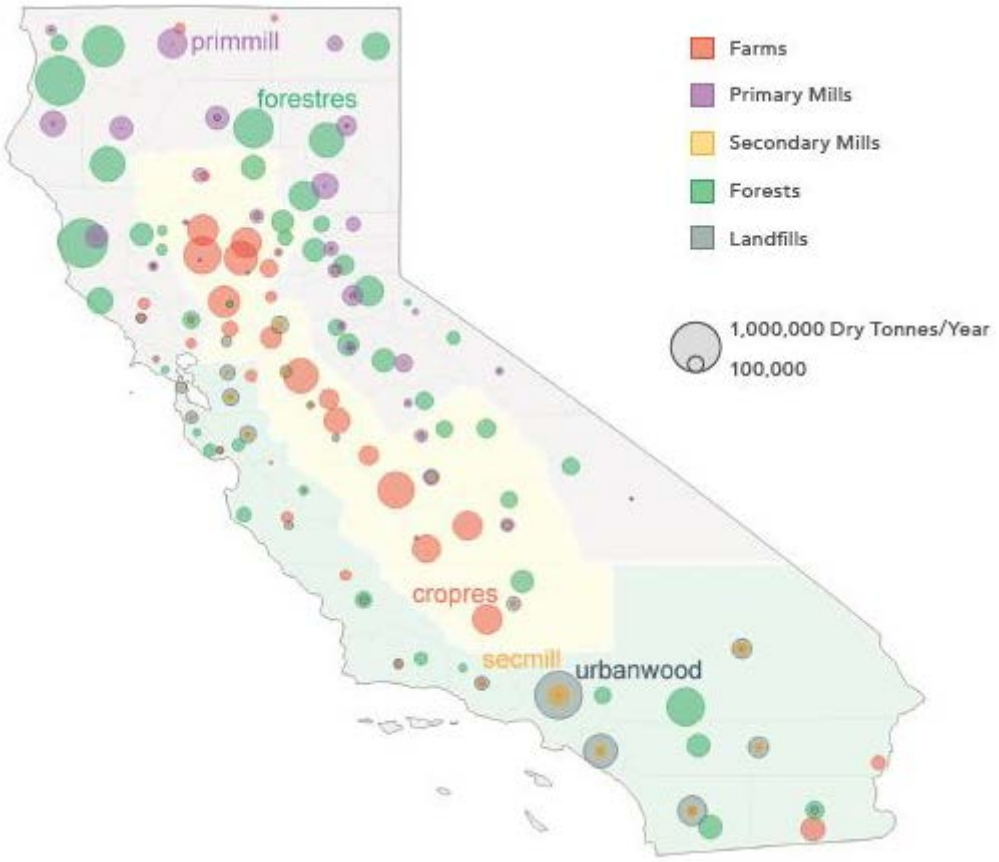


Figure 10: Distribution of California's solid biomass resources.

CARB's past work on alternative fuel production in California has collectively provided the foundation for a project initiated in fiscal year 2016-17 that is investigating the best use of alternative fuels to fuel the heavy-duty sector to 2050. Future research should build on these results to devise region-specific strategies for the best use of local biomass resources. This is particularly important given California's diverse agricultural industries that include forestry, orchards, plant crops, and livestock production. Urban areas also provide a source of food waste, including fats oils and grease. In many cases, the climate, air quality, and economic

impacts of the pathways to utilize these resources for the production of energy, fuel, and other products (e.g., compost and biochar) remain unclear.

Dairy operations in California are a significant source of emissions of multiple air pollutants including methane (CH_4), N_2O, ammonia (NH_3), and volatile organic compounds (VOCs). The State Legislature has repeatedly demonstrated commitments to reducing GHGs (and powerful, climate-forcing SLCPs) through the passage of multiple bills, including AB 32, SB 605, SB 32, and SB 1383. This commitment to reducing GHGs is complemented by CARB's ongoing commitments to reducing criteria pollutants, toxic air contaminants, PM (PM10 and PM 2.5), and ozone precursors. These efforts can produce important improvements in ambient air quality and secure reductions that contribute to the goals outlined in the State Implementation Plan. These commitments make it imperative that CARB evaluates and understands dairy manure management practices and evaluates the emissions reduction effectiveness of potential mitigation strategies. A study that initiated in fiscal year 2017-18 will look at both the GHG and air quality impacts of implementing the AMMP that is coordinated by the California Department of Food and Agriculture.

Beyond dairies, the reduction of GHG emissions from the agricultural sector includes strategies to lower the use of synthetic fertilizers by direct application via fertigation or replacement with organic soils amendments, such as compost and manure. The creation of compost also facilitates the diversion of food waste from landfills. However, the air quality impacts of the creation and application of compost in California are largely unknown. The incorporation of chipped orchard biomass is another strategy to improve air quality because it is an alternative to biomass burning. Preliminary results have indicated that it may also lead to soil carbon sequestration. The impact of this strategy on GHG emissions from soils remains unclear and is complicated by the fact that GHG emissions from soils may be site-specific. The use of biochar as a soil amendment has been well studied in short term trials, but the long-term benefits on soil carbon, the management recommendations for application, and the air quality impacts of different application methods remain a source of uncertainty.

Transportation Research Highlight - Electric Cars Move Up the Learning Curve

California's smog used to be legendary, but today the Golden State's air is much cleaner than it was just a few decades ago. Still, air pollution continues to cause negative health effects, and cars and trucks remain the largest contributors. Large cuts to greenhouse gases from the transportation sector are needed to meet statewide climate goals, spanning different fuels and vehicle technologies, and reducing people's need to drive. Figure 11 shows the total reduction in "well-to-wheel" greenhouse gas emissions that are needed through 2035 and out to 2050. The "baseline" shows what emissions would be without California's efforts to mitigate climate change. Reductions are expected to come from vehicle miles traveled (VMT), renewable portfolio standards (RPS), and zero emission vehicles (ZEVs). California is counting on electric, plug-in hybrid, and hydrogen cars to meet our air quality and climate goals. The State has set a target to have 1.5 million of these cars on the road by 2025 and 5 million by 2030. Electric cars (and other advanced technology vehicles) are much cleaner than their predecessors, but their real-world air quality benefits depend on how quickly they replace dirtier cars, the way that they're driven, and whether the electricity and hydrogen used to power them comes from renewable sources. CARB-funded research is yielding insights into what motivates drivers to purchase, drive, and plug in their cars, and seeks to understand and address barriers that prevent low- and moderate-income drivers from purchasing these cars. Two-thirds of respondents to a recent survey of new car buyers knew very little about electric, plug-in hybrid, or hydrogen-powered cars. Providing buyers with more information appears to lead to more interest: 38 percent of respondents expressed a preference for these cars when provided with minimal information about them, and drivers who have experience with these cars are more likely to consider buying one. Research also found that in 2015, used plug-in hybrid cars were holding their value better than electric-only cars, typically selling for about 10 percent more than electric cars compared to their MSRP. In the same time period, used electric cars with carpool stickers sold for an average of $715 more than similar cars without the sticker. As these cars become more widespread, there will be an increasing need to manage the demand that charging them places on the electrical grid, to develop policies and pricing structures that encourage plug-in hybrid drivers to plug in instead of relying on gasoline, and to provide more drivers with the opportunity to experience these vehicles, such as through "ride and drive" events and car-sharing programs, and innovative financing and incentive programs.

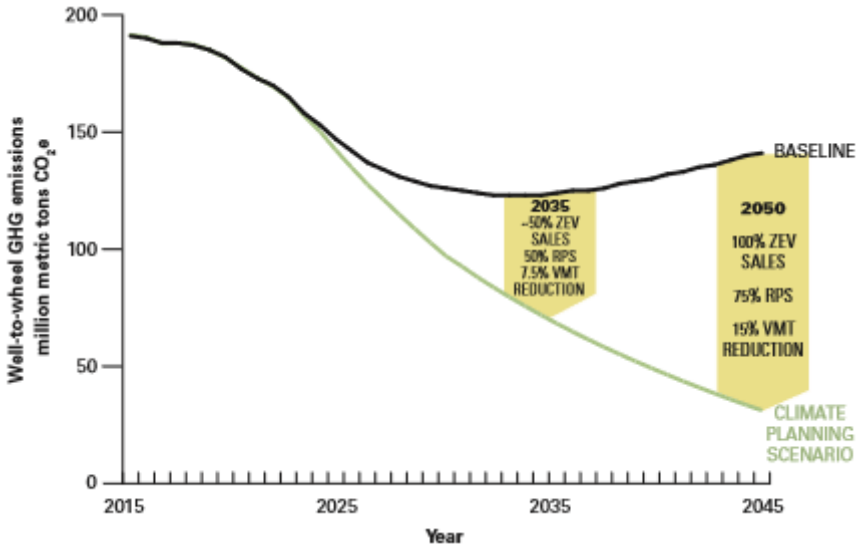


Figure 11: Total reduction in "well-to-wheel" greenhouse gas emissions that are needed through 2035 and out to 2050.

Transportation Research Initiative for FY 2018-21

POTENTIAL OF ADVANCED TECHNOLOGY

This triennial plan will address these research questions related to the potential of advanced technology:

- What is the feasibility and cost of the hybridization and electrification of certain heavy-duty vehicle and off-road vehicle fleets?
- What is the best use of alternative fuels, near-zero, and zero-emission vehicle (ZEV) technologies across all sectors, and how can we encourage their use without unintended impacts on vehicle miles traveled?

Near-term exposure mitigation strategies are being addressed by real-world clean transportation projects, such as the Low Carbon Transportation program, Air Quality Improvement Program (AQIP), VW 3.0-Liter Settlement, Carl Moyer Program, and Prop 1B. CARB has funded several research projects that informed the best use of these funds to maximize criteria pollutant, air toxic and greenhouse gas emissions. For example, to inform CARB's ZEV program and the use of incentive funds aimed at accelerating consumer adoption of plug-in electric vehicles (PEVs), a recent study found that PEV sales are positively associated with household income, gasoline prices, and proximity to high-occupancy vehicle lanes.

As part of the midterm review of advanced clean cars, CARB conducted in-house emission testing to evaluate the cold start performance of several blended PHEVs. The testing confirms

that cold-start emissions under high-power demand conditions can be significantly higher than criteria pollutant emissions from traditional engine cold starts. However the cumulative impact on emissions from this fraction of starts has not yet been determined. In order to address this issue, a project that was initiated in fiscal year 2017-18 will characterize the activity profiles of cold start emissions produced by blended plug-in hybrid vehicles in order to understand the real-world scale of the increased emissions previously measured in the lab. The result of this study will be used to improve the emission inventory estimates of PHEV start emissions and guide the development of future clean car standards. The projects above are examples of benefits and unintended impacts of advanced technologies in the transportation sector. Additional research is needed to ensure that these technologies evolve in a way that allows California to accelerate towards its air quality and climate goals.

The impacts of advanced transportation technologies, such as the use of connected and automated vehicles, shared vehicle fleets, and electric vehicles, will be a priority research area for CARB over the next three years. Future research should focus on providing the data and tools necessary to assist policy makers and local governments in their efforts to ensure that connected, shared and electrified vehicles do not have the unintended consequence of increasing vehicle miles traveled and degrading air quality. A project initiated in fiscal year 2017-18 will begin to quantify the projected impacts of varying penetration levels of light-duty connected and automated vehicles on GHG and criteria pollutant emissions, and vehicle miles traveled. However, as the penetration of electrified, connected, automated, and shared vehicles into California's light-duty fleet accelerates, information will be needed on their real-world use, charging needs and the emission benefits of their integration into the grid. Results from research on these topics would help to inform investments in charging infrastructure and develop strategies to increase the use of ZEVs by gaining a better understanding of what applications in shared and connected uses provide the most benefit.

CARB also funds research on the use of advanced technologies in the heavy-duty and off-road sectors to guide CARB's incentive, regulatory and voucher programs aimed at reducing their climatic and air quality impacts. A project initiated in fiscal year 2017-18 is investigating geofencing as a strategy to lower emissions from heavy-duty vehicles in urban areas that are also disadvantaged communities. The project will evaluate the potential for virtual geospatial fences that would enable hybrid-electric heavy-duty vehicles to automatically switch to zero-emission operations when they enter these urban areas. The results will identify strategies that the freight industry could employ to mitigate near roadway impacts and to quantify the cumulative effect of multiple mitigation measures. CARB intends to utilize fiscal year 2018-19 research on a project that will examine the economic and practical feasibility of the electrification and hybridization of off-road equipment. Going forward, CARB will continue to prioritize research to support the use of advanced technologies to reduce emissions in the heavy-duty and off-road sectors.

Economics Research Highlight - Solving the Clean Vehicle Incentive Puzzle

How big a rebate should be offered – and to whom – to maximize additional plug-in electric vehicle (PEV) sales? Carpool lane access and new vehicle purchase rebates appear to be helping to expand the early electric car market. UCLA researchers assessed new-car buyers' interest in PEVs, analyzed rebate data to estimate how PEV demand varies with income, and evaluated the relationship between PEV ownership and access to carpool lanes. The researchers found that carpool lanes are an effective nudge toward PEV ownership, with an estimated 2.6 percent increase in sales for every 20 percent increase in miles of nearby carpool lanes. They also found that rebate dollars are important – there is an approximately 7 percent increase in PEV sales as a result of rebates – but rebates are more effective at nudging low-income households toward buying a new PEV than they are for higher-income households with similar vehicle preferences (Figure 12).

Independently, University of Denver researchers sampling real-world emissions from California's light-duty fleet found that the share of emissions from the highest-emitting 1 percent of cars nearly tripled between 1999 and 2015. CARB Contract 12-303 Both findings underscore the value of vehicle retirement and replacement incentives like those offered by the Enhanced Fleet Modernization Program (EFMP) for low- and moderate-income households in disadvantaged communities. Among households with similar income, rebate dollars are also more effective at swaying buyers with lower initial preferences for PEVs. This research confirms the wisdom of offering bigger rebates for all-electric vehicles – since car-buyers needed a stronger nudge toward those than they did for plug-in hybrid cars (that can run on either gasoline or electricity). It also supports recent changes to eligibility guidelines for CARB's Clean Vehicle Rebate Project (CVRP), reaffirmed in recent legislation (AB 615), capping applicant income and increasing rebate amounts for lower-income households. This research will also inform CARB's upcoming reports to the legislature, as required by SB 615 and SB 498, which will evaluate the extent to which clean vehicle incentives, and other efforts to increase PEV adoption, are meeting their goals.

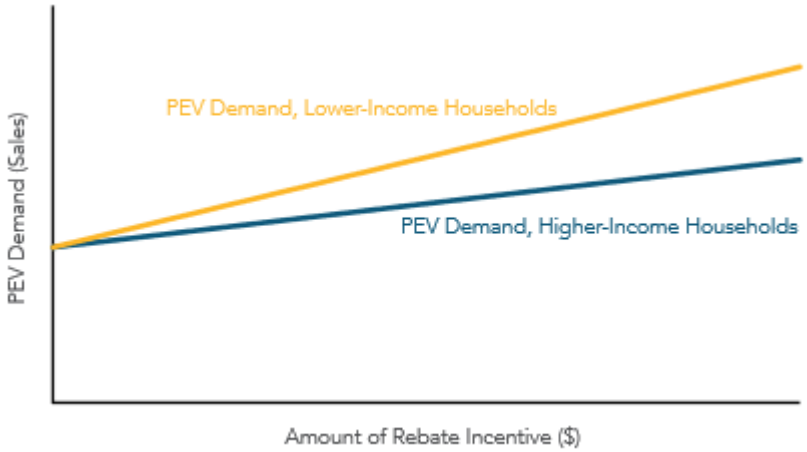


Figure 12: Lower-income households are more responsive to plug-in electric vehicle (PEV) incentive payments.

Economics Research Initiative for FY 2018-21

MARKET TRANSFORMATION

This Plan will address these research questions related to market transformation:

- How can incentive dollars best be spent to encourage consumers, fleets, and sectors to accelerate conversion to advanced technology (e.g., zero emission vehicles, dairy methane reduction, etc.)?
- What are the barriers to sustainability of new markets (e.g., for low-emission vehicles and low-global-warming-potential refrigeration technology) and how can these be overcome?
- What economic, health, and environmental metrics are needed to track that investments are benefiting disadvantaged communities equitably?

CARB oversees several incentive programs to promote the use of low-emission, clean vehicle technology that needs to be incorporated into our light-, medium-, and heavy-duty fleets to meet long-term air quality and climate goals. CARB has sponsored research projects to help optimize our use of incentive funds for new and used light-duty vehicles, and to optimize incentives for low- and moderate-income households to retire highly polluting vehicles and acquire advanced technology vehicles. These projects have found that carpool lane access and new vehicle purchase rebates appear to be helping to expand the early electric car market, with an estimated 2.6 percent increase in sales for every 20 percent increase in miles of nearby carpool lanes, and an estimated 7 percent increase in plug-in vehicles sales as a result of rebates. In 2015, used plug-in hybrid cars were holding their value better than electric-only cars, typically selling for about 10 percent more compared to their MSRP than electric cars.

A project initiated in fiscal year 2016-17 will determine the costs, emissions, and impacts of multiple long-term scenarios to transition to advanced vehicle technologies and alternative fuels in the heavy-duty sector. Results from this project will inform the State on the best use of electricity and fuel to power the heavy-duty sector and identify the best policies and economic mechanisms to encourage pathways that allow California to achieve its long-term goals. Another current project was designed to assist in the development of cost-effective methods to reduce emissions from agricultural equipment in the San Joaquin Valley (SJV). The results from this work will provide CARB with data on agricultural-related businesses to enhance CARB's existing cost and economic impact methodologies. This information will be used to develop a program for mobile agricultural equipment in the SJV to transform their fleet to the clean technologies at the lowest cost.

CARB's economic research is also supporting the implementation of sustainable community strategies adopted under SB 375. An ongoing project is collecting a variety of baseline information with the ultimate goal of developing metrics that can be used in a future statewide

monitoring system for tracking progress toward achieving SB 375 goals. One indicator in this project is access to residential proximity to the workplace. The California Employment Development Department is participating in the advisory committee for this project, and may provide employment data to support the exploration of job access and/or jobs-housing balance as an indicator of progress toward reducing VMT, and thus GHGs under SB 375.

Past regulations and incentive funding has put California on the path towards meeting our 2020 GHG and air quality targets, However, additional research is needed to inform the best uses of incentive funding to meet stricter long-terms goals and ensure that economic prosperity and environmental sustainability can be achieved together. Research on the efficient deployment of incentives is needed to ensure emission reductions are optimized across vehicle and driver populations. Continued research on this topic will ensure that California obtains the greatest emission reductions possible per dollar of incentive funding spent. In addition to supporting transportation-related incentive programs, further Information is needed to help identify financing options to reduce costs and improve the economic feasibility of dairy methane reduction projects. The barriers to the sustainability of new markets also need to be assessed, particularly for low-emission vehicles and low-global-warming-potential refrigeration technology. Future research should also focus on developing a methodology to track the State's use of incentive funding and greenhouse gas reduction fund investments in disadvantaged communities to assess the economic, health, and environmental benefits of these programs.

NEXT STEPS

Each fiscal year, CARB staff will present research projects that fulfill the stated research initiatives in the Triennial Plan. The proposed projects for fiscal year 2018-19 are listed in Appendix 1. Following Board approval of the presented research projects every fiscal year, staff will proceed to work with researchers to develop these research projects into complete proposals, to be reviewed by CARB's Research Screening Committee, and then brought to the Board for final funding approval. Results are anticipated in three to five years after a project commences.

APPENDIX A – FISCAL YEAR 2018-19 PROPOSED RESEARCH PROJECTS

The projects proposed for Fiscal Year 2018-19 are designed support attainment of upcoming air quality and greenhouse gas targets, track implementation of existing programs, ensure the benefits of longer-term strategies and will advance the state of the science in the areas of health and exposure, environmental justice, air quality and climate. Some of these studies are long-term, and build on unique data sets, while others address specific implementation or knowledge gaps. Together, they will provide essential data and tools to support actions to meet California's air quality and climate goals and protect public health, the economy, and vulnerable populations. A research budget of approximately $4.4 million is anticipated to fund 15 new projects in fiscal year 2018-2019. In-house research projects that fulfill the research initiatives outlined in this Plan are also included in this list, but not included in our budget.

FY 2018-19 Research Projects			
Health and Environmental Justice Research Projects			**Cost**
Research Initiative 1 - Short-term health exposures			
	1	White paper and symposium: Research roadmap for the development of a 1-hour PM2.5 standard	$50,000
Research Initiative 2 - Cumulative impacts			
	2	Impact of cumulative environmental exposures and SES on health outcomes in communities near oil and gas activities and other methane/VOC super-emitters	$300,000
	3	Integrating a Community Cumulative Impacts Framework In the Implementation of AB 617 and SB 673	$400,000
	4	In-house project: Total exposures to air pollutants and noise in environmental justice communities	in-house
Research Initiative 4 - Satellite data, toxics, odors			
	5	White Paper: Odor complaints; Health impacts and monitoring methods	$25,000
	6	White Paper: PAH emissions from off-road, light-duty, heavy-duty, and stationary sources	$25,000
	7	In-house project: Near real-time satellite PM2.5 data at 2 km resolution	in-house
Research Initiative 5 -Sustainable communities and health			
	8	Particulate matter health impacts: work loss days, asthma, and other health measures	$400,000
Air Quality Research Projects for Fiscal Year 2018-2019			
Research Initiative 2 - Real-world & lab emission discrepancies (LD)			
	9	Real-world tire and brake wear emissions	$400,000
	10	In-house project: Light-duty vehicle activity study for real-world fuel economy, energy use, duty cycles, and braking activity	in-house
Research Initiative 4 - Reductions from off-road and freight			
	11	Comparison of Tier 4 off-road diesel engines with and without aftertreatment	$500,000
Research Initiative 6 - SJV PM2.5			
	12	Environmental chamber experiments to improve secondary organic aerosol (SOA) model prediction	$400,000
	13	In-house project: Evaluation of ammonia emissions in the San Joaquin Valley from agricultural sources	in-house
Climate Research Projects for Fiscal Year 2018-2019			
Research Initiative 2 - Refine emission estimates			
	14	F-Gas Inventory update for smaller refrigeration and air conditioning systems	$200,000
	15	In-house project and coordinated work: Methane emission monitoring and modeling - Continue ground-level and aerial monitoring of methane and backfill reductions in federal funding for these efforts	In-house
Research Initiative 4 - Tracking progress & quantify co-benefits			
	16	Built environment social determinants of health screening tool and monitoring map	$300,000
	17	Induced travel for congested corridors: quantify short- and long-run induced travel elasticities of non-general purpose lanes on arterials	$350,000
Research Initiative 5 - Evaluating reductions in GHGs from VMT, landuse, & buildings			
	18	White paper: Framework to evaluate the environmental and equity impacts of congestion management strategies	$150,000
Cross-Cutting Research Projects for Fiscal Year 2018-2019			
Research Initiative 1 - Optimizing use of organic waste streams			
	19	White Paper: The best use of California's biomass to meet air quality and climate goals	$25,000
Research Initiative 2 - Potential of advanced technology			
	20	Hybridization and full electrification potentials of off-road applications	$350,000
Research Initiative 3 - Optimizing incentive fund use			
	21	Determinants of medium- and heavy-duty truck fleet turnover and composition	$500,000

1) **White paper and symposium: Research roadmap for the development of a 1-hour PM2.5 standard**

There is currently no standard to protect the population from possible health effects arising from short-term (1-hour) PM2.5 which may occur in cases of high localized emissions such as those associated with traffic or significant stationary sources. The primary objective of this project is to determine a possible methodology for an assessment and to identify knowledge gaps related to the establishment of a short-term PM2.5 standard and to convene a panel of experts to determine the feasibility of bridging these knowledge gaps. The greatest challenge for the investigation of short-term PM2.5 health impacts is the lack of studies focusing on this averaging time as well as statistical evaluation for the scaling of longer-term studies for application into a 1-hour standard. Therefore, an investigator will be chosen to complete a literature review and analysis on the methodology and background information needed for the evaluation, as well as the possible use of monitoring data from impacted communities, for this analysis. A panel of experts will then be convened to discuss and analyze the investigator's findings. The results of this study will be used for development of a possible roadmap for CARB staff to follow for the establishment of a short-term PM2.5 standard.

2) **Impact of cumulative environmental exposures and SES on health outcomes in communities near oil and gas activities and other methane/VOC super-emitters**

Notably, CARB has identified 329 methane super-emitters of oil and gas activities from the California Methane Survey Phase 1, and Phase 2 results will be available in fall 2018. Moreover, CARB will investigate the co-emissions of gaseous toxics and other VOCs from these methane super-emitters through a contract with FluxSense Inc. FluxSense Inc. will be able to look at issues such as persistence and measure actual emission rates and BTEX/VOC/methane ratios. This data will allow for a more detailed analyses of the relationship between health risks, equity impacts, methane super-emitters, and their associated co-emissions from gaseous toxics and other VOCs from oil and gas development and activities in the State. Previous studies in Pennsylvania, Texas, and Colorado have found adverse birth outcomes associated with proximity to unconventional natural gas development (UNDG) activities. The proliferation of domestic oil and gas exploration activities in California has raised concerns about the potential health and equity impacts on local communities due to increases in air pollution, noise, and water contamination, among other factors. In addition, California is unusual than other states in that it has large oil reserves located under densely populated areas, primarily in the San Joaquin Valley and South Coast Air Basins. This study can elucidate the impacts of cumulative environmental exposures and equity impacts on health outcomes in communities near methane/VOC super-emitters associated with oil and gas activities such as refineries, storage tanks, wells, ponds, and gas stations statewide. This study will help to better characterize the potential health and equity impacts on local communities and help provide a better understanding for policy and strategies for conducting targeted research and monitoring in areas of concern.

3) Integrating a Community Cumulative Impacts Framework In the Implementation of AB 617 and SB 673

As required by AB 617 (C. Garcia), CARB must develop an approach to prioritize locations for deployment of community air quality monitoring systems and community emissions reduction programs. This research will support CARB in developing methods, specific to AB 617, for assessing cumulative impacts from environmental health hazards, socioeconomic stressors, and other indicators of community vulnerability. Much of this research will also be conducted for the Department of Toxic Substances Control (DTSC), since SB 673 requires DTSC to consider community vulnerability and cumulative impacts prior to hazardous waste facility permit decisions. The research team will provide analytical support to identify appropriate datasets and develop novel indicators that can be integrated into CalEnviroScreen, an existing cumulative impacts screening approach. This project will advance methods for assessing cumulative impacts and community vulnerability, through a process that engages community stakeholders and evaluates current progress on community air monitoring and emissions reduction programs. The results will provide CARB with the community feedback, data sources, and analytical tools required for refining the criteria with which CARB will implement AB 617.

4) In-house project: Total exposures to air pollutants and noise in environmental justice communities

Accurate estimation of exposures to air pollutants and noise and identification of all sources and factors contributing to high exposures in environmental justice (EJ) communities are essential to achieving the goals of AB 617. This in-house research is a pilot study to obtain daily profiles of personal exposures to air pollutants and noise in EJ communities in northern California and develop methods for a larger study. The work will complement ambient monitoring and assessment to be conducted in selected EJ communities. We will recruit 5 – 7 participants from each of 2 – 3 local EJ communities. We will collect data on participants' time-activity patterns and on their exposure levels to air pollutants and noise over the course of a 24-hour period using a lightweight backpack with air monitoring instruments, a noise meter and a GPS tracker. This pilot study will provide preliminary results regarding the sources, activities, and microenvironments that contribute most to exposures in the EJ communities studied. It will also provide guidance for a comprehensive, statewide exposure study of EJ communities that will support CARB's development of a strategy to reduce air pollutant exposures and noise within EJ communities and thus help meet the requirements of
AB 617.

5) White Paper: Odor complaints; Health impacts and monitoring methods

Despite complaints about unpleasant odors emitted by a variety of facilities within a community, verification of possible pollutants and their sources responsible for these odors remains a challenge. The objective of this study is to investigate methods for determining which pollutants may be responsible for odor complaints from a variety of possible sources, such as foundries, diaries, industrial facilities, and fuel storage facilities. The study will also focus on the

health impacts and monitoring methods for identified pollutants. The science of human odor detection is normally comprised around three tests for olfactory function: odor threshold, discrimination, and identification. However, these studies have rarely been applied to odiferous air pollutants. For this study, an investigator will examine emissions from a variety of facilities which have been identified as producing nuisance odor complaints, and submit a white paper summarizing knowledge gaps and current methods for assessing odor thresholds, monitoring methods, and threshold levels for possible health impacts for these emissions. The results of this study would provide CARB staff with information on the identification of possible odiferous air pollutants, their sources within a community, and a process for initiating an investigation for these type of air pollutants.

6) **White Paper: PAH emissions from off-road, light-duty, heavy-duty, and stationary sources**

Polycyclic Aromatic Hydrocarbons (PAHs) are a class of hydrocarbons, many of which are carcinogenic and/or otherwise toxic, and often their derivatives (e.g., nitro-PAHs) are more harmful than their parent compounds. The objective of this research is to review the literature on PAH emission factors, as well as PAH sampling and analytical methodologies, such that CARB's California Toxics Inventory (CTI) may be improved and expanded to include additional compounds. CARB currently has test methods for 19 PAHs, a subset of which are included in speciation profiles. This literature review will compile published emission factors for combustion sources of PAHs and PAH derivatives, with an emphasis on off-road sources. It will also examine methodological questions such as those related to sampling semi-volatile compounds and hydrocarbon derivatives. This white paper will inform the development of a PAH emissions inventory both by refining emissions estimates for compounds currently included in the California Toxics Inventory (CTI), which will allow speciation profiles used in the CTI to be expanded and therefore advance CARB's ability to quantify Californians' exposure to toxic substances.

7) **In-house project: Near real-time satellite PM2.5 data at 2 km resolution**

Satellite-based PM2.5 monitoring has been performed by using daily satellite aerosol data, but near real-time PM2.5 has not yet been reliably monitored. The objective of this research is to estimate ambient PM2.5 concentrations using satellite remote sensing data (i.e., Aerosol Optical Depth; AOD) at high temporal (every 15 minutes) and spatial (2 km) resolutions in California. This work will complement existing PM2.5 monitoring networks while providing temporally resolved PM2.5 data in areas without a ground PM2.5 monitor. In this project, the sub-hourly relations between measured PM2.5 and satellite AOD will be identified in each air basin, leading to PM2.5 estimations in all areas of the air basin. The final product of this study will be useful in identifying PM2.5 hotspots, tracking PM2.5 transport and thus source areas, and assessing the diurnal change in population exposures to PM2.5 during the day.

8) Particulate matter health impacts: work loss days, asthma, and other health measures

CARB estimates the potential health benefits of regulations and policies to help determine and demonstrate the effectiveness of these actions. Health endpoints used in these calculations include cardiovascular mortality and cardiovascular and respiratory hospitalizations. However, air pollutants have the potential to be associated with additional adverse effects on other health endpoints. The objective of this research is to evaluate the health impacts from PM exposure using various health outcomes, such as work loss days, upper or lower respiratory symptoms, asthma exacerbation, emergency room visits for cardiovascular disease, and hospital admission from asthma and other respiratory illnesses. Investigations of the potential associations between PM exposure and these other health outcomes using more current PM levels and methods of estimation of PM concentrations, will be needed to help extend CARB's health benefits analyses. The results of this project will be useful in quantifying the more complete health impacts of CARB's regulations and policies, and would help to demonstrate the full impact of policy decisions by CARB to protect public health.

9) Real-world tire and brake wear emissions

Particulate matter (PM) emissions from vehicle tailpipe exhaust have been linked with various health issues and regulatory measures have strived and succeeded in significantly reducing those emissions. Consequently, the unregulated portion of vehicle emissions, which include non-exhaust sources such as airborne dust from brake and tire wear, have become increasingly important. The objective of this research is to better characterize these non-exhaust sources and determine their overall contribution to the air quality downwind of major roadways. This work will leverage results from a parallel program examining brake wear PM measured under controlled laboratory conditions. The project will consist of measuring PM emissions near roadway locations and be designed to distinguish the exhaust from the non-exhaust. The results of this study will be useful in determining the fractional contribution of non-exhaust PM in nearby receptor sites and provide a better understanding of the impact this increasingly important source has on air quality.

10) In-house project: Light-duty vehicle activity study for real-world fuel economy, energy use, duty cycles, and braking activity

Activity and engine performance data is essential for accurate assessments of the real-world emissions, energy use, and operating patterns of light-duty vehicles (LDVs), as well as comparison of real-world duty cycles with certification cycles. Using both on-board diagnostic (OBD) wireless transmitters with smartphone applications and OBD dataloggers, this study will collect second-by-second activity data from internal combustion engines and advanced propulsion technologies such as hybrid, plug-in hybrid, and battery electric vehicles. Many sets of LDV activity data are currently available, such as those from Caltrans' Household Travel Survey and that provided to the U.S. EPA by Verizon. Data collected for this project will be standardized and combined with existing data to build a larger database. This database will be used to evaluate real-world energy use (derived from either fuel use or battery use) and to

determine how this energy use is influenced by operation conditions (e.g., vehicle speed, road grade, engine start, braking events, etc.) and vehicle characteristics (propulsion technologies, vehicle size, model year, etc.). This data will be also examined to see if braking events can be identified and if energy consumption from auxiliary components (e.g., air conditioning) can be quantified. Findings from this study will help understand real-world vehicle activity patterns and energy use patterns and examine the cost effectiveness of operating advanced technology vehicles compared to internal combustion vehicles.

11) Comparison of Tier 4 off-road diesel engines with and without aftertreatment

Off-road diesel engines will remain an important source of air pollution in California. The objective of this project is to measure criteria and non-criteria pollutants from selected off-road diesel engines, certified to the same emission standards using different aftertreatment configurations. This work will help advance the development of more stringent off-road emission standards that will result in deploying lower-emitting diesel equipment into several existing sectors in both freight and non-freight applications. For two diesel engines: one with selective catalytic reduction (SCR) only and one with diesel particulate filter and SCR, the project will conduct a comprehensive evaluation of emissions including nitrogen oxides (NOx), particulate matter (PM), non-methane hydrocarbons (NMHC), and carbon monoxide (CO) emissions, carbon dioxide (CO2), volatile organic compounds (VOCs), metals, polycyclic aromatic hydrocarbons (PAHs), and others. The findings from this project will help better understand the characteristics of emissions from engines with different aftertreatment configurations used to meet Tier 4 Final emission standards. The results will also help identify the emissions benefits, of both criteria pollutants and air toxics, associated with various aftertreatment configurations that may be used to meet more stringent PM and NOx certification standards.

12) Environmental chamber experiments to improve secondary organic aerosol (SOA) model prediction

Recent research concluded that non-vehicular sources of reactive gas-phase organics in urban areas are now contributing to significantly larger fraction of the total volatile organic compounds (VOC) emissions. These non-vehicular sources must be better characterized to fully understand their impact on ambient secondary organic aerosol (SOA) and PM2.5 formation. The objective of this research is to characterize SOA precursors that are emitted from a variety of consumer products (CPs) listed in the most recent and comprehensive California Consumer Product Survey data. Furthermore, the project will utilize multiple environmental chambers to determine the SOA yields from CP-derived SOA precursors. The project will also evaluate multiple environmental chambers using existing SOA experimental data, and will design and conduct additional multiple environmental chamber experiments, including measurement of aerosol size distributions, and gas-particle phase composition. The results of this study will aid in the improvement of regulatory air quality models used to develop the State Implementation Plan, and will enhance our ability to develop regulatory strategies that reduce ambient ozone and PM2.5.

13) In-house project: Evaluation of ammonia emissions in the San Joaquin Valley from agricultural sources

Ammonia (NH_3) contributes significantly to the formation of particulate matter in the San Joaquin Valley (SJV). Development of effective air pollution mitigation strategies requires additional spatiotemporal understanding of atmospheric NH_3 emissions that are currently lacking as a result of limited data. The objective of this research is to characterize gaseous NH_3 emissions from agricultural activities in the SJV by expanding the spatial coverage of NH_3 measurements using a next-generation mobile measurement platform equipped with various advanced analytical instruments. The research efforts will include facility-level characterization, localized air pollution assessment, mitigation strategy evaluation, and source apportionment of NH_3 and other important air pollutants (e.g., methane (CH_4)) emitted from dairy and livestock operations. In addition to supporting the pre- and the post-alternative manure management practice studies funded by the California Department of Food and Agriculture and the California Air Resources Board (CARB), the project will also evaluate the air quality in other agricultural areas that are not captured within the scope of the two companion studies. This work will leverage existing efforts on quantifying dairy manure CH_4 emissions to ensure that current and future CH_4 emission mitigation strategies are effectively satisfying the greenhouse reduction goals (e.g., AB 32 and SB 1383) without the potential dis-benefit to local and regional air quality. The results of this study will help future development of CARB's NH_3 emission inventory, State Implementation Plan, Short-Lived Climate Pollutant Reduction Strategy, and community air protection program (AB 617).

14) F-Gas Inventory update for smaller refrigeration and air conditioning systems

CARB has been charged with a legislative mandate to reduce hydrofluorocarbon (HFC) emissions in California by 40 percent below 2013 levels by 2030 (SB 1383). CARB utilizes a comprehensive F-Gas Inventory to estimate emissions in California and characterize the relative emissions from different sectors. CARB uses these emissions estimates to support sector-specific regulations for HFC usage in California. CARB utilizes national estimates of equipment inventories and emission factors scaled for California, data from CARB's Refrigerant Management Program as well as external studies and reports to refine the F-Gas Inventory. However, there are some sectors for which estimates require further refinement. The objective of this research is to improve CARB's understanding of the number of units and emission characteristics of small stationary refrigeration and air conditioning equipment in use in California. CARB will use this data to update the F-Gas Inventory and better characterize emissions from these sectors. This information will be used as a basis to analyze the effectiveness of emissions reduction measures, better implement existing measures and develop further regulations.

15) In-house project and coordinated work: Methane emission monitoring and modeling - Continue ground-level and aerial monitoring of methane and backfill reductions in federal funding for these efforts

Methane is an important short-lived climate pollutant, with air quality issues associated with co-emitted air toxics from certain industrial sources. Significant reductions in methane emissions are seen as a way to provide immediate benefits to limit global warming and play an important part in California's GHG emission reduction strategy. It is therefore essential to understand methane source characteristics, evaluate mitigation strategies and assess the air quality impact of methane sources in surrounding communities. California has made significant progress on understanding methane emissions in the State, and the results provide crucial information to inform the State's climate change mitigation program under the requirements of AB32 and SB32. The Methane Research Program at the California Air Resources Board (CARB) utilizes a variety of scientific approaches to understand methane emission and mitigation measures, including top-down inverse modeling estimation, regional aircraft remote sensing, facility-level emission quantification and source-specific characterization. The research efforts include CARB in-house studies, CARB funded research contracts, collaboration with local, State and federal organizations, and national labs and leveraged research outcome from other State agencies. Future research on methane emission will need to translate facility-level emission snapshots to relevant emission factors, and evaluate the opportunities and effectiveness of the mitigation measures. Efforts will focus on better understanding the fundamentals of the source characteristics, identifying process-level emission profiles, investigating the contribution from super-emitters, evaluating the best management practices and tracking methane emission trends.

16) Built environment social determinants of health screening tool and monitoring map

Effective policy and investment decisions require robust and reliable data on the needs of communities and opportunities for improvement. Existing tools identify communities that are disadvantaged according to a variety of environmental and socioeconomic factors, but these tools currently do not incorporate accessibility to clean transportation options, accessibility to jobs, transportation cost and time burdens, and other social determinants of health. Developing a straightforward methodology to consider those additional factors would help public agencies better target their investments and policies to alleviate transportation-related disparities, which is critical for ensuring that California meets its greenhouse gas reduction goals equitably. This research will result in the development of a screening tool and monitoring map that fills this gap. It will leverage and build build upon frameworks, tools, and data created via other tools and efforts like CalEnviroScreen, UC Davis's Regional Opportunity Index, CARB-funded displacement research, CARB's SB 350 and SB 150 programs, and more. Based on previous scientific findings, the researchers will design a screening method and a tool along with a map that makes it possible to identify areas where transportation-related and other investments can be targeted to have the greatest benefit, and can be used to evaluate whether planned investments align with community needs. The tool is expected to be incorporated into

performance evaluation for the SB 375 program via its reporting to the State legislature, as required by SB 150.

17) Induced travel for congested corridors: quantify short- and long-run induced travel elasticities of non-general purpose lanes on arterials

Travel demand forecasting models are important tools for SB 375 implementation. The objective of this study is to analyze the extent to which current integrated land-use and transportation planning models account for induced travel and identify methods to improve modeling of short- and long-term induced travel impacts. This project will leverage existing literature and quantitative analyses of induced travel demand. This research will quantify the vehicle miles traveled (VMT) response to roadway capacity expansion for various road types, land uses, and time horizons. This research will also provide CARB the methods/analysis necessary to assess the degree of induced VMT not currently accounted for in the MPO RTP/SCSs. The results of this study will be used to inform existing California travel demand models and improve statewide estimates of VMT reductions from planned transportation and land-use changes.

18) White paper: Framework to evaluate the environmental and equity impacts of congestion management strategies

As local jurisdictions in California try to manage increasing congestion and anticipate the impacts of integrating new mobility options and services and automated vehicles, some are beginning to implement innovative congestion and parking management strategies through pilot projects. The objective of this study is to develop a framework for tracking and evaluating the performance of these pilots with respect to greenhouse gas and criteria pollutant emissions and equity. Researchers will review relevant pilot projects and literature and conduct interviews in order to assess what metrics would be most useful for this purpose as well as examine the synergies between the various strategies. The resulting framework will support public agencies in their efforts to implement congestion and parking management strategies and pilots that work well together and are aligned with the State's equity, climate and air quality goals.

19) White Paper: The best use of California's biomass to meet air quality and climate goals

In order for the State to achieve its climate and air quality goals, there is an urgent need to reduce fuel loading in forests that could cause catastrophic wildfires, reduce pile burning in agricultural settings, divert organic material from landfills, and use these waste streams to displace fossil-based alternatives for fuel and electricity production or increase terrestrial carbon sequestration. The objective of this white paper is to review the literature and current research efforts to determine how the California Air Resources Board's (CARB) research program can address the highest priority research questions to advance the most efficient use of biomass waste to meet California's air quality and climate goals. The project will review literature on all waste sources and uses that are relevant in California and the policy analysis should identify success cases and implementation barriers. Existing studies on the impacts of

biomass utilization strategies on health and the economy, particularly on vulnerable and disadvantaged communities should also be a primary focus. The results of this study will identify the highest priority research gaps that CARB should pursue to inform policy makers and industry with respect to further development and direction of biomass policy and best uses of biomass to meet both climate and air quality goals.

20) Hybridization and full electrification potentials of off-road applications

The off-road equipment sector is a major source of greenhouse gases (GHGs), criteria pollutants, and toxic air contaminants. Thus, off-road equipment is one of the important targets for increasing the adoption of zero-emission technologies to help meet CARB's emission reduction goals. However, the off-road sector includes a variety of applications, in both freight and non-freight sectors, with widely ranging performance requirements. The objective of this research is to propose new pathways toward electrifying off-road equipment using both cost effective and durable technology. This work will use existing off-road activity data to help summarize real-world duty cycles and energy needs as well as data and information from recent electrification efforts and pilot projects. This project will consist of summarizing the power demands and operational characteristics of the various off-road equipment applications by proposing pathways toward partial or full electrification for sectors that will maximize emissions reductions. This analysis will include a cost/benefit analysis to demonstrate the economic feasibility of the proposed pathways. The results of this study may inform CARB's future incentive and regulatory programs.

21) Determinants of medium- and heavy-duty truck fleet turnover and composition

Medium and heavy-duty trucks operating in California must transition to low-NO_X, low-GHG emission technology to meet long-term air quality and GHG reduction goals. To help achieve this, CARB needs to understand the factors that determine truck fleet turnover decision-making. This study will identify the determinants of medium and heavy-duty truck fleet turnover in California and evaluate how their influence varies by fleet type, size and location. The study's goal is to better understand how fleet operators decide what vehicles to acquire and dispose of, as well as when to buy, sell or scrap them. Recent research from the University of California, Davis modeled fleet decision processes for a range of fleet types based on a comprehensive set of predictive factors. This study will combine qualitative and quantitative research to develop a detailed understanding of the factors influencing acquisition and disposal of medium and heavy duty trucks (Classes 4-8) by fleets operating in California. Results will be used to enhance CARB's modeling of medium-and heavy-duty fleet composition and to assess the potential effectiveness of regulatory and incentive programs designed to alter normal patterns of vehicle acquisition and disposal.

APPENDIX B – RECENT FINAL REPORTS: JANUARY 2012 – MARCH 2018

HEALTH AND EXPOSURE

Contract Number 03-315. Balmes, John. *Effects of GSTM1 genotype on ozone-induced allergic airway inflammation.* (March 2012)

Contract Number 08-305. Bradman, Asa. *Environmental exposures in early childhood education environments.* (April 2012)

Contract Number 06-331. Wexler, Anthony. *Toxicity of source-oriented ambient submicron particulate matter.* (May 2012)

Contract Number 07-309. Meng, Ying-Ying. *Is disparity in asthma among Californians due to higher pollutant exposures, greater susceptibility, or both?.* (May 2012)

Contract Number 07-310. Delfino, Ralph. *In-vehicle air pollution exposure measurement and modeling.* (June 2012)

Contract Number 09-357. Paulson, Suzanne, and Arthur Winer. *Mobile platform III: Characterizing spatially inhomogeneous non-criteria pollutants in the Los Angeles air basin.* (November 2012)

Contract Number 07-307. Kleinman, Michael T. *Cardiopulmonary health effects: Toxicity of semi-volatile and non-volatile components of ultrafine PM.* (April 2013)

Contract Number 08-307. Delfino, Ralph and Scott Bartell. *Personal, indoor, and outdoor particulate air pollution and heart rate variability in elderly subjects with coronary artery disease.* (April 2013)

Contract Number 10-303. Miller, Lisa. *Persistent immune effects of wildfire PM exposure during childhood development.* (July 2013)

Contract Number 10-302. Wilson, Dennis . *Location specific systemic health effects of ambient particulate matter.* (January 2014)

Contract Number 09-342. Morrison et al. *In-duct air cleaning devices: Ozone emission rates and test methodology.* (March 2014)

Contract Number 08-306. Kleinman, Michael. *Central nervous system effects of ambient particulate matter: the role of oxidative stress and inflammation.* (April 2014)

Contract Number 09-341. Delfino, Ralph. *Peripheral blood gene expression in subjects with coronary artery disease and exposure to particulate air pollutant components and size fractions.* (April 2014)

Contract Number 10-320. Destaillats et al. *Evaluation of pollutant emissions from portable air cleaners*. (December 2014)

Contract Number 10-319. Delfino, Ralph, and Michael Kleeman. *Risk of pediatric asthma morbidity from multipollutant exposures.* (February 2015)

Contract Number 09-330. Wexler, Anthony. *Health effects of Central Valley particulate matter*. (March 2015)

Contract Number 11-310. Zhu, Yifang. *Reducing air pollution exposure in passenger vehicles and school buses.* (April 2015)

Contract Number 11-311. Singer, Brett, and Iain Walker. *Reducing in-home exposure to air pollution.* (May 2016)

Contract Number 13-306. Paulson, Suzanne. *Effectiveness of Sound Wall-Vegetation Combination Barriers as Near-Roadway Pollutant Mitigation Strategies.* (May 2017)

Contract Number 13-309. Kleinman, Michael. *Cardiovascular Effects of Multipollutant Exposure: Mechanisms and Interactions.* (September 2017)

Contract Number 13-311. Tablin, Fern. *Co-Exposure to PM and O-3: Pulmonary C Fiber Platelet Activation in Decreased HRV.* (September 2017)

Contract Number 14-303. Destaillats, Hugo. *Characterizing Formaldehyde Emissions from Home Central Heating and Air Conditioning Filters.* (February 2018)

SIP PROGRAM SUPPORT

Contract Number 07-332. Yates, Scott. *Reducing emissions of volatile organic compounds (VOCs) from agricultural soil fumigation : Comparing emission estimates using simplified methodology.* (January 2012)

Contract Number 07-318. DePaolo, Donald. *Using Pb and Sr isotopes to assess asian aerosol impacts in urban and interior California.* (February 2012)

Contract Number 08-318. Stutz, Jochen. *Nocturnal chemistry in the urban boundary layer of Los Angeles.* (April 2012)

Contract Number 07-333. Schauer, James. *Source apportionment of carbonaceous aerosols using integrated multi-variant and source tracer techniques and a unique molecular marker data set.* (May 2012)

Contract Number 08-326. Carter, William P. L. *SOA formation: Chamber study and model development.* (May 2012)

Contract Number 09-337. Russell, Lynn and Ranjit Bahadur. *Are There Any Counteracting Effects that Reduce the Global Warming Benefits Attributed to Black Carbon Controls? Assessment of Cloud Drop Number Concentration Changes and its Importance in Modeling Cloud Albedo Effects on Climate.* (December 2012)

Contract Number 08-316. Goldstein, Allen and Ronald Cohen. *Characterization of the atmospheric chemistry in the southern San Joaquin Valley.* (May 2013)

Contract Number 08-319. Jimenez, Jose-Luis. *Characterization of ambient aerosol sources and processed during CALNEX 2010 with aerosol mass spectrometry.* (May 2013)

Contract Number 08-327. Sullivan, David W. *Development of an updated base case ambient VOC mixture for assessing atmospheric reactivity.* (May 2013)

Contract Number 09-328. Russell, Lynn. *Improved characterization of primary and secondary carbonaceous particles.* (June 2013)

Contract Number 09-316. Goldstein, Allen. *Hourly in-situ quantitation of organic aerosol marker compounds during CALNEX 2010.* (July 2013)

Contract Number 09-356. Russell, Lynn. *Cal-Mex 2010: US and Mexico collaborative project on air quality and climate change in the California-Mexico border region.* (July 2013)

Contract Number 09-333. Prather, Kimberly. *Three-dimensional measurements of aerosol mixing state during CALNEX 2010 using aircraft aerosol time-of-flight mass spectrometry.* (September 2013)

Contract Number 09-317. Volkamer, Rainer. *AMAX-DOAS trace gas column observations from the research aircraft over California.* (February 2014)

Contract Number 10-305. Zhang, Qi. *Extended analysis of the CARES aerosol chemistry data to characterize sources and processes of organic aerosol in the Sacramento Valley of California.* (February 2014)

Contract Number 10-313. Kleeman, Michael. *Understanding primary organic aerosol volatility at atmospherically realistic concentrations for SIP analysis.* (February 2014)

Contract Number 10-326. Parrish, David and Joost de Gouw. *Synthesis of policy relevant findings from the Calnex 2010 field study.* (March 2014)

Contract Number 09-339. Goldstein, Allen. *Improving regional biogenic VOC emission estimates using an airborne PRTMS eddy flux measurement system.* (April 2014)

Contract Number 10-312. Durbin, Thomas. *Construction of a DOAS instrument for installation at CARB for the low level measurement of SO_2 to investigate the relation between SO_2 and sulfate.* (May 2014)

Contract Number 09-318. Stutz et al. *Determination of the spatial distribution of ozone precursor and greenhouse gas concentrations and emissions on the LA-Basin*. (February 2015)

Contract Number 13-304. Bennett, Deborah. *Environmental fate of low vapor pressure - volatile organic compounds from consumer products: a modeling approach*. (July 2015)

Contract Number 11-305. Jimenez, Jose-Luis. *Source speciation of Central Valley greenhouse gas emissions using in-situ measurements of volatile organic compounds*. (October 2015)

Contract Number 11-315. Goldstein, Allen, and Marc Fischer. *Source speciation of Central Valley greenhouse gas emissions using in-situ measurements of volatile organic compounds*. (April 2016)

Contract Number 13-302. Cocker, David. *Air quality impacts of low vapor pressure-volatile organic compounds*. (December 2016)

Contract Number 12-312. Wexler, Anthony. *Improving Chemical Mechanisms for Ozone And Secondary Organic Carbon*. (March 2017)

MOBILE SOURCES AND TRANSPORTATION SYSTEM STRATEGIES SUPPORT

Contract Number 08-302. Jung, Heejung. *Measurement of diesel solid nanoparticle emissions using a catalytic stripper for comparison to Europe's PMP Protocol*. (November 2012)

Contract Number 09-303. Dwyer, Harry. *Evaluation of potential for refrigerant recovery from decommissioned shipping containers at California ports.* (April 2012)

Contract Number 08-315. Durbin, Thomas. *Study of in-use emissions from diesel off-road equipment.* (April 2013)

Contract Number 09-340. Harley, Robert. *On-road measurement of emissions from heavy-duty diesel trucks: impacts of fleet turnover and CARB's drayage truck regulation*. (November 2014)

Contract Number 10-311. Johnson, Kent, and Thomas Durbin. *Development of a portable in-use reference PM measurement system*. (December 2014)

Contract Number 13-313. Pannone, Greg. *Technical analysis of vehicle load-reduction potential for Advanced Clean Cars*. (April 2015)

Contract Number 11-316. Ritchie, Stephen. *Development of a new methodology to characterize truck body types along California freeways*. (January 2016)

Contract Number 12-320. Jung, Heejung. *Very low PM measurements for light-duty vehicles (E-99)*. (January 2016)

Contract Number 12-332. Kurani, Kenneth. *New car buyers' valuation of zero-emission vehicles: California*. (April 2016)

Contract Number 12-303. Stedman, Donald, and Gary Bishop. *Measuring real-world emissions from the on-road passenger car fleet*. (October 2016)

Contract Number 11-322. Mokhtarian, Patricia, and David Rapson. *Modeling Household Vehicle and Transportation Choice and Usage*. (April 2017)

Contract Number 13-312. Webb, Cynthia. *Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles*. (April 2017)

Contract Number 13-301. Boriboonsomsin, Kanok. *Collection of Activity Data from On-Road Heavy-Duty Diesel Vehicles*. (May 2017)

Contract Number 14-317. Jaffe, Amy. *Potential to Build Current Natural Gas Infrastructure to Accommodate the Future Conversion of Near-Zero Transportation Technology*. (July 2017)

Contract Number 14-305. Bein, Keith. *Protocol Development for Vehicle PM Emission Toxicity Testing*. (September 2017)

Contract Number 11-309. Stedman, Donald. *Investigate the Durability of Diesel Engine Emissions Controls*. (March 2018)

SUSTAINABLE COMMUNITIES PROGRAM SUPPORT

Contract Number 09-306. Wagner, Mark and Pamela Mathis. *Greenhouse gas performance analysis for commercial buildings with large refrigeration and air conditioning systems.* (May 2012)

Contract Number 09-344. Kammen, Daniel M. and Chris Jones. *Measuring the climate impact of residential buildings: GreenPoint-rated climate calculator version 2.* (September 2012)

Contract Number 08-325. Kahn, Mathew E. *A field experiment to assess the impact of information provision on household electricity consumption.* (January 2013)

Contract Number 09-326. Meier, Alan. *Identifying determinants of very low energy consumption rates observed in some California households.* (April 2013)

Contract Number 10-308. Arens, Edward. *Air movement as an energy efficient means toward occupant comfort.* (November 2013)

Contract Number 10-323. Mozingo, Louise. *Residential energy use and greenhouse gas emissions impacts of compact land use types.* (November 2013)

Contract Number 09-327. Meier, Alan. *Behavioral strategies to bridge the gap between potential and actual savings in commercial buildings.* (February 2014)

Contract Number 10-332. Delmas, Magali. *Behavioral responses to real-time individual energy usage information: a large scale experiment*. (March 2014)

Contract Number 09-343. Salon, Deborah. *Quantifying the effect of local government actions on vehicle miles traveled (VMT).* (February 2014)

Contract Number 10-321. Levinson et al. *Using remote sensing to quantify albedo of roofs in seven California cities.* (March 2014)

Contract Number 09-346. Yeh, Sonia and Christopher Yang. *Modeling optimal transition pathways to a low carbon economy in California.* (April 2014)

Contract Number 11-323. Arens, Edward, and Louise Mozingo. *Quantifying the comprehensive greenhouse gas co-benefits of green buildings*. (August 2014)

Contract Number 10-325. Kammen, Daniel. *The CoolCalifornia. org Challenge: a pilot inter-city household carbon footprint reduction competition*. (November 2014)

Contract Number 12-313. Houston, Douglas. *Evaluating the benefits of light rail transit*. (April 2015)

Contract 11-326. Chatman, Daniel. *Analyzing the economic benefits and costs of smart growth strategies*. (March 2016)

Contract Number 11-312. Zhu, Yifang. *Effects of complete streets on travel behavior.* (April 2016)

Contract Number 12-308. Paulson, Suzanne. *Identifying urban designs and traffic management strategies for southern California that reduce air pollution exposure*. (February 2017)

Contract Number 11-310. Chapple, Karen. *Developing a New Methodology for Analyzing Potential Displacement.* (March 2017)

Contract Number 12-314. Levinson, Ronnen. *Life Cycle Assessment and Co-Benefits of Cool Pavements.* (March 2017)

CLIMATE STRATEGIES SUPPORT

Contract Number 07-322. Horvath, Arpad. *Retail climate change mitigation: Life-cycle emission and energy efficiency labels and standards.* (January 2012)

Contract Number ICAT 6-12. Werts, Hack, McDonell. *Adaptive low emission microturbine for renewable fuels.* (January 2012)

Contract Number 09-348. Fischer, Marc L. and Seongeun Jeong. *Inverse modeling to verify California's greenhouse gas emission inventory.* (April 2012)

Contract Number 08-324. Horwath, William R. *Assessment of baseline nitrous oxide emissions in California cropping systems.* (June 2012)

Contract Number 08-323. Ramanathan, V. *Black carbon and the regional climate of California.* (April 2013)

Contract Number 09-325. Horwath, William R. *Assessment of baseline nitrous oxide emissions in California's dairy systems.* (November 2013)

Contract Number 09-329. Horwath, William R. *Determining NO_X emissions from soil in California cropping systems to improve ozone modeling.* (November 2013)

Contract Number 10-309. Li, Changsheng. *Calibrating, validating, and implementing process models for California agriculture greenhouse gas emissions.* (February 2014)

Contract Number 11-307. Dabdub et al. *Assessment of the emissions and energy impacts of biomass and biogas use in California*. (February 2015)

Contract Number 11-313. Burger, Martin. *Evaluating mitigation options of nitrous oxide emissions in California cropping systems*. (January 2016)

Contract Number 11-306. Fischer, Marc, and Seongeun Jeong. *Atmospheric measurement and inverse modeling to improve greenhouse gas emission estimates*. (February 2016)

Contract Number 11-325. Mitloehner, Frank. *Quantification of the emission reduction benefits of mitigation strategies for dairy silage*. (April 2016)

Contract Number 11-308. Yesiller, Nazli. *Emissions of potent greenhouse gases from appliance and building waste in landfills*. (May 2016)

Contract Number 13-307. Myers Jaffe, Amy. *The feasibility of renewable natural gas as a large-scale, low-carbon substitute*. (June 2016)

Contract Number 13-308. Horvath, Arpad. *The future of drop-in fuels: Life-cycle cost and environmental impacts of bio-based hydrocarbon fuel pathways*. (August 2016)

Contract Number 14-306. Li, Changsheng. *Improving DNDC Modeling Capability to Quantify Mitigation Potential of Nitrous Oxide from California Agricultural Soils*. (August 2016)

Contract Number 14-318. Miller, Marshall. *The Development of Lifecycle Data for Hydrogen Fuel Production and Delivery*. (October 2016)

APPENDIX C – RESEARCH DIVISION STAFF PEER-REVIEWED PUBLICATIONS: JANUARY 2000 – DECEMBER 2017

[CARB staff member names are underlined.]

ENVIRONMENTAL JUSTICE

Ritz, B., Yu, F., Chapa, G., and Fruin, S. (2000) "The Effect of Air Pollution on Preterm Birth Among Children Born in Southern California Between 1989-1993," *Epidemiology*, **11**(5):502-511.

Ritz, B., Yu, F., Fruin, S., Chapa, G., Shaw, G.M., and Harris, J.A. (2002) "Ambient Air Pollution and Risk of Birth Defects in Southern California," *American Journal of Epidemiology*, **155** (1):17-25.

Westerdahl, D., Fruin, S.A., Fine, P.L., and Sioutas, C., (2008) "The Los Angeles International Airport as a Source of Ultrafine Particles and Other Pollutants to Nearby Communities," *Atmospheric Environment,* 42(13):3143–3155.

Kozawa, K., Fruin, S.A., and Winer, A.M. (2009) "Near-Road Air Pollution Impacts of Goods Movement in Communities Adjacent to the Ports of Los Angeles and Long Beach," *Atmospheric Environment,* **43**(18):2950-2959.

Hu, S., Paulson, S.E., Fruin, S., Kozawa, K., Mara, S., and Winer, A.M., (2011) "Observation of Elevated Air Pollutant Concentrations in a Residential Neighborhood of Los Angeles California Using a Mobile Platform," *Atmospheric Environment,* **51**:311-319.

Hu, S., Fruin, S., Kozawa, K., Mara, S., Winer, A.M., and Paulson, S.E. (2012) "Aircraft Emission Impacts in a Neighborhood Adjacent to a General Aviation Airport in Southern California," *Environmental Science & Technology*, **43**(21):8039-8045.

Yap, P.S., Gilbreath, S., Garcia, C., Jareen, N., Goodrich, B. (2013), "The Influence of Socioeconomic Markers on the Association Between Fine Particulate Matter and Hospital Admissions for Respiratory Conditions Among Children," *American Journal of Public Health*, **103**(4):695-702.

Park, S.S., Vijayan, A., Mara, S.L., Herner, J.D. (2016) "Investigating the real-world emission characteristics of light-duty gasoline vehicles and their relationship to local socioeconomic conditions in three communities in Los Angeles, California," *Journal of the Air & Waste Management Association*, **66**(10):1031-1044.

AIR POLLUTION/ENERGY POLICY

Croes, B.E., et al. (2007) "National Academy of Engineering and National Research Council in collaboration with Chinese Academy of Engineering and Chinese Academy of Sciences Energy Futures and Urban Air Pollution: Challenges for China and the United States," *National Academy Press, Washington, D.C.*

Craig, L., Brook, J.R., Chiotti, Q., Croes, B., Gower, S., Hedley, A., Krewski, D., Krupnick, A., Krzyzanowski, M., Moran, M.D., Pennell, W., Samet, J.M., Schneider, J., Shortreed, J., Williams, M. (2008) "Air Pollution and Public

Health: A Guidance Document for Risk Managers," *Journal of Toxicology and Environmental Health, Part A*, **71**(9-10):588-698.

Edgerton, S.A., MacCracken, M.C., Jacobson, M.Z., Ayala, A., Whitman, C.E., Trexler, M.C. (2008) "Critical Review Discussion: Prospects for Future Climate Change and the Reasons for Early Action," *Journal of Air & Waste Management Association,* **58**:1386-1400.

Croes, B.E. (2012) "New Directions: California's Programs for Improving Air Quality and Minimizing Greenhouse Gas Emissions," *Atmospheric Environment,* 47:562–563.

Parrish, D. D., Xu, J., Croes, B., & Shao, M. (2016) "Air quality improvement in Los Angeles—perspectives for developing cities," *Frontiers of Environmental Science & Engineering*, **10**(5):1-13.

AIR QUALITY STUDIES

Croes, B.E., and Fujita, E.M. (2003) "The 1997 Southern California Ozone Study (SCOS97-NARSTO) Dedicated to the Memory of Dr. Glen Cass (1947-2001)," *Atmospheric Environment,* **37**(S2):S1-S2.

Croes, B.E., and Fujita, E.M. (2003) "Overview of the 1997 Southern California Ozone Study (SCOS97-NARSTO)," *Atmospheric Environment,* **37**(S2):S3-S26.

Fitz, D.R., Bumiller, K., and Lashgari, A. (2003) "Measurement of NO_Y During the SCOS97-NARSTO," *Atmospheric Environment*, **37**(S2):S119-S134.

Livingstone, P., Magliano, K., Gurer, K., Allen, P., Zhang, K., Ying, Q., Jackson, B., Kaduwela, A., Kleeman, M., Woodhouse, L., Turkieqicz, K., Horowitz, L., Scott, K., Johnson, D., Taylor, C., O'Brien, G., DaMassa, J., Croes, B., Binkowski, F., and Byun, D. (2009) "Simulating PM Concentration During a Winter Episode in a Subtropical Valley: Sensitivity Simulations and Evalulation Methods," *Atmospheric Environment,* 43(37):5971–5977.

Jacob, D.J., Crawford, J.D., Maring, H., Clarke, A.D., Dibb J.E., Emmons, L. K., Ferrare, R.A., Hostetler, C.A., Russell, P.D., Singh, H.B., Thompson, A. M., Shaw, G.E., McCauley, E., Pederson, J.R., Fisher, J. (2010) "The Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) Mission: Design, Execution, and First Results," *Atmospheric Chemistry and Physics,* **10:**5191–5212.

Liang, J., and Jacobson, M., (2011) "CVPS: An Operator Solving Complex Chemical and Vertical Processes Simultaneously with Sparse-Matrix Techniques," *Atmospheric Environment,* 45(37):6820–6827.

Dolislager, L., VanCuren, R., Pederson, J., Lashgari, A., and McCauley, E. (2012) "A Summary of the Lake Tahoe Atmospheric Deposition Study (LTADS)," *Atmospheric Environment,* **46**:618-630.

Dolislager, L., VanCuren, R., Pederson, J., Lashgari, A., and McCauley, E. (2012) "An Assessment of Ozone Concentrations Within and Near the Lake Tahoe Air Basin," *Atmospheric Environment,* **46**:645-654.

VanCuren, R., Pederson, J., Lashgari, A., Dolislager, L., and McCauley, E. (2012) "Air Pollution in the Shore Zone of Large Alpine Lake - 1 - Road Dust and Urban Aerosols at Lake Tahoe, California-Nevada," *Atmospheric Environment*, **46**:607-617

VanCuren, R., Pederson, J., Lashgari, A., Dolislager, L., and McCauley, E. (2012) "Aerosol Generation and Circulation in the Shore Zone of a Large Alpine Lake - 2 - Aerosol Distributions over Lake Tahoe, California," *Atmospheric Environment,* **46**:631-644.

Chen, J., and Luo, D. (2012) "Ozone Formation Potentials from Different Emission Sources of Organic Compounds in the South Coast Air Basin of California," *Atmospheric Environment*, **14**:585-593.

ASIAN AEROSOL TRANSPORT

VanCuren, R.A., and Cahill, T.A. (2002) "Asian Aerosols in North America: Frequency and Concentration of Fine Dust," *Journal of Geophysical Research,* **107**(D24):4804 (16 pages).

Liu, W., Hopke, P.K. and VanCuren, R.A. (2003) "Origins of Fine Aerosol Mass in the Western United States using Positive Matrix Factorization," *Journal of Geophysical Research,* **108**(D23):4716 (18 pages).

VanCuren, R.A. (2003) "Asian Aerosols in North America: Extracting the Chemical Composition and Mass Concentration of the Asian Continental Aerosol Plume from Long-term Aerosol Records in the Western United States," *Journal of Geophysical Research*, **108**(D20):4623 (16 pages).

VanCuren, R.A., Cliff, S.S., Perry K.D., and Jimenez-Cruz M. (2005) "Asian Continental Aerosol Persistence above the Marine Boundary Layer over the Eastern North Pacific: Continuous Aerosol Measurements from International Transport and Chemical Transformation 2002 (ITCT 2K2)," *Journal of Geophysical Research*, **110**:D09S90 (19 pages),

CLIMATE CHANGE IMPACTS

Cayan, D., Luers, A. L., Franco, G., Hanemann, M., Croes, B., and Vine, E. (2008) "Overview of the California Climate Change Scenarios Project," *Climatic Change,* **87**(Suppl 1):S1-S6.

Motallebi, N., Mihriban, S., McCauley, E., and Taylor, J. (2008) "Climate Change Impact on California On-Road Mobile Source Emissions," *Journal of Climate Change,* **87**:293-308.

Shindell, D., Faluvegi, G., Walsh, M., Anenberg, S., Van Dingenen, R., Muller, N., Austin, J., Koch, D., and Milly, G. (2011) "Climate, Health, Agricultural and Economic Impacts of Tighter Vehicle-Emission Standards," *Nature Climate Change*, **1**:59-66.

VanCuren, R.A. (2012) "The Radiative Forcing Benefits of "Cool Roof" Construction in California: Quantifying the Climate Impacts of Building Albedo Modification," *Climatic Change,* **112**(3-4):1071-1083.

Brown, H.E., Comrie, A.C., Drechsler D.M., Barker, CM, Basu, R., Brown, T., Gershunov, A., Kilpatrik, A.M., Reisen, W.K., Ruddell, D.M., Garfin, G., Jardin, A., Merideth, R., Black, M., LeRoy, S. (2013) "Human Health" in "Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment," *A report by the Southwest Climate Alliance,* pp.312-339. Washington, DC: Island Press.

DIESEL (GENERAL)

Lloyd, A.C., and Cackette T.A. (2001) "Diesel Engines: Environmental Impact and Control," *Journal of the Air & Waste Management Association*, **51**:809-847.

Lloyd, A.C., and Cackette T.A. (2001) “Diesel Engines: Environmental Impact and Control,” *EM,* 34-41, June

Dwyer, H., Ayala, A., Zhang, S., Collins, J., Huai, T., Herner J., and Chau, W. (2010) “Emissions from a diesel car during regeneration of an active diesel particulate filter,” *Journal of Aerosol Science*, **41**(6):541-552.

Dwyer, H., Ayala, A., Zhang, S., Collins, J., Huai, T., Herner, J., and Chau, W. (2010) “A Study of Emissions from a Euro 4 Light Duty Diesel Vehicle with the European Particulate Measurement Programme,” *Atmospheric Environment,* **44**(29):3469-3476.

Shafer, M.M., Toner, B.M., Overdier, J.T., Schauer, J.J., Fakra, S.C., Hu, S., Herner, J.D., and Ayala, A. (2012) “Chemical Speciation of Vanadium and Application to Particulate Matter Emitted from Diesel Vehicles and Urban Atmospheric Aerosols,” *Environmental Science & Technology*, **46**(1):189–195.

DIESEL AND CNG TRANSIT BUSES

Ayala, A., Kado, N.Y., Okamoto, R.A., Holmén, B.A., Kuzmicky, P.A., Kobayashi, R., and Stiglitz, K.E. (2002) "Diesel and CNG Heavy-duty Transit Bus Emissions over Multiple Driving Schedules: Regulated Pollutants and Project Overview," *SAE Transactions Journal of Fuels and Lubricants,* 735-747.

Holmén, B.A., and Ayala, A. (2002) “Ultrafine PM Emissions from Natural Gas, Oxidation-Catalyst Diesel and Particle-Trap Diesel Heavy-Duty Transit Buses,” *Environmental Science & Technology*, **36:**5041-5050.

Ayala, A., Gebel, M.E., Okamoto, R.A., Rieger, P.L., Kado, N.Y., Cotter, C., and Verma, N. (2003) “Oxidation Catalyst Effect on CNG Transit Bus Emissions,” SAE Technical Paper 2003-01-1900.

Kado, N.Y., Okamoto, R.A., Kuzmicky, P.A., Kobayashi, R., Ayala, A., Gebel, M.E., Rieger, P.L., Maddox, C., and Zafonte, L. (2005) “Emissions of Toxic Pollutants from Compressed Natural Gas and Low Sulfur Diesel-Fueled Heavy-Duty Transit Buses Tested over Multiple Driving Cycles,” *Environmental Science & Technology*, **39:**7638-7649.

Okamoto, R.A., Kado, N.Y., Kazumicky, P.A., Ayala, A., and Kobayashi, R. (2006) “Unregulated Emissions from Compressed Natural Gas (CNG) Transit Buses Configured with and without Oxidation Catalyst,” *Environmental Science & Technology*, **40**:332-341

DIESEL TRUCKS

Gautam, M., Clark, N.N., Riddle, W., Nine, R.D., Wayne, W.S., Maldonado, H., Agrawal, A., and Carlock, M. (2002) "Development and Initial Use of a Heavy-Duty Diesel Truck Test Schedule for Emissions Characterization," SAE Technical Paper 2002-01-1753.

Traver, M.L., Tennant, C.J., McDaniel, T.I, McConnell, S.S, Bailey, B.K., and Maldonado, H. (2002) "Interlaboratory Cross-check of Heavy-Duty Vehicle Chassis Dynamometers," SAE Technical Paper 02FFL-284 (FFL26).

Clark, N.N., Gautam, M., Wayne, W.S., Nine, R.D., Thompson, G.J., Lyons, D.W., Maldonado, H., Agrawal, A., and Carlock, M. (2003) "Creation and Evaluation of a Medium-Heavy-Duty Truck Test Cycle," SAE Technical Paper 2003-01-3284.

Clark, N.N., Gautam, M., Wayne, W.S., Thompson, G.J., Nine, R.D., Lyons, D.W., Buffamonte, T., Xu, S., and Maldonado, H. (2004) "Regulated Emissions from Heavy Heavy-Duty Diesel Trucks Operating in the South Coast Air Basin," Society of Automotive Engineers, Inc. 06FFL-18.

Ayala, A., Chernich, D.J., Huai, T., Johnson, K.C. and Miller J.W. (2005) "Emissions Correlation Between a Partial-Flow Diluter and The Full-Flow Constant Volume Sampler (CVS) for a Heavy-Duty Vehicle Under Steady-State Operation," SAE Technical Paper 2005-01-3798.

Ayala, A., and Herner, J.D. (2005) "Transient Ultrafine Particle Emission Measurements with a New Fast Particle Aerol Sizer for a Trap Equipped Diesel Truck," SAE Technical Paper 2005-01-3800.

Huai, T., Shah, S.D., Miller, J.W., Younglove, T., Chernich, D.J., and Ayala, A. (2006) "Analysis of Heavy-Duty Diesel Truck Activity and Emissions Data," *Atmospheric Environment*, **40**:2333-2344.

Herner, J.D., Robertson, W.H., and Ayala, A. (2007) "Investigation of Ultrafine Particle Number Measurements from Clean Diesel Truck using the European PMP Protocol," SAE Technical Paper 2007-01-1114

Durbin, T.D., Johnson, K., Miller, J.W., Maldonado, H., and Chernich, D. (2008) "Emissions from Heavy-Duty Vehicles Under Actual On-Road Driving Conditions," *Atmospheric Environment* **42**:4812-4821.

Biswas, S., Hu, S., Verma, V., Herner, J., Robertson, W., Ayala, A., and Sioutas, C. (2008) "Physical Properties of Particulate Matter (PM) from Late Model Heavy Duty Diesel Vehicles Operating with Advanced PM and NO_X Emission Control Technologies," *Atmospheric Environment,* **42**(22):5622-5634.

Hu, S., Herner, J., Shafer, M., Robertson, W., Schauer, J., Dwyer, H., Collins, J., Huai, T., and Ayala, A. (2009) "Metals Emitted from Heavy-Duty Diesel Vehicles Equipped with advanced PM and NO_X Emission Controls," *Atmospheric Environment,* **43**(21):2950-2959.

Herner, J., Hu, S., Robertson, W., Huai, T., Collins, J., Dwyer, H., and Ayala, A. (2009) "Effect of Advanced Aftertreatment for PM and NO_X Control on Heavy-Duty Diesel Truck Emissions," *Environmental Science & Technology,* **43**(15):5928-5933.

Johnson, K., Durbin, T., Jung, H., Chaudhary, A., Cocker, D. III., Herner, J., Robertson, W., Huai, T., Ayala, A., and Kittelson, D., (2009) "Evaluation of the European PMP Methodologies During On-Road and Chassis Dynamometer Testing for DPF Equipped Heavy Duty Diesel Vehicles," *Aerosol Science and Technology*, **43**(10):962-969.

Herner, J., Hu, S., Robertson, W., Huai, T., Chang, O., Rieger, P., and Ayala, A. (2011) "Effect of Advanced Aftertreatment for PM and NO_X Reduction on Heavy-Duty Diesel Engine Nanoparticle Emissions," *Environmental Science & Technology*, **45**(6):2413-2419.

Misra, C., Collins, J.F., Herner, J.D., Sax, T., Krishnamurthy, M., Sobieralksi, W., Burntizki, M., Chernich, D. (2013), "In-Use NO_X Emissions from Model Year 2010 and 2011 Heavy-Duty Diesel Engines Equipped With Aftertreatment Devices," *Environmental Science & Technology*, **47**(14):7892–7898.

Hu, S., Herner, J.D., Robertson, W., Kobayashi, R., Chang, M.C.O., Huang, S., Zielinska, B., Kado, N., Collins, J.F., Rieger, P., Huai, T., Ayala, A. (2013), "Emissions of Polycyclic Aromatic Hydrocarbons (PAHs) and Nitro-PAHs From Heavy-Duty Diesel Vehicles with DPF and SCR," *Journal of the Air & Waste Management Association*, **63**(8):984-996.

Yoon, S., Collins, J.F., Thiruvengadam, A., Herner, J.D., Gautam G., Ayala, A. (2013), "Criteria Pollutants and Greenhouse Gas Emissions from CNG Transit Buses with Three-Way Catalysts Compared to Lean-Burn Engines and Engine and Oxidation Catalyst Technologies," *Journal of the Air & Waste Management Association,* **63(**8):926-933.

Gordon, T.D., Tkacik, D.S., Presto, A.A., Zhang, M., Jathar, S.H., Nguyen, N.T., Massetti, J., Truong, T., Cicero-Fernandez, P., Maddox, C., Rieger, P., Chattopadhyay, S., Maldonado H., Maricq, M.M., Robinson, A.L. (2013), Primary Gas- and Particle-Phase Emissions and Secondary Organic Aerosol Production from Gasoline and Diesel Off-Road Engines" *Environmental Science & Technology* **47**:14137-14146.

Yoon, S., Hu, S., Kado, N.Y., Thiruvengadam, A., Collins, J.F., Gautam, M., Herner, J.D., Ayala, A. (2013) "Chemical and toxicological properties of emissions from CNG transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies," *Atmospheric Environment*, **83**:220-228.

Dwyer, H., Yoon, S., Quiros, D., Collins, J. (2014) "Ambient Emission Measurements from Parked Regenerations of 2007 and 2010 Diesel Particulate Filters," SAE Technical Paper 2014-01-2353, 2014.

Quiros, D., Yoon, S., Collins, J., Huai, T., Zhu, Y., Dwyer, H. (2014), "Measuring Particulate Matter Emissions during Parked Active Diesel Particulate Filter Regeneration of Heavy-Duty Diesel Trucks," *Journal of Aerosol Science*, **73**:48-62.

Thiruvengadam, A., Besch, M., Yoon, S., Collins, J., Kappanna, H., Carder, D., Ayala, A., Herner, J., Gautam, M. (2014), "Characterization of Particulate Matter Emissions from a Current Technology Natural Gas Engine," *Environmental Science & Technology,* **48**(14):8235-8242.

Yoon, S., Quiros, D., Dwyer, H., Collins, J., Burnitzki, M., Chernich, D., Herner, J. (2015), "Characteristics of Particle Number and Mass Emissions during Heavy-Duty Diesel Truck Parked Active DPF Regeneration in an Ambient Air Dilution Tunnel," *Atmospheric Environment*, **122**:58-64.

Bishop, G., Hottor-Raguindin, R., Stedman, D., McClintock, P., Theobald, E., Johnson, J., Lee, D.W., Zietsman, J., Misra, C. (2015) "On-Road Heavy-Duty Vehicle Emissions Monitoring System,"*Environmental Science & Technology*, **49**(3):1639-1645.

Ruehl, C., Herner, J., Yoon, S., Collins, J., Misra, C., Na, K., Robertson, W.H., Biswas, S., Chang, M.O., Ayala, A. (2014) "Similarities and Differences between 'Traditional' and 'Clean' Diesel PM," *Emission Control Science & Technology*, **49**.

Sharp, C., Webb, C., Neely, G., Sarlashkar, J., Yoon, S. et al., (2017) "Achieving Ultra Low NO_X Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine and an Advanced Technology Emissions System- NO_X Management Strategies," *SAE Int. J. Engines* **10**(4), pp. 1736-1748.

Sharp, C., Webb, C., Neely, G., Yoon, S., Carter, M. et al., (2017) "Achieving Ultra Low NO_X Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine and an Advanced Technology Emissions System - Thermal Management Strategies," *SAE Int. J. Engines* **10**(4), pp. 1697-1712.

Sharp, C., Webb, C., Yoon, S., Carter, M. et al., (2017) "Achieving Ultra Low NO_X Emissions Levels with a 2017 Heavy-Duty On-Highway TC Diesel Engine - Comparison of Advanced Technology Approaches," *SAE Int. J. Engines* **10**(4), pp. 1722-1735.

Yoon, S., Collins, J.F., Misra C., Herner, J.D., Carter, M.W., and Sax, T.P., (2017) "In-Use Emissions from 2010-Technology Heavy-Duty Trucks Impact on Air Quality Planning in California," *Journal of the Transportation Research Board*, No. 2627, pp. 1-8., National Research Council, Washington, D.C.

EMISSIONS

Cadle, S. H., Croes, B. E., Minassian, F., Natarajan, M., Tierney, E. J., and Lawson, D. R. (2004) "Real-World Vehicle Emissions: A Summary of the Thirteenth Coordinating Research Council On-Road Vehicle Emissions Workshop," *Journal of the Air & Waste Management Association*, **54**:8-23.

Younglove, T., Malcom, C., Durbin, T.D., Smith, M.R., Ayala, A., and Kidd, S. (2004) "Unregistration Rates for On-Road Vehicles in California," *Journal of Transportation and Statistics*, **V7**, N2/3.

Huai, T., Durbin, T.D., Younglove, T., Scora, G., Barth, M., and Norbeck J.M. (2005) "Vehicle Specific Power Approach to Estimating On-Road NH_3 Emissions from Light-Duty Vehicles," *Environmental Science & Technology*, **39**:9595-9600.

Cadle, S.H., Ayala, A., Black, K.N., Fulper, C.R., Graze, R.R., Minassian, F., Murray, H.B., Natarajan, M., Tennant, C.J., and Lawson, D.R. (2007) "Real-World Vehicle Emissions: A Summary of the Sixteenth Coordinating Research Council On-Road Vehicle Emissions Workshop," *Journal of the Air & Waste Management Association*, **57**:139-145.

Durbin, T.D., Miller, J.W., Younglove, T., Huai, T., and Cocker, K. (2007) "Effects of Fuel Ethanol Content and Volatility on Regulated and Unregulated Exhaust Emissions for the Latest Technology Gasoline Vehicles," *Environmental Science & Technology,* **41**:4059-4064.

Li, W., Collins, J.F., Durbin, T.D., Huai, T., Ayala, A., Full, G., Mazzoleni, C., Nussbaum, N.J., Obrist, D., Zhu, D., Kuhns, H.D., and Moosmüller, H. (2007) "Detection of Gasoline Vehicles with Gross PM Emissions," *SAE International*, **01**:1113-1126.

Cadle, S.H., Ayala, A., Black, K.N., Graze, R.R., Koupal, J., Minassian, F., Murray, H.B., Natarajan, M., Tennant, C.J., and Lawson, D.R. (2008) "Real-World Vehicle Emissions: A Summary of the 17th Coordinating Research Council On-Road Vehicle Emissions Workshop," *Journal of Air & Waste Management Association,* **58**:3-11.

Wang, G., Bai, S., and Ogden, J.M. (2009) "Identifying Contributions of On-Road Motor Vehicles to Urban Air Pollution Using Travel Demand Model Data," *Transportation Research Part D: Transport and Environment,* 14(3):168–179.

Bishop, G.A., Peddle, A.M., Stedman, D. H., and Zhan, T. (2010) "On-road Emission Measurements of Reactive Nitrogen Compounds from Three California Cities," *Atmospheric Environment,* **44**:3616-3620.

Maricq, M.M., and Maldonado, H. (2010) "Directions for Combustion Engine Aerosol Measurements for the 21st Century," *Journal of the Air & Waste Management Association*, **60**(10):1165-1176.

Pisano, J., Durbin, T., Karavalakis, G., Collins, J., Huai, T., and Ayala, A. (2011) "Characterization of PM and PM Instruments for High Emitting Light-Duty Gasoline Vehicles," *Society of Automotive Engineers of Japan, Inc.,* **01**:2056.

Zheng, Z., Johnson, K., Liu, Z., Durbin, T., Hu, S., Huai, T., Kittelson, D., and Jung, H. (2011) "Investigation of Solid Particle Number Measurement: Existence and Nature of Sub-23 nm Particles Under PMP Methodology," *Journal of Aerosol Science,* **42**:883-897.

Watson, J., Chow, J., Antony Chen, L.W., Lowenthal, D., Fujita, E., Kuhns, H., Sodeman, D., Campbell, D., Moosmuller, H., Zhu, D., and Motallebi, N. (2011) "Particulate Emission Factors for Mobile Fossil Fuel and Biomass Combustion Sources," *Science Total Environment*, **409**(12):2384-2396.

Park, S.S., Kozawa, K., Fruin, S., Mara, S., Hsu, Y., Jakober, C., Winer, A., and Herner, J. (2011) "Emission Factors for High-Emitting Vehicles Based on On-Road Measurements of Individual Vehicle Exhaust with a Mobile Measurement Platform," *Journal of the Air & Waste Management Association*, **61**(10):1046-1056.

Kozawa, K., Park, S., Ham, W., Mara, S., Vijayan, A. (2013), "Mobile Measurement Platform - An Innovative Tool for Studying the Impacts of Traffic Emissions," *EM*, pp.18-22.

Natarajan, M., DiCicco, D., Black, K., Tennant, C., Herner, J.D., Ayala, A., Graze, R., Hawkins, D., Hogo, H., Koupal, J., Long, T., Thornton, M. (2013), "Highlights from the Coordinating Research Council: 23rd Real-World Emissions Workshop," *EM*, pp.24-28.

Collet, S., Hoekman, S.K., McCauley, E., Wallington, T.J. (2015) "Highlights from the Coordinating Research Council 2015 Mobile Source Air Toxics Workshop," *EM*, pp.28-32.

Misra, C., Ruehl, C., Collins, J.F., Chernich, D., & Herner, J.D., (2017) "In-use NO_X emissions from diesel and liquefied natural gas refuse trucks equipped with SCR and TWC respectively", *Environmental Science & Technology* **51**(12), pp. 6981–6989.

EXPOSURE

Fruin, S.A., Denis, M.J. St., Winer, A.M., Colome, S.D., and Lurmann, F.W. (2001) "Reductions in Human Benzene Exposure in the California South Coast Air Basin," *Atmospheric Environment*, **35:**1069-1077.

Maddalena, R.L., McKone, T.E., and Kado, N.Y. (2002) "Exposure Chamber Measurements of Mass Transfer and Partitioning at the Plant/Air Interface," *Environmental Science & Technology,* **36:**3577-3585.

Behrentz, E., Fitz, D.R., Pankratz, D.V., Sabin, L.D., Colome, S.D., Fruin, S.A., and Winer, A.M. (2004) "Measuring Self-Pollution in School Buses Using A Tracer Gas Technique," *Atmospheric Environment*, **38:**3735-3746.

Fruin, S.A., Winer, A.M., and Rodes, C.E. (2004) "Black Carbon Concentrations in California Vehicles and Estimation of In-Vehicle Diesel Exhaust Particulate Matter Exposures," *Atmospheric Environment*, **38:**4123-4133.

Sablin, L.D., Behrentz, E., Winer, A.M., Jeong, S., Fitz, D.R., Pankratz, D.V., Colome, S.D., and Fruin S.A. (2005) "Characterizing the Range of Children's Air Pollutant Exposure During School Bus Commutes," *Journal of Exposure Analysis and Environmental Epidemiology*, **15**:377-387.

Westerdahl, D., Fruin, S.A., Sax, T., Fine, P.M., and Sioutas C. (2005) "Mobile Platform Measurements of Ultrafine Particles and Associated Pollutant Concentrations on Freeways and Residential Streets in Los Angeles," *Atmospheric Environment*, **39**:3597-3610.

Kobayashia, R., Okamotob, R., Maddalenac, R., and Kado, N. (2008) "Polycyclic Aromatic Hydrocarbons in Edible Grain: A Pilot Study of Agricultural Crops as a Human Exposure Pathway for Environmental Contaminants Using Wheat as a Model Crop," *Environmental Research,* **107**(2):145-151.

Hu, S., Fruin, S., Kozawa, K., Mara, S., Paulson, S.E., and Winer, A.M. (2009) "A Wide Area of Air Pollutant Impact Downwind of a Freeway during Pre-Sunrise Hours," *Atmospheric Environment,* **43**(16):2541-2549.

Luo, D., Corey, R., Propper, R., Collins, J., Komorniczak, A., Davis, M., Berger, N., and Lum, S. (2011) "Comprehensive Environmental Impact Assessment of Exempt Volatile Organic Compounds in California," *Environmental Science & Policy*, **14**:585-593.

Ham, W., Vijayan, A., Schulte, N., Herner, J.D., (2017), "Commuter exposure to PM2.5, BC, and UFP in six common transport microenvironments in Sacramento, California," *Atmospheric Environment*, Volume 167, pp. 335-345.

EXPOSURE MITIGATION

Ning, Z., Hudda, N., Daher, N., Kam, W., Herner, J., Kozawa, K., Mara, S., and Sioutas, C. (2010) "Impact of Roadside Noise Barriers on Particle Size Distributions and Pollutants Concentrations Near Freeways," *Atmospheric Environment,* **44**(26):3118-3127.

Lee E.S., Ranasinghe D.R., Ahangar F.E., Amini S., Mara S., Choi W., Paulson S., Zhu Y. (2017) "Field evaluation of vegetation and noise barriers for mitigation of near-freeway air pollution under variable wind conditions", *Atmospheric Environment*, Volume 175, pp. 92-99.

GREENHOUSE GAS EMISSIONS

Vincent, R., Cleary, K., Ayala, A., and Corey, R. (2004) "Emissions of HFC-134a from Light-Duty Vehicles in California," *SAE Technical Paper Series*.

Hsu, Y., VanCuren, T., Park, S., Jakober, C., Herner, J., FitzGibbon, M., Blake, D., and Parrish, D. (2010). "Methane Emissions Inventory Verification in Southern California," *Atmospheric Environment*, **44**(1):1-7.

Chow, J., Watson, J., Lowenthal, D., Chen, L.W., and Motallebi, N. (2010) "Black and Organic Carbon Emission Inventories," *Journal of the Air & Waste Management Association,* **60**(4):497-507.

Barletta, B., Nissenson, P., Meinardi, S., Dabdub, D., Rowland, S.F., VanCuren, R. A., Pederson, J., Diskin, G.S., and Blake, D.R. (2011) "HFC-152a and HFC-134a emission estimates and characterization of CFCs, CFC replacements, and other halogenated solvents measured during the 2008 ARCTAS campaign (CARB phase) over the South Coast Air Basin of California," *Atmospheric Chemistry & Physics*, **11**:2655-2669.

Guo, L., Gunasekara, A.S., and McConnell, L.L. (*Eds.*), (2011) *"Understanding Greenhouse Gas Emissions from Agricultural Management,"* American Chemical Society, Washington, DC.

Guo, L., Gunasekara, A.S., and McConnell, L.L. (2011) "Preface" in "Understanding Greenhouse Gas Emissions from Agricultural Management," pp. xi-xii, American Chemical Society, Washington, DC.

Guo, L., Luo, D., Li, C.S. and FitzGibbon, M. (2011) "Development of Spatial Inventory of Nitrous Oxide Emissions from Agricultural Land Uses in California Using Biogeochemical Modeling" in "Understanding Greenhouse Gas Emissions from Agricultural Management," pp. 387-403, American Chemical Society, Washington, DC.

Zhan, T., Clodic, D., Palandre, L., Trémoulet, A., Riachi, Y. (2013) "Determining Rate of Refrigerant Emissions from Nonprofessional Automotive Service through a Southern California Field Study," *Atmospheric Environment*, **82**:362-368.

Gallagher, G.F., Zhan, T., Hsu, Y., Gupta, P., Pederson, J., Croes, B.E., Blake, D., Barletta, B., Meinardi, S., Ashford, P., Vetter, A., Saba, S., Slim, R., Palandre, L., Clodic, D., Mathis, P., Wagner, M., Forgie, J., Dwyer, H., Wolf, K. (2013), "High-Global Warming Potential F-Gas Emissions in California: Comparison of Ambient-Based versus Inventory-Based Emission Estimates, and Implications of Refined Estimates," *Environmental Science & Technology.***48**:1084-1093.

Zhan, T., Potts, W., Collins, J., Austin, J. (2014) "Inventory and Mitigation Opportunities for HFC-134a Emissions from Nonprofessional Automotive Service," *Atmospheric Environment*, **99**:17-23.

Jeong, S., Hsu, Y., Andrews, A.E., Bianco, L., Vaca, P., Wilczak, J., Fischer, M.L. (2013) "A Multitower measurement network estimate of California's methane emissions," *Journal of Geophysical Research: Atmospheres*, **118**:1-13.

Jakober, C., Mara, S., Hsu, Y.K., Herner, J. (2015), "Mobile Measurements of Climate Forcing Agents: Application to Methane Emissions from Landfill and Natural Gas Compression," *Journal of the Air & Waste Management Association*, **65**(4):404-412.

Newman, S., Xu, X., Gurney, K.R., Hsu, Y.K., Li, K.F., Jiang, X., Keeling, R., Feng, S., O'Keefe, D., Patarasuk, R. and Wong, K.W. (2015) "Toward Consistency between Bottom-Up CO_2 Emissions Trends and Top-Down Atmospheric Measurements in the Los Angeles Megacity," *Atmospheric Chemistry and Physics Discussions*, **15**(20):29591-29638.

HEALTH EFFECTS

Chun, H.-S., Kuzmicky, P.A., Rucoba, L., Kado, N.Y., and Rice, R.H. (2000) "Cytotoxicity and Keratinocyte Microsome-mediated Mutagenic Activation of Carcinogens in Cultured Epidermal Cells," *Toxicology Letters,* **115:**165-172.

Chun, H.-S., Kuzmicky, P.A., Kado, N.Y., and Rice, R.H. (2000) "Toxicity of Trp-P-2 to Cultured Human and Rat Keratinocytes," *Chemico-Biological Interactions,* **127:**237-253.

Kado, N.Y., Okamoto, R.A., Karim, J., and Kuzmicky, P.A. (2000) "Airborne Particle Emissions from 2- and 4-Stroke Outboard Marine Engines: Polycyclic Aromatic Hydrocarbon and Bioassay Analyses," *Environmental Science & Technology*, **34:**2714-2720.

De Martinis, B.S., Okamoto, R.A., Kado, N.Y., Gundel, L.A., and Carvalho, L.R.F. (2002) "Polycyclic Aromatic Hydrocarbons in a Bioassay-fractionated Extract of PM10 Collected in São Paulo, Brazil," *Atmospheric Environment*, **36:**307-314.

Swanson, K., Kado, N., Funk, W., Pleil, J., Madden, M., Ghio, A., (2009) "Release of the Pro-Inflammatory Markers by BEAS-2B Cells Following In Vitro Exposure to Biodiesel Extracts," *Open Toxicology Journal*, **3**:815.

Ostro, B, Lipsett, M, Reynolds, P, Goldberg, D, Hertz, A, Garcia, C., Henderson, K.D., Bernstein, L. (2010) "Long-Term Exposure to Constituents of Fine Particulate Air Pollution and Mortality: Results from the California Teachers Study," *Environmental Health Perspectives* **118(3)**:363-369.

Lipsett, M.J., Ostro, D., Reynolds, P., Goldberg, D., Hertz, A., Jerrett, M., Smith, D., Garcia, C., Chang, E., and Bernstein, L. (2011) "Long-Term Exposure to Air Pollution and Cardiorespiratory Disease in the California Teachers Study Cohort," *American Journal of Respiratory and Critical Care Medicine,* **184**(7):828-835.

Yap, P.S., Garcia, C. (2015), "Effectiveness of Residential Wood-Burning Regulation on Decreasing Particulate Matter Levels and Hospitalizations in the San Joaquin Valley Air Basin," *Journal of Public Health*, **105**(4):772-778.

Garcia, C.A., Yap, P-S., Park, H-Y., Weller, B.L. (2016) "Association of long-term PM2.5 exposure with mortality using different air pollution exposure models: impacts in rural and urban California." *International Journal of Environmental Health Research* **26**:2:145-157.

Smith, G.S., Van Den Eeden, S.K., Garcia, C., Shan, J., Baxter, R., Herring, A.H., Richardson, D.B., Van Rie, A., Emch, M., Gammon, M.D. (2016). "Air Pollution and Pulmonary Tuberculosis: A Nested Case-Control Study among Members of a Northern California Health Plan," *Environmental Health Perspectives*.

Park H.Y., Gilbreath S., Barakatt E., (2017) "Respiratory outcomes of ultrafine particulate matter (UFPM) as a surrogate measure of near-roadway exposures among bicyclists," *Environ. Health* 16(1):6.

INDOOR AIR QUALITY

Bradman, A., Castorina, R., Gaspar, F., Nishioka, M., Colón, M., Weathers, W., Egeghy, P.P., Maddalena, R., Williams, J., Jenkins, P.L., McKone, T.E. (2014), "Flame Retardant Exposures in California Early Childhood Education Environments," *Chemosphere*, **116**:61-66.

Bradman, A., Gasper, F., Castorina, R., Williams, J., Hoang, T., Jenkins, P., McKone, T. E., Maddalena, R. (2016) "Formaldehyde and Acetaldehyde Exposure and Risk Characterization in California Early Childhood Education Environments," *Indoor Air: International Journal of Indoor Environment and Health,* ??.

Hoang, T., Castorina, R., Gaspar, F., Maddalena, R., Jenkins, P., Zhang, Q., McKone, K., Benfenati, E., Shi, A., Bradman, A. (2016) "VOC exposures in California early childhood education environments", *Indoor Air*, ??

Zhang, Q., Jenkins, P. (2016) Evaluation of ozone emissions and exposures from consumer products and home appliances, *Indoor Air*, 27(2), 386-397.

PARTICULATE MATTER

Lloyd, A.C. (2000) "Particulate Pollution Challenges in California," *EM*, 17-22, June.

Croes, B.E., et al. (2001) "National Research Council Research Priorities for Airborne Particulate Matter: III. Early Research Progress," *National Academy Press, Washington, D.C.*

Motallebi, N., Taylor, C.A. Jr., Turkiewicz, K., and Croes, B.E. (2003) "Particulate Matter in California: Part 1 – Intercomparison of Several $PM_{2.5}$, PM_{10-25}, and PM_{10} Monitoring Networks," *Journal of the Air & Waste Management Association*, **53**:1509-1516.

Motallebi, N., Taylor, C.A. Jr., and Croes, B.E. (2003) "Particulate Matter in California: Part 2 – Spatial, Temporal, and Compositional Patterns of $PM_{2.5}$, PM_{10-25}, and PM_{10}," *Journal of the Air & Waste Management Association*, **53**:1517-1530.

Croes, B.E., et al. (2004) “National Research Council Research Priorities for Airborne Particulate Matter: V. Continuing Research Progress,” *National Academy Press, Washington, D.C.*

Herner, J.D., Ying, Q., Aw, J., Gao, O., Chang, D.P.Y., and Kleeman, M.J. (2006) “Dominant Mechanisms that Shape the Airborne Particle Size and Composition Distribution in Central California,” *Aerosol Science and Technology,* **40:**827-844.

Herner, J.D., Green, P.G., and Kleeman, M.J. (2006) “Measuring the Trace Elemental Composition of Size-Resolved Airborne Particles,” *Environmental Science & Technology*, **40:**1925-1933.

Park, K., Chow, J.C., Watson, J.G., Trimble, D.L., Doraiswamy, R., Arnott, W.P., Stroud, K.R., Bowers, K., Bode, R., Petzold, A., and Hansen, A.D.A. (2006) “Comparison of Continuous and Filter-Based Carbon Measurements at the Fresno Supersite,” *Air & Waste Management Association*, **56**:474-491.

Ham, W., Herner, J., Green, P., and Kleeman, M. (2010) “Size Distribution of Health-Relevant Trace Elements in Airborne Particulate Matter during a Severe Winter Stagnation Event: Implications for Epidemiology and Inhalation Exposure Studies,” *Aerosol Science and Technology*, **44**(9):753-765.

Blanchard, C., Tanenbaum, S., and Motallebi. N. (2011) “Spatial and Temporal Characterization of PM2.5 Mass Concentrations in California,” *Journal of the Air & Waste Management Association*, **61**(3):339-351.

Chow, J., Watson, J., Lowenthal, D., Chen, L.W., and Motallebi, N. (2011) “PM2.5 Source Profiles for Black and Organic Carbon Emission Inventories,” *Atmospheric Environment,* **45**:5407-5414.

TOXIC AIR CONTAMINANTS

Propper, R., Wong, P., Bui, S., Austin, J., Vance, W., Alvarado, A., Croes, B., Luo, D. (2015) “Ambient and Emission Trends of Toxic Air Contaminants in California,” *Environmental Science & Technology*, **49**(19):11329-11339.

WEEKEND EFFECT

Austin, J. (2003) "Day-of-Week Patterns in Toxic Air Contaminants in Southern California," *Journal of the Air & Waste Management Association*, **53:**889-896.

Croes, B.E., Dolislager, L.J., Larsen, L.C., and Pitts, J.N. Jr. (2003) "The O_3 'Weekend Effect' and NO_X Control Strategies - Scientific and Public Health Findings and Their Regulatory Implications," *EM*, 27-35, July.

Motallebi, N., Tran, H., Croes, B.E., and Larsen, L.C. (2003) “Day-of-Week Patterns of Particulate Matter and its Chemical Components at Selected Sites in California,” *Journal of the Air & Waste Management Association*, **53:**876-888.