



# **Annual Research Plan**

*Fiscal Year 2017-2018*



The statements and conclusions in this report are not necessarily those of the California Air Resources Board (ARB). 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 website at [www.arb.ca.gov/research/apr/apr.htm](http://www.arb.ca.gov/research/apr/apr.htm).

*ANNUAL RESEARCH PLAN*  
*FISCAL YEAR 2017 - 2018*

# Table of Contents

<b>Introduction</b>	<b>4</b>
<b>Research to Guide Policy and Advance Science</b>	<b>5</b>
<b>Program History</b>	<b>8</b>
<b>Trends in Research Quality and Scientific Impact</b>	<b>12</b>
<b>ARB-Funded Research in World Class Publications</b>	<b>12</b>
<b>ARB’s Research Staff Produce High-Impact Publications</b>	<b>12</b>
<b>Research Coordination and Dissemination</b>	<b>13</b>
<b>Communicating Results</b>	<b>13</b>
<b>Current and Proposed Research to Support ARB’s Programs</b>	<b>14</b>
<b>Comprehensive Program Support</b>	<b>14</b>
Health & Exposure	14
Health impacts of emissions from tire and brake wear	16
The impact of combined exposures to PM2.5 and ozone on human health	17
Environmental Justice	18
Sources contributing to higher levels of PM2.5 in disadvantaged communities	21
Geofencing as a strategy to lower emissions in disadvantaged communities	22
Sources contributing to higher levels of benzene and other air toxics in disadvantaged communities	23
Development of real-time, portable monitoring methods for toxic metals	24
Economics	25
Specific Program Support	27
Transportation System Strategies Support	27
Activity data of off-road engines in construction	30
Identification of high emitting light-duty vehicle makes and models	31
Light-duty vehicle trends from a remote sensing measurement campaign	31
Cold start emission impacts of blended plug-in hybrids	32
Vehicle brake and tire wear emissions	33
SIP Program Support	34
Vertical ozone distribution over California	36
Long-term characterization of PM2.5 in the San Joaquin Valley	37
Sustainable Communities Program Support	38
Updating the Integrated Transport and Health Impact Model (ITHIM)	40
Policy, planning and program frameworks for zero-net carbon communities	41
Emissions impact of connected and automated vehicle deployment in California	42
Climate Strategies Support	43
Multiple pollutant mitigation strategies from dairy sources	47
Strategies to reduce methane emissions from enteric and lagoon sources	48
F-gas emissions from small commercial and industrial refrigeration equipment	49
Brown carbon modeling and source attribution	50
<b>Next Steps</b>	<b>51</b>
<b>Appendix 1: Research Project Timelines</b>	<b>52</b>
<b>Appendix 2 – Recent Final Reports</b>	<b>59</b>
<b>Appendix 3</b>	<b>64</b>

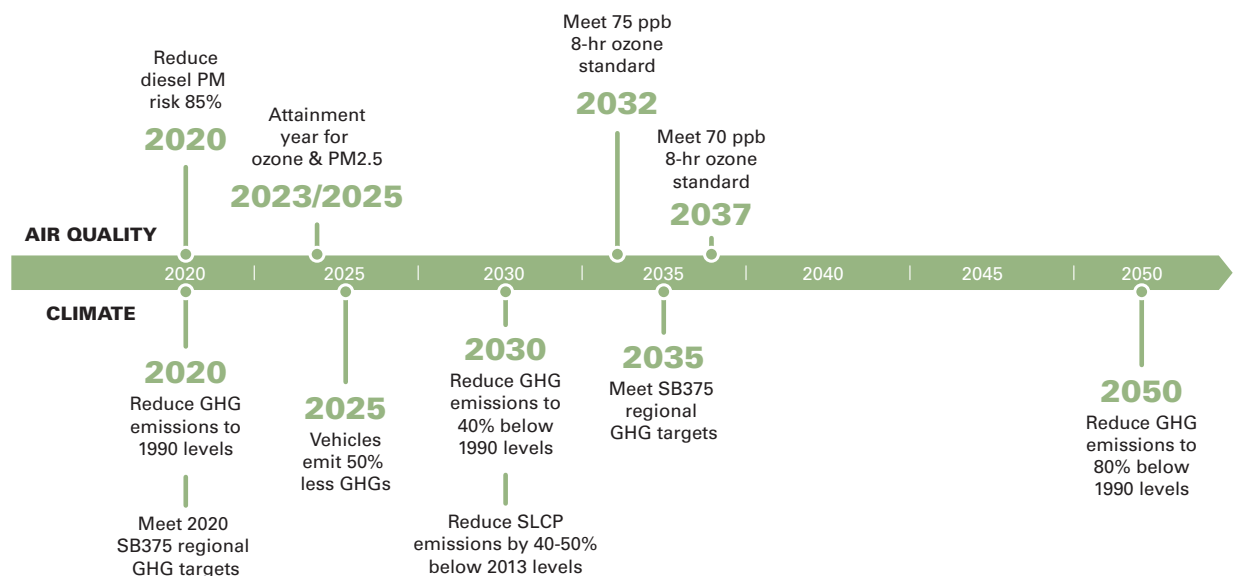


# Introduction

As required by State law (Health and Safety Code Section 39700), the California Air Resources Board (ARB or Board) sponsors a research program that is guided by the mission of providing sound and timely scientific results to support ARB’s policies and programs. The Board’s research program was established by the Legislature in 1971 and has formed the basis of ARB’s regulatory programs since its inception. Over the past 46 years, ARB’s research goals of informing health-based air quality standards, reducing air pollution exposures, and protecting California from the potential impacts of climate change are met through a diverse portfolio of projects. ARB’s research program develops a research plan on an annual basis to outline past and current research, and describe new research initiatives in a given year. This report, *Annual Research Plan, Fiscal Year 2017-2018 (Plan)*, reflects a concerted effort to identify the highest priority needs of ARB, and maximize leveraged research dollars through coordination efforts.

The projects outlined in this Plan build on past research, and 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. Foundational studies on the impacts of greenhouse gases, criteria pollutants, and air toxic reduction strategies on health, disadvantaged communities, and the economy continue to be a main emphasis of ARB’s research program, which has grown in scope over time in response to legislative mandates. This Plan also continues a growing trend over the years to fund program-driven projects that provide needed information, data, and approaches to address key questions for meeting California’s air quality and climate goals over the next four decades, including federal deadlines for national air ambient air quality standards (NAAQS), and greenhouse gas (GHG) reduction goals in 2020, 2030, and beyond (Figure 1). The projects are designed to support the development of new policies and regulations, track implementation of existing programs, and ensure the benefits of longer-term strategies. 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.

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



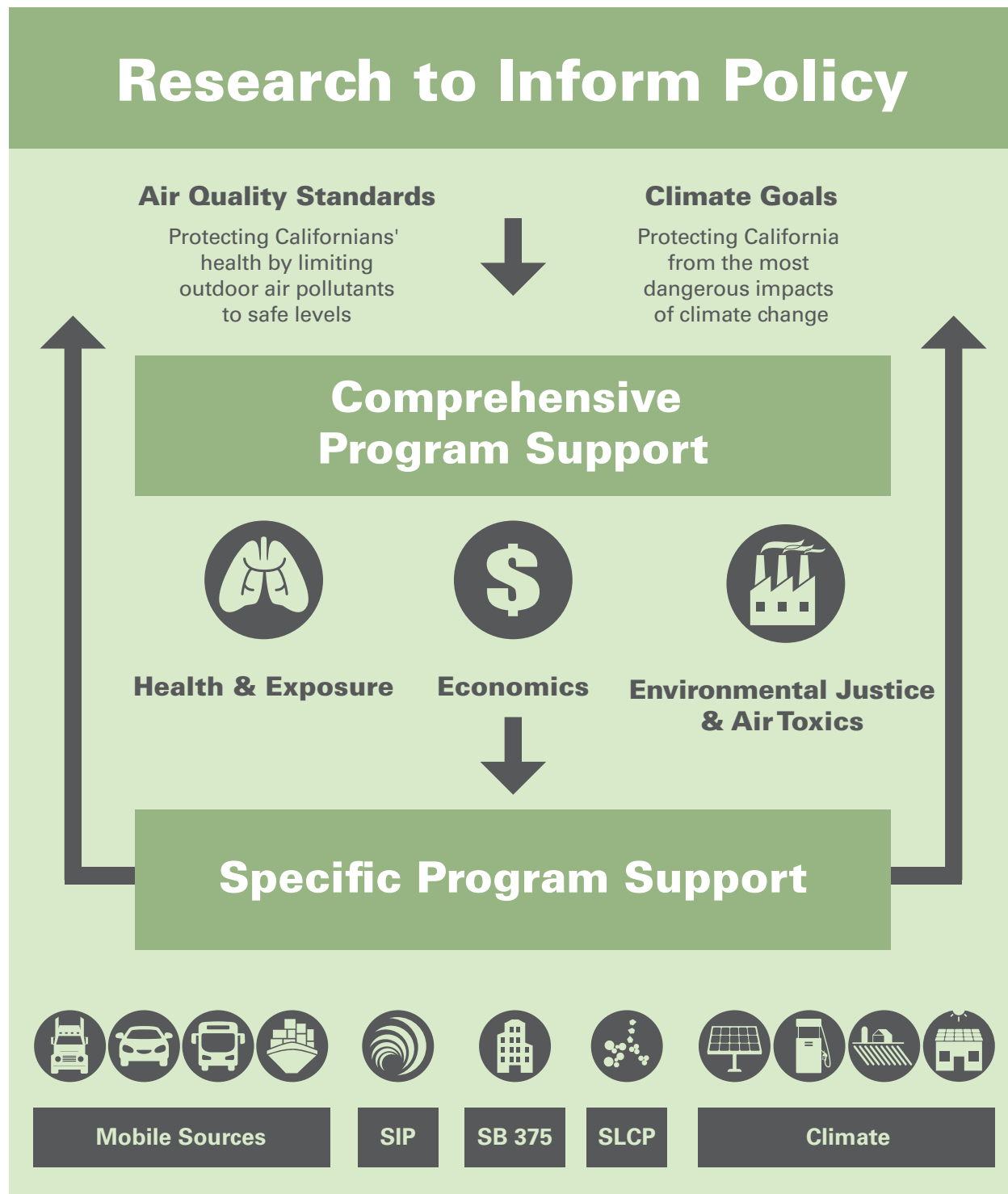
# Research to Guide Policy and Advance Science

The foundation of ARB's research program provides comprehensive program support to inform health-based air quality standards, reduce air pollution exposures, and protect all communities and vulnerable individuals from the potential impacts of climate change. In-house expertise on health, exposure, and environmental justice, as well as a diverse portfolio of external contracts, provides state of the science research results to support the development, and sustainable implementation, of all ARB programs (Figure 2).

ARB's research program also supports specific ARB programs to ensure that they are guided by the best and latest science. The research program's efforts to support these programs have required a broad portfolio of research studies, and in-house research initiatives, that have helped in the development and implementation of mobile source emission reduction strategies, State Implementation Plans (SIPs) for ozone and PM<sub>2.5</sub>, SB 375 per capita transportation targets, the Short-lived Climate Pollutant (SLCP) Strategy, and the AB 32 Scoping Plan for GHG reduction.

ARB's air quality research program has supported the development of SIPs through improvements in emission inventories, chemical mechanisms, and air quality models. To support these efforts, numerous field 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. ARB's mobile source emissions research program supports California's effort to meet NAAQS and GHG reduction goals by examining the effectiveness and durability of technologies that reduce these emissions. The mobile source research program also monitors the progress of emission reduction rules currently in place. The climate change research program has supported the development of multiple State planning efforts to reduce GHG emissions, and investigates the societal impacts of recommended actions. Research results from these programs are also intended to inform the development of new policies and programs.

**Figure 2: Research results from ARB’s projects aim to ensure the policies that are designed to meet air quality and climate goals are successfully implemented, avoid unintended impacts, and provide information for future policy development.**

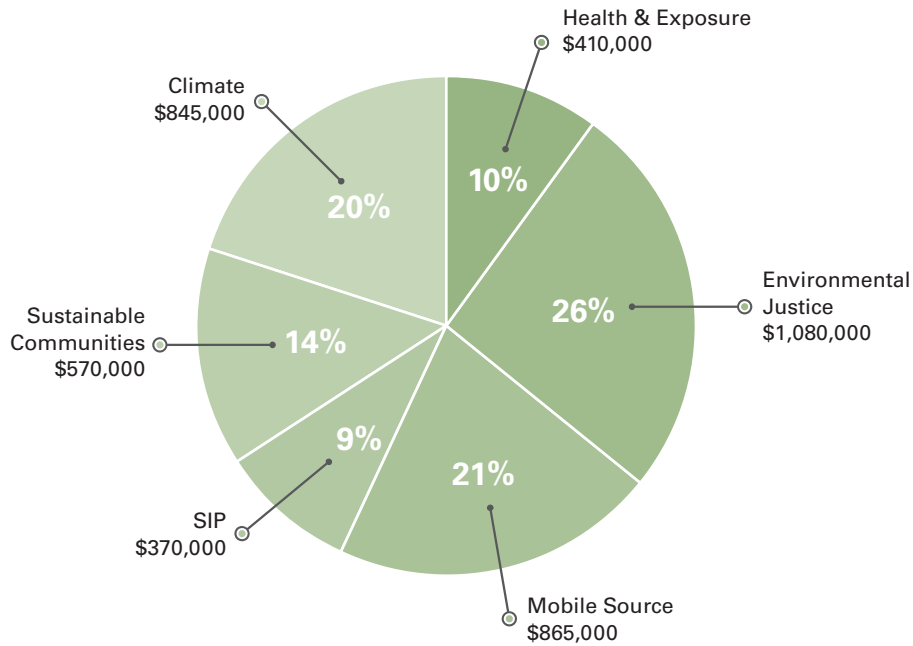




## Funding Distribution for Fiscal Year 2017-18 Research

The Fiscal Year 2017-18 Research Plan includes 20 research concepts, requiring approximately \$4.18 million in funding. As shown in Figure 3, funding is allocated to research related to health and exposure (10%), environmental justice (26%), mobile source (21%), SIP support (9%), sustainable communities (14%), and climate strategies (20%).

**Figure 3: Proposed ARB research funding allocation for Fiscal Year 2017-18.**



# Program History

For the past 46 years, ARB and key public and private partners have collaborated to make California a center for pioneering air pollution research. ARB's forward-thinking ARB research has produced results that inspire legislative actions and regulatory solutions in California, often leading to national - even global - solutions. Below are a few examples of how groups of studies, within a given program area, filled gaps in the scientific literature to inform the development and successful implementation of ARB programs.

## Health & Exposure – Creating Safe Environments Near Roadways and Indoors

ARB's health effects research helped inform the scientific basis for state and national ambient air quality standards through multiple studies that added to the body of evidence on the impacts of fine particulate matter (PM2.5), ultrafine particulate matter (UFPM), ozone, and multi-pollutant exposures on public health. ARB also sponsored several pioneering research projects that prompted similar national studies such as those on the impact of air pollution on children's health. As California cities build more compact, transit-oriented communities, ARB funded multiple studies that have identified the efficacy of changes in the built environment, such as complete street design and sound walls, which can reduce exposure to harmful traffic-associated pollutants.



ARB's indoor air quality research has led to new State laws, including the first legislation in the nation to protect people from some of the most harmful indoor exposures to formaldehyde from building materials and ozone from air cleaners. ARB's study of air quality in portable classrooms contributed to a number of state and school district policy changes that improved health conditions in California schools.

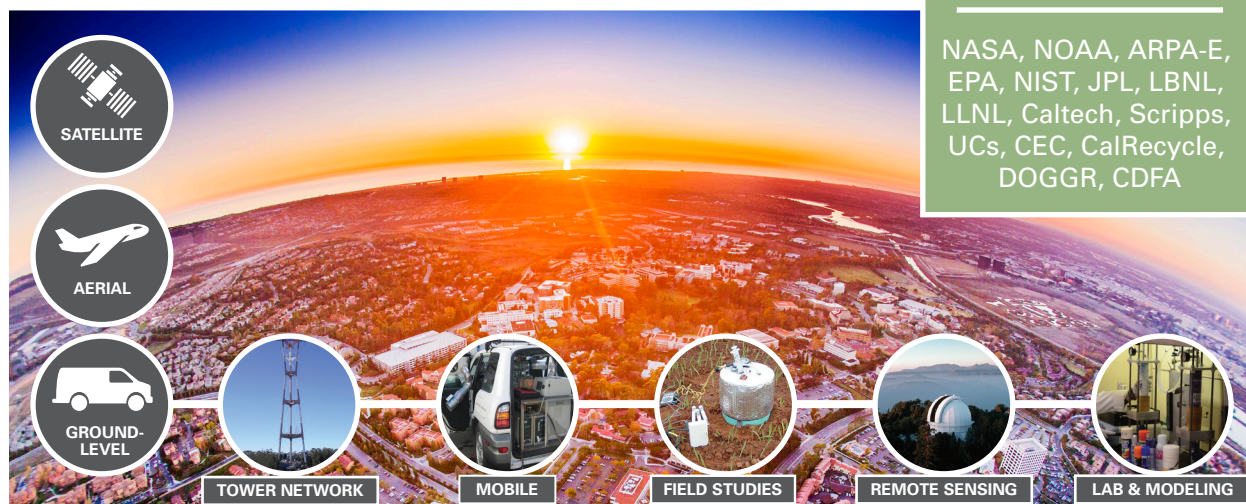
## SIP Support – Developing Science-based Strategies to Improve Air Quality

ARB's air quality research program has collaborated with other partners on multiple large-scale field studies. These field studies brought instrumented aircraft, a research ship, ground-based laser, and other state-of-the-science instruments to the state to provide a better understanding of the influence of emissions, meteorology, long-range transport on surface ozone and PM2.5, and 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 ( $\text{NO}_x$ ) emission control for simultaneous reductions in both ozone and  $\text{PM}_{2.5}$ , and identification of the potential for warming temperatures to slow progress toward ozone standard attainment. The findings informed the development of the SIPs and helped to track and model progress towards attaining California's air quality and climate goals.

## $\text{CO}_2$ , $\text{CH}_4$ , $\text{N}_2\text{O}$ , F-gases, Black Carbon



## Climate - Tracking and Reducing Emissions of Climate Pollutants

ARB's research continues to improve our understanding of emissions of important climate forcing pollutants, such as carbon dioxide ( $\text{CO}_2$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), and the short-lived climate pollutants (SLCPs, which include methane [ $\text{CH}_4$ ], fluorinated gases or F-gases, and black carbon). 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  $\text{CH}_4$  and  $\text{N}_2\text{O}$  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 ARB's state-wide inventory. Satellite, aerial, and ground-based measurements of  $\text{CH}_4$  are leading to emission inventory improvements for all important source categories. ARB's dense network of  $\text{CH}_4$  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 (i.e., Refrigerant Management Program, Small Can Regulation, Cap and Trade Offset Program for Ozone-Depleting Substances).

Collectively, these research efforts have helped to identify sources, evaluate the emissions from these sources, develop new emission reduction strategies, and track progress in achieving GHG reduction goals across all sectors of the economy. These research efforts also allowed for a quick response when ARB was required to develop the SLCP Strategy (Senate Bill 605 in 2014)

and implement legislative mandates to reduce emissions of these powerful climate forcers (Assembly Bill 1496 in 2015 and Senate Bill 1383 in 2016).

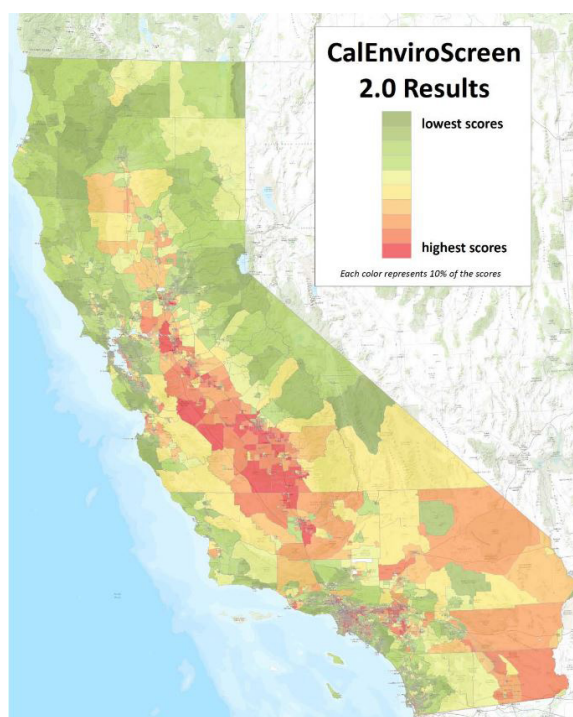
## Ensuring Clean Air for All Communities

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 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 inform the Senate Bill 352, which prohibits school siting within 500 feet of a freeway.

To support ARB's environmental justice initiatives for all its programs, ARB funded the development of the Environmental Justice Screening Method (EJSM). ARB'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 ARB's regulatory strategies have impacted disadvantaged communities.

## Going Forward – Facing Future Challenges through Collaborative Research

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. ARB 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



## Research and Review Process

### Research Plan Development

- Solicit research ideas from the public
- Identify program-driven research needs and priorities
- Input from the Board's external Research Screening Committee (RSC)
- Coordinate with other funding organizations (e.g., air districts, state and federal agencies)
- Board approves proposed research plan

### Contract Development

- Develop scopes of work and proposal solicitations for priority projects
- The RSC and stakeholders provide input on proposals
- Board approves funding for proposals

### Project Oversight

- Staff manage projects and solicit input from interested parties quarterly
- Large projects include advisory panels of subject matter experts
- The RSC reviews draft final reports and recommends revisions
- Researchers give a webcast research seminar to present final results

economic challenges. These challenges often disproportionately impact underserved populations in California. Research will continue to focus on making sure that ARB programs benefit all communities. The continued development of partnerships with other research entities and stakeholders will be essential to supporting effective program implementation by providing information on emission inventories, tracking progress, modeling projections, and ensuring the effective implementation of ARB 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

## ARB-Funded Research in World Class Publications

Since 1995, ARB 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 ARB-funded publications are cited about 82 times each by other articles, and 79 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 ARB's long-standing research strengths. ARB research also has been cited in reviews of the National Ambient Air Quality Standards and in dozens of ARB regulatory documents. Publications resulting from ARB research contracts have won multiple Haagen-Smit Prizes for outstanding papers published in the journal Atmospheric Environment, and the Arthur C. Stern Distinguished Paper award from the Journal of the Air and Waste Management Association.

### Research Communication Tools

- ARB Research Website
- ARB 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 ARB's research website (<http://www.arb.ca.gov/research/research.htm>)

## ARB'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 (on average about 20 times each by other articles).

# Research Coordination and Dissemination

Coordinating our research with other State agencies, federal agencies, local air districts, and research institutions is an important goal to avoid duplication of effort, leverage funding, identify opportunities for collaborative efforts, and maximize 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 the participation in interagency working groups, such as the Climate Action Team Research Working Group, and the Transportation Research Roundup. These groups provided a forum for ARB staff to present research results and proposed research activities. ARB 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.

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

## Communicating Results

ARB staff disseminates new research results to the public through seminars, press releases, newsletters, final reports, and updates at Board Meetings. ARB 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.

## Leveraging Research Dollars

ARB 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. ARB 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

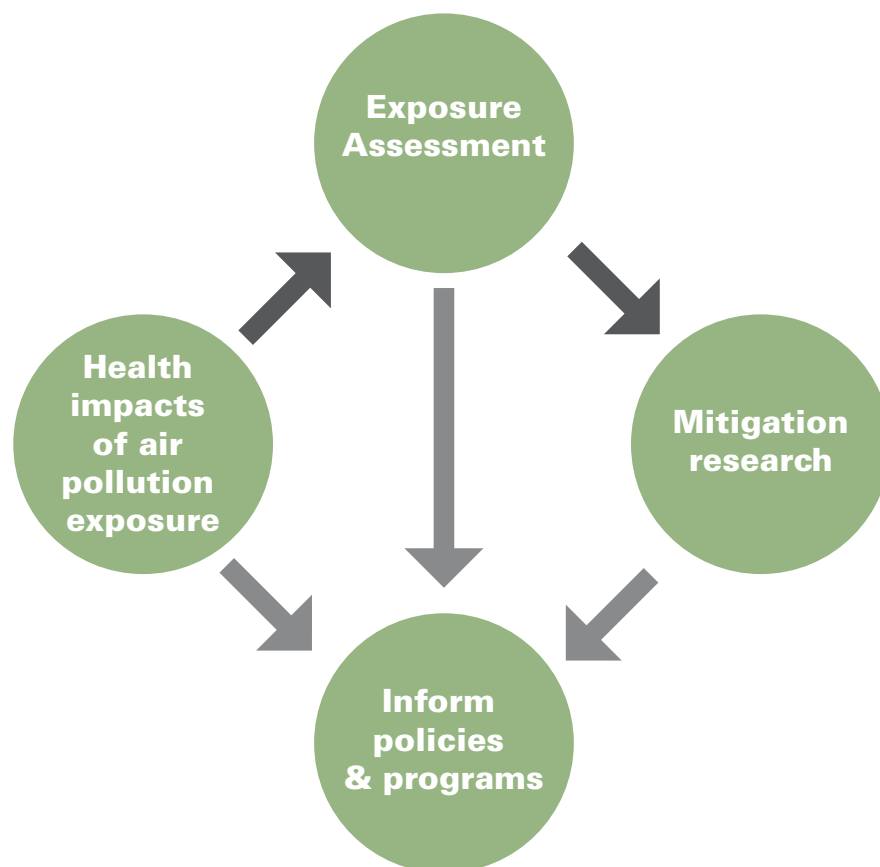
- Federal Agencies
- State Agencies
- NGOs
- Air Districts
- University of California
- California State Universities
- Land Grant Institutions
- National Labs

# Current and Proposed Research to Support ARB's Programs

## Comprehensive Program Support

### HEALTH & EXPOSURE

ARB'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. ARB's health program provides in-house health assessments that are guided by the latest science. These assessments inform all ARB 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 air pollution health effects, to exposure studies, and mitigation strategies. Topics of interest include multipollutant exposures, effects on vulnerable populations, and micro-environmental exposures from both outdoor and indoor sources.





## Current Research and Coordination Efforts

ARB continues to fund research to improve our understanding of the near-roadway health impacts of exposure to PM<sub>2.5</sub> and (UFPM) and mixtures of air pollutants, particularly in vulnerable populations. While single pollutant studies have been essential to the process of establishing health protective levels for NAAQS, ARB has expanded its research portfolio to look at how concurrent exposure to ozone and PM<sub>2.5</sub> may affect public health, which is the focus of a research project now underway.

Exposure of vulnerable populations, especially women, to air pollutants also continues to be a focus of study for ARB. Recent epidemiological evidence has pointed to an increased sensitivity to PM<sub>2.5</sub> in women. ARB has responded to this research gap by funding a study to address this disparity using a toxicological approach. In addition, the health effects of 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. This project will leverage other ongoing research at the California National Primate Research Center to perform cutting-edge air pollution research at relatively low cost. In order to leverage limited research funding, ARB health staff will continue on-going efforts to coordinate with experts at State and federal research institutions, such as the Health Effects Institute.

A major priority of ARB is to assess the microenvironments that contribute to pollutant exposures of Californians including ozone, PM, UFPM, and toxics. In one in-house study, staff investigated exposure to UFPM in different microenvironments. In this pilot study, 12 volunteers were followed for 24-hour periods using small, portable monitors. The results showed that most 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 a future study, ARB staff will measure 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.

The indoor microenvironment is another area of interest. ARB is evaluating formaldehyde exposures of Californians living in mobile homes. This in-house research is being conducted because mobile homes tend to contain more composite wood products than traditional homes and are poorly ventilated, and thus, in the past, have had notably higher levels of formaldehyde than other homes and indoor environments. Results showed that nearly one-third of the homes had formaldehyde levels above OEHHA's acute reference exposure level for formaldehyde, and most (like other indoor environments) exceeded OEHHA's chronic and 8hour reference exposure level for formaldehyde.

## RESEARCH HIGHLIGHT



### Reducing In-Home Exposure to Air Pollution by Filtration

Current building codes only require ventilation in new homes to reduce air pollution generated indoors. In order to reduce outdoor air pollution from entering homes, a recent study assessed the efficacy of eight different combinations of ventilation and air filtration system. The researchers found substantial benefits of high efficiency filtration in improving indoor air quality, but that these systems have a wide range of energy costs. The results will improve California's building ventilation codes and therefore reduce indoor exposures to air pollution. ARB Contract 11-311.

Improving air quality of the indoor environment is a priority of the ARB, as well. In collaboration with other state and federal agencies and research centers in the University of California system, ARB leverages expertise to continue to drive research that will evaluate the effectiveness and cost of indoor air filtration as a strategy to mitigate exposure to air contaminants. One major study is investigating how effective high efficiency indoor air filtration is for reducing indoor PM levels in homes of children with asthma, and the children's associated asthma symptoms. Another study is examining formaldehyde emissions from residential fiberglass compared to synthetic central system air filters, 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.

## **Proposed Research**

The two research projects proposed for health and exposure will build on previous research and inform multiple ARB programs by investigating the potential source of exposure from tire and brake wear in near roadway microenvironments, and examining the importance of combined pollutant exposure to the prevalence of cardiovascular disease.

- Health impacts of toxic metal emissions from tire and brake wear
- The impact of combined exposures to PM<sub>2.5</sub> and ozone on human health

## **Health impacts of emissions from tire and brake wear**

**Objective:** The overall objective is to investigate the potential of particles from tire and brake wear to cause health impacts.

**Background:** Regulations have resulted in meaningful decreases in combustion-related emissions from road traffic, but have not been followed by similar decreases in emissions from brake and tire wear. In fact, the contribution of non-exhaust PM to total traffic emissions has been predicted to increase to 80–90% by the end of 2020. In addition, many regional land use and transportation plans project a larger percentage of the population living closer to major roads, thereby potentially leading to increasing exposure to re-suspended tire and brake wear particles. Given the expected increase in exposure and the potential for health impacts from the metals and other components of tire and brake wear, study of the health impacts from this source is needed.

**Method:** The study will examine health impacts of different types of particles in various Los Angeles locations. The study will compare particles sampled in areas that have higher tire and brake wear emissions to investigate their association with health outcomes, including mortality and morbidity, using the American Cancer Prevention II cohort or another large cohort study in Southern California. To estimate exposure, particles will be sampled at different locations in LA and at areas such as intersections and downhill locations that should have elevated proportions of tire and brake wear particles. In the Los Angeles Metropolitan area, filter-based samplers for PM<sub>2.5</sub> and PM<sub>2.5-10</sub> will be deployed and chemical speciation will be conducted on the filters to determine the sources by using specific marker chemicals known to be associated with tire and brake wear particles. This information could be used to develop modeled estimates of PM<sub>2.5-10</sub> resulting from tire and brake wear and could be combined with existing PM<sub>2.5</sub> models and previous work in this area to help evaluate associations with mortality and morbidity. The study will also look at the possible confounding by co-pollutants, such as NO<sub>x</sub>.

**Utility of Results:** With the need to support SB 375 through compact growth and the reduction in tailpipe emissions, there will be a potential for increased tire and brake wear exposure in people living closer to traffic in dense residential areas. This study would help ARB understand the potential health impacts of these exposures

**Proposed level of funding: \$250,000**

## **The impact of combined exposures to PM2.5 and ozone on human health**

**Objective:** The objective of the project currently in progress is to improve understanding of the relationship between PM2.5 and ozone exposure and adverse cardiac health effects. Supplemental funds will be used to analyze samples from different parts of the lung, as well as heart tissue, which the researchers obtained from the core project but were unable to process due to funding limitations. The added analysis will help determine whether simultaneous exposure to PM2.5 and ozone results in a greater degree of oxidative damage and/or cytotoxic effects compared to either pollutant alone.

**Background:** Exposure to ambient PM2.5 and/or ozone has been associated with increased adverse health impacts, particularly in people with pre-existing cardiovascular disease. Many studies have demonstrated pulmonary, vascular and neuronal contributions to increased cardiovascular morbidity and mortality; however the mechanisms by which these three systems converge has not yet been defined. To address this research gap, researchers at UC Davis are currently conducting an animal exposure study (using normal and hypertensive rats) under ARB contract #13-311, in which they are investigating the combined effects of PM2.5 and ozone. The proposed extension of this study will allow them to directly assess whether these combined pollutants are increasingly toxic compared to single pollutants at a systemic level. Further, these findings will provide insight into whether individuals with cardiovascular disease are increasingly susceptible to combined pollutant toxicity. Importantly, no additional experiments (i. e. for additional exposures, or additional animals) are needed; all supplemental funding will be used to analyze samples already collected.

**Method:** The cranial, medial, and caudal lung lobes and heart tissue have been preserved as part of the core project and are awaiting analysis. These samples, which have been fixed using a 10% formalin solution and are stored at 4°C in 70% ethanol, will be examined by immunohistochemical methods to determine the abundance and spatial distribution of cytotoxicity and phase II antioxidant enzymes resulting from exposure to PM2.5 and ozone. This analysis will allow us to directly assess whether combined pollutants are increasingly toxic compared to single pollutant at a systemic level.

**Utility of Results:** Due to the global importance of combined pollutant exposure and the prevalence of cardiovascular disease, these additional analyses are critical for scientific understanding and future investigations.

**Proposed level of funding: \$160,000**

### **Remaining Needs**

ARB continues to seek collaborative research endeavors, and focus in-house efforts, on the identification of situations and environments with harmful levels of pollutants, and develop strategies to mitigate them. California has made substantial progress in reducing ambient concentrations of criteria air pollutants and toxic air contaminants, but exposure to pollutants in communities and in microenvironments still remains a concern. For example, research should evaluate 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.

New technologies and building materials also present the potential for new exposures to harmful air contaminants. Measuring for indoor sources of formaldehyde and acrolein, and investigating the health impacts of exposure to elevated levels of CO<sub>2</sub> (recently shown to impair thinking and decision-making functions at levels commonly found in schools, cars and other enclosed environments) are a research priority, as well as mitigating any potential exposure to harmful

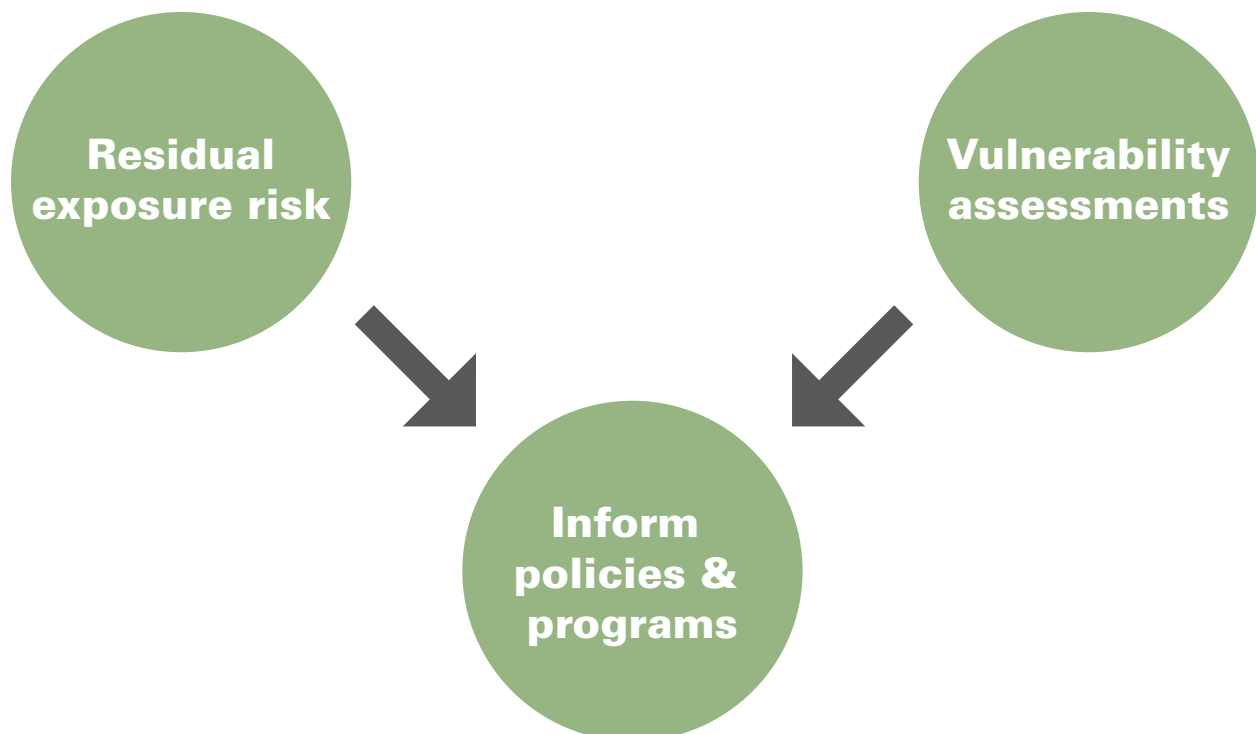
concentrations of these pollutants. The impact of heat waves on the indoor concentrations of indoor- and outdoor-origin pollutants in the homes of seniors and low-income groups, and the trade-offs between indoor air quality and energy use during heat waves should also be investigated in order to develop practices that better protect the health of those vulnerable populations.

## ENVIRONMENTAL JUSTICE

Environmental justice is one of the most important objectives of air quality management, and ARB has continued its commitment to reducing the disproportionate exposure to air pollutants in disadvantaged communities. ARB 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.

### Current Research and Coordination Efforts

ARB’s research program continues to monitor levels of harmful pollutants 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, ARB 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 ARB 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. This study on community exposure is in collaboration with Manuel Pastor, Rachel Morello-Frosch, and James Sadd. Diesel PM and other primary



pollutants are decreasing everywhere, especially in the most impacted communities. PM2.5 is also going down everywhere, but the disparity between the most and least disadvantaged communities persists. To further explore PM2.5 hotspots, we are using satellite data to identify high PM2.5 areas for follow-up investigations.

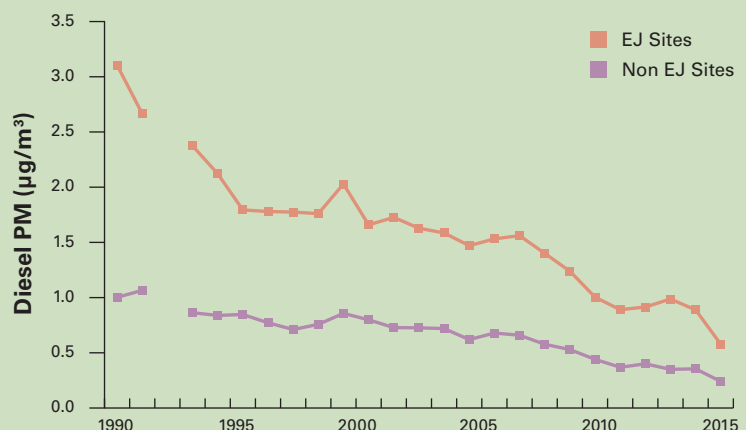
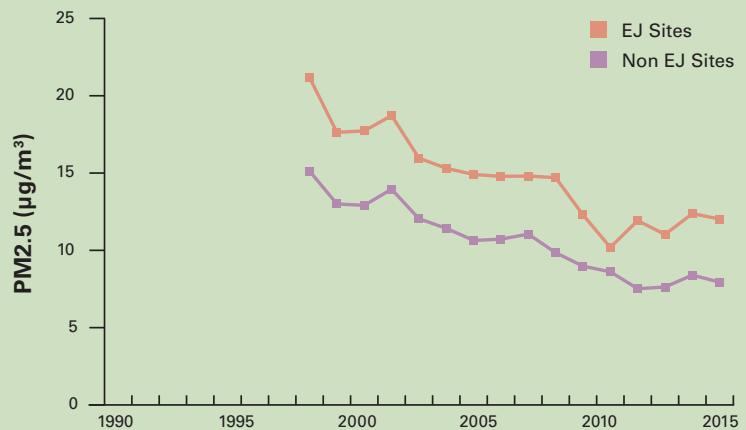
The research program is also funding a pilot study to characterize the potential health and equity impacts of oil and gas extraction activities in California. The proliferation of oil and gas exploration activities in California and nationally has raised concerns about the potential health and equity impacts on local communities due to increases in air pollution and water contamination. Residential proximity to production may increase exposures to air pollutant emissions and other results of oil and gas development activities. This study will look 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.

ARB also researches the implications of SB 375 and regulatory actions like the Zero-Emission Vehicle (ZEV) program for disadvantaged communities. ARB funded a research project to evaluate the potential for displacement of lower-income residents as a result of compact, transit-oriented development investment stemming from SB 375. ARB is also researching how to structure ZEV incentives so that they are more accessible to low- and moderate income Californians. The project will assess the barriers that low and moderate income households face in accessing incentives for ZEVs and other low emission transportation options, and provide insights that will enhance ARB’s efforts to distribute incentives equitably.

## RESEARCH HIGHLIGHT

### Diesel Particulate Matter (DPM) and PM2.5 Disparity Remains but is Declining

To track the impact of ARB’s emission reduction regulations and enforcement programs, a recent study analyzed available long-term monitoring data in environmental justice (EJ) and non-EJ communities. The results indicate that pollutants with controls that impacted near-source concentrations – DPM, NO<sub>2</sub>, and CO – had 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. These results will inform continued efforts to reduce local exposures of these regional pollutants.



ARB is also providing technical support for monitoring studies by Edmund Seto in Imperial Valley and San Ysidro, and ARB is lending 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 will focus 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.

New research on environmental justice is focusing on identifying the locations of stationary, area, and mobile sources on the Mexico side of the US-Mexico Border as inputs to CalEnviroScreen. CalEnviroScreen identifies the census tracts with the greatest cumulative exposure and social and health vulnerability. In addition to the data at each census tract, CalEnviroScreen uses the information from nearby census tracts to evaluate cumulative exposure, including the location of potential air pollution sources. This information is lacking on the Mexico side of the US-Mexico border leading to the appearance that there is very little pollution in border communities. The investigators will use Mexico’s version of the Toxic Release Inventory (Registro de Emisiones y Transferencia de Contaminantes) 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 by Edmund Seto of the University of Washington in the Imperial Valley and San Ysidro.

ARB regulations have reduced air toxics emissions from vehicles and their fuels, 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, ARB has implemented 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.

ARB’s research program performed an in-house study on the historical trends of toxic air contaminants that 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 unhealthy emissions from these air 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 well designed program to reduce public exposure to toxic air pollution.

## **Proposed Research**

- Sources contributing to higher levels of PM2.5 in disadvantaged communities
- Geofencing as a strategy to lower emissions in disadvantaged communities
- Sources contributing to higher levels of benzene and other air toxics in disadvantaged communities
- Development of real-time, portable screening methods for toxic metals

## Sources contributing to higher levels of PM2.5 in disadvantaged communities

**Objective:** The objective of this research is to develop intake fraction (iF) maps for primary and secondary PM2.5 in CA and use the maps to prioritize sources contributing to higher levels of PM2.5 observed in environmental justice (EJ) communities.

**Background:** PM2.5 concentrations measured at air monitors located in EJ communities are higher than those located in non-EJ communities, despite elimination or the narrowing of this difference for other pollutants, including carbon monoxide, nitrous oxide, and diesel PM (DPM). Identification of PM2.5 sources (both primary and secondary) that contribute to higher exposures in EJ communities is critical to achieve ARB's goal to provide safe, clean air to all Californians. Sources of air pollution vary dramatically in their impacts on human exposures because of the differences in their proximity to people. Priority should be given to sources that may provide greater health benefits per unit emission reduction.

Intake fraction (iF) is the fraction of air pollutants emitted by a source that are actually inhaled by people. A higher iF means, per unit mass emission, there is a larger amount of air pollutants inhaled by people, and thus might be a greater impact on health. iF can be used to compare the relative importance of different emission sources based on their resulting exposures, and therefore is a useful metric for prioritizing sources for control. For example, utilizing metrics including iF, Marshall et al. (2014) evaluated the impacts of emission reductions from different sources for fine DPM in Southern California, and found that per unit mass reduction, control in train emissions produce the greatest reductions in population exposures and exposure disparities between high-income whites and low-income nonwhites. ARB staff are currently developing an iF database for primary PM2.5 emitted by major point sources in CA, and the preliminary results show great variability of exposure impacts from different sources, emphasizing the importance of source prioritization for emission reductions. However, currently available iF datasets are mainly for primary PM2.5 from a few source categories and/or in a few regions. There is a need to expand current iF datasets to include both primary and secondary PM2.5 for both ground-level and elevated emission sources in all major air basins.

**Method:** The investigators will use InMAP (the Intervention Model of Air Pollution) to develop 1-km<sup>2</sup> resolution iF maps for primary PM2.5 and its secondary precursors (nitrous oxide, Sulfur dioxide, volatile organic compounds, and ammonia) from ground-level and elevated emission sources in California. InMAP is a computationally efficient emission-to-impact model that incorporates a reduced-form version of state-of-the-science chemical transport simulation for primary and secondary PM2.5. Combined with CalEnviroScreen, sources that contribute to higher levels of PM2.5 in major EJ communities will be identified and prioritized. In addition, the investigators will provide training to ARB staff to generate iF estimates using InMAP for future program needs.

**Utility of Results:** The results of this study will be useful in the identification of emission sources that need further control to reduce higher levels of PM2.5 in EJ communities and minimize exposure disparities in CA.

**Proposed level of funding: \$180,000**

## **Geofencing as a strategy to lower emissions in disadvantaged communities**

**Objective:** The objective of this research is to evaluate strategies in the heavy-duty sector that could lower emissions through the use of geofencing in disadvantaged communities, during certain times, or in areas of poor air quality.

**Background:** Geofencing allows a user to define virtual boundaries on top of a real-world view of a specific geographical area. When a device crosses the geofence perimeter, such as a device mounted to a heavy-duty vehicle, both the device's user and the geofence operator are alerted. These triggers can be designed to be accompanied by specific instructions for the user to modify his or her current activities or to employ strategies that would lower pollutant emissions in a specified area.

Geofencing is already being used by today's heavy-duty fleets to provide real-time vehicle location information that can be used to optimize productivity, security, and cost efficiency. The real-time data also facilitates route optimization and better fleet management. Geofencing capabilities are currently being tested to lower emissions in high traffic areas using Class 8 drayage trucks as part of a South Coast Air Quality Management District project funded by a \$23.6 million grant from the State of California. These trucks are using geofencing to switch between zero-emission and conventional hybrid operating modes. When a truck enters the zero-emission geofenced area, which is typically a location with heavy freight traffic, such as a port, the truck operates in pure electric mode. When outside the zero-emission area, such as on the way to a rail yard or distribution center, the diesel engine is enabled, allowing for hybrid operation and recharging of the batteries.

**Method:** The investigators will examine the potential for geofencing strategies to reduce the emissions of toxic air contaminants, criteria pollutants and greenhouse gases. These strategies could include reduced acceleration rates, lowering maximum speeds, switching to electric mode in hybrid vehicles, and changing engine calibration. The project will estimate emission impacts through modeling that simulates traffic and emissions using existing emissions data. The project will consider which vehicles and which areas in California are the best candidates for this technology, and would experience the greatest reduction in exposure to heavy-duty related emissions to protect California's most vulnerable populations.

**Utility of Results:** The results would identify strategies that the freight industry could employ to mitigate near roadway impacts and to quantify the cumulative effect of multiple mitigation measures. These results could be used to inform the use of incentive funding and the development of sustainable freight strategies, particularly strategies that reduce pollutant emissions in disadvantaged communities.

**Proposed level of funding: \$300,000**



## **Sources contributing to higher levels of benzene and other air toxics in disadvantaged communities**

**Objective:** The objective of this research is to conduct a statewide survey of air toxics monitoring in selected disadvantaged communities with the highest EJSM scores to quantify local air quality levels, and to identify potential sources contributing to the air pollution hotspots.

**Background:** Although ARB and local air districts have implemented an impressive air quality monitoring network for criteria air pollutant monitoring throughout California, the network does not provide adequate coverage for air toxics monitoring, especially at community scales. Furthermore, air toxics monitoring usually requires longer-term sampling and subsequent laboratory analysis, which limits both real-time feedback as well as useful information on spatial resolution of hot spots.

**Method:** The project will utilize the service offered by FluxSense, Inc., which has a unique mobile monitoring capability to measure real-time concentrations of alkanes, alkenes, the chemicals benzene, toluene, ethylbenzene and xylene (BTEX), formaldehyde, and methane at a community-scale, and characterization and quantification of emissions behavior of contributing sources in a limited time. This team is currently conducting several local campaigns in the South Coast funded by South Coast Air Quality Management District, and have already measured higher-than-expected BTEX and VOC emissions from local refineries and oil and gas wells, gas treatment facilities, and gas stations in the Long Beach area. This technology can be implemented to identify and quantify high pollution hotspots. In addition to conducting community monitoring in areas likely to have high-emitting BTEX sources, the FluxSense technology could also be utilized to characterize emission sources that are responsible for the high air toxic hotspots.

**Utility of Results:** The results from this study would offer useful screening information to identify high-risk communities for prioritizing air pollution mitigation efforts. The data will also be useful to extrapolate community-level exposures and cancer risk to identify the highest impact sources. The data would also be useful to support enforcement efforts to address high BTEX sources, and may be useful to conduct real-world verification of the impact of the oil and gas regulation (effective Jan 1, 2018) on CH<sub>4</sub> and BTEX emissions. This project compliments planned community monitoring efforts by ARB staff that will measure speciated VOCs and other toxics of concern around oil and gas infrastructure.

**Proposed level of funding: \$200,000**

## Development of real-time, portable monitoring methods for toxic metals

**Objective:** The objective of this project is to sponsor a technology challenge for portable, real-time screening technologies to detect ambient concentrations of toxic metals that may drive health risk concerns.

**Background:** The California Air Toxics Program established a process for identifying and controlling of toxic air contaminants and includes provisions to make the public aware of significant toxic exposures, and to reduce the risk to below levels deemed significant. To meet the demand for information on levels of air toxics around the state, the ARB currently operates an air toxics monitoring network comprised of 14 monitoring stations. These monitoring stations are strategically located throughout California urban areas to represent regional areas of highest toxic exposures. The monitoring program has developed a long-term, statewide monitoring database of 40 toxic compounds and provides guidelines for monitoring toxic substances.

Although technologies to screen for toxic compounds, such as benzene, toluene and many criteria pollutants are available, the same level of efficacy for community monitoring is not available for toxic metals. Deploying portable devices that can monitor for toxic metals in real-time will help ARB and communities to determine the source of these metals and develop strategies to reduce their emissions. Real-time measurements of metals from low-cost community monitoring efforts, and the ability to rapidly deploy portable devices will allow air districts to quickly identify and respond to emission events, and thereby minimize the impacts of health hazardous incidents. These efforts are particularly important, and should be prioritized in disadvantaged communities, and those located close to industrial sources.

The objective of this research project overlaps with the interests of the air districts and other research entities, such as SCAQMD and the Environmental Defense Fund. ARB staff is collaborating with these organizations to ensure that concurrent efforts are not duplicated, and to seek co-funding opportunities.

**Method:** The investigators will examine the efficacy of various portable technologies to measure concentrations of metals in real time. Tested technologies can include those that are commercially available, as well as those still in the research and development phase. Examples of metals that should be focused on during this investigation include lead, hexavalent chromium, and others such as cadmium, nickel, arsenic, iron, copper, zinc, mercury, and beryllium.

**Utility of Results:** The results of this project will identify the most cost effective and efficient technologies to support ARB'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.

**Proposed level of funding: \$400,000**

### Remaining Needs

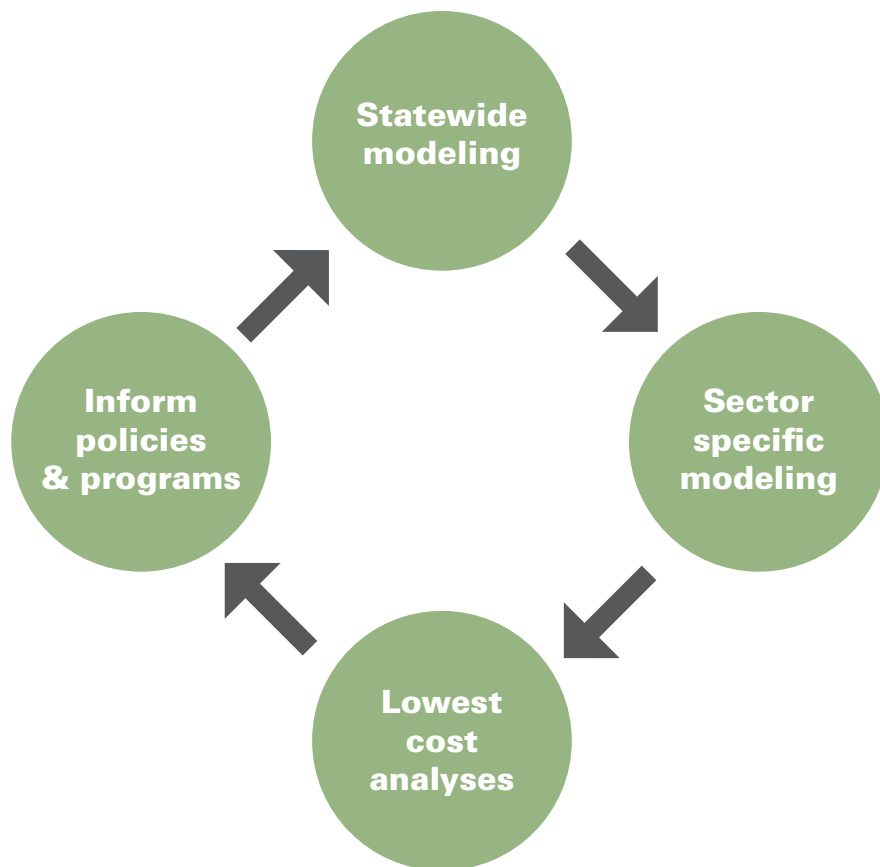
Given that past research efforts have established that environmental justice communities suffer disproportionately from asthma or asthma-like symptoms, additional research is needed to identify factors that increase vulnerability to pollutant effects in these sensitive populations. Research to support 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. The development of a methodology to track the State's use of incentive funding and greenhouse gas reduction fund investments in disadvantaged communities is also needed to assess the economic, health, and environmental benefits of these programs. Additional research is also needed to assess the effectiveness of ARB's regulatory programs in disadvantaged communities by building databases to track GHG and co-pollutant reductions from ARB programs to develop a basis for testing patterns of disparity in these communities.

The research project proposed in this year's Research Plan that aims to identify low-cost technology to make real-time measurements of toxic metals is a first step to developing community monitoring systems and identifying hotspots. Additional research initiatives to develop community monitoring systems for a broad suite of toxic air contaminants still 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. The highest priority toxic air contaminants include dioxin from diesel exhaust, acrolein from light and heavy duty vehicles, polycyclic aromatic hydrocarbons (PAHs) from light-, heavy-duty, and off-road mobile equipment, and improved speciation profiles for hexavalent chromium in total chromium concentrations.

## ECONOMICS

### Current Research and Coordination Efforts

One of ARB's current projects 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 are intended to provide ARB with the best available data on farmers, and agricultural-related businesses, to enhance ARB'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 least cost.



Several current projects inform ARB's light-duty zero and near-zero emission vehicle programs. One project supports ZEV policy development by analyzing how socioeconomic, demographic, market, and regulatory factors influence the growth of ZEV sales in California. Using historical vehicle registration and incentive program data at the census-tract level, the study assesses the impacts of changing fuel prices, alternative incentive structures, and other parameters on ZEV sales. A second project consists of an economic assessment of the used PEV market in California, including a survey to identify who purchases used PEVs, their motivations, concerns, purchase details, and driving/charging behavior. This project will help determine if ARB policy modifications are needed based on the health of the used PEV market. A third project will provide a better understanding of low- and moderate-income household vehicle retirement and purchase decisions, including the role different incentives play in those decisions.

ARB'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 jobs. 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.

Ongoing research is also examining the co-benefits and impacts of cap and trade investments, including an analysis that will estimate the number of jobs created by this funding program. ARB is also funding a research project that will develop standardized methods to quantify and report on a number of co-benefits of cap and trade investments, including job creation, air quality, and cost savings.

## **Remaining Needs**

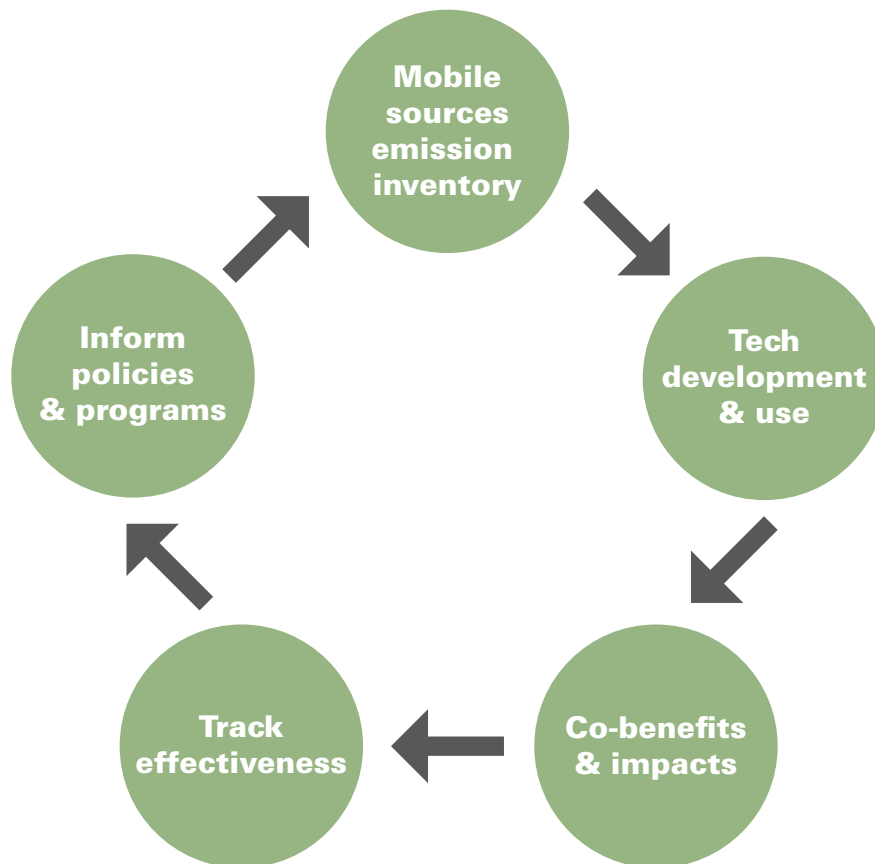
Additional economic research is needed to support ARB's programs and ensure that economic prosperity and environmental sustainability can be achieved together. Estimating the economic impact of ARB's regulatory programs can provide insight into future regulatory implementation and has been identified as a near-term research need. The development of methods for monetizing regulatory benefits of avoided Social Cost of Carbon and mortality risk are also a priority since new methods are needed for integrating these values into rulemaking estimates of regulatory economic impacts. 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.

Economic research on the use of incentives can also benefit ARB's current suite of programs. ARB 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. 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.

## Specific Program Support

### TRANSPORTATION SYSTEM STRATEGIES SUPPORT

ARB'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. Research on vehicles and fuels supports the development and implementation of regulations and incentive programs that reduce transportation related emissions. ARB research promotes 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. Research results from this suite of projects inform policy makers to ensure the policies aimed at reducing emissions don't have any unintended impacts, and provide information for future policy development.



### Current Research and Coordination Efforts

To support the midterm review for the Advanced Clean Cars program and in support of the Clean Vehicle Rebate Project and other light-duty incentive programs, ARB has been sponsoring new and used light-duty vehicle research aimed at optimizing our use of incentive funds and consumer acceptance of new vehicle technologies, such as plug-in hybrid electric vehicles (PHEVs) and battery electric (BEV) vehicles (collectively referred to here as PEVs) and Fuel Cell Electric Vehicles (FCEVs). A research project is surveying low- and moderate-income Californian households to gain insight into their vehicle retirement and purchase decisions, including the role that different incentives play in those decisions. New and current research focused on adoption and use will quantify the electricity powered miles driven by emerging technology vehicles, and analyze the charging and refueling behavior of electric and fuel cell vehicle households in

order to quantify emission benefits based on real-world driving. Current research on dynamics of PEVs in the secondary market will determine the longer term emissions benefits of these vehicles and whether the used PEV market is expanding access to a wider array of consumers. While manufacturer compliance with the Zero Emission Vehicle (ZEV) program is based on new vehicles sales, the expected emissions benefits will require that these vehicles, including PEVs, remain in the fleet past the first owner. The results of this study will be useful to refine long-term projections of emissions benefits from PEVs, and to inform future policy decisions, on the treatment of these vehicles by various ARB programs, such as incentives, durability requirements, or vehicle crediting.

Reducing transportation emissions will have dramatic air quality and public health benefits, especially in many of California's environmental justice communities. Therefore, ARB's mobile source research also monitors the effectiveness of emission reduction strategies to ensure that the expected air quality and public health benefits are achieved. For light-duty vehicles, research is investigating the long-term trend in measurements of emissions from light duty vehicles in Los Angeles using remote sensing, which continues to provide an understanding of how well the emission controls continue to perform in vehicles subject to LEV I and LEV II. Projects proposed in this Plan will continue this monitoring and build on this work by leveraging existing emission measurement data and using new technologies to measure emissions from the light-duty fleet to improve our inventory, support enforcement efforts, and continue to ensure that our emission reduction programs are successful.

ARB's research monitors emissions from the heavy-duty sector in order to improve our understanding of trends in on-road emissions. This research also tracks the effectiveness of current regulations (i.e., Drayage and Truck and Bus Rules), and programs to reduce DPM emissions by 85 percent by 2020. Research on diesel emissions is multipronged, and includes research on the effect of in-use rules for heavy-duty diesel vehicles, the durability, degradation, and failure rates of aftertreatment that reduces NO<sub>x</sub> and DPM, and the real-world efficacy of NO<sub>x</sub> controls. This will be accomplished by measuring emissions from the in-use fleet on laboratory dynamometers, in tunnels, at ports, and at weigh-in-motion stations in California. Research is also underway to explore the ability of current diesel control technology to achieve NO<sub>x</sub> reductions beyond the current emission standards, which will be needed to meet increasingly stringent NAAQS over the next decade.

Current research on heavy-duty diesel vehicles is underway to adapt diesel filter use to a wider variety of engines, develop and deploy zero-emission technology and infrastructure, and identify the emission benefits from alternative fuels. To support and inform the Sustainable Freight Action Plan, the 2016 SIPs, and other ARB emission reduction planning efforts, ARB and the South Coast Air Quality Management District have been conducting technology and fuel assessments for a variety of source categories. Work that began last year expanded this effort to assess emissions of in-use NO<sub>x</sub> from vocational trucks with multiple engine types and alternative fuels. These

## RESEARCH HIGHLIGHT



### **Zero Emission Vehicles in CA – Who's Buying 'em?**

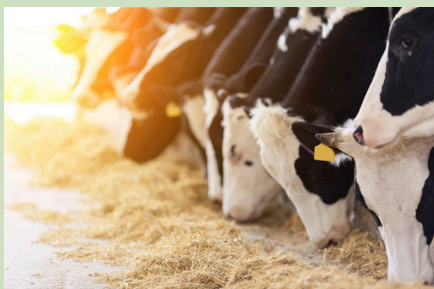
To inform ARB's Zero-Emission Vehicle program and the use of incentive funds aimed at accelerating consumer adoption of PEVs, a recent survey of new vehicle car buyers found that PEV sales are positively associated with household income, gasoline prices and proximity to high-occupancy vehicle lanes. ARB Contract 13-303

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 this year will also 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.

Current research is also focused on reducing and tracking emissions in the off-road sector. In the off-road sector, emissions standards have allowed smaller engines to be made and sold with minimal aftertreatment control technologies. The assumption has been that advanced aftertreatment would severely impact the cost of these smaller engines. However, given the need for further emission reductions, research into whether more advanced aftertreatment is feasible and cost-effective for these smaller engines has been initiated. Additional research is looking at the impact of an alternative to current allowances for averaging fleet emissions to demonstrating compliance to gain a better understanding of the distribution of engines with the best available controls and emission impacts of current rules. Research proposed in this plan will add to these projects by characterizing the use of off road equipment in the construction sector. This work will improve the emissions inventory and thereby inform future testing and regulations.

Current research is also underway to reduce GHG emissions from the transportation sector through the use of alternative fuels. This research also supports the implementation of ARB's Low Carbon Fuel Standard (LCFS), which calls for a reduction of at least 10 percent in the carbon intensity of California's transportation fuels by 2020. Projects that were completed in 2016 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. Results from this research helped to inform the Short-lived Climate Pollutants Strategy and internal modeling efforts that inform the LCFS. Projects that will be completed this year include one that is developing lifecycle assessments for production pathways of renewable hydrogen fuel. These pathways will help expand the portfolio of the LCFS. Another project is investigating how natural gas infrastructure can be built in the near-term to accommodate a long-term shift to the use of alternative fuels. Costs of dual-purpose infrastructure that can accommodate both fossil natural gas and hydrogen will be compiled and used for an assessment of the potential for policies and incentives to be used to encourage the switch to alternative fuels.

## RESEARCH HIGHLIGHT



### **Renewable Natural Gas is a Feasible Substitute for Fossil Natural Gas**

To inform ARB's Low Carbon Fuel Standard and Short-lived Climate Pollutant Strategy, a recent study of the potential to produce renewable natural gas (RNG) in California 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. ARB Contract 13-307.

## Proposed Research

The five research projects proposed for the transportation system build on the comprehensiveness of California's existing emission inventory, monitoring, and modeling research efforts. The projects will improve emission inventories and our understanding of the emissions reductions that have occurred in response to recent ARB regulations.

- Activity data of off-road engines in construction
- Identification of high emitting Light-duty vehicle emission makes and models
- Light-duty vehicle emission trends from a remote sensing device measurement campaign
- Cold start emission impacts in hybrids
- Vehicle brake, tire, and clutch wear emissions

### Activity data of off-road engines in construction

**Objective:** The objective of this research is to characterize the activity profiles (e. g. operation duration on an average working day, load factor variation during operation, and exhaust temperature) for heavy-duty off-road diesel vehicles and engines used for construction purposes. The research should also put these results in context of the emission certification test cycles, and provide an analysis of the representativeness of the certification cycles to real-world emissions of NO<sub>x</sub> for the types of off-road vehicles and engines considered.

**Background:** Construction and agricultural equipment is estimated to contribute about 8% of the NO<sub>x</sub> emissions in the State; and this relative contribution is expected to increase as the heavy-duty on-road fleet gets cleaner in response to increasingly stringent emission standards and in-use compliance measures for the on-road sector. In sharp contrast with the 8-mode steady-state engine dynamometer certification test cycle for new off-road diesel engines, real-world engine/equipment operation is highly transient, with rapid and repeated changes in engine speed and load. In a previous ARB-sponsored study (Durbin et al. , 2013), the tailpipe emissions of 27 pieces of construction equipment were measured, along with their activity profiles.

**Method:** Through literature review and discussion with ARB staff and industry representatives, the investigator will determine the five most prevalent types of construction vehicles or equipment, and three most representative power levels for each type. The investigator will recruit no less than 10 pieces of equipment for each type, and collect activity data (operation duration, load factor, and exhaust temperature) from engine control unit or on-board diagnostics data loggers. The investigator will analyze the results to assess the representativeness of existing engine certification cycles and to assess suitability for effective NO<sub>x</sub> control by SCR.

**Utility of Results:** The findings will be used to improve the emission inventory and evaluate the need for updating off-road certification cycles and regulations.

**Proposed level of funding: \$200,000**



## Identification of high emitting light-duty vehicle makes and models

**Objective:** The objective of this research project is to identify specific vehicle makes and models that on average have on-road emission rates very much higher than expected.

**Background:** It was recently discovered through emission measurements of vehicles in the real world use 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 makes and models of vehicles exhibiting similar behavior, and whether or not this is a widespread problem. Contractor OPUS Inspection conducts Remote Sensing Device (RSD) measurements as part of state mandated Inspection and Maintenance (I/M) programs in several different states (not in California). Through these I/M programs, OPUS has accumulated over 10 million emission measurements of in-use vehicles. The individual data records are used to take action with respect to individual vehicle owners as part of the I/M program, but are not utilized as a comprehensive data set. Combined into a comprehensive database, these data offer an excellent opportunity for data mining.

**Method:** The contractor would combine data from various state and regional I/M programs into a common database. The database would then be systematically searched to identify specific make/model/year combinations that exhibit emissions very much higher than their peers, i.e. to identify outliers. The average emission factors and the ratios to peer-group averages would be reported for the outlier make/model/year combinations. Individual vehicle results would not be reported.

**Utility of Results:** The data would establish the extent to which anomalously high emitting makes and models are a problem, which could be used to inform inventory estimates and to guide future regulation development. Identification of the specific makes and models could be used as the basis to initiate targeted investigations of manufacturer’s makes and models to support regulatory compliance actions.

**Proposed level of funding: \$200,000**

## Light-duty vehicle trends from a remote sensing measurement campaign

**Objective:** The objective of this study is to conduct a measurement campaign in West Los Angeles during spring of 2018, measuring emissions of CO, HC, NO, NO<sub>2</sub>, SO<sub>2</sub>, and NH<sub>3</sub>, using remote sensing devices.

**Background:** Starting with the 2004 model year, California significantly strengthened the exhaust emission standards and durability requirements for light-duty vehicles under its LEV II regulation. But there is not sufficient data that tracks the long-term effect of the regulation in reducing exhaust emissions and improving durability in the real-world. Between 1999 and 2015, seven campaigns were conducted by the University of Denver to use RSD to collect on-road vehicle emission measurements at the on-ramp of S. La Brea Ave. southbound to I-10 eastbound in West Los Angeles, California. Each campaign consists of approximately 20,000 records collected during several days of measurement. This historical record has been used to study general emission trends and to examine specific emission issues, such as high mileage vehicles and NO<sub>x</sub> emissions from diesel passenger vehicles.

**Method:** The investigators will collect on-road measurements of emissions of pollutants including carbon monoxide, hydrocarbons, nitrogen oxide, nitrogen dioxide, sulphur dioxide and ammonia using RSD at the same West Los Angeles location during spring of 2018. The investigators will convert those measurements to fuel-based emission rates, extend the historical trends previously established, and identify any significant anomalies.

**Utility of Results:** The extended historical record will be used to verify the effectiveness of ARB’s various light-duty vehicle emission reduction programs, improve the understanding of deterioration of emission controls, identify issues important to SIP compliance, and assess disproportionate exposure in disadvantaged communities.

**Proposed level of funding: \$40,000**

## **Cold start emission impacts of blended plug-in hybrids**

**Objective:** The objective of this research project is to characterize the activity profiles related to cold start emissions produced by blended plug-in hybrid vehicles in order to understand the real-world scale of the increased emission profiles measured in the lab.

**Background:** In the current market, most plug-in hybrid electric vehicles (PHEV) are “blended” in that an internal combustion engine (ICE) can start to help power the vehicle before the battery is depleted. These ICE starts can occur when the electric drivetrain is not sufficient to meet immediate high torque demand, regardless of the battery state of charge.

As part of the midterm review of advanced clean cars, ARB conducted emission testing to evaluate the cold start performance of several blended PHEVs<sup>1</sup>. The testing confirms that cold-start emissions under high-power demand conditions can be significantly higher than emissions from traditional engine cold starts. However the cumulative impact on emissions from this fraction of starts has not yet been determined.

In an on-going study to understand plug-in electric vehicle (PEV) travel and charging behavior<sup>2</sup>, second by second data are being collected from a target of 264 PEV households for the duration of one year. These data include GPS, state of charge, speed, revolutions per minute (RPM), charging events, and numerous other parameters.

**Method:** The contractor would use the data from the PEV behavior study along with other available data sources to assess: 1) conditions that lead to medium/high power cold starts; 2) frequency of medium/high power cold starts; 3) severity (power draw) of medium/high power cold starts; and suggest a framework that could be utilized by the EMFAC model to account for medium/high power cold starts in the inventory

**Utility of Results:** The result of this study will be used to improve the emission inventory model (EMFAC) in estimating PHEV start emissions. The result will also be used to guide the development of future clean car standards.

**Proposed level of funding: \$75,000**

---

1 ARB, January 18,2017. California’s Advanced Clean Cars Midterm Review, Appendix H: Plug-in Hybrid Electric Vehicle Emissions Testing. [https://www.arb.ca.gov/msprog/acc/mtr/appendix\\_h.pdf](https://www.arb.ca.gov/msprog/acc/mtr/appendix_h.pdf)

2 Nicholas, M.A., G. Tal, and Turrentine, T.S. 2017. Advanced Plug-in Electric Vehicle Travel and Charging Behavior Interim Report. UCD-ITS-RR-16-10. [https://itspubs.ucdavis.edu/wp-content/themes/ucdavis/pubs/download\\_pdf.php?id=2692](https://itspubs.ucdavis.edu/wp-content/themes/ucdavis/pubs/download_pdf.php?id=2692)

## Vehicle brake and tire wear emissions

**Objective:** This project will investigate non-tailpipe emission factors from light- and heavy-duty vehicles. Distance-based emission factors of particle mass and number for brake and tire wear will be determined, to support improvement of CARB's EMFAC emission model. Samples of these particles will be collected for particle size distribution and chemical analysis, providing data to support future source apportionment and health impact evaluation studies.

**Background:** Non-tailpipe sources of PM<sub>2.5</sub> from light-duty vehicles (LDVs), including tire and brake wear, currently contribute about half of all PM<sub>2.5</sub> from LDVs. As tailpipe emissions from LDVs are further reduced in the coming decades, this portion is expected to increase. The same is true of heavy-duty brake and tire wear. The Particle Measurement Program (PMP) of the Joint Research Centre of the European Commission has sponsored substantial research in this area, and in fact their "REBRAKE" program could serve as a model for the laboratory testing of brake wear emissions. The materials used in brake pads, however, as well as other factors influencing brake wear emissions, are different in Europe than in California. The PMP has also measured emissions from other non-tailpipe sources in controlled laboratory settings such as tire wear, but as with brake wear differences between tire materials and roadway surfaces require that California-specific measurement be made for use in EMFAC.

Recent receptor modeling has identified sources from non-tailpipe emissions, but often the various specific sources (e. g., road dust, tire wear, brake wear) are difficult to separate and are therefore combined into a single source. Laboratory experiments are needed to fully distinguish between tire and brake wear emissions.

**Method:** Size resolved PM<sub>2.5</sub> emission rates for light-duty tire and brake wear will be measured using a dynamometer under controlled laboratory settings. Surfaces typical of California roadways should be incorporated into tire wear experiments. If experimentally feasible, heavy-duty brake and tire wear emission factors should also be quantified (assuming sufficient funds are available). Tires and brake components that are representative of the California light- and heavy-duty fleets should be selected, and therefore a statewide inventory of these products should be developed.

Emissions will be measured under standard driving cycles including the FTP, US06, and UC cycles. A 1-Hz time series of particle mass and number emissions should be measured so that emission factors can be estimated as a function of braking event characteristics. PM<sub>2.5</sub> samples for each type of wear should also be collected on filters and analyzed for chemical composition, including total metals, organic carbon, elemental carbon, and water-soluble metals.

**Utility of Results:** This project will produce distance-based emission factors for tire and brake wear from light- and heavy-duty vehicles. These measurements will be used to update non-exhaust emission factors in EMFAC. The chemical composition of these emissions can be used in source profiles to estimate the contribution of brake and tire wear to ambient PM<sub>2.5</sub> via receptor modeling, and to evaluate health impacts.

**Proposed level of funding: \$350,000**

### Remaining Needs

In order to improve the emission inventory, and ensure that certification cycles accurately represent real-world emissions of NO<sub>x</sub> for off-road vehicles and engines used in the agricultural sector, research is needed to characterize their activity profiles (e. g., operation duration on an average working day, load factor variation during operation, and exhaust temperature). This work would complement a project in this plan that proposes to characterize the activity profiles of off-road construction equipment. Field measurements of off-highway recreational vehicles are also needed to support the emissions inventory.

For the heavy-duty sector, research is needed to evaluate the evolving state of telematics technology to identify potential security weaknesses in order to minimize fraud and ensure that all transmitted data is secure. This research would help inform a large-scale heavy-duty vehicle (HDV) 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.

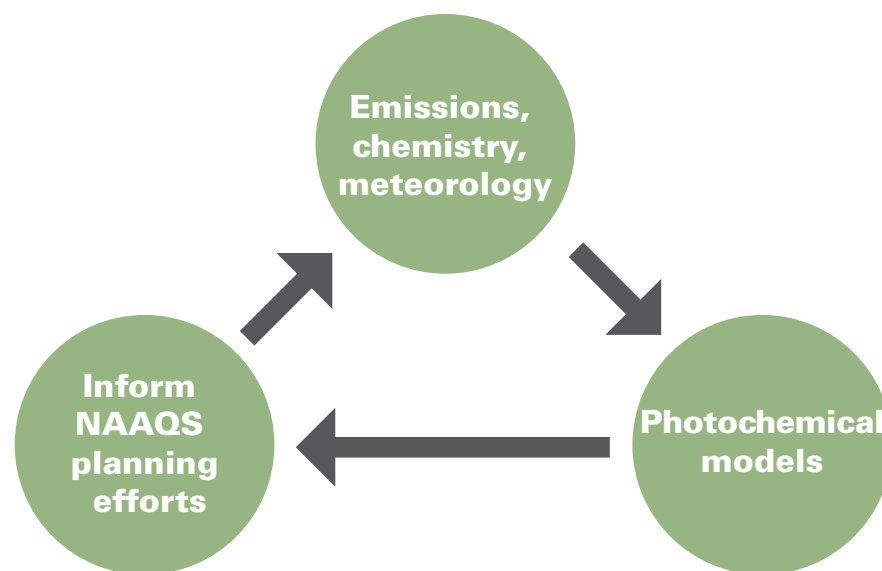
The implementation of California’s Sustainable Freight Strategy (SFS) would benefit from the creation of modeled scenarios that demonstrate the effects of e-commerce growth on demand for transportation services and related emissions impacts. The characterization of power use profiles and the development of new strategies to reduce emissions from transportation refrigeration units are needed to support multiple ARB programs, including the SFS.

In order to support California’s goals of emissions reductions and plug-in electric vehicle (PEV) deployment, additional research is needed on the behavior of EV use, charging needs, and the emission benefits of vehicle to grid integration. Results from this research could inform investments in charging infrastructure and develop strategies to increase the use of EVs by gaining a better understanding of what applications provide the most benefit.

Projects aimed at reducing GHGs in the transportation sector would also benefit from analyses of impacts on GHGs and other co-benefits before and after the project is implemented. Analysis is also needed to improve techniques for inventory of changes in land use as a result of the LCFS in order to assess the policies and programs designed to protect agricultural lands, forests, wetlands, and natural ecosystems.

## SIP PROGRAM SUPPORT

ARB’s research continues to improve the scientific foundation that supports the development of effective strategies to meet Clean Air Act requirements for State Implementation Plans (SIPs) for meeting National Ambient Air Quality Standards (NAAQS). ARB’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.



## Current Research and Coordination Efforts

To improve air quality models, ARB continues to support research to address the complex problem of modeling secondary organic aerosol (SOA) formation. Organic aerosols are a significant component of PM<sub>2.5</sub> in California. 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 will improve PM<sub>2.5</sub> modeling used in SIPs. ARB has also funded projects to address questions concerning organic compounds used in consumer products. These projects will answer 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.

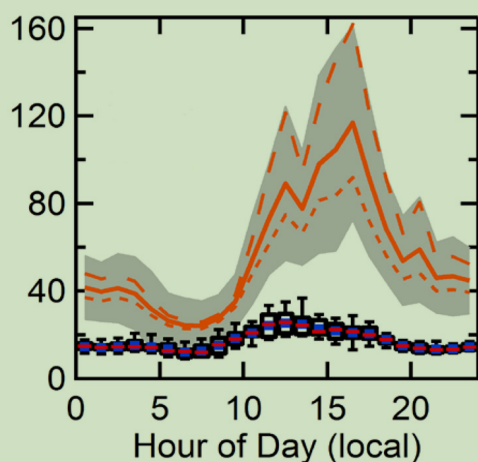
A large number of observations around the world have documented the presence of elevated ozone concentrations aloft that could potentially contribute to ground level exceedances. While some field studies have collected measurements of aloft ozone near and over California, these relatively short-term 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 exceedances in the San Joaquin Valley (SJV). 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 SJV. CABOTS is a coordinated effort with San Jose State University and NOAA. Aircraft flown by two NASA programs, as well as two additional ARB funded contracts and a surface ozone monitoring site in the Coast Ranges supported by the San Joaquin Valley Air Pollution Control District contributed significantly to

# RESEARCH HIGHLIGHT

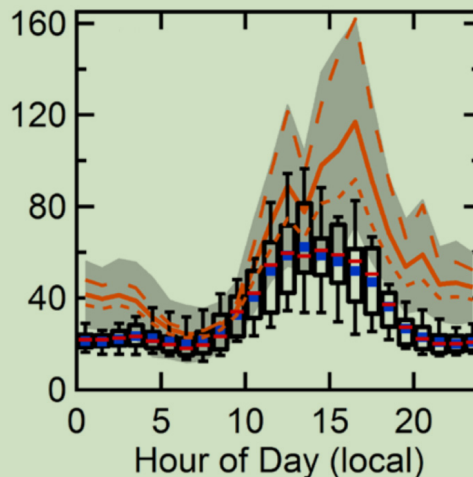
## Taming Smog Formation by Thinking Inside the Box

To inform ARB's SIP modeling of ozone formation, a recent study investigated how some chemicals emitted by industry can interact with airborne substances in the atmosphere to form smog-forming ozone. The researchers were able to significantly improve modeled results by accounting for the difference between chemical reactions in the open air versus inside lab chamber experiments. Accounting for this difference will improve the ability of air quality regulators to predict and improve California air quality. ARB Contract 12-312.

Without "Vapor Wall Loss"



With "Vapor Wall Loss"



Observed values  
Modeled values

the study. The field measurements will provide key data to begin to quantify the contribution of baseline ozone aloft to surface ozone exceedances in the SJV.

In addition, a couple of ongoing projects will support updates to the PM modeling for the San Joaquin Valley Air Basin needed to address the more stringent annual-average PM<sub>2.5</sub> standard adopted by the U.S. EPA in 2012. These projects will incorporate recent field observations into improved models for the stagnation events leading to PM<sub>2.5</sub> exceedances.

In order to disseminate research results, increase collaboration and leverage concurrent research activities, ARB 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.

## Proposed Research

The two proposed projects will contribute to the state of the science by improving the understanding of the transport and impact of baseline ozone, and provide a clearer linkage between PM<sub>2.5</sub> concentrations and major sources in the San Joaquin Valley (SJV). Results from these projects will contribute towards regulatory policy addressing ozone attainment in the SJV, and help ARB to improve the effectiveness of future PM<sub>2.5</sub> control strategies.

- Vertical ozone distribution over California
- Long-term characterization of PM<sub>2.5</sub> in the San Joaquin Valley

## Vertical ozone distribution over California

**Objective:** The objective of this research is to analyze the data collected by the NASA AJAX group during the California Baseline Ozone Transport Study (CABOTS) to better understand the transport and impact of baseline ozone on ozone exceedances in the San Joaquin Valley (SJV).

**Background:** Because health effects research has consistently led to more stringent ambient air quality standards for ozone, California must continue to achieve significant new reductions in ozone precursor emissions. At the same time, baseline ozone concentrations have been increasing. Increasing out-of-state contributions are making attainment of the more stringent ozone standards increasingly difficult. To better understand the contributions of external pollution sources and atmospheric processes to ozone exceedances in the SJV, the California Baseline Ozone Transport Study (CABOTS) produced a three-month dataset of aloft ozone data collected with ozonesondes and an ozone lidar. The NASA Alpha Jet Atmospheric eXperiment (AJAX), an unfunded collaborator, conducted eight flights designed to investigate incoming air, the variability of free-tropospheric ozone, and transport across the State. AJAX flights linked ozone sonde launches at the coast to lidar measurements in Visalia. Analysis and integration of the AJAX flight data will provide insights into ozone processes in the passage from the Pacific Ocean to the SJV.

**Method:** This project will finalize the data collected by the NASA AJAX group during CABOTS, completing the calibrations and quality screening. Then the AJAX data will be analyzed in the context of other (sonde, lidar, and surface ozone) measurements made during the campaign. The vertical profiles of ozone along North-South and West-East transects will be compared. The analysis of multiple, near-simultaneous vertical profiles will yield a conceptual model of the transport and impact of ozone from the Pacific Ocean to the SJV.

**Utility of Results:** The results of this study will help to better understand the transport and impact of baseline ozone, and contribute towards regulatory policy addressing ozone attainment in the San Joaquin Valley.

**Proposed level of funding: \$50,000**

## **Long-term characterization of PM<sub>2.5</sub> in the San Joaquin Valley**

**Objective:** The objective of this research is to acquire and deploy an Aerosol Chemical Speciation Monitor (ACSM) in the San Joaquin Valley (SJV) to collect a high temporal resolution aerosol chemical speciation dataset for elucidation of the key sources and chemical pathways leading to aerosol formation in the SJV, serving to improve the effectiveness of ARB's PM<sub>2.5</sub> control strategies.

**Background:** Although the air quality in the SJV has improved in recent years, the area still exceeds the federal 24 hour and annual PM<sub>2.5</sub> standards. Wintertime PM pollution in the SJV continues to be among the worst in the nation. The major aerosol species contributing to the poor air quality in the SJV are ammonium nitrate (AN) and organic aerosol (OA). It is important to better understand the key sources and chemical pathways leading to aerosol formation in the SJV, and track the effectiveness of current and future NO<sub>x</sub> and VOC controls on AN and OA in the SJV. Long-term filter-based measurements have provided insights into annual trends in PM<sub>2.5</sub>, but lack sufficient temporal resolution to allow for full elucidation of the key sources and chemical pathways. Periodic targeted field campaigns have provided more detailed information, but only for short periods of time thereby prohibiting statistical analysis.

**Method:** This project will acquire and deploy an Aerosol Chemical Speciation Monitor (ACSM) in the San Joaquin Valley (SJV) for a minimum of two consecutive years. The ACSM is designed for long-term deployment and quantitatively measures the key non-refractory components comprising PM<sub>2.5</sub> in the SJV, e. g., AN and OA, with 30 minute resolution. Differences in diurnal behaviors between seasons and years, and between weekends and weekdays, will be analyzed. These long-term high temporal resolution measurements will allow for direct observation of trends in secondary aerosol formation chemistry. Measurements will also provide data to determine exposure to these pollutants at the community level that will inform future policies.

**Utility of Results:** The results of this study will provide a clearer linkage between PM<sub>2.5</sub> concentrations and major sources in the SJV, and help ARB to improve the effectiveness of future PM<sub>2.5</sub> control strategies.

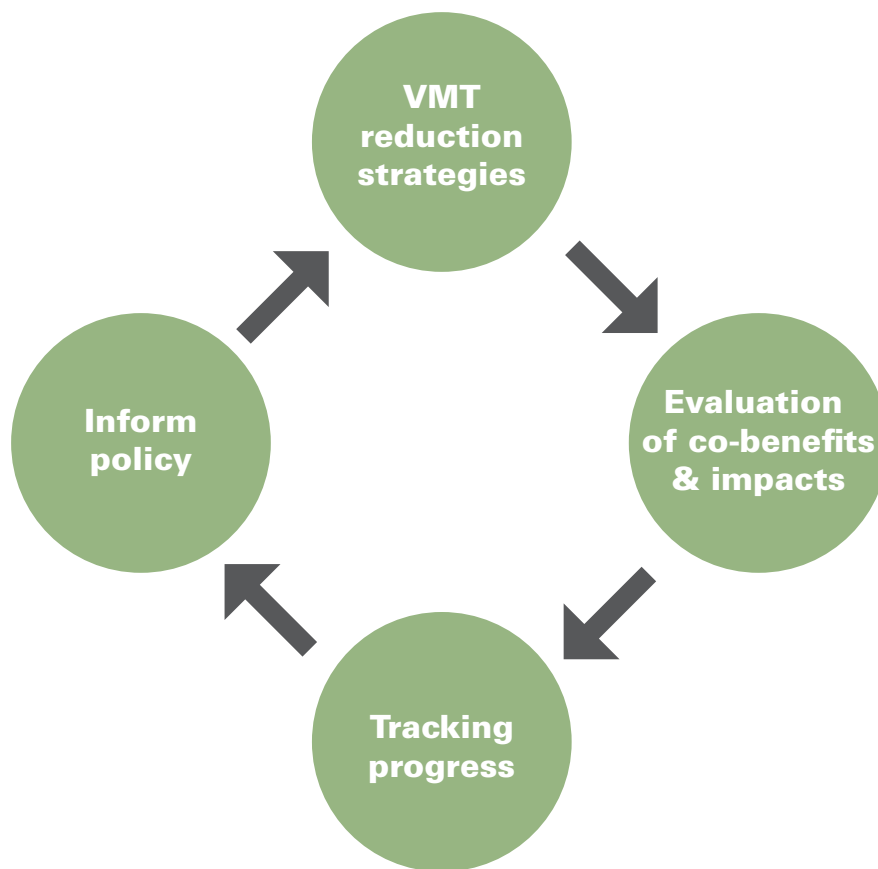
**Proposed level of funding: \$320,000**

## **Remaining Needs**

Although there is a significant amount of current in-house, sponsored, and leveraged research activity to support SIP development, additional research is needed for further understanding 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 air pollution issues will help to support the development of control strategies for achieving stringent air quality standards as well as California's greenhouse gas targets. For instance, in the San Joaquin Valley, modeling of ammonium nitrate, the single largest component of PM<sub>2.5</sub>, could be improved through targeted collection of ambient ammonia data and improved chemical mechanisms. Inter-laboratory comparisons of chamber results would provide improved quantification of SOA yields, which is critical for validating chemical mechanisms. In addition, the regional and long-range transport of air pollutants and their precursors need to be further investigated as local emissions are reduced.

## 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. ARB's sustainable communities research program supports implementation of Senate Bill (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.





## Current Research and Coordination Efforts

ARB continues to conduct research evaluating the potential co-benefits and impacts of SB 375, in order to identify how all Californians can benefit from a transition toward more sustainable communities. A project that was completed last year examined the impacts of implementing complete streets designs and policies, which are intended to reduce vehicle miles traveled and associated emissions by enhancing active travel. The study found that land use context is an important factor in determining the success of these strategies. The researchers observed that complete streets were associated with more positive impacts—e.g., reductions in vehicle traffic, more use of non-auto modes, and air quality improvements—when implemented in densely populated downtown business settings.

Studies indicate that air pollution is not the only cause of near roadway health impacts; noise may also be a significant contributor to health impacts associated with proximity to traffic. ARB 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.

A project that began recently is assessing the travel demand and co-benefit impacts of affordable transit oriented developments (TOD). This work will build on previous research that found synergies between GHG reductions and improved housing affordability by quantifying, with primary data collection, the GHG benefit of pursuing a smart growth strategy like TOD housing. The study will also examine other co-benefits, such as impacts on the health, economics, and the wellbeing of low income residents.

Tracking progress toward meeting the goals of SB 375 is important for ensuring that adopted SCSs and the long-term strategies they contain help the state achieve its climate change goals. Tracking progress requires consideration of both the effectiveness of strategies as well as the implementation of SCSs, which in many cases must happen at a local level. ARB has funded research, in collaboration with Caltrans, to lay the foundation for a future statewide monitoring system that will track implementation of strategies contained in SCSs. The ARB-funded portion will identify, evaluate, and select indicators, indices, and data sources that can be used for monitoring and will pilot recommended indicators for Los Angeles County. Caltrans is funding a second phase of this project that will scale-up these indicators and metrics to the statewide level.

## 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 ARB-funded studies have revealed a suite of possible exposure reduction strategies. For example, high efficiency filters in ventilation systems have been shown to remove 50-99 percent of particles in indoor environments, and pollution dispersion models can 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 ARB staff has determined—based on scientific literature and ARB studies—can effectively reduce air pollution exposure near high-volume roadways. The strategies also emerged from comprehensive coordination 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 included direct links to ARB's Technical Advisory for planners and stakeholders seeking more information. [www.arb.ca.gov/ch/landuse.htm](http://www.arb.ca.gov/ch/landuse.htm)

Buildings also play a key role in creating more sustainable communities. Research results from zero carbon buildings will be essential as we continue to pursue an integrated approach to reduce the greenhouse gas 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, which can put California on track to achieve mid-term and long-term climate goals.

## Proposed Research

The proposed projects will allow policy makers and planners to successfully implement transportation-related greenhouse gas reduction strategies while minimizing unintended impacts on health, will leverage an existing zero net energy (ZNE) community to quantify additional non-energy GHG reductions of California ZNE communities that are needed to achieve the 2050 GHG target, and will explore the environmental implications of connected and automated vehicles, given the uncertainty in how this emerging technology may affect vehicle miles traveled.

- Updating the Integrated Transport and Health Impact Model (ITHIM)
- Policy, planning, and program frameworks for zero-net carbon communities
- Emissions impact of connected and automated vehicle deployment in California

## Updating the Integrated Transport and Health Impact Model (ITHIM)

**Objective:** This project will create an easy to use, open source, updated version of ITHIM to help policy makers and planners calculate the health impacts of transportation strategies to reduce GHG that incorporate active-transportation.

**Background:** California planners and policy makers face increasing demands for information on the health impacts of strategies to reduce GHG emissions from transportation, the single largest sector in the State's GHG emissions inventory. SB 375 requires metropolitan planning organizations to reduce GHG emissions through land use and other strategies. Studies worldwide 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. In California, an estimated 23,000 annual deaths statewide are due to physical inactivity. Several Metropolitan Planning Organizations (MPOs) have set voluntary health targets in their Sustainable Communities Strategies (SCS), and have used a spreadsheet version of ITHIM to estimate the health impacts of their preferred scenarios. Increasing the ease of using ITHIM will provide users with a consistent methodology that can help organizations engage in better informed decision making on issues related to transportation and health.

**Previous Efforts:** ITHIM was conceived in 2010 by researchers in the United Kingdom to integrate the health impacts of physical activity from active travel, road traffic injuries, and PM2.5 pollution in a single model. Under the direction of Dr. Neil Maizlish (then at the California Department for Public Health) using California data sources, a spreadsheet version of ITHIM was created in collaboration of the Metropolitan Transportation Commission (MTC) and the Bay Area Air Quality Management District. In addition to annual deaths from road traffic injuries and specific chronic diseases related to physical inactivity and PM2.5 pollution, the California version of ITHIM monetizes health outcomes and estimates changes in carbon emissions from cars. Since 2011, large and small CA MPOs (MTC, Fresno COG, and SANDAG), the State of Oregon, and the Nashville, Tennessee MPO have successfully implemented ITHIM. Implementations are currently being planned for Los Angeles and Sacramento counties and the States of Maryland and Delaware. Dr. Maizlish has facilitated the collaboration of ITHIM developers in the United States

and is the informal liaison to the ongoing development at the University of Cambridge, under the direction of Dr. James Woodcock. The goal of this effort is to create a free, open source, updated version of ITHIM, using open source software applications in R and Shiny.

**Method:** Developers have identified the following essential components of an updated version: 1) an analytic engine in R, 2) database structures to facilitate the uploading of data, 3) a user-friendly graphical interface to manage data and analysis options, 4) a dashboard for presenting travel and health results at varying levels of detail, and 5) documentation and links to training and decision-support materials (best practices). The investigator (Dr. Maizlish) will leverage the functionality and components of existing ITHIM R/Shiny prototypes and will integrate them with the CA spreadsheet ITHIM. A small group of current and potential ITHIM users at large and small MPOs, state agencies, local health departments, and other stakeholders will be invited to help in the design of the user interface, input data management, data dashboard/reporting, documentation, and decision-support materials.

**Utility of Results:** The results of this research will produce a thoroughly documented, easy to use tool to assist policy makers and planners in a variety of transportation and health settings to quantify the health impacts of strategies for greenhouse gas reductions in the transportation sector. This tool will allow participants and users to access a consistent methodology, and run “what-if” scenarios and downscale to the municipality level. 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.

**Proposed level of funding: \$100,000**

## **Policy, planning and program frameworks for zero-net carbon communities**

**Objective:** The objective of this research is to leverage an existing zero net energy (ZNE) project that will fund the planning, permitting, and design of low-income ZNE housing to create a benchmarking framework for zero net carbon (ZNC) communities. Research will also build upon the zero carbon building research underway and expand the focus to evaluate GHG emission reduction strategies that can be implemented at the community level by municipalities.

**Background:** At the end of 2016, the California Energy Commission (CEC) released a competitive solicitation titled “The EPIC Challenge: Accelerating the Deployment of Advanced Energy Communities” under the Electric Program Investment Charge (EPIC) Program. Thirteen projects were awarded through this solicitation. The purpose of this solicitation is to fund a competition that will challenge project teams comprised of building developers, local governments, technology developers, researchers, utilities, and other project partners to develop innovative and replicable approaches for accelerating the deployment of Advanced Energy Communities (AECs), which the CEC defines as “community-scale developments based on systems integration in which energy efficiency, renewable energy, and storage technologies meet the energy supply and demand needs of its residents and supports local grid reliability and safety.”<sup>3</sup> The initial phase of this solicitation is on researching barriers and opportunities, designing frameworks and master plans, and developing models and tools for target pilot communities. These projects will be eligible for a second phase, which will focus on developing specific projects in the pilot communities, most of which aim to develop microgrids or advance zero net energy implementation.

The program, which is intended to create replicable models of energy systems of the future, is the perfect starting point to broaden the scope of goals beyond GHG emission reductions in energy use in buildings, to include community-level land use, transportation, water, and waste GHG reduction strategies.

3 [http://www.energy.ca.gov/research/notices/2015-07-29\\_request\\_for\\_draft\\_grant\\_funding.pdf](http://www.energy.ca.gov/research/notices/2015-07-29_request_for_draft_grant_funding.pdf)

**Method:** The investigators will leverage the City of Richmond Advanced Energy Community Project (Richmond AEC Project) that has been awarded \$2.6M from the California Energy Commission EPIC challenge for disadvantaged communities. The current scope of the project, ending in early 2018, includes the development of a ZNE reach code and zoning ordinance, a building energy use benchmarking ordinance, the planning and permitting of 20 affordable ZNE homes, incentive program design for early ZNE adopters and low-income ZNE housing, and development of an EV Action Plan.

The investigators will develop and implement a zero carbon community-scale framework for evaluating community-level GHG emission reduction strategies that may otherwise not be accounted for in a ZNE framework. The framework will 1) develop methods to calculate baseline current emissions – energy used by transport, buildings, other commerce and industry, plus emissions from waste and land use (including negative emissions); 2) evaluate mitigation strategies in the community and model the potential to reduce emissions, and; 3) apply these methods to Richmond’s AEC policy and program development and provide a template for other municipalities to adopt strategies within the framework of a Climate Action Plan.

**Utility of Results:** This research project will serve as a pilot program to demonstrate how other municipalities can achieve zero carbon community-scale performance. 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.

**Proposed level of funding: \$250,000**

## **Emissions impact of connected and automated vehicle deployment in California**

**Objective:** The objective of this study is to quantify the projected impacts of varying penetration levels of light-duty connected and automated vehicles (CAV) on greenhouse gas and criteria pollutant emissions and vehicle miles traveled (VMT) at the transportation system-level in California.

**Background:** The transportation sector is undergoing a rapid transformation towards automated vehicles, which could result in opposing forces: increased vehicular travel demand and increased efficiencies. Recently published work has shown that CAVs have the potential to greatly increase or decrease overall energy usage and greenhouse gas emissions, depending on actual utilization and deployment. In contrast, previous work has not quantified air quality impacts of CAVs nor focused on California specific CAV deployment scenarios. California needs to take these divergent environmental impacts into account when planning to meet the long-term climate and air quality goals. This project will leverage ongoing CAV and smart infrastructure efforts at various federal and state agencies, local jurisdictions, research institutions, etc.

**Method:** In order to forecast the emissions and VMT bounds of fully automated vehicles at the system level through 2050, investigators will perform simulations of efficiency improvements and travel demand based on different CAV deployment scenarios in California that vary penetration levels over time and region compared to a baseline. These simulations will form the basis of energy usage and emissions projections. The scenarios investigated will include: a) different ownership profiles ranging from conventional, individually-owned vehicles utilized exclusively by the individual’s household, to shared or fleet-based ownership dominated by shared-use and shared-ride vehicles, b) various powertrains from zero emission to internal combustion vehicles, c) varied smart infrastructure diffusion across the state and over time, d) a variety of vehicular, road-use, and land-use policies.

**Utility of Results:** The results of this study will inform the next generation of Advanced Clean Cars regulations and Sustainable Community Strategies by quantifying the emissions and VMT impacts of this emerging technology.

**Proposed level of funding: \$220,000**

## Remaining Needs

While the unintended impacts of SB 375-related strategies have been addressed in a number of research projects sponsored by ARB and other research institutions, several concerns and knowledge gaps remain. Research should combine near-road sensor data with emission and dispersion models to develop concentration maps within urban areas to help identify exposure, particularly for vulnerable populations. Noise is a variable that will likely continue to be an issue even as advanced technologies are deployed. This issue is particularly true near high-speed roads where most of the sound is generated by tire contact with pavement, not engines.

More research is also 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. However, in established sustainable communities that have complete streets that reduce exposure to traffic-related pollution, strategies should be developed to promote active transportation.

While recent research begins to better quantify GHG emission reductions of green buildings, additional research is needed to fully understand 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 look at treating multi-family housing units as an emission source and combining cool roofs, solar and EV charging and storage strategies to look at total net emission reduction potential. Further research is also needed to consider life cycle performance to develop state-of-the-art equipment and technologies that provide a lower carbon footprint. One example is to determine the energy efficiencies of various small low global warming potential refrigeration equipment throughout California's sixteen climate zones.

## CLIMATE STRATEGIES SUPPORT

California's seminal Global Warming Solutions Act, AB 32 (Nuñez, Chapter 488, Statutes of 2006), charges ARB with developing a Scoping Plan that describes the approach California will take to reduce GHGs to achieve the goal of reducing emissions to 1990 levels by 2020. The Scoping Plan was first approved by the Board in 2008, with an update to the Plan in 2014. Senate Bill 32 recently codified a new 2030 GHG emissions target of 40 percent below 1990 levels by 2030. Governor Brown has identified "five pillars" to meet the 2030 goal, focused on reducing demand for petroleum up to fifty percent, energy efficiency savings in existing buildings, reducing emissions of short-lived climate pollutants, ramping up renewable energy production, and carbon sequestration in the land base (Executive Order B-30-15). Key drivers for these reductions will come from 2030 targets for 50% renewable electricity and a doubling of energy efficiency savings in existing buildings, which are now required by statute (SB 350). ARB is moving forward with a second update to the Scoping Plan to reflect the 2030 target.

Climate science underscores the need to immediately reduce emissions of short-lived climate pollutants (SLCPs), which include black carbon (soot), CH<sub>4</sub>, and F gases (including hydrofluorocarbons, or HFCs). These gases are powerful climate forcers, and harmful air pollutants that have an outsized impact on climate change in the near term, compared to longer-lived GHGs, such as CO<sub>2</sub>. SLCP emission reductions are critical to achieving California's GHG emission reduction goals set by AB 32, SB 32 and SB 1383. ARB's research program has sponsored external research, and developed in-house research initiatives to support the agency's efforts to inventory, mitigate, and track the emissions of SLCPs. In addition, SB 1383 specifically requires ARB and the California Department of Food and Agriculture to conduct or consider livestock and dairy operation research on dairy CH<sub>4</sub> emission reduction projects including solids separation, enteric fermentation, and conversion of flush systems to solid manure management systems.

## RESEARCH HIGHLIGHT



### **Identification of Agricultural Management Practices that Reduce GHG Emissions**

To achieve California's GHG reduction goals, a recent study found that the use of nitrification inhibitors, subsurface drip irrigation, and increasing the spatial frequency of fertilizer application, consistently reduced emissions of nitrous oxide - a potent GHG. ARB Contract No. 11-313.

## Current Research and Coordination Efforts

New studies have suggested that certain fractions of organic carbon known as “brown carbon” could be a stronger absorber of solar radiation than previously understood. The warming effect of brown carbon may offset the cooling impact of other organic carbon particles; hence, quantification of that absorption is necessary so that climate models can 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, a current ARB-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. Proposed research in this Plan will add to this effort by continuing to enhance global and regional model capabilities, and enhance impact analysis of brown carbon on climate and air quality in California and globally.

Current research on GHG mitigation in the agricultural sector is building on previous work to develop a California-specific model that predicts GHG emissions from soils that result from specific management practices by refining this tool to allow for the quantification of potential N<sub>2</sub>O emission reductions from various mitigation strategies that have been identified through previous ARB research. ARB has two new projects focused on improving California’s CH<sub>4</sub> emission estimates from dairy operations. California dairy operations are a major source of greenhouse gases, including CH<sub>4</sub> and N<sub>2</sub>O. The emissions estimates in the California inventory, however, rely on assumptions based on global or national default values due to lack of California-specific information. A project on manure management 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<sub>4</sub> and N<sub>2</sub>O from California dairies. A second project will collect California-specific feed data to improve California’s estimate of CH<sub>4</sub> emissions from enteric fermentation. ARB is also continuing to fund a variety of research efforts including a statewide airborne CH<sub>4</sub> emission flux measurement survey, continuation of GHG measurements, as well as characterizing and improving emissions estimates from dairy manure and enteric fermentation emissions from the California dairy infrastructure. These projects are expected to improve our estimates of total and sectoral emission inventories, and will aid in the identification of cost-effective measures for emission mitigation.

ARB is currently managing the operations of some key research efforts including the statewide GHG monitoring network which measure a host of pollutants including CH<sub>4</sub>, isotopic CH<sub>4</sub>, CO<sub>2</sub>, N<sub>2</sub>O, black carbon, and f-gases, a series of Mobile Platforms with research-grade GHG, air quality, and trace chemical measurement capabilities, GC/MS analyzers for fluorinated gases and VOC tracers, and infrared imaging tools, as well as a series of research contracts which utilize innovative research tools. ARB 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. ARB is further expanding GHG measurement and analysis efforts by initiating innovative and ground-breaking research efforts, such as emission flux measurements using aircraft measurements, ground-level emission flux estimation using remote sensing techniques, and high-fidelity VOC and toxics emissions and concentration measurements in environmental justice communities.

ARB staff has fostered the development of a host of research partnerships and collaborations that have greatly increased the impact of limited research dollars. These collaborations include partnerships with local, state, and federal organizations, as well as national labs like the Lawrence Berkeley National Lab (LBNL) and the Lawrence Livermore National Lab (LLNL). One of our long-standing research collaborations in Southern California, the Megacities Carbon Project, is a collaboration with NASA Jet Propulsion Lab (JPL), as well as National Oceanic and Atmospheric Administration (NOAA), and the National Institute of Standards and Technology (NIST) to study

regional carbon emissions in the Los Angeles Megacity. This project utilizes a tiered monitoring approach for the investigation of CH<sub>4</sub> hotspots and emission sources in the region, which includes the use of satellite data, airborne remote sensing of CH<sub>4</sub> “super-emitters”, remote sensing of emissions, ground-truthing with mobile monitors, and integration with ARB’s statewide GHG network and inverse modeling efforts.

ARB is also completing a first-of-its-kind Statewide Airborne Methane Survey with NASA/JPL which will aid in the detection of potential super emitting sources from agricultural and waste sectors in California. Specifically, this project is allowing us to identify and quantify relatively small leaks in the natural gas distribution system and dairy infrastructure, study poorly operated landfills, and check all the natural gas reservoirs in the State, and will also study rice fields, fracking operations, and reservoir dams later this year. Our partnerships were also instrumental in developing the final determination of CH<sub>4</sub> leaks from the Aliso Canyon natural gas leak incident. ARB also has ongoing partnerships with State and local government, including a variety of energy sector research with the California Energy Commission (CEC), as well as waste system emissions from California landfills with the California Department of Resources Recycling and Recovery (CalRecycle), along with ongoing measurement and analysis collaborations with local air districts throughout the State. ARB is also initiating efforts to monitor CH<sub>4</sub> and associated air toxics emissions from the oil and gas sector and examine their potential impacts on nearby communities.

ARB’s research program is 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 also allow us to measure VOC 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- global warming potential commercial refrigeration.

Not only is science needed to guide ARB’s efforts to reduce SLCPs in response to recent legislative mandates, research is needed to guide the use of the Greenhouse Gas Reduction fund (GGRF), which is funded by Cap-and-Trade auction proceeds 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<sub>4</sub> reduction projects. Several research projects described above have helped to guide the use of these investment funds. Continuing to support research related to SLCP mitigation is essential to guide future investments and ensure that SLCP mitigation strategies are successful, cost-effective, and do not lead to unintended consequences.

## RESEARCH HIGHLIGHT

### **Improving Greenhouse Gas Emission Estimates**

To inform ARB’s GHG inventory and assess progress towards achieving California’s GHG reduction goals, a recent study modeled emissions based on atmospheric measurements collected from a network of towers. The study found that the livestock sector is the major contributor to statewide methane emissions, while agricultural activities are likely a significant source of anthropogenic nitrous oxide emissions in California. ARB Contract 11-306



## Proposed Research

The four proposed projects will investigate mitigation strategies from dairy sources, improve our understanding of refrigerant emission sources and determine the impacts of brown carbon on the climate and air quality. The results are expected to improve ARB's understanding of the impact of SLCPs and contribute to the development of mitigation strategies.

- Multiple pollutant mitigation strategies from dairy sources
- Food additives and methane inhibitors for enteric and lagoon emissions
- F-gas emissions from small commercial and industrial refrigeration equipment
- Brown carbon modeling and source attribution

### Multiple pollutant mitigation strategies from dairy sources

**Objective:** The objective of this study is to investigate mitigation strategies for multiple pollutants, including CH<sub>4</sub> (an SLCP), nitrous oxide (N<sub>2</sub>O, a potent GHG), ammonia (NH<sub>3</sub>, a PM precursor), and VOCs (which are ozone and PM precursors) from dairy manure sources.

**Background:** Dairy operations in California are a significant source of emissions of multiple air pollutants including CH<sub>4</sub>, N<sub>2</sub>O, NH<sub>3</sub>, and VOCs. The State Legislature has repeatedly demonstrated commitments to reducing greenhouse gases (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 ARB's ongoing commitments to reducing criteria pollutants, toxic air contaminants, PM (PM<sub>10</sub> and PM<sub>2.5</sub>), 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 ARB evaluate and understand dairy manure management practices and evaluate the emission reduction effectiveness of potential mitigation strategies. ARB is currently sponsoring two limited scope dairy-related studies, one focused on modeling enteric fermentation emissions for California feedstocks and one focusing on characterizing anaerobic manure storage lagoons. More comprehensive investigation is needed to address not only the baseline emissions from manure management practices, but also potentially effective emission mitigation strategies.

Quantifying dairy emissions can be challenging due to the inherent complexity of dairy systems. Manure management is a significant emission source for these pollutants, especially at dairy operations utilizing anaerobic storage lagoons and liquid manure management practices. Emissions from manure management practices can vary due to a variety of factors including, animal type (breed, sex, lactation status), animal age, diet or total mixed ration composition, dairy type (e.g., freestall/confined animal facility, pasture and pasture hybrid), manure management practices (e.g., flush management, solid scrape management, vacuum collection, composting, open drying, pasturage, and solid separation including vibrating screens, screw presses, weeping walls/gravity settling basins, and centrifuges) and environmental factors (e.g., season, time of day, temperature, precipitation, ambient conditions, etc.). As a result, emission estimates (and well characterized baseline emission factors) that can support the development of a regulatory measure for manure management practices have not been established with sufficient certainty and require initial or complementary additional investigation to reduce uncertainty.

**Method:** This project will focus on emissions associated with manure management. Field measurements from California dairies that employ various manure management strategies will be conducted to provide more accurate emission estimates and baselines for various activities. Flux measurements of selected pollutants (i.e., CH<sub>4</sub>, N<sub>2</sub>O, NH<sub>3</sub>, and VOCs) will be taken and ancillary physical and chemical characteristics and environmental data from common or alternative manure management systems (e.g., flush management, solid scrape management, vacuum collection, composting, open drying, pasturage, and solid separation including vibrating screens, screw presses, weeping walls/gravity settling basins, and centrifuges), will be collected and recorded.

**Utility of Results:** The results of this study will improve estimates and inventories of certain pollutants from manure management at dairies, characterize emission baselines for identified manure management practices, and help identify effective emission mitigation strategies. These mitigation strategies are integral components in emission reduction strategies and will inform the development of regulatory measures. They can also help secure emission reductions from California dairies that can help achieve ARB's climate and GHG reduction goals, while also achieving important criteria pollutant reductions for the State Implementation Plans.

**Proposed level of funding: \$400,000**

## **Strategies to reduce methane emissions from enteric and lagoon sources**

**Objective:** The objective of this research is to determine the economic and logistical feasibility of strategies to inhibit CH<sub>4</sub> production from enteric fermentation and anaerobic manure storage lagoon sources at California dairy operations.

**Background:** The Short-Lived Climate Pollutant Reduction Strategy, in conjunction with AB 32 and SB 1383, aims to decrease CH<sub>4</sub> emissions from dairy and livestock manure management by 2030. Additionally, per SB 1383, voluntary reductions will be pursued for CH<sub>4</sub> reductions from enteric fermentation, with potential regulatory mandates if certain specific findings outlined in SB 1383 are reached. Enteric fermentation and manure management emissions from California's 1.8 million dairy cows contribute approximately half of the state's total CH<sub>4</sub> emissions, making achieving significant CH<sub>4</sub> emission reductions from these sources critical for meeting the goals of SB 1383 and ARB's broader climate change policies.

Several potential products have been identified as potential additives that may reduce CH<sub>4</sub> emissions from California dairy operations. These products fall into two categories: feed additives focused on enteric fermentation emission reductions, and anaerobic manure storage lagoon additives to lower emissions from manure storage.

For example, 3-Nitrooxypropanol (3-NOP) has been identified as a potentially successful CH<sub>4</sub> mitigation feed additive for beef cattle, reducing emissions by up to 84% when introduced to feed at optimal rates. Similar—and significant—CH<sub>4</sub> emission reductions may be possible through introduction of 3-NOP (or similar additives) into dairy feed regimens. Reductions may also be possible by introducing such additives into anaerobic manure storage lagoons.

The optimal introduction rate for feed additives like 3-NOP is, particularly under California-specific conditions, has not been investigated sufficiently to date, and should be evaluated further. To date, 3-NOP has not been evaluated for effectiveness at reducing CH<sub>4</sub> emissions from anaerobic manure storage lagoons when directly applied to the lagoon, nor have any similar additives. Additionally, certain modifications to feed delivery systems and feeding schedules have been shown to achieve CH<sub>4</sub> emission reductions from enteric fermentation, but the impact of these strategies remains unclear for California dairy operations.

**Method:** Researchers will perform a literature review on identified emission reductions strategies that are currently available to reduce CH<sub>4</sub> emissions from dairy and livestock sources. The analysis will help determine the potential feasibility of these strategies for use at California dairy and livestock operations and inform the need for further investigation of these strategies. The literature review will include review of impacts on animal welfare and performance, estimated emission reductions, cost analyses, and barriers to implementation.

Field measurements should be conducted for the most promising CH<sub>4</sub> emission reduction strategies, pending availability of research funding. Methane emissions should be measured using head chamber (i.e., a gas-tight, transparent box to measure enteric emissions from the head) and flux chamber (i.e., dome-like measurement structures placed over lagoon water) systems attached to a mobile air quality emissions monitoring laboratory.

**Utility of Results:** The results of this study will be useful for identifying potential CH<sub>4</sub> emission reduction strategies worthy of further investigation or demonstration in the field at California dairy and livestock operations. Methane reduction strategies that are identified as being effective and cost-effective can provide significant greenhouse gas and short-lived climate pollutant emission reductions from the California dairy and livestock sector. These important emission reductions can help the State achieve its climate change goals while ensuring there are no adverse effects on animal health and productivity or the environment.

**Proposed level of funding: \$150,000**

## **F-gas emissions from small commercial and industrial refrigeration equipment**

**Objective:** This research project will improve the GHG emissions inventory from commercial and industrial stationary refrigeration systems containing less than 50 pounds of refrigerant, by conducting an inventory survey of types and numbers of equipment, types of refrigerant used, and annual leak rates. This project will research the cost, feasibility, and energy efficiency of using low-GWP alternative refrigerants for these smaller refrigeration systems.

**Background:** Due to ARB's Refrigerant Management Program (RMP), ARB has a good inventory of larger stationary refrigeration equipment using high-GWP F-gases. However, facilities using only smaller refrigeration systems containing 50 pounds or less of high-GWP refrigerant are not required to register with RMP. Therefore, ARB's understanding of the emissions from this smaller commercial and industrial refrigeration equipment is limited. Preliminary data indicate that there may be more than 300,000 of these smaller units in California using refrigerants with global-warming potentials 2,000 to 4,000 times greater than CO<sub>2</sub>. Emissions from these smaller refrigeration units may also be more than 2 million metric tons of CO<sub>2</sub>-equivalents per year. In order to reduce the GHG emissions from smaller refrigeration systems, we must first understand the numbers and types of equipment, and their overall GHG impact. Lower-GWP alternatives for refrigeration equipment using less than 50 pounds of refrigerant can then be researched on their technical feasibility, cost, and energy efficiency.

**Method:** The investigators will conduct an inventory of smaller refrigeration systems (using less than 50 pounds of refrigerant) in California by using equipment sales data, California Commercial End-Use Survey (CEUS) data, and market data; confirming initial data through multiple field surveys of facilities where the systems are used, and interviews with HVAC technicians and equipment distributors. Determining the cost, feasibility, and energy efficiency of using low-GWP alternative refrigerants for these smaller refrigeration systems will be accomplished by a thorough review of available technical and industry literature and reports. In addition to new low-GWP systems, the feasibility and cost of retrofitting existing systems will also be researched (a retrofit is when high-GWP refrigerant is removed from an existing system and replaced by an alternative refrigerant). The literature review will be followed by remote surveys and personal interviews with the following: equipment manufacturers, government agencies (DOE, U. S. EPA); electrical utilities, NGOs, and end-users of low-GWP equipment (retail food such as grocery stores and convenience stores; food service and restaurants, pharmacies, food manufacturing and distribution, and small manufacturing facilities).

**Utility of Results:** The results of this study will be used to guide and inform HFC reductions measures laid out by SB 1383, the Short-Lived Climate Pollutant bill (Lara, 2016), which requires a 40% reduction in HFC emissions below 2013 baseline levels by 2030.

**Proposed level of funding: \$250,000**

## Brown carbon modeling and source attribution

**Objective:** To better assess the net contribution of brown carbon to California climate, supplemental funding is requested to further explore global and regional model capabilities, and enhance the analysis of brown carbon on climate and air quality in California and globally.

**Background:** Light-absorbing organic carbon that is not black, called “brown carbon,” was recently discovered to be a potentially large contributor to global warming. Potential sources of brown carbon include emissions from biomass burning, incomplete combustion of fossil fuels, and secondary organic aerosols. However, there exists major uncertainty concerning the relative contribution of each of these source-types to total brown carbon concentrations. For instance, several studies have identified biomass burning as a potentially significant source<sup>4, 5</sup> while other studies show large variations in the percentage of absorption due to brown carbon.

To differentiate sources of brown carbon from black carbon and understand their climate impact in California, an ongoing ARB-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. Supplemental funding will be used to enhance technical work specified under Task 3; i.e. , to assess the globally and regionally-averaged climate response of brown carbon.

**Method:** The investigators will perform additional regional and global model simulations to properly capture the climate effects of brown carbon, and to compare the relative impacts of brown carbon particles to all fossil-fuel and bio-fuel soot particles. Based on ARB’s new emissions inventories for the 2014-15 climate modeling periods corresponding to the years when field measurements are available, the investigators will further update certain elements of this new inventory. For example, the traditional summer rangeland burning inventory will be replaced using Fire Inventory from NCAR (FINN) to provide better spatial and temporal descriptions of burn events, and the MEGAN biogenic inventory will be updated to the latest version.

**Utility of Results:** The supplemental funding would ensure that all of these new inputs can be used to the maximum extent. The results of this study are expected to improve ARB’s understanding of the fundamental processes that dominate brown carbon formation and its evolution in the atmosphere and help ARB to determine the climate benefit of the ongoing mitigation of brown carbon emission sources in California.

**Proposed level of funding: \$45,000**

### Remaining Needs

Wildfires represent a potentially large portion of the California black carbon (BC) inventory. Estimated BC emissions are very sensitive to the choice of source profile used to convert PM<sub>2.5</sub> to BC. Additional representative source measurements are needed to better characterize BC emissions (and speciated profiles) by emissions source, fuel type, and combustion conditions. These data are needed to improve BC emission factors and inventories, and to help reduce emissions and modeling uncertainties.

The SLCP Strategy calls for the development of regulations to ensure emission reductions of CH<sub>4</sub> from the dairy and livestock sector. To support these efforts, expanded and continued research in addition to what is proposed is needed to help characterize dairy emission baselines, as well as the usage and effectiveness of solid separation technologies, solid manure management systems, and conversion to pasture dairy models to reduce CH<sub>4</sub> emissions. Additionally, this research

4 McMeeking, et al., (2014). Impacts of non-refractory material on light absorption by aerosols emitted from biomass burning, *Journal of Geophysical Research: Atmospheres*, 119, 12272–12286, doi:10.1002/2013JD021272.

5 Washenfelder, et al., (2015). Biomass burning dominates brown carbon absorption in the rural southeastern United States, *Journal of Geophysical Research Letter*, 42, 653–664, doi:10.1002/2014GL062444, 201

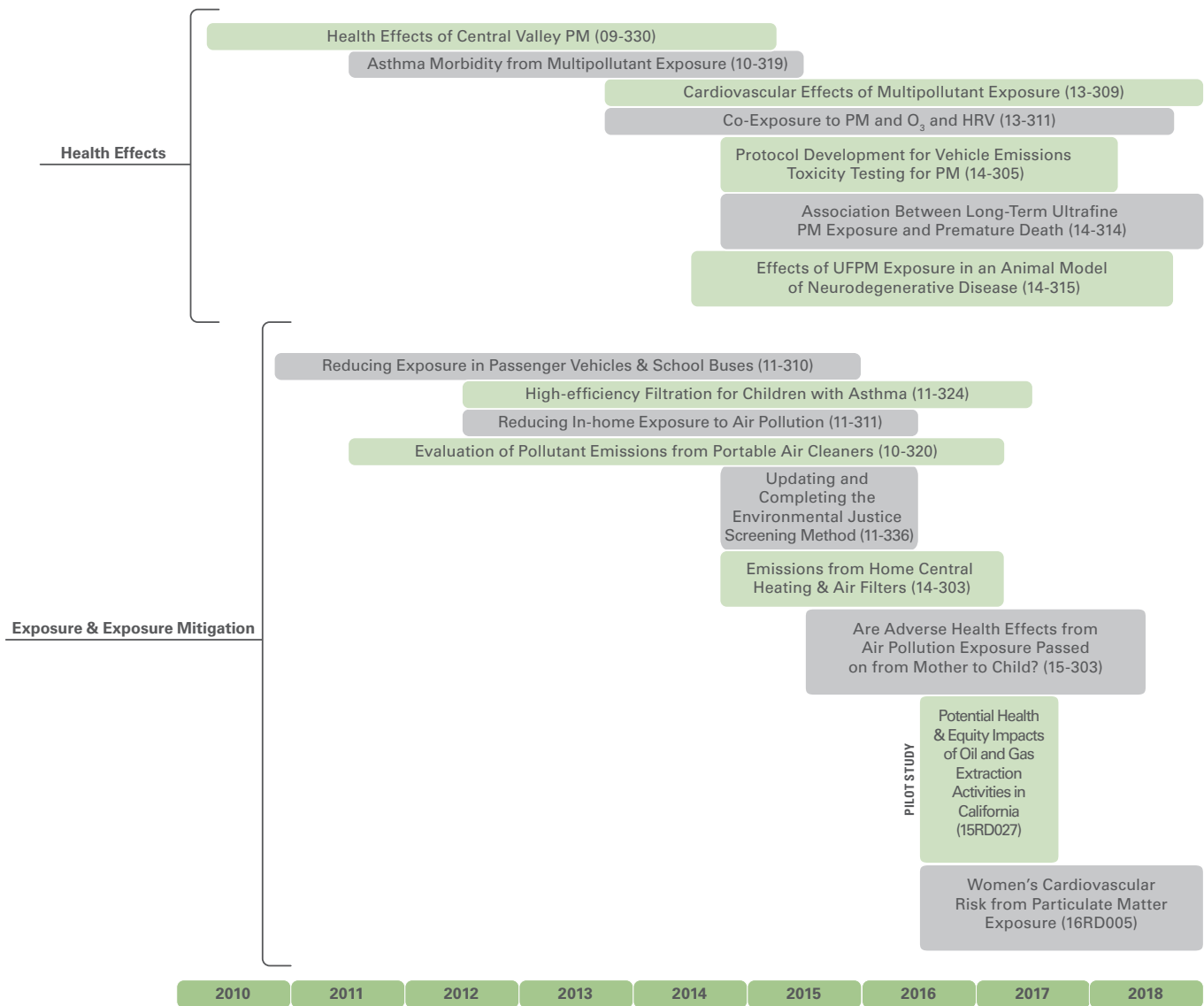
should evaluate the potential air and water quality impacts associated with these mitigation strategies. Further Information is needed to help identify financing options to reduce costs and improve the economic feasibility of dairy CH<sub>4</sub> reduction projects. Finally, further research is needed to fully evaluate the viability of enteric fermentation emission reduction strategies in California, and to assess their associated costs and co-benefits, potential impacts on animal and human health, other environmental impacts, and lifecycle GHG and air toxic emission impacts.

## **Next Steps**

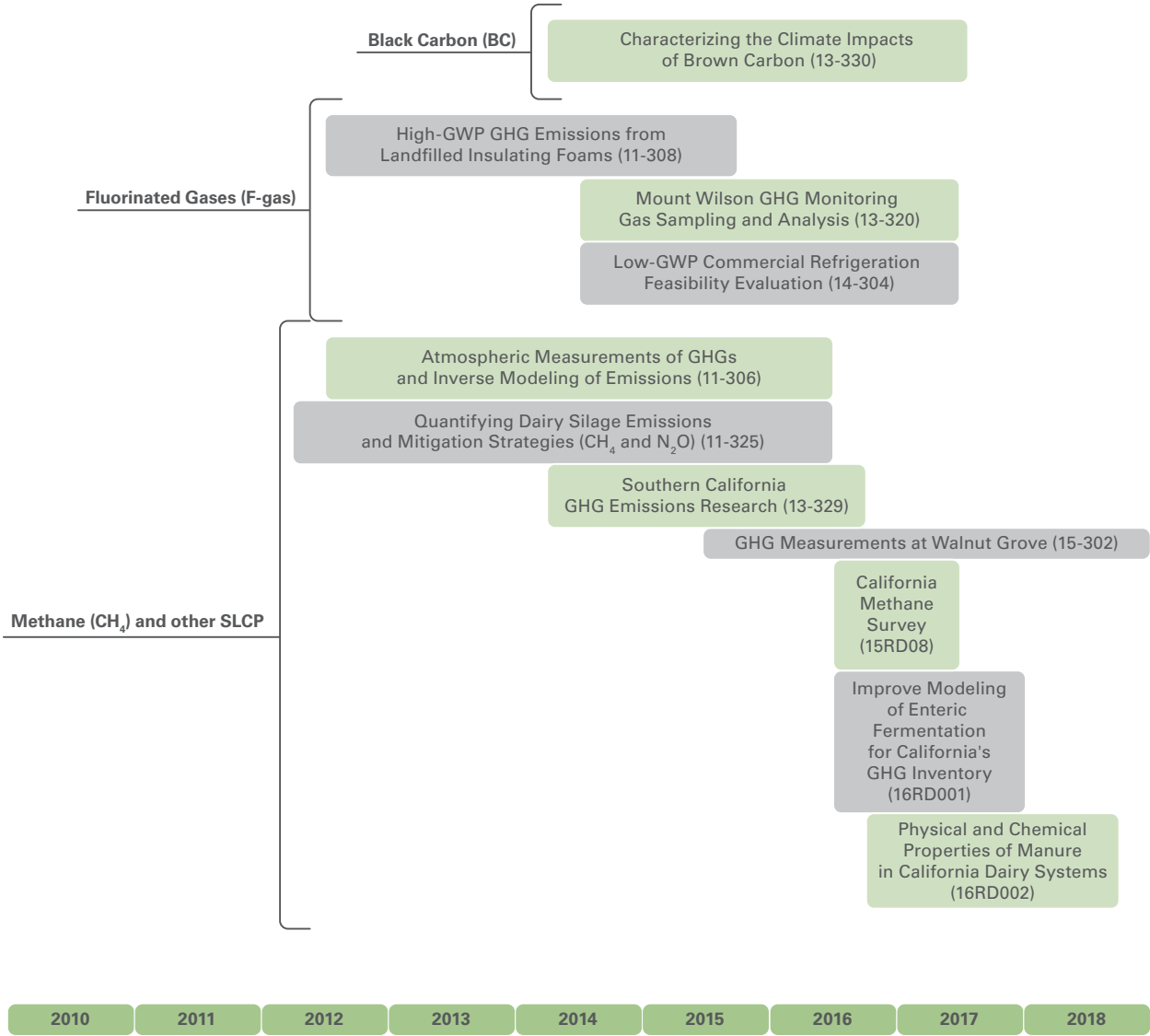
The twenty research projects proposed in this plan address key knowledge gaps and will strengthen the scientific foundation of health, air pollution, and climate control programs, help develop future clean air regulations and programs, and measure the effectiveness of ARB's programs. Following Board action on the plan, staff will proceed to work with researchers to develop these research projects into complete proposals to be reviewed by ARB's Research Screening Committee and then brought to the Board for final funding approval. Results are anticipated in three to five years.

# Appendix 1: Research Project Timelines

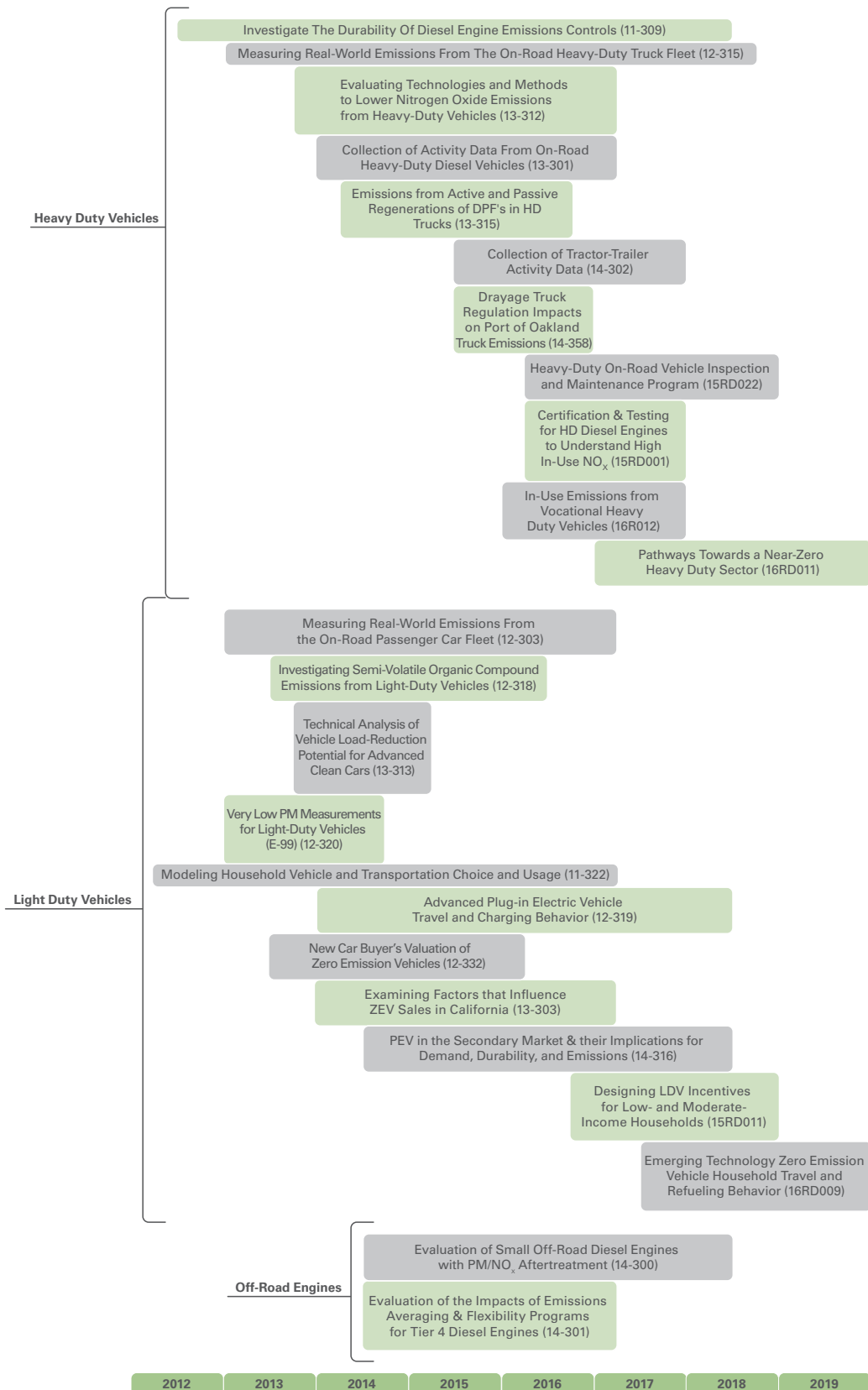
## Health and Exposure Research



# Research to Support Short-Lived Climate Pollutant Strategies

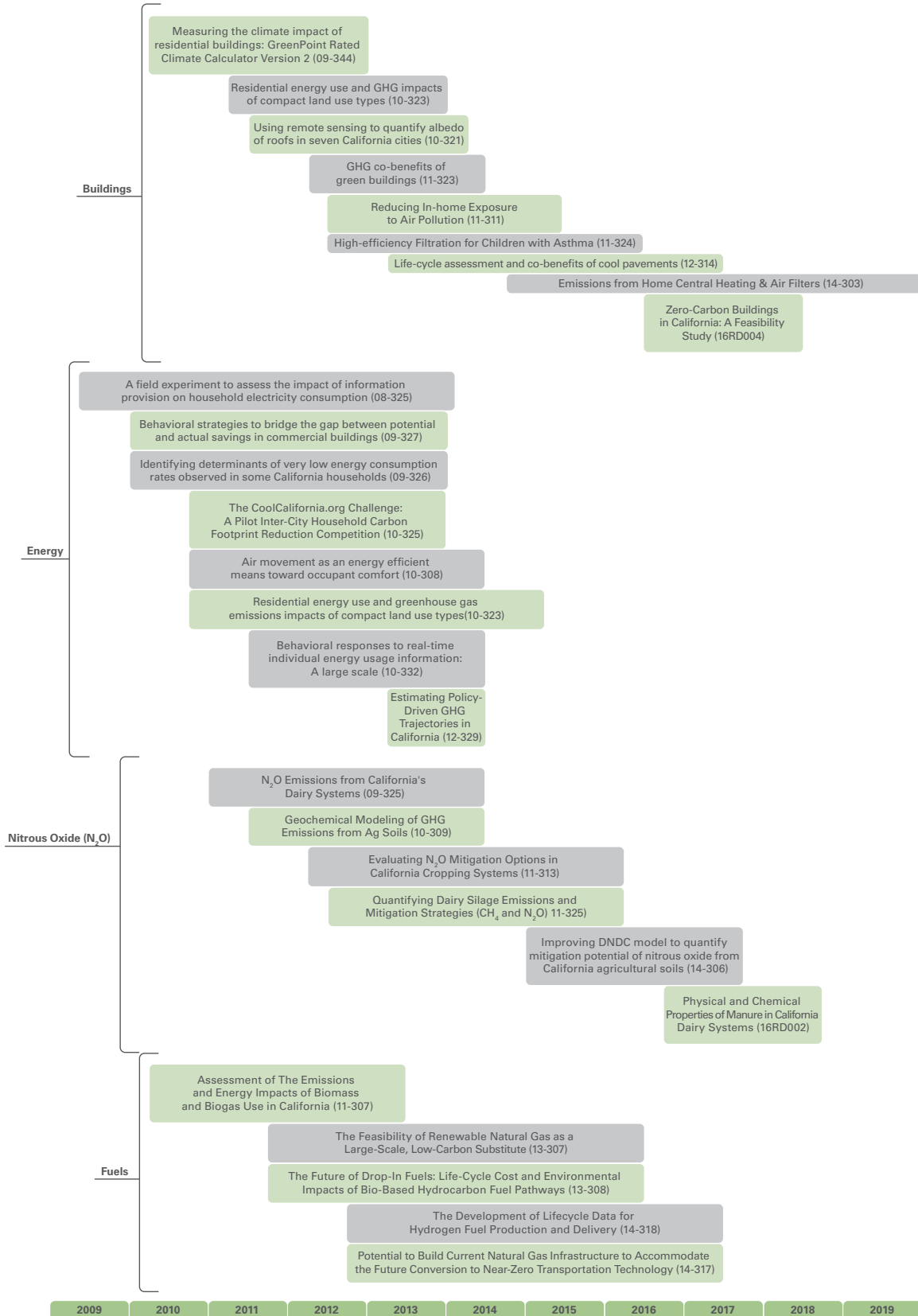


# Research to Support Mobile Source Strategies

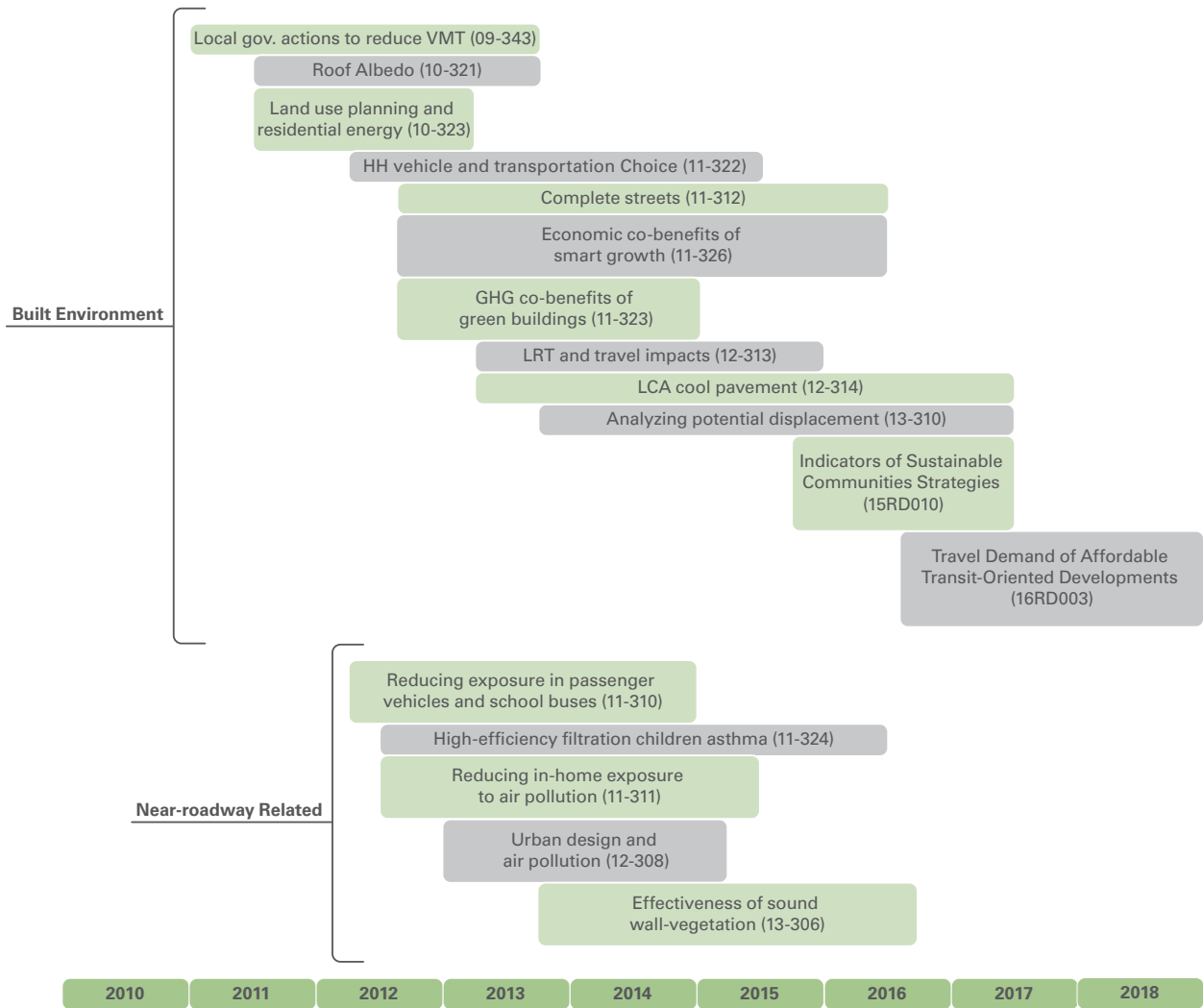




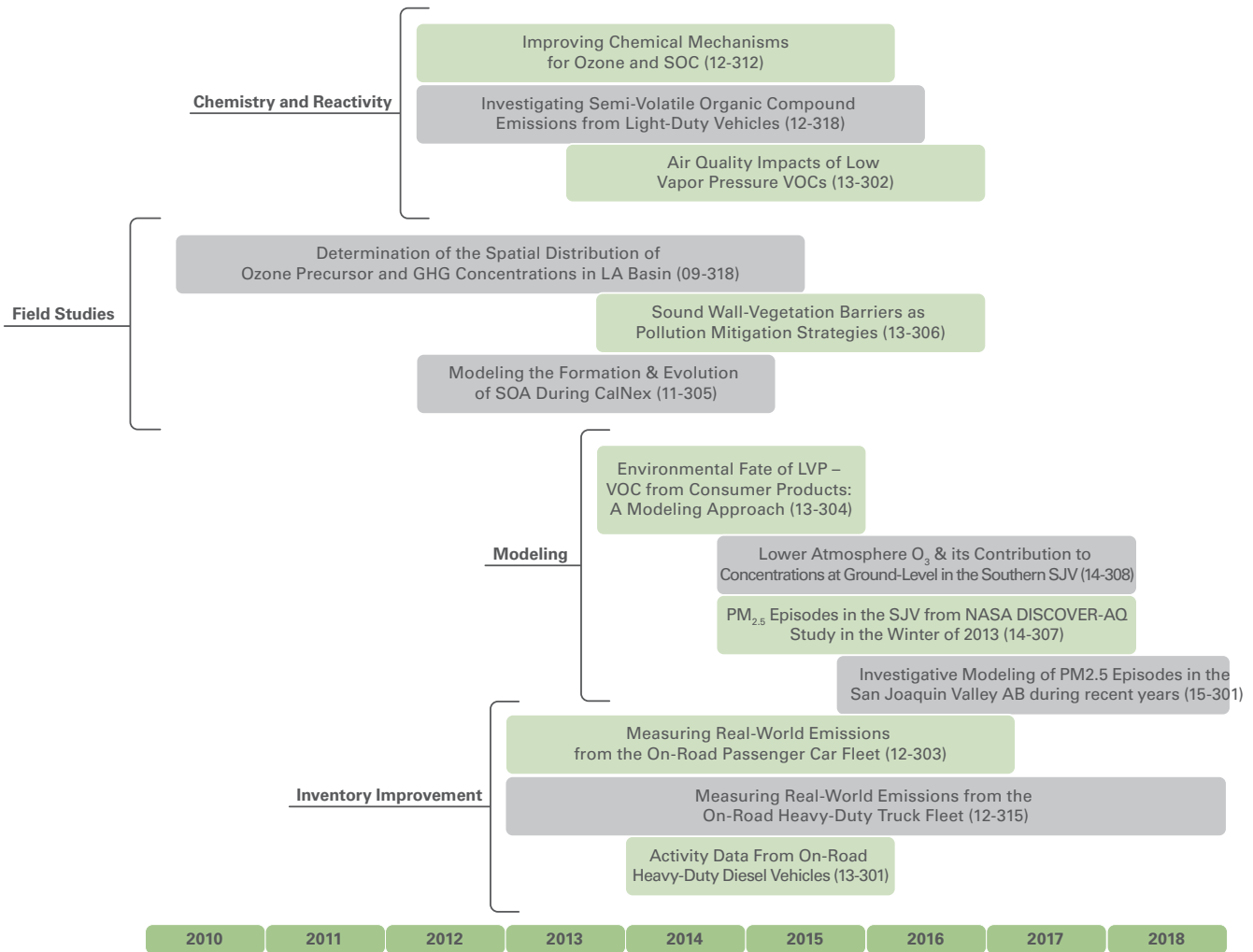
# Research to Support Scoping Plan Development



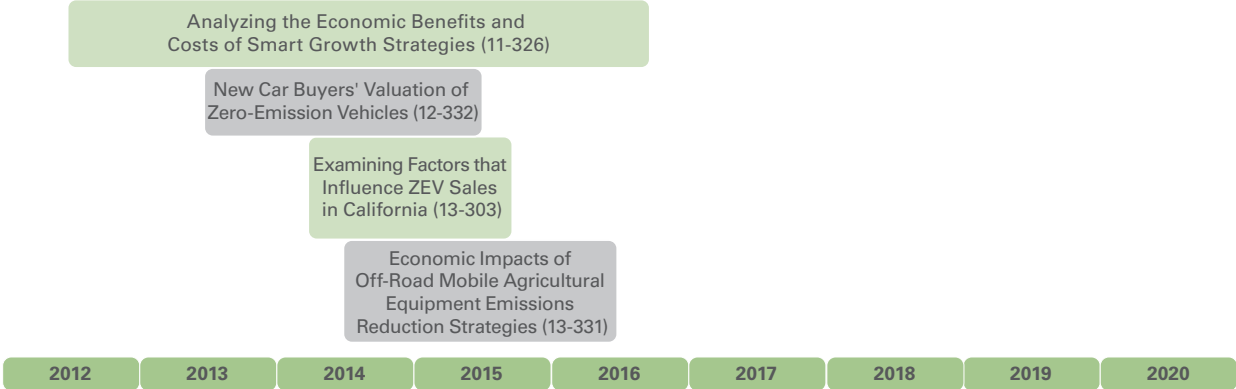
# Research to Support SB 375



# Research to Support SIP Development and Implementation



# Economics Research



# Appendix 2 – Recent Final Reports

## 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.* Destailats 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)

## **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<sub>2</sub> to investigate the relation between SO<sub>2</sub> 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)

## **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 ARB'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)

## **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)



## 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.* Horvath, 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.* Horvath, William R. Assessment of baseline nitrous oxide emissions in California's dairy systems. (November 2013)

*Contract Number 09-329.* Horvath, William R. Determining NO<sub>x</sub> 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)

---

i Rexeis, M.; Hausberger, S. Trend of vehicle emission levels until 2020 – Prognosis based on current vehicle measurements and future emission legislation. *Atmos. Environ.* 2009, 43, 4689–4698.

# Appendix 3

Research Division Staff Peer-Reviewed Publications: January 2000 – December 2016

[RD/ARB staff member names are underlined.]

## **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*, 58:13861400.

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 NOY During the SCOS97NARSTO," *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 Evaluation 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*, 46:631644.

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):S1S6.

Motallebi, N., Mihriban, S., McCauley, E., and Taylor, J. (2008) "Climate Change Impact on California On-Road Mobile Source Emissions," *Journal of Climate Change*, 87:293308.

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., Kilpatrick, 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*, 39:76387649.

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. 06FFL18.
- 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 200501-3800.
- 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> 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., Sobieralski, W., Burntizi, M., Chernich, D. (2013), "In-Use NO<sub>x</sub> 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(??):??-??.

## **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<sub>3</sub> Emissions from LightDuty 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*, 42:883897.
- 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.

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.

## **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., Okamoto, R., Maddalena, 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.

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.

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.

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.



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):31183127.

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.

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*, 51:311319.

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.

## **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<sub>2</sub> Emissions Trends and Top-Down Atmospheric Measurements in the Los Angeles Megacity," *Atmospheric Chemistry and Physics Discussions*, 15(20):29591-29638.

## **Health Effects**

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):502511.

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.

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.

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., 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.

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*, ??

## **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., Gaspar, 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 PM2.5, PM10-25, and PM10 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 PM2.5, PM10-25, and PM10," *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 PM<sub>2.5</sub> 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) "PM<sub>2.5</sub> 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<sub>3</sub> 'Weekend Effect' and NO<sub>x</sub> 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.

**California Air Resources Board**  
**1001 I Street**  
**P.O. Box 2815**  
**Sacramento, CA 95812**  
**(916) 323-2514**  
***www.arb.ca.gov***