CALIFORNIA
AIR RESOURCES BOARD

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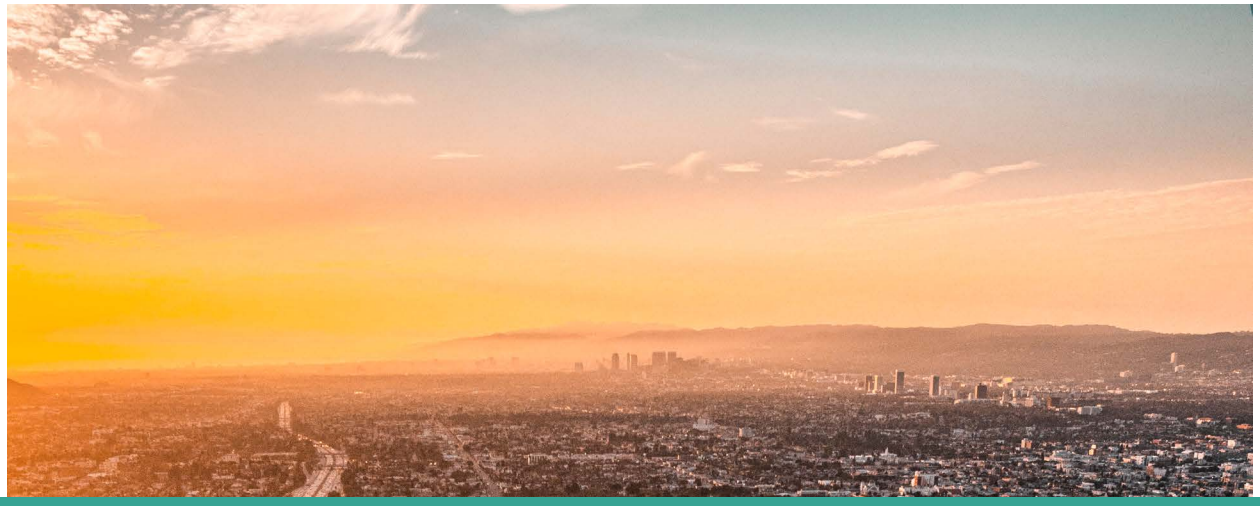
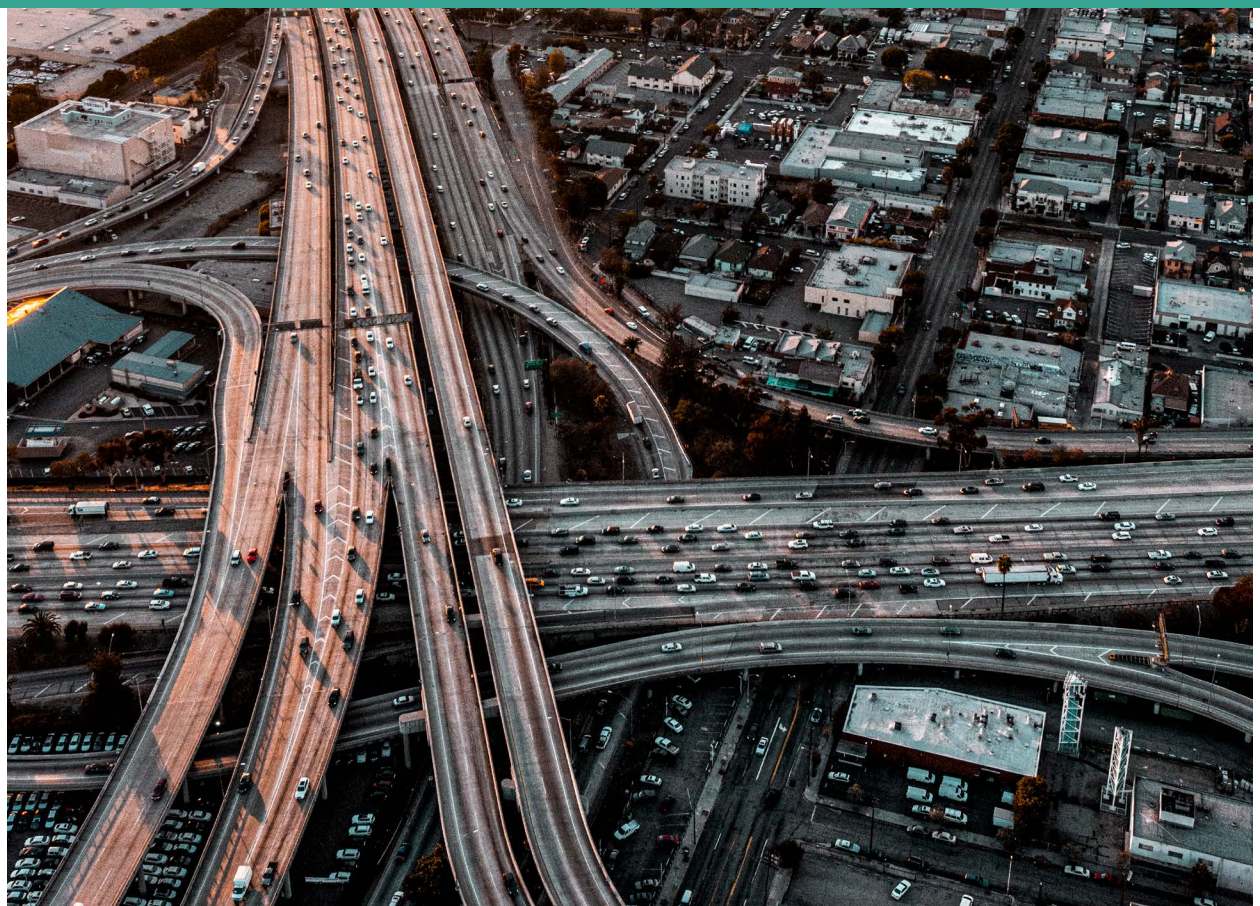


Triennial Strategic Research Plan for Fiscal Years 2021-2024



CARB's mission is to promote and protect public health, welfare, and ecological resources through effective reduction of air pollutants while recognizing and considering effects on the economy. CARB is the lead agency for climate change programs and oversees all air pollution control efforts in California to attain and maintain health-based air quality standards.

Contents

Executive Summary

The Triennial Strategic Research Plan (the Plan) describes the California Air Resources Board (CARB) research priorities for the next three fiscal years (2021-2024) and guides the selection of research projects on an annual basis. These research priorities are described in the Plan's 26 research initiatives. Due to a limited research budget, annual projects will ideally address multiple initiatives. The research initiatives were developed to help the state achieve its climate, and air quality goals as outlined by legislative statutes and the Governor's executive orders. The recently released CARB Vision and Roadmap,[1] outlines the agency's priorities and strategies to achieve these mandated goals:

- **Provide Healthful Air for all Californians** by attaining all ambient air quality standards, reducing cancer risk due to toxic air contaminants, and identifying and reducing exposure in communities at risk.
- **Achieve Carbon Neutrality and Net Negative Thereafter** by meeting the 2030 mandate and 2045 goals, reducing vehicle miles traveled while transitioning to all-electric vehicle sales and increasing the carbon sink potential of natural and working lands (NWL) while maximizing co-benefits for equitable outcomes.
- **Reduce Emissions in Heavily Burdened Communities** by actively building understanding and capacity within CARB and communities, effectively engaging communities with an emphasis on communities of color, creating inclusive and equitable processes that reflect environmental justice principles, develop and track metrics to monitor progress in communities, and applying lessons learned through the metrics to further reduce pollution.

CARB views these goals as opportunities to achieve multiple benefits. CARB's research reflects this approach with multi-disciplinary projects that address more than one research initiative, where feasible. Projects may be fulfilled through in-house work, external university contracts, or a combination of both, via collaborative research projects. CARB often leverages in-house expertise to collaborate with university contractors to augment their work with additional monitoring, modeling, or analyses. The focus on multi-disciplinary projects may be achieved by increasing capacity throughout the university system, and encouraging inter-university and inter-disciplinary project teams. In future, CARB will be increasing research capacity at smaller universities on topics affecting their local communities. CARB has significantly grown its in-house expertise, which increases the ability to provide foundational research, provides flexibility to address new priorities or near-term projects, and expands CARB's internal knowledge-base with new expertise, such as behavioral economists, modelers, and "big-data" experts. Over the coming years, the Research Program would like to expand its in-house engagement and communication expertise in order to improve community engagement and better communicate results and health impacts to the public.

On October 22, 2020, the Board adopted Resolution 20-33, stating CARB's commitment to racial equity and social justice at every level of CARB's operations. In support of this resolution, CARB's Research Program is beginning the work of operationalizing racial equity in its research process and projects. Racial equity is defined as "transforming behaviors, institutions and systems that disproportionately harm people of color and increasing access to power, redistributing and providing additional resources, and eliminating barriers to opportunity in order to empower low-income communities of color to thrive and reach full potential."[2]

The section of this Plan titled "How Do We Operationalize Racial Equity In CARB Research?" describes a starting point for CARB in applying a model of change learned from two years of

1 CARB Vision and Roadmap: *ww2.arb.ca.gov/sites/default/files/2021-01/CARB_vision_roadmap_0121.pdf*

2 "Making Racial Equity Real in Research," Hana Creger, Greenling Institute, 2020

participating in the Government Alliance on Race and Equity.[3] The model of change centers on a shared vision of racial equity for the organization. Normalizing calls for developing a common internal understanding of the levels of racism, the role of government over time in perpetuating structural racism and the difference between equality and equity as well as acting with urgency, transparency, and accountability. Organizing relies on building internal capacity to recognize structural racism and in partnering with community organizations. Finally, operationalizing racial equity means being driven by data and using racial equity tools. It means asking how much did we do, how well did we do it, and is anyone better off.

Through this Plan, CARB is initiating a long-term engagement process with communities to operationalize racial equity in CARB's research planning, contract implementation, and outreach processes. In order to effectively serve communities and create research projects that are impactful and equitable, it is important to prioritize engaging communities during the research planning process. In particular, CARB needs to address regionally specific air quality concerns. Future engagement efforts should include both community members and researchers from local university in the research planning process to create more effective research projects and priorities. CARB needs and benefits from community input and collaboration, especially for projects that aim to help mitigate air quality issues in priority communities. It is the aim of the Research Program to work with community members and co-create research projects, priorities, and initiatives in the future. CARB will start a discussion on promising practices to incorporate community voices into the research planning process, while recognizing there are many requests for community groups' time and expertise.

With a limited annual research budget of approximately $4 million to support these important priorities, the annual list of prioritized projects has to be focused, holistic, and leverage funds from external sources where feasible.

CARB's goals aim to provide clean air statewide, achieve carbon neutrality and net-negative thereafter, and significantly reduce emissions in heavily-burdened communities. These goals will be achieved using regulatory measures and incentives to promote the transition to zero emission passenger and freight vehicles, as well as by promoting land use changes that reduce vehicle miles traveled and create healthy, sustainable communities. These goals also reflect the need to make these transitions equitably. CARB's Research Program integrates these goals and provides the foundational science for CARB programs.

This Plan is divided into seven research categories: Health, Environmental Justice, Economics, Air Quality, Mobile Sources, Climate, and Sustainable Communities. Within those research categories are initiatives with targeted research questions that reflect the evolution of ongoing research. The summaries below explain how the research initiatives tie into the research categories and goals of this Plan and make note of new initiatives that reflect emerging topics. **Health.** How can we most effectively expand our health analysis to quantify and communicate the health benefits of clean indoor and outdoor air?

Public health is at the core of our policies and regulations. As such, the health initiatives support many of the major goals and themes by providing the underlying science for our policies. In particular, this Plan adds an initiative on expanding health analysis. CARB quantifies and monetizes the health benefits of air quality and climate policies, including regulations, strategies and programs. Where quantification is not possible, CARB uses qualitative evaluations of benefits. Both the quantitative and qualitative evaluations of benefits are referred to as "health analysis." CARB policies and incentive programs have numerous health benefits beyond what is currently being quantified. Over the next three years, a key priority area that supports all goals will be expanding CARB's health analysis to include more health endpoints. Research will prioritize the quantification

3 The Government Alliance on Race and Equity is a national network of government working to achieve racial equity and advance opportunities for all through a commitment to achieving racial equity, by focusing on the power and influence of their own institutions, and, working in partnership with others *www.racialequityalliance.org/*.

and monetization of additional health endpoints that are known to exist but that have not yet been translated into monetized health benefits and support broader analysis of non-quantifiable outcomes. The expanded health analysis aims to bring these additional benefits into CARB policy and regulatory assessments over time through both quantitative and qualitative methods. While residing predominately in the health research category, the results will lay the foundation for work throughout all research categories. In addition to health analysis, the health research initiatives include questions on indoor air, short-term exposures including wildfire smoke, health communication, and air pollution linkages to overall health vulnerability.

1. **Environmental Justice.** What is the health impact of air pollution for priority communities and can we develop metrics to measure and track changes in health over time at the community level?

Environmental justice is an important pillar of CARB programs and research and is defined as "...the fair treatment and meaningful involvement of people of all races, cultures, incomes, and national origins with respect to the development, adoption, implementation, and enforcement of environmental laws, regulations, and policies.[4] Priority communities[5] include neighborhoods of California that disproportionately suffer from historic environmental, health, and other social burdens. These burdens include, but are not limited to, poverty, high unemployment, inadequate access to educational resources and training opportunities to secure high-road jobs, air and water pollution, presence of hazardous wastes, high incidence of asthma, heart disease, and other chronic illnesses. Due to historic discrimination, these communities often include high levels of residents and households with people of color, low-income status, seniors, people with disabilities, non-English speakers, and those who have limited awareness of or access to clean transportation and mobility options. This definition recognizes the need to be inclusive and deliberate in acknowledging past and current policies resulting in the accrual of these burdens and minimizing further harms as paramount in meeting the State's equity goals and fostering actions that distribute community benefits intentionally and equitably. Multiple studies have shown that air pollution disproportionately impacts the health of priority communities and their residents. CARB research supports this fact with analysis showing the disparities in air quality due to community proximity to sources. Although the disparity in air quality has narrowed, priority communities are still burdened with worse air quality on average, and are compounded with additional environmental, social, and economic concerns. Assembly Bill (AB) 617[6] established the Community Air Protection Program to focus on reducing emissions and air pollution exposure in overburdened communities and provided funding for community-led monitoring and new tools. Work to date has elevated the need for CARB to expand environmental justice research with a focus on identifying sources, cumulative exposure, and stressors, and investigating health metrics.

2. **Economics.** What opportunities are there to develop strategies that equitably accelerate the transition to zero-emission technologies?

CARB's air quality and climate change legislatively mandated programs are designed to have health and economic benefits. CARB conducts health and economic analyses for all proposed programs to understand the wide range of benefits. For example, meeting zero-emission targets will require transforming markets and behavior. A new initiative will consider opportunities for accelerating the transition to zero-emission vehicles, buildings, and other sectors. How to best communicate and quantify benefits and progress will also be key. There is a new initiative on behavioral economics that will help CARB improve access to information on the benefits of choosing low-polluting consumer goods, particularly in priority communities. Outreach informed by behavioral economics, an expanded health analysis, and other tools can improve communication on the benefits of lower polluting choices.

4 Assembly Bill 1628, Rivas, Chapter 360, 2019

5 Priority communities include disadvantaged communities (DACs), low-income communities, and underserved communities, which are specific terms used in many of the statutes and regulations in the Strategy (e.g., Senate Bill 535 (De León, 2012), Senate Bill 350 (De León, 2015), Assembly Bill 1550 (Gomez, 2016), Assembly Bill 841 (Ting, 2020)

6 Community Air Protection Program, C. Garcia, Chapter 136, Statutes of 2017

3. **Air Quality.** What are the priorities to better understand ozone and PM exceedances, particularly with an increase in wildfires due to climate change? Are there insights on mitigation strategies that can be drawn from measurement analysis?

CARB has implemented multiple strategies to reduce criteria pollutant emissions. However, various regions of California have air quality levels that exceed mandated limits, especially for ozone and $PM_{2.5}$. The baseline level of ozone can fluctuate significantly and its sensitivity to other precursors can lead to exceedances. Although CARB has performed a significant amount of research on ozone, the Research Program has pivoted towards investigating ozone sensitivity as well as mitigation strategies for precursors. Wildfires have always been a concern as sources of air pollution, but the recent increase in fire activity has led to prolonged smoke days with $PM_{2.5}$ concentrations reaching hazardous levels for ever longer periods of time. CARB's Research Program is putting greater emphasis on the health effects of wildfire smoke as well as its effect on air quality.

4. **Mobile Sources.** What technology, efficiency, and behavior strategies provide the best opportunities to accelerate the transition to zero-emission vehicles for passenger cars, trucks, buses and off-road equipment? What are the remaining sources of air pollutants (e.g. tire- and brake-wear) and their mitigation options?

The transportation landscape has changed significantly since the introduction of clean vehicles, e-commerce and telematics, and there is huge potential to guide the transportation sector into a more sustainable and equit future. In addition, Governor Newsom's Executive Order N-79-20 sets goals for:

- 100 percent zero-emission passenger vehicle sales by 2035
- 100 percent zero-emissions vehicles for medium- and heavy-duty vehicles by 2045 for all operations where feasible and by 2035 for drayage trucks
- Transition to 100 percent zero-emission off-road vehicles and equipment by 2035 where feasible

Research can support these goals and the research initiatives described in this Plan reflect the changing nature of transportation in California due to recent technology advances, increases in telecommuting, and CARB's 2035 and 2045 zero-emission goals. There are new research initiatives focused on freight efficiency and advanced technologies. These will explore new methods of maximizing efficiency in the changing mobility landscape, opportunities to promote greater uptake of zero-emission vehicles, the role of automation and telematics, and how connected vehicles and telematics can be leveraged to create zero-emission zones. Finally, an initiative on non-exhaust emissions has been added to build upon the recent research on brake-wear emissions, to further explore tire-wear emissions and the effects of new technologies such as regenerative braking. In particular, this source of emissions may be impacting communities located near major roadways, and health studies will continue to explore the potential health effects of this source of emissions. Research within this group is linked to health, economics, equity, and sustainable communities.

5. **Climate.** What research can support our carbon neutrality goals through technology, emission mitigation opportunities, voluntary consumer actions, and comprehensive evaluation and communication of benefits?

As California moves towards carbon neutrality by 2045, CARB research will focus on opportunities to reduce GHG emissions through comprehensive analysis ranging from emissions to air quality, societal (e.g. preserving ecosytems and species), land use, and health benefits. This research area will be coordinated with work in inter-related research categories such as mobile sources and health.

CARB continues to fund work to analyze trends and refine emissions estimates and explore new mitigation opportunities for carbon dioxide, nitrous oxide, and short-lived climate pollutants (SLCP), which include F-gases, black carbon, and methane. Research will consider how best to communicate the benefits of GHG reductions, acceleration of low-global warming potential (GWP) alternatives,

carbon sequestration advances, and how best to utilize existing and emerging measurement tools, including satellites.

6. **Sustainable Communities**. What are the barriers and opportunities to achieve sustainable communities for priority communities?

The transportation sector continues to be the state's largest source of greenhouse gas emissions. Land use determines driving patterns and is a key area of consideration. CARB is highly focused on helping Metropolitan Planning Organizations, or MPOs, successfully implement Senate Bill (SB) 375.[7] The objective of this legislatively mandated program is to better align regional transportation, land use, and housing planning and require that MPOs prepare plans that will meet greenhouse gas reduction goals set by CARB. These actions may lead to more sustainable communities, make communities more livable and walkable and promote investments in clean mobility options that can help reduce how much people need to drive for their daily activities. Research aimed at promoting investments will also include retrospective analyses to identify and overcome systemic barriers that have led to the exclusion of investments in priority communities. Although this is not a new research initiative, greater emphasis is placed on this topic compared to the previous plan. Research is especially needed on ways to track how program implementation leads to desired outcomes, including air quality, equity, and sustainability.

Research Methods

CARB fulfills its research priorities through externally funded research contracts, collaborative efforts with other state agencies and through in-house research. CARB conducts all externally funded research with a robust scientific process by requiring a review of all research proposals and final reports by an independent Research Screening Committee. CARB staff also engage external stakeholders through technical advisory committees to provide feedback and direction throughout project execution. CARB's Research Program will remain responsive to emerging topics and new priorities while fulfilling its mission to provide a solid scientific foundation. The Research Program will continue to fulfill this mission with multidisciplinary and collaborative projects and with a greater emphasis on equity and improving the health of priority communities.

7 Steinberg, Chapter 728, Statutes of 2008

How to Use This Document

Thank you for your interest in California Air Resources Board's (CARB) Research Program. The Research Program provides the scientific foundation for the successful development and implementation of legislatively mandated policies and programs. Each year, CARB directs funds to the Research Program to perform scientific research that serves CARB programs. This document is meant to guide the annual selection of research contracts and act as a resource for those interested in CARB's research priorities for the 2021-2024 fiscal years.

The **Introduction, Research Planning, Research Coordination and Dissemination** and **Research Methods** sections provide an overview of the Research Program. If you are new to CARB's Research Program, these sections will provide a foundation for the rest of the document with an overview of priorities and how they connect to policy considerations. If you are more familiar with CARB's Research Program, the Introduction will provide a good basis and orient you to the new features of the Research Program. For example, CARB is improving research to be more equitable by ramping up engagement, partnering more with community groups and disseminating research results more widely and in more accessible formats. See the section titled **How Do We Operationalize Racial Equity in CARB Research?**

The chapter titled **Research to Support CARB Programs** is the core of the document. This chapter is subdivided into the major research categories, which can be read independently. Each research category (e.g. **Health**) contains research initiative sections. In the **Health** research category, there are four research initiatives: **Exposure Impacts and Mitigation, Health Analysis, Indoor Exposure and Mitigation,** and **Sustainable Communities and Health.** Each research initiative contains descriptions of the motivation for the work performed and examples of past, current, and remaining research needs. The research needs culminate in succinct research questions that summarize CARB's research priorities. Throughout these sections, extramural and in-house research projects are highlighted to complement the main text. Due to the multidisciplinary nature of CARB research projects, some projects are described under more than one research initiative. This allows the research category sections to be read independently of each other.

The appendices provide comprehensive lists of recently approved projects, recently released final reports, current projects by category, recently published journal articles, and a summary of feedback staff received at recent public research roundtable meetings.

Questions about CARB's Research Program can be directed to *research@arb.ca.gov*. More information is available at *ww2.arb.ca.gov/our-work/programs/research-planning*, and details on our Research Planning activities can be found at *ww2.arb.ca.gov/our-work/programs/research-planning*.

Introduction

The California Air Resources Board (CARB) conducts and sponsors research to provide sound and timely scientific results to support CARB's policies and programs, as directed by statute (Health and Safety Code Section 39700). CARB develops a Triennial Strategic Research Plan (Plan) to provide clarity and guidance on key research initiatives that CARB intends to prioritize over the next three fiscal years.

These research initiatives address CARB's goals, which are driven by legislative statutes and Governor's executive orders. The recently released CARB Vision and Roadmap,[8] describes how the agency is implementing those directives through multiple priority goals:

- **Provide Healthful Air for all Californians** by attaining all ambient air quality standards, reducing cancer risk due to toxic air contaminants, and identifying and reducing exposure in communities at risk
- **Achieve Carbon Neutrality and Net Negative Thereafter** by meeting the 2030 mandate and 2045 goals, reducing vehicle miles travelled while transitioning to all-electric vehicle sales and increasing the carbon sink potential of natural and working lands (NWL) while maximizing co-benefits for equitable outcomes
- **Reduce Emissions in Heavily Burdened Communities** by actively building understanding and capacity within CARB and communities, effectively engaging communities with an emphasis on communities of color, creating inclusive and equitable processes that reflect environmental justice principles, develop and track metrics to monitor progress in communities, and applying lessons learned through the metrics to further reduce pollution.

The research initiatives form the core of the plan and consist of broad topics defining the most pressing research priorities driven by CARB's air quality and climate goals and guide the selection of annual research projects. The Plan also describes on-going work that forms the basis of what is known and informs future research.

The Plan will provide guidance for the annual selection of research projects. Projects may be fulfilled through in-house work, external contracts, or collaborative research projects (Figure 1). CARB often leverages in-house expertise to collaborate with contractors to augment their work with additional monitoring, modeling, or analyses.

CARB receives input from interested stakeholders at various stages throughout the annual and triennial plan development processes. The annual research planning process is initiated with an annual public solicitation for research concepts. To improve this effort, CARB staff will continue to engage with community advocates to develop a strategy to operationalize racial equity in research planning, contract implementation, and the dissemination of research results. More information can be found in the section titled **How Do We Operationalize Racial Equity in CARB Research?**

The Proposed 2021-2024 Triennial Strategic Research Plan outlines the full scope of CARB-funded in-house and contracted research, and seeks to address research initiatives with multi-disciplinary projects to ensure the successful implementation of CARB programs. Although this Plan is divided into discrete research categories, all CARB research projects aim to prioritize strategies that address anticipated challenges associated with achieving long-term air quality and climate goals, and ensure that CARB successfully implements its programs with equitable outcomes and benefits for the economy and health. Meeting these goals will continue to require innovative thinking, working across disciplines, and engaging all stakeholders.

8 CARB Vision and Roadmap *ww2.arb.ca.gov/sites/default/files/2021-01/CARB_vision_roadmap_0121.pdf*

Figure 1: Representation of major categories included in research projects

CARB's Research Program continues to play an important role in meeting increasingly stringent federal ambient air quality standards and long-term climate goals. These goals are intertwined and will therefore require holistic, forward-looking, multidisciplinary research to identify strategies that address the challenges of meeting multiple goals simultaneously. Assessing the impacts of air quality and climate mitigation strategies on the health and well-being of Environmental Justice (EJ) communities is critically important. It is CARB's mission to tackle both air quality and climate while ensuring improved health outcomes for all Californians, and in particular for priority communities (Figure 2). The research initiatives in this Plan are designed to maintain focus on long-term goals and reflect CARB's evolving priorities.

Figure 2: CARB programmatic goals

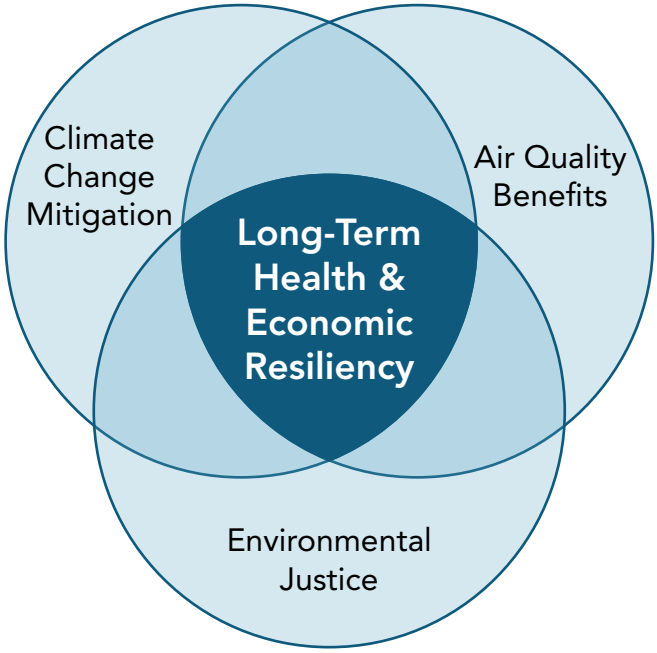


Table 1: California's key air quality and climate change goals through 2050 along with Environmental Justice goals through the Toxics program, AB 617 and focus on equity for all regulatory programs

Year	Climate Change	Mobile Sources	Air Quality	Environmental Justice
2020	Reduce GHG emissions to 1990 levels Meet 2020 SB 375 regional GHG targets	-	Reduce diesel PM risk 85%	Implement community emission reduction programs
2025	-	Vehicles emit 50% less GHGs	Attainment year for ozone and $PM_{2.5}$ (2023/2025)	Identify toxics in communities Improve tools to guide decisions for the Air Toxics Program
2030	Reduce GHG emissions to 40% below 1990 levels Reduce SLCP emissions 40-50% below 2013 levels Preserve 30% of CA land by 2030 per N-82-20[9]	-	75 ppb 8-hr ozone standard (2032)	Obtain lasting emissions reduction in AB 617 communities Reduce toxics of major concern
2035	Meet SB 375 regional GHG targets	100% of in-state sales of new passenger cars and trucks are zero-emission; 100% of drayage trucks, off-road vehicles and equipment will be zero-emission (where feasible) per EO N-79-20[10]	70 ppb 8-hr ozone standard (2037)	-
2040	-	-	-	-
2045	Achieve carbon neutrality per EO B-55-18[11]	100% of medium- and heavy-duty vehicles in state will be zero-emission per EO N-79-20	-	-
2050	Achieve 80% reduction below 1990 levels of GHG emissions, per EO-S-03-05[12]	-	-	-

9 Governor Newsom's Executive Order N-82-20, 2020
10 Governor Newsom's Executive Order N-79-20, zero-emission by 2035, 2020
11 Governor Brown's Executive Order B-55-18 to achieve carbon neutrality, 2018
12 Governor Schwarzenegger's Executive Order S-03-05, climate change emission reduction goals

What's New in FY 2021-2024 Triennial Plan?

Since the release of the FY 2018-2021 Triennial Plan (Plan) in March 2018, the focus of CARB's Research Program has evolved to address new legislative mandates and emerging challenges. The research initiatives in each successive Plan change - some previously stated initiatives have been sufficiently addressed and emerging topics require new initiatives. For example, in the FY 2018-2021 Triennial Plan, a research initiative was developed to support the development of the Heavy-Duty Inspection and Maintenance Program. After the successful completion of landmark projects on this topic, CARB has determined that lessons learned can now be incorporated in monitoring and enforcement programs and there is no longer need for a priority research initiative in this area. The topics described below are receiving greater or new emphasis since the last Triennial Plan.

Wildfires

Since the last Triennial Plan, California has had more frequent and severe fires due, in part, to warmer and drier conditions driven by climate change. In recent fire seasons, fires in California have broken records for monetary damage, area burned, human casualties and the percentage of the population impacted by exposure to smoke, as well as increased lengths of smoke exposure from days to weeks. CARB's Research Program will continue to prioritize research on both the short-term and the long-term health impacts of exposure to smoke and the impacts of both prescribed burning and wildfire on air quality. This work involves improving models that estimate the ecological impacts of fires, and leveraging large scale air quality measurement campaigns to understand the effects of wildfire smoke in impacted areas. New research aims to develop new guidelines on the health impacts of short-term exposure to smoke and leverage behavioral economics to effectively provide information to the public. Research to identify toxics in wildfire emissions that result from the ignition of human-made materials and the health risks of exposure to ash during remediation efforts will be a priority in future funding cycles.

COVID-19

While research has established the association between air pollution exposure and increased vulnerability of the lungs to viral infections including colds and flu, in 2020 a new virus threat emerged with a link to air pollution. The COVID-19 pandemic quickly became a global issue and research was conducted at the national level in the U.S. to discover the correlation between COVID-19 mortality and long-term exposure to air pollutants. Orders to limit the spread of disease transmission also impacted transit availability and travel behavior. These direct and indirect effects of the pandemic have been felt inequitably across the population, on the basis of race, ethnicity and essential-worker status, making strategies to alleviate these burdens a high priority.

CARB responded quickly to initiate research focused on a finer-grained look at the relationship between long-term exposure to air pollution and COVID-19 cases using California data and to assess whether air pollution exposures lead to worse outcomes in confirmed COVID-19 cases. This research will improve understanding of the relationship of chronic exposure to air pollutants with COVID-19 case and death rates generally in California and provide more information about disease impacts in priority communities in California. Although the COVID-19 pandemic may be temporary, it has uncovered vulnerabilities among priority communities to new illnesses and underscores the importance of clean air for everyone. These findings will help CARB understand how to best protect the most vulnerable communities moving forward.

Health measures to reduce infection rates toward the beginning of the pandemic (such as stay-at-home orders and telework policies) led to a temporary drop in vehicle miles traveled (VMT) and thus large decreases in greenhouse gas (GHG) and criteria air pollutant emissions. Air quality data from

this period is being analyzed to better understand how decreasing emissions affect atmospheric chemistry and resulting air quality. This information is vitally important to better understand how future regulatory measures will impact air quality in locations that struggle to attain air quality standards, such as the San Joaquin Valley.

New research at CARB will also assess the real-world impacts of the pandemic response on VMT to determine if and how different socioeconomic groups changed travel behavior and home residence, survey changing travel behavior and preferences, and examine the emission and equity impacts of potential policy responses. Results from these studies will inform a variety of CARB programs and efforts, including reviews of Senate Bill 375 (SB 375) Sustainable Community Strategies, CARB's Vision Model, and VMT reduction impacts.

Carbon Neutrality

Since 2005, California has established a series of regulations and Executive Orders plotting a path toward reducing climate pollutants and achieving carbon neutrality. These include Assembly Bill (AB) 32[13], Senate Bill (SB) 32[14], Governor Schwarzenegger's Executive Order S-03-5 and culminating in Governor Brown's Executive Order B-55-18, committing California to total, economy-wide carbon neutrality by 2045. Carbon neutrality means that all GHG emissions emitted into the atmosphere are balanced in equal measure by GHGs that are removed from the atmosphere, either through carbon sinks or carbon capture and storage. California will build on the success in meeting the 2020 target to achieve the state's 2030 GHG Reduction Mandate of 40 percent as a steppingstone to Carbon Neutrality by 2045.

This will be achieved by significantly reducing GHG emissions in every sector by 2045, and by utilizing carbon sequestration. This includes reducing per-capita vehicle miles traveled by 25 percent from today's levels by 2035. This also includes the move to 100% zero-emission passenger vehicle sales by 2035, as stated in Governor Newsom's Executive Order EO N-79-20. Additional strategies will be developed that can be adopted elsewhere and that maximize public health, environmental, and economic co-benefits to achieve equitable outcomes in priority communities.

Natural and mechanical/chemical carbon sequestration will play a role in achieving carbon neutrality. Natural and working lands have great potential for sequestering carbon in soils and standing biomass. These carbon sinks can be enhanced through land and ecosystem management practices. Likewise, natural and working lands can also represent a source of GHG emissions, due to land use changes such as deforestation and wildfires. Governor Newsom's recent Executive Order N-82-20 sets a goal of conserving 30% of California land by 2030. CARB and other state agencies are continuing to research and collect data on the state's historic and current carbon flux from natural and working lands to help inform a more complete view of the path to carbon neutrality in the state. Future research will address the role of natural and working lands as an emissions source and as a potential sink alongside the transportation, energy, and industrial sectors. Ongoing research is investigating the comprehensive health benefits of NWL strategies and will support the identification of the most health beneficial programs. Future research will continue to investigate these health and economic benefits.

Focusing on Communities and Equity

Emissions have decreased significantly on a regional scale due to CARB and Air District regulations, but air quality disparities exist on localized levels and disproportionately impact low income communities of color. Research has corroborated these disparities and shown that proximity to major roadways, ports, and major stationary emission sources subjects these communities to greater toxic contaminant exposure and thus leads to greater health disparities. Recent legislation and research has focused on reducing exposure and improving air quality in disproportionately

13 Nuñez, Chapter 488, Statutes of 2006, the California Global Warming Solutions Act of 2006

14 Pavley, Chapter 249, Statutes of 2016, California Global Warming Solutions Act of 2016

impacted communities and identifying the most equitable methods for creating healthy and sustainable communities. The AB 617 Community Air Protection Program requires community-based monitoring and emissions and exposure reduction as well as community engagement. Additionally, the Air Toxics Program is focused on 1) determining what drives community exposure, 2) improving and expanding available tools, such as health analysis, to guide decision making, and 3) reducing emissions from sources of greatest concern. CARB's Research Program will expand on additional health endpoints and better understanding of cumulative impacts in response to multiple toxic contaminant exposures.

CARB staff will work with communities to flag areas of concern related to health and exposure and communicate effectively to provide communities with the information they need to protect their health during short-term, high exposure events. Moving forward, CARB's Research Program will engage with priority communities to design and prioritize projects that support equity. In particular, CARB needs to address regionally specific air quality concerns. Future engagement efforts should include both community members and researchers from local universities in the research planning process to create more effective research projects and priorities. CARB will also work to increase the research capacity at smaller universities to address topics affecting their local communities. More information on new engagement efforts can be found in the section titled **How Do We Operationalize Racial Equity in CARB Research?**

Transportation Trends

CARB's Research Program supports the implementation of the Sustainable Communities and Climate Protection Act of 2008 (SB 375), which is a key component for California's achievement of the 2050 climate goal. SB 375 requires that California's metropolitan planning organizations (MPOs) develop regional Sustainable Communities Strategies (SCS) containing land use, housing, and transportation strategies that, when implemented, meet the per-capita passenger vehicle GHG emission reduction targets set by CARB for 2020 and 2035.

The goal of an SCS is to foster healthier and more equitable communities that reduce VMT. The plans should align regional land use and transportation planning to focus housing and job growth in existing urbanized areas, expand transit and active transportation networks and infrastructure, and conserve natural resources and farmland. Senate Bill (SB) 150[15] requires CARB to prepare a report to the Legislature starting in 2018, and every four years thereafter, to evaluate progress in meeting the goals of SB 375. Based on current estimates in the first SB 150 report released in 2018, metro areas in the state are falling short of the GHG reduction goals stipulated by SB 375. Although transportation planning efforts across the state have identified strategies intended to reduce VMT and thereby GHGs, real-world implementation of these strategies is not yielding the anticipated reductions.

CARB's Research Program on sustainable transportation and communities is multi-faceted and builds upon the 2018 SB 150 report and more recent information. Research includes the use of big data and emerging transportation technologies and travel patterns. A series of studies using "big data" and policy analysis will assess real-world reductions from on-the-ground changes as well as the influence of policies on those changes to determine barriers and best practices.

Transportation patterns are evolving quickly. New mobility services (e.g. ridehailing), automated vehicles, and other micro-transit options have been transforming the way people travel for almost a decade, with rapid growth in urban areas. CARB is developing the Clean Miles Standard regulation in response to SB 1014[16] to set GHG-per-passenger mile for ride-sharing services.

Future research will prioritize identifying strategies for managing rapid transportation changes so that they lead to equitable deployment and reduced emissions impacts. An unanticipated driver of change to transportation occurred with the COVID-19 pandemic. During the initial stay-at-

15 Allen, Chapter 646, Statutes of 2017, regional transportation plans

16 Skinner, Chapter 369, Statutes of 2018, Clean Miles Standard

home order for COVID-19, VMT changed significantly and led to an increase in telecommuting, a decrease in commute-related VMT, and a decrease in transit ridership and service; however those VMT changes did not last, nor were they consistent across communities, socioeconomic groups, sectors, or occupations. The long-term impacts of these changes are unclear. Research projects are ongoing to examine not only the impact of emerging transportation technologies but also how the pandemic has impacted mobility and access, and spurred changes in travel behavior. The projects will also identify what CARB, other state agencies, and policymakers can do to alleviate hardships while facilitating the continuation of trends and practices that reduce VMT while increasing personal mobility and improve air quality without inhibiting economic productivity, job growth, and accessibility. Going forward, CARB will continue to track transportation trends to inform the successful implementation of SB 375 and ensure the success of transportation-related incentive programs to help transform California's transportation systems to be more equitable and sustainable.

Overarching Goals

The new research initiatives in this current plan reflect CARB's need to develop new tools and methods for achieving California's air quality and climate goals while operationalizing racial equity. For example, behavioral economics can help support incentives and information promoting the adoption of cleaner and sustainable transportation modes and products. Behavioral tools developed through CARB's Research Program can be used to assess how well a program's dissemination of information actually serves users, and how it can improve to make information more easily accessed, understood, and acted upon. Careful consideration of the user experience will help support more environmentally sustainable products and choices and ultimately help support CARB program goals. New health analysis methods will help to provide more information and monetization for negative health impacts due to exposure to toxics. Attending to equity in data collection and analysis associated with all CARB research projects will support the disaggregation of findings by race and ethnicity or other socioecomic factors that will inform more specific strategies for interventions.

CARB's Research Program, guided by the Triennial Strategic Research Plan, will continue to be responsive to evolving scientific unknowns and to legislative needs with the aim of attaining long-term air quality and climate goals, benefiting all California residents equitably, regardless of home address, race, gender, or income level.

Research Going Forward

CARB's Research Program was established by the Legislature in 1971 and has helped support CARB's regulatory programs since its inception. Over the last 50 years, California has seen dramatic improvements in air quality and has more recently made significant advances in reducing GHG emissions. Despite this progress, many Californians still do not experience clean, healthy air and the effects of climate change (e.g. wildfires) are impacting air quality and health. These health burdens fall disproportionately on priority communities. CARB's research process and objectives will continue to be refined to focus on identifying how CARB programs can benefit priority communities.

CARB will continue to support the state's efforts to lead the world by example and apply science to policy to show that healthy air and a sustainable future are attainable. Building upon and growing partnerships with other research entities and stakeholders will be essential to support effective program implementation. The research initiatives included in this Plan will guide the annual selection of research projects. Collectively, these initiatives will explore the benefits of longer-term strategies. Below is a summary of the research initiatives outlined in this plan by research category. Research initiatives are highlighted in bold and the page numbers for more details on each initiative are provided in parentheses.

Health

Public Health is at the core of our policies and regulations. As such, the health initiatives support many of CARB's goals by strengthening the science that underlies CARB policies. CARB's health Research Program will continue to advance the science on the health impacts of air pollution, inform health based air quality standards, and examine the health benefits of longer-term strategies. An important aspect of this is performing health analysis on proposed policies, regulations and programs to quantify the benefits of emission reduction goals.

Moving forward, **CARB's health Research Program aims to understand: how do we effectively expand health analysis to quantify and communicate health benefits for clean indoor and outdoor air?** CARB's health Research Program will be addressing this need with a series of research initiatives:

- Research on **exposure impacts and mitigation** (Page 26) has focused on the health impacts of long-term exposure to single and multiple criteria pollutants, particularly among sensitive groups such as children and the elderly. CARB will continue to prioritize research on the health impacts of pollutants and exposure pathways, as well as to identify the most effective strategies to mitigate these exposures. In particular, CARB will continue to assess the disproportionate environmental burdens borne by priority communities, and to advance mitigation strategies to reduce community exposure and related health burdens.
- It has long been known that there are numerous health benefits derived from CARB policies, regulations and programs beyond what is currently being quantified. A new research initiative on **health analysis** (Page 28) has been added to assess the best methods for calculating the health impacts of specific policies and regulations and to improve understanding of the links between pollutants and health burdens, including criteria and toxic pollutants. The research initiative will include a focus on impacts in priority communities.
- CARB's **indoor exposure and mitigation** (Page 30) research has led to building code changes requiring improved filtration, among other important research findings. Future work will continue to focus on improving mitigation strategies and identifying new sources of pollutants from new building materials, appliances and consumer products. This work will be especially important as building materials and technologies advance to improve energy efficiency and reduce combustion emissions.

- Recently, CARB has begun researching **sustainable communities and health** (Page 31), which aims to develop strategies to ensure that sustainable communities develop with net benefits for health. This research helps link how land use changes and the built environment affect exposure to harmful pollutants from vehicles. This work will continue to provide guidance to local planners and advance policies that maximize the health benefits of smart growth and sustainable community strategies.

Environmental Justice

Environmental justice is an important pillar of CARB programs and research. Priority communities have been heavily burdened with multiple sources of pollution and environmental stressors. Multiple studies have shown that air pollution has a larger impact on the health of priority communities and their residents than on the general population. CARB's environmental justice Research Program supports CARB's commitment to reducing the disproportionate exposure to air pollutants and providing a greater understanding of the resulting health impacts in priority communities.

Moving forward, CARB's environmental justice Research Program aims to identify: **What is the health impact of air pollution for priority communities, and can we develop metrics to track and evaluate changes in health over time at the community level?** In order to address this overarching research need, the Research Program is focusing on various research initiatives:

- **Identifying emission sources** (Page 39) of air pollutants includes monitoring and tracking commonly known air pollutants in new areas, as well as examining new technologies and industrial processes for emerging pollutants. CARB will continue to leverage innovative methods, such as satellites, to identify sources of pollutants and other exposures and hot spots associated with health risks. Research will continue to focus on advanced screening tools and better understanding of what these tools reveal about previously hard-to-detect sources, particularly in priority communities.
- CARB's work on **reducing disparities** (Page 42) in priority communities has made progress, but key questions remain. Meteorological changes due to climate change impacts, external factors such as the current COVID-19 pandemic, and other stressors may all have impacts on existing air quality disparities. As new issues arise, research must focus on finding the most effective methods for further reducing disparities and finding new opportunities to improve air quality for priority communities.
- **Cumulative impacts** (Page 33) research examines the health risks for residents in priority communities that are exposed to multiple sources of toxics, criteria pollutants, odors, and noise from outside sources in addition to indoor sources. Research will continue to identify health indicators that can be used to guide decisions on monitoring and mitigation. New research will also prioritize innovative tools and methods that will aid in identifying and tracking cumulative exposures.
- By contrast, **short-term health exposure** (Page 36) and health research is focused on understanding how sub-chronic exposure events – such as wildfire smoke incidents lasting anywhere from a few hours to a few days – affect health, and how these incidents compare to longer-term cumulative exposures. More information is also needed on how best to communicate those impacts to the public.

Economics

CARB's air quality and climate change legislatively mandated programs are designed to have both health and economic benefits. CARB ensures that there are wide-ranging benefits by performing health and economic analysis of proposed programs. Economic research aims to evaluate and minimize any adverse economic impacts of CARB's programs, and optimize the use and benefits of incentive funds. It also aims to build a research framework to understand the aggregate impact

of millions of purchase and investment decisions on the uptake of new technologies that affect air quality and climate change. Moving forward, this research aims to address the following overarching research need: **What opportunities are there for economics to equitably accelerate the transition to zero-emissions?** The tools and methods described in the following research initiatives provide a way forward in addressing this research need:

- Research on **market transformations** (Page 45) aims to understand how CARB can optimize incentive funds to increase the uptake of clean transportation technologies that reduce emissions from mobile sources and any opportunities to accelerate the transition to zero-emission vehicles, buildings, and other goods. It is also important to track how investments are impacting air quality, especially in priority communities.
- This work feeds into **program assessment** (Page 46), which aims to understand the impacts of incentive programs on air quality and climate change and ensure that they benefit historically marginalized communities.
- CARB will expand this work to leverage **behavioral economics** (Page 48) to facilitate improved regulatory compliance for new and existing regulations and to increase the impact of incentive dollars by improving communication of the benefits of low-polluting consumer options. This new research initiative will help to better communicate the benefits of CARB programs, but also advance analytical methods to inform policies and streamline enforcement.

Air Quality – State Implementation Plans

CARB's air quality research provides the technical and the scientific foundation that supports the development of the State Implementation Plans (SIPs). With information from this work, CARB has implemented multiple strategies to reduce criteria pollutant burdens. However, various regions of California still have air quality levels that exceed mandated limits, particularly for ozone and $PM_{2.5}$. Moving forward, the air quality Research Program will investigate the following overarching research need: **What are the priorities to better understand ozone and PM exceedances, particularly with an increase in wildfires due to climate change? Are there insights on mitigation strategies that can be drawn from measurement analysis?** The air quality Research Program will address this need with various research initiatives:

- Although CARB has performed a significant amount of research on ozone, the Research Program has pivoted towards investigating ozone sensitivity as well as strategies to reduce ozone precursors. In order to improve understanding of the various sources of ozone, the research initiative on **ozone sensitivity and transport** (Page 50) investigates sources of locally emitted precursors, and includes CARB's efforts to measure and model ozone transported from outside the state. Identifying the dominant precursors that lead to ozone formation is an ongoing and crucial area of research. However, regulatory actions have led to significant emissions reductions, which have made regional ozone concentrations more sensitive to changing meteorology and climate change effects. CARB will continue to investigate how these changes will offset the air quality benefits expected from California's air regulations and policies.
- The Research Program is also focused on **identifying sources of $PM_{2.5}$** (Page 54), or particulate matter smaller than 2.5 µm in diameter. Research is focused on $PM_{2.5}$ monitoring and modeling for the San Joaquin Valley and identifying sources of $PM_{2.5}$ from agriculture and consumer products. These efforts are needed to address the increasingly stringent annual-average $PM_{2.5}$ Federal Ambient Air Quality Standard. Wildfires have always been a concern as a source of air pollution, but the recent increase in fire activity has led to prolonged smoke days with $PM_{2.5}$ concentrations reaching hazardous levels for ever longer periods of time. CARB's Research Program is putting greater emphasis on the health effects of wildfire smoke as well as its effect on air quality. Research will be investigating the air quality impacts of both

prescribed burns and wildfires to improve understanding of the differences in their emissions and to more clearly identify the benefits of prescribed burns intended to reduce the incidence of catastrophic wildfires.

- CARB's Research Program is also adding a new initiative on **emission reduction strategies** (Page 59) to identify opportunities for controlling sources of both $PM_{2.5}$ and ozone precursors, such as volatile organic compounds (VOCs) and ammonia. CARB's Research Program will also focus more heavily on research that leads to air pollution reduction, mitigation and health improvement strategies in the Imperial Valley region.

Mobile Sources

Mobile sources include both on-road and off-road vehicles, and together these sources comprise the largest emitter of GHGs and a major source of toxic and criteria pollutants in California. Air quality and climate change regulations have dramatically reduced emissions from mobile sources and improved air quality, even as VMT and vehicle population have increased steadily. However, much work is still needed to meet National Ambient Air Quality Standards. Mobile source research will continue to employ a variety of methods, including remote sensing and on-road portable emission measurement systems to support enforcement efforts, update inventory estimates, and guide future regulatory development.

The transportation landscape has changed significantly with a greater emphasis on clean vehicles, e-commerce, and telematics. There is huge potential to guide the transportation sector into a more sustainable future to address remaining air quality issues related to mobile sources. CARB's Research Program will prioritize the following overarching research needs: **What technology, efficiency and behavior strategies provide the best opportunities to accelerate the road to zero-emission vehicles as well as retire older, highly polluting vehicles? What are the challenges and opportunities specific to the off-road sector? What are the remaining sources (e.g. tire- and brake-wear) and their mitigation options?** To address this and other remaining research needs, mobile sources research will maintain an active and varied set of research priorities:

- Even as ZEVs become more common under the new Executive Order mandate, internal combustion engine vehicles will continue to operate on the road. **Light-duty fleet deterioration and high emitter tracking** (Page 61) will remain an active area of research. Determining whether high emitters are impacting certain communities will be important because they could contribute to air quality disparities impacting priority communities.
- Adapting monitoring efforts to detect new defeat technologies will continue to be crucial for enforcement activities. Identifying **real-world and laboratory emission discrepancies** (Page 63) will also be an active area of research moving forward, and leveraging new tools and methods will evaluate vehicle activity and engine performance for assessing regulatory compliance.
- The **potential of advanced technologies** (Page 63) to reduce GHG emission from mobile sources is promising, but research must continue to assess unintended impacts of the use and proliferation of new technologies on air quality. Research will also continue to investigate how to maximize emission reductions equitably, by optimizing incentives and affordability of zero-emission vehicles, and prioritizing reductions in California's most impacted communities.
- Off-road vehicles lag behind in terms of emissions reductions, therefore achieving **reductions from off-road** (Page 68) equipment is an important area of research involving effective monitoring strategies and optimizing the introduction of zero-emission technologies to reduce GHG and criteria pollutant emissions.
- In-line with promoting advanced and zero-emission technologies and reducing VMT, **increased freight efficiency** (Page 72) research will identify strategies and benefits to boosting the efficiency of freight deployment. Research will also focus on the impacts of

increased e-commerce activity. Various tools and surveys will be leveraged to quantify these potential reductions and innovative transport technologies and operational strategies will be investigated as additional solutions for achieving air quality and climate goals.

- Despite adoption of advanced technology vehicles, **non-tailpipe emission sources** (Page 76), such as brake- and tire-wear, will continue to affect air quality, particularly in localized hot spots. This could especially affect communities near large freeways and heavily trafficked transportation corridors. Moving forward, CARB research will focus on characterizing these emissions, improving monitoring methods, and refining estimates as brake and tire technologies evolve.

Climate Pollutant Inventories and Mitigation

CARB continues to fund work to analyze trends and refine emissions estimates and explore new mitigation opportunities for climate pollutants such as carbon dioxide, nitrous oxide, and short-lived climate pollutants, which include F-gases, black carbon, and methane. As California moves towards carbon neutrality by 2045, CARB research will focus on informing mitigation opportunities for these climate pollutants through comprehensive analysis ranging from emissions to air quality benefits, societal, land use, and health benefits. Research will consider how best to communicate benefits of GHG reductions, acceleration of low-GWP alternatives, carbon sequestration advances, and how best to utilize existing and emerging measurement tools including satellites. CARB's climate research will prioritize the following overarching research need: **What research can support California's carbon neutrality goals through technology, emission and mitigation opportunities, voluntary consumer actions, and comprehensively evaluating and communicating benefits?**

- This overarching research need will be addressed by funding work to **evaluate trends and refining emissions estimates** (Page 82) of greenhouse pollutants. Some important research needs include better utilizing existing tools and developing emerging measurement techniques, such as satellites, to advance understanding of GHG emissions.
- Research will also explore new opportunities to expand and improve **mitigation options** (Page 88) for carbon dioxide, nitrous oxide, and short-lived climate pollutants. Addressing these research needs will inform policies and programs and may find new opportunities to further reduce emissions. Communicating the benefits of these reductions is important as well, therefore, advancing understanding of the air quality and health benefits associated with GHG mitigation strategies is a research priority. Other mitigation priorities include the acceleration of low-GWP refrigerants and further developing carbon sequestration methods. Finally, information from emerging monitoring technologies, such as satellites, may provide additional opportunities to implement mitigation and enforcement strategies for point sources.

Sustainable Communities Program Support

The transportation sector continues to be the state's largest source of greenhouse gas emissions, partly due to long-established land use patterns that have and continue to lead to high amounts of driving. To address this, CARB is highly focused on helping regions throughout the state create long-range land use and transportation plans that reduce Californian's automobile dependency. This work is legislatively manded by SB 375, which requires that MPOs, create SCSs that, if implemented, reduce VMT and GHGs in line with CARB-set targets. The objectives at the heart of this legislative program are to promote sustainable communities, make communities more livable and walkable, prioritize housing development that is close to jobs and other key destinations, and invest in new mobility options that can help reduce how much people need to drive for their daily activities. Sustainable communities are neighborhoods with safe, reliable and affordable transportation choices, and equitable and affordable location-efficient housing options.

Although this is not a new research initiative, this Proposed Triennial Plan places greater emphasis on this topic, in part because CARB's 2018 analysis of SB 375 progress found that the State is not on track to meet the GHG targets. One challenge of the SB 375 program is tracking and incentivizing implementation of SCSs. Moving forward, the Research Program will emphasize efforts toward the following overarching research question: **What are the barriers and opportunities to achieve sustainable communities for all Californians, and in particular, for priority communities?** CARB's Research Program will address this need with two research initiatives.

- **Tracking progress and co-benefits** (Page 93) will help CARB and others understand why the state is not yet on track to meet SB 375 goals, how it can return to a trajectory toward success, and what co-benefits exist that can further incentivize SCS implementation. Developing tools and highlighting best practices to assist local governments in the development of their SCS will help to maximize VMT reductions and public health benefits. This research is also focused on identifying the most equitable implementation of these strategies and how efforts should be modified to further equitable outcomes. This work will also include retrospective analyses to identify and overcome systemic barriers that have led to the exclusion of investments in priority communities.
- The Research Program will also continue to prioritize research aimed at **evaluating reductions in GHGs from VMT, land use and buildings** (Page 96). The built environment directly impacts VMT and personal carbon footprints. As changes to land use and housing are implemented, there is great potential for reductions in VMT and associated GHGs by improving the efficiency of traveling through that environment and increasing transportation options. CARB will also continue to develop new metrics and innovative methods, such as the use of "big data," to evaluate GHG reductions that result from declining VMT, sustainable land use patterns, and from buildings themselves.

Changes to Research Methods

The Proposed 2021-2024 Triennial Strategic Research Plan includes several recent updates to research planning, project implementation, and engagement. Moving forward, the Research Program will engage with communities to develop a more equitable research planning process. In order to effectively serve communities and create research projects that are impactful and equitable, it is important to prioritize research methods that give communities a seat at the table. CARB needs community input and collaboration, especially for projects that aim to help mitigate air quality issues in priority communities. It is CARB's aim to collaborate with community members and advocates on research projects, priorities, and future research initiatives. The discussion on these proposed changes provides initial thoughts as well as an invitation for further development with the goal of operationalizing racial equity in the research planning process and projects.

Finally, CARB's Research Program will remain responsive to emerging topics and new priorities while fulfilling its mission to provide a solid scientific basis for CARB's legislatively mandated programs. The Research Program will continue to fulfill this mission with large, multidisciplinary projects with a greater emphasis on equity and improving the health outcomes for priority communities.

How Do We Operationalize Racial Equity in CARB Research?

CARB is initiating engagement with communities to inform how the Research Program can operationalize racial equity in CARB's research planning, contract implementation, and outreach processes. Racial equity is defined as "transforming behaviors, insitutions and systems that disproportionately harm people of color and increasing access to power, redistributing and providing additional resources, and eliminating barriers to opportunity in order to empower low-income communities of color to thrive and reach full potential."[17] On October 22, 2020, the Board adopted Resolution 20-33[18] stating CARB's commitment to racial equity and social justice at every level of CARB's operations. The Research Program will play an important part in fulfilling this commitment and in this Plan a process to begin operationalizing racial equity in CARB research is proposed.

What Changes Are Needed?

The Research Program is tasked with providing the scientific basis of CARB programs and plays an important role in CARB's commitment to racial equity and social justice. In order to ensure the most impactful science is performed, research needs to be reframed to take into account the lived experience, expertise, and needs of communities directly affected by the environmental injustices that should drive CARB's research priorities. The research itself needs to address the disproportionate effects of air pollutants impacting communities of color and reduce the harmful effects of these emissions where socioeconomic and racial disparities are most pronounced. There are two key ways CARB's research program needs to evolve – incorporating community members and leaders equitably in research planning, projects, and outreach, and including research questions related to equity in research projects. Therefore, **a new strategy for addressing equity should address both the research process and the research content.**

In order to begin this conversation, CARB staff have drawn from various resources to help frame the discussion on operationalizing racial equity in CARB research. The Government Alliance on Race and Equity (GARE) has created a framework and racial equity toolkit[19] to guide agencies through a model of change focused on normalizing, organizing and operationalizing racial equity. The Greenlining Institute has created an extensive report of recommendations on practices research institutes can implement, based on community input and positive real world examples, that advance racial equity.

To inform its outreach and engagement efforts, the Research Program will be drawing from parallel efforts occurring within CARB, such as the Strategic Outreach Roadmap under SB 350,[20] and the Community Air Protection Program's community engagement roadmap,[21] among others. Finally, CARB staff have done preliminary outreach and engagement with internal stakeholders, sister agencies, and community advocates to collect feedback on past engagement efforts and potential actions the Research Program can implement moving forward. This section of the Plan sets up a process to improve the way research is developed and implemented, foster meaningful partnerships with communities, and help CARB more fully realize its racial equity and social justice commitments.

Identifying Past Issues and Barriers to Racial Equity in Research

The Research Program recognizes that operationalizing racial equity goals will require

17 "Making Racial Equity Real in Research," Hana Creger, Greenling Institute, 2020
18 *Resolution 20-33 A Commitment to Racial Equity and Social Justice (ca.gov)*
19 *GARE-Racial_Equity_Toolkit.pdf (racialequityalliance.org)*
20 *ww2.arb.ca.gov/sites/default/files/2020-06/SB350_report_final_6.1.2020_0.pdf*
21 ww2.arb.ca.gov/community-engagement-resources

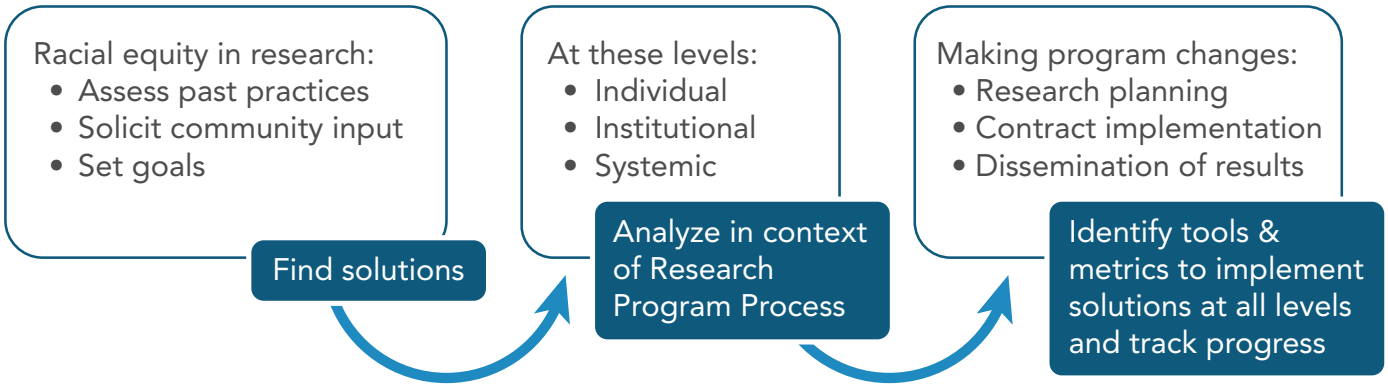
acknowledgement of where the Research Program has failed to operationalize Racial Equity issues in the past, and finding new solutions at the individual, institutional and systemic levels. The Research Program will begin by understanding the context of racism in CARB's programs and by identifying the barriers that persist in excluding communities from fully engaging in the Research Program.

In anticipation of releasing this Plan, CARB staff sought input from various sources to begin understanding past issues related to racial equity and meaningful community engagement. In September 2020, CARB hosted two public Research Roundtables to collect input on the proposed research initiatives in this plan and to gather input on current outreach efforts (public comments summarized in Appendix E). Various community advocates and stakeholders expressed a desire to see CARB diversify who performs research and improve its engagement efforts. In subsequent meetings, Research Program Staff received further input on CARB's past engagement efforts. Below is a list summarizing feedback on past engagement efforts and research equity topics:

- Community members should be involved earlier in the research planning process
- Continuous engagement is needed while respecting community members' time
- The project selection process should be more transparent and accessible and more diverse contractors should be selected
- More projects should focus on equity considerations
    - The Research Program should create research opportunities in often overlooked communities such as Black and Vietnamese communities
    - Repeated requests from Salton Sea and Imperial Valley communities to address air quality issues with cutting edge research should be addressed
- Research results should be disseminated in more accessible formats

Moving forward, further acknowledgement can occur by examining various aspects of the Research Program, including but not limited to: who has received funding in the past, how many research projects focus on equity concerns, how often have communities co-created research projects with CARB, and how accessible have results been to communities. This assessment could help establish a baseline and define quantitative and qualitative metrics to track progress as the Research Program evolves. CARB is interested in conducting an equity assessment of the Research Program with input from community members and stakeholders.

Figure 3: Goals for future research planning that addresses equity issues



Setting Goals at All Levels

Operationalizing racial equity in CARB research should be addressed at the individual, institutional and systemic level. At the **individual level,** CARB staff, contracted researchers, external stakeholders, and community members should interact during the various phases of the Research Program process. Racial equity outcomes depend on these individual interactions, and many

solutions may be adopted to improve relationships and decision making opportunities by individuals involved in the process. Solutions could include, but are not limited to: training on implicit bias and racial equity, communication, and community engagement for CARB staff and academic researchers; acknowledging cultural differences and power dynamics to avoid harm to communities; strengthening partnerships through authentic engagement and creating opportunities for academic and community representative partnerships.

At the **institutional level**, CARB needs to examine its research program, processes and policies to identify, regardless of intent, barriers to racial equity and develop corresponding solutions. This could include, but is not limited to: reframing conceptions of engagement with communities from providing input to co-creation and partnership; establishing long-term engagement across all stages of project development that are not limited by contract timing requirements; identify strategies to overcome existing barriers to compensating community partners appropriately for their expertise; requiring engagement plans from contractors at the proposal stage for projects that clearly need them; creating more transparency in project selection; providing more accessibility to data and results in more inclusive formats and translated to languages beyond English; and, getting community input on desired data products to be in-line with community needs and include more varied data types, including more qualitative data, and data that can be disaggregated by race and ethnicity or other socioeconomic factor.

Finally, a Research Program that commits to advance racial equity can effect change at the **systemic level** through partnering with other entities and institutions with deep expertise in using data and science for equity. The Research Program can also effect systemic change by working with collaborators and encouraging them to adopt similar solutions to advance racial equity in the greater research ecosystem. In particular, CARB can work with other state agencies on common barriers to operationalizing racial equity. With more projects focused on equity, the Research Program can provide results that aid CARB in fulfilling its environmental justice and racial equity goals.

Equity in the Research Program Process

The various levels of change described above affect every part of the Research Program process. These include: research planning, contract implementation, and dissemination of research results. Various tools can be adopted at each stage to improve transparency, increase opportunities for input, and reduce barriers to authentic partnerships with communities. CARB will be working with communities over the long-term to identify those tools and the best strategies to implement them. Some tools that can be implemented in the short-term include: online tools and resources, changes to contracts, continuous engagement efforts; and internal changes to CARB's processes. CARB is committed to working with communities to identify the most effective tools.

A Starting Point

CARB realizes that the first step to developing and implementing strategies to improve equity in research is to get community member, community group, and academic input on feasible, realistic, and meaningful engagement. The initial ideas outlined in this Plan are a starting point for this engagement and the next step will be to outline a process to have an effective dialogue without overburdening communities. After the March 2021 Board hearing, CARB Research Program staff will begin further engagement to collect input and suggestions to develop a strategy for inclusion in the Research Program through listening sessions with stakeholders and pilot testing ideas. Staff will update the Board on the progress made and lessons learned for the draft strategy over the next several years. The goal is to establish an ongoing and inclusive process to develop a flexible framework that can evolve over time.

Some strategies will be implemented this year because some more inclusive aspects of the research process can be tested and will provide lessons learned. With that perspective, beginning this year, CARB will be piloting ideas both in the annual research process and in the implementation

of research contracts that include a community focus. CARB will continue to ask for input from community members and other research entities while developing new strategies in the 2021-2022 fiscal year, and intends to implement additional elements over the next three years.

Identified Tools for Pilot Testing

1. One potential strategy for increasing engagement is to provide appropriate and diverse tools for connecting academic researchers with community research partners. CARB is required to prioritize contracting with UC/CSU researchers. As a consequence, community partners are excluded from being principal investigators in many cases. However, UC/CSU researchers can be incentivized to work with community research partners and non-academic research institutes as sub-contractors. Fiscal year 2021-2022 research projects will pilot the use of an online forum called Empower Innovation. Empower Innovation was created by the California Energy Commission to facilitate new collaborative connections between academic and community researchers.
2. Additional online tools are being considered to provide greater transparency on project successes and milestones and provide technical guidance to communities research partners in order to reduce barriers to accessing research funds.
3. Hosting annual workshops on upcoming solicitations for research proposals can provide assistance for applying to these solicitations and creates a forum to connect academic and community researchers. These workshops can be hosted in person once it is safe to do so.
4. Increased community engagement in research will have to be carefully planned to avoid overburdening communities and ensuring their involvement early in the process. A requirement for a community engagement plan and/or cultural competency statements can help principal investigators center community voices and increase their awareness of their own implicit biases when working with communities different from their own. Community engagement could also include participatory budgeting for community surveys, focus groups, and expert interviews. CARB will identify one or two fiscal year 2021-2022 contracts where this engagement is appropriate as pilots to inform best practices in future funding cycles.
5. CARB-funded research results are publicly available in final reports located on the CARB website. Assembly Bill 2192[22] requires that some taxpayer funded research results be made publicly available within 12 months of publication. Beyond CARB reports, the most common method for academic researchers to release research results is in scientific journals. However, both the article format and language may be inaccessible to many communities. An important aspect of effective engagement and communication that crosses all goals is providing transparent and broader access to research results. This includes disseminating information on research results in multiple languages, through various, culturally appropriate media, and crafted for a broad audience so that it is more relevant and captivating. This effort can potentially include disseminating educational material related to Research Program results that is interesting and approachable for all ages as a way to build public support for CARB programs. Moving forward, CARB will work with researchers and communities to get input on the interpretation of results from those communities and create plain-language summaries in accessible formats to disseminate results more widely – especially to the communities affected, who may be able to use this information for advocacy and decision making.

Moving Forward to Operationalize Equity in CARB Research

Using this starting point, CARB will begin a broader conversation that will be part of a long-term process. This will begin through public workshops, likely in the summer of 2021, to discuss goals, processes, and consider and expand upon the ideas and strategies laid out above to develop

22 Bill Text - AB-2192 State-funded research: grant requirements. (ca.gov)

informed strategies. The workshops will provide draft documents and other materials that include the initial ideas and strategies to allow for robust discussion and input. The process will begin with understanding if these are the correct goals and discuss if and how they align with community needs and resources. A stand-alone document with a plan for operationalizing racial equity in CARB research will be developed and include all proposed tools and priorities established during the engagement process. One of the important tools that should be developed is a checklist or assessment tool that helps direct future research priorities that address racial equity issues in all aspects of CARB research. Moving forward, various elements will be phased in and scaled up based on priorities identified through future engagement.

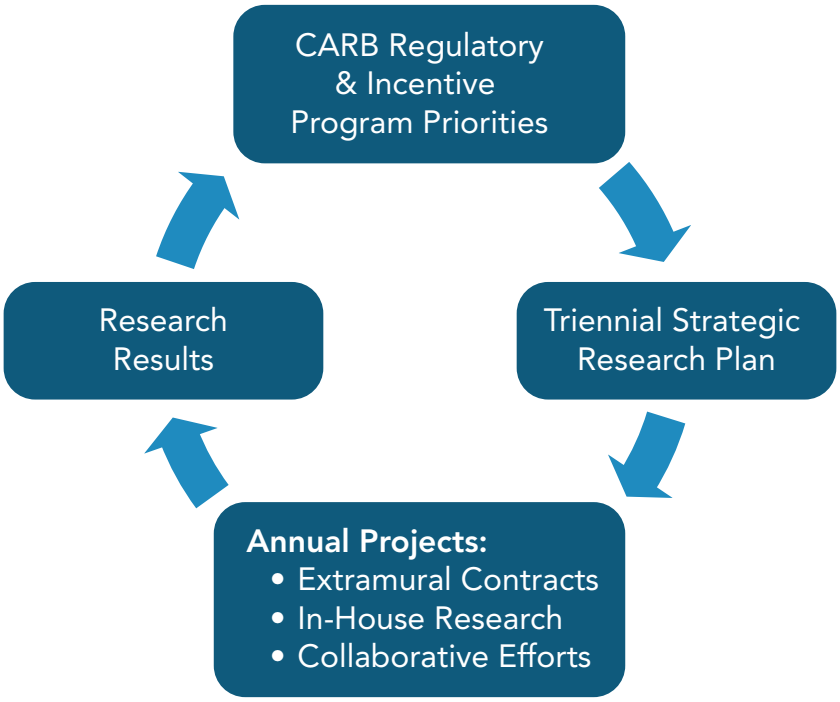
Table 2: Summary of proposed near and longer-term goals

Near-Term Goals	Longer-Term Goals
• Make public solicitation for research concepts more accessible and widely available • Release solicitation for proposals for FY21-22 projects on Empower Innovation and incentivize partnerships between academic and non-academic researchers; Host workshop on solicitation • Require community engagement on research efforts centered on communities • Begin to create online tools and resources to increase transparency on research planning and contracting processes	• Host listening sessions in summer 2021 to expand on initial equity elements and solicit input on community engagement • Start work on a formal strategy to operationalize equity in CARB research with robust community engagement (separate, stand-alone document) • Create opportunities for community-driven research projects and improve engagement at all project steps • Center community voices, provide opportunities to train both CARB staff and academic partners in implicit bias and racial equity and require cultural competency statements when applying for contracts centered on communities • Improve contracting practices and pilot test elements on 1-2 projects in the coming fiscal years • Establish baseline/past practices, create metrics and track progress • Identify barriers to operationalizing racial equity and work with other state agencies facing similar barriers to find common solutions • Annual updates on progress at annual Board meetings and in future Triennial Plans

An important racial equity tool is using results-based accountability and tracking how much is accomplished, how well is it accomplished and if community stakeholders actually benefit from actions taken. CARB will collect feedback from stakeholders as these strategies for increased equity are created and implemented and track metrics to evaluate progress and options for a longer term process. Metrics may include, but are not limited to, the number of new research partners introduced to CARB's Research Program, the number of public workshops hosted by CARB to discuss research processes and priorities, and the number of projects developed in partnership with community members. The 2024-2027 Triennial Strategic Research Plan will include a more established framework with community buy-in, including lessons learned and specific contract requirements, which will provide guidance for future research. Although equity is addressed in many of the research initiatives summarized in this Plan, the next Plan will more thoroughly address racial equity under the guidance of the tools developed through the planned community engagement efforts proposed here.

Research Methods

Figure 4: Schematic of relationship between CARB program needs and Research Program elements

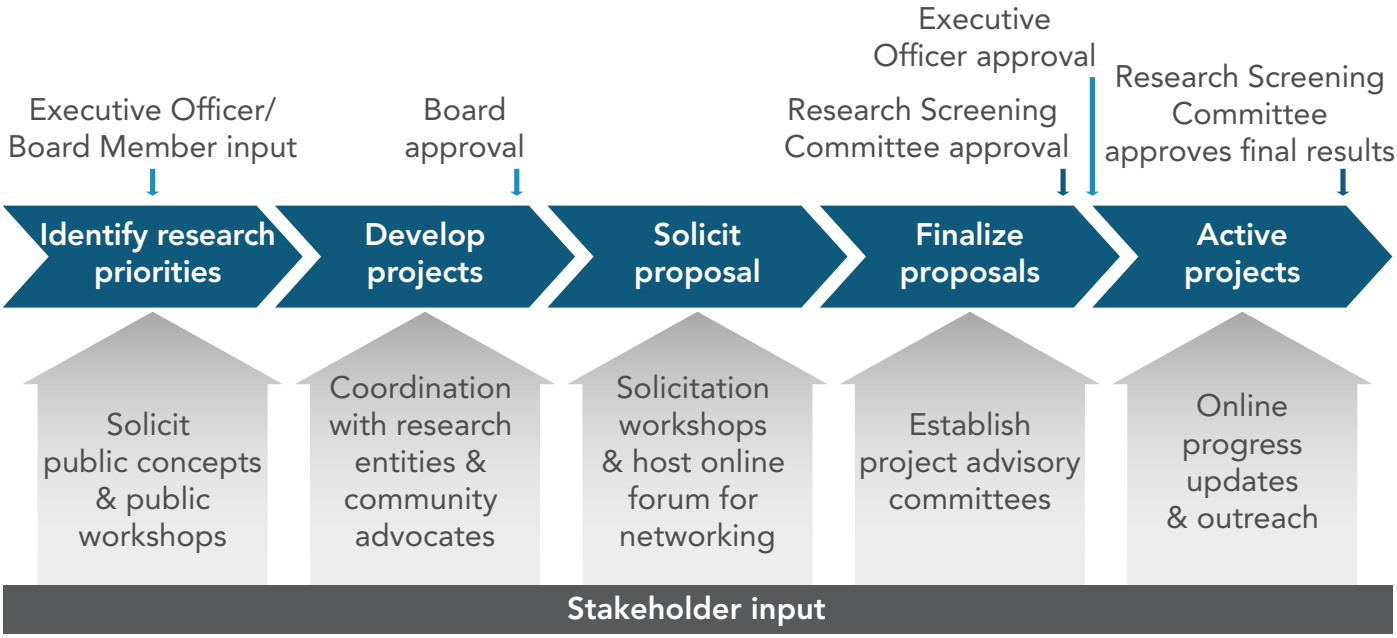


The research methods used to fulfill CARB programmatic research needs consist of extramural contracts (awarded to academic partners), in-house research (performed by CARB staff), and collaborative research efforts (performed in coordination with other research entities). In-house expertise is utilized to perform independent research projects, or in coordination with extramural research contracts. These in-house efforts are directed in support of CARB programs or to identify new areas of research. In-house projects often leverage data collected through CARB programs, as well as completed extramural research projects, to address new research questions, thereby maximizing their utility and applicability. In-house projects also include the development of instrumentation platforms and monitoring campaigns to study emissions from various pollution sources. Finally, in-house research projects leverage CARB laboratory facilities designed to test vehicle emissions, analyze field samples, and certify air monitoring equipment, to improve the robustness of research. Various in-house research projects are highlighted throughout this Plan.

Research Planning and Scientific Rigor

CARB undertakes an extensive planning process every year to solicit input on the annual selection of research projects and ensure that the Research Program is meeting agency priorities while utilizing robust, sound science to address the needs of Californians. CARB's Research Program is re-considering its planning processes and ramping up efforts to engage more community members and advocates throughout the process and encourage collaboration across disciplines. New or additional steps and processes will be added in the future.

Figure 5: Research plan development timeline



CARB initiates the annual research planning process with an open, public solicitation for research concepts (Figure 4). Research concepts are informed by the research initiatives described in this Plan and prioritized through internal and external coordination meetings. CARB coordinates with stakeholders, including state and federal agencies, local air districts, and research institutions, in order to avoid duplication of effort, leverage funding, and identify opportunities for collaborative efforts.

CARB realizes that the process has been more oriented towards input from academic and government stakeholders than from the public, and that CARB research needs to better reflect community voices. To do so, CARB will be broadening its outreach, adjusting its process, and encouraging more community-academic partnerships in future solicitations. Staff will be starting a discussion with priority community members to better understand and address the needs of these communities. Staff will be hosting virtual public meetings, and in-person ones when safe to do so, to foster community engagement throughout the research development and implementation process.

After identifying priority research concepts, they are presented to the Board for approval. If approved, staff will then initiate a solicitation for full research proposals from researchers in the University of California (UC) and California State University systems (CSU). As required by state law (Health and Safety Code Section 39700), CARB must solicit for principal investigators within the UC/CSU systems first, but may go out for bid if the appropriate expertise does not exist in the UC/CSU system.

CARB undertakes a rigorous review process to select winning proposals, which are then reviewed by the Research Screening Committee (RSC). The RSC is a legislatively- mandated committee comprised of a multi-disciplinary set of experts who provide formal external peer review and ensure the scientific rigor of both proposed and completed research. The RSC consists of professors, scientists, and engineers from academia, scientific agencies and industry. They have experience in air pollution, health, climate, and environmental justice. Proposals for research are reviewed by the committee and approved if the proposed scientific methods are sound and cost- effective. Final research reports are reviewed in a similar manner.

Once a project proposal is peer-reviewed and approved by the RSC, the Executive Officer approves the contract and then work can begin. CARB staff manage projects and hold quarterly update meetings to provide input and to seek input from internal and external stakeholders. Large or complex projects are assigned technical advisory panels for oversight. Final reports are released to the public, and available on the CARB website after approval from the RSC.

Coordination and Collaboration

CARB coordinates research with other state agencies, federal agencies, local air districts, and research institutions to avoid duplication of effort, leverage funding, identify opportunities for collaborative efforts, and maximize the utility and applicability of research results. Sharing lessons learned across programs and agencies is another key element of coordination and collaboration across agencies and institutions.

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

Research Coordination and Dissemination

Partnering with other research entities is another way that CARB's Research Program coordinates and leverages expertise in the research community. Sponsorships also provide an opportunity for CARB to collaborate on research initiatives at other institutions and ensure that CARB's research results are elevated to national and international platforms. CARB has historically partnered with, among others, the National Center for Sustainable Transportation (NCST) and the Sustainable Transportation Energy Pathways (STEPS) Center at the University of California, Davis. CARB also coordinates with the Coordinating Research Council (CRC), the Health Effects Institute, the Transportation Research Board, National Oceanic and Atmospheric Administration (NOAA), and other federal agencies. CARB will seek to partner with research organizations with deep expertise in racial equity.

Research Communication Tools

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

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

Communicating Results

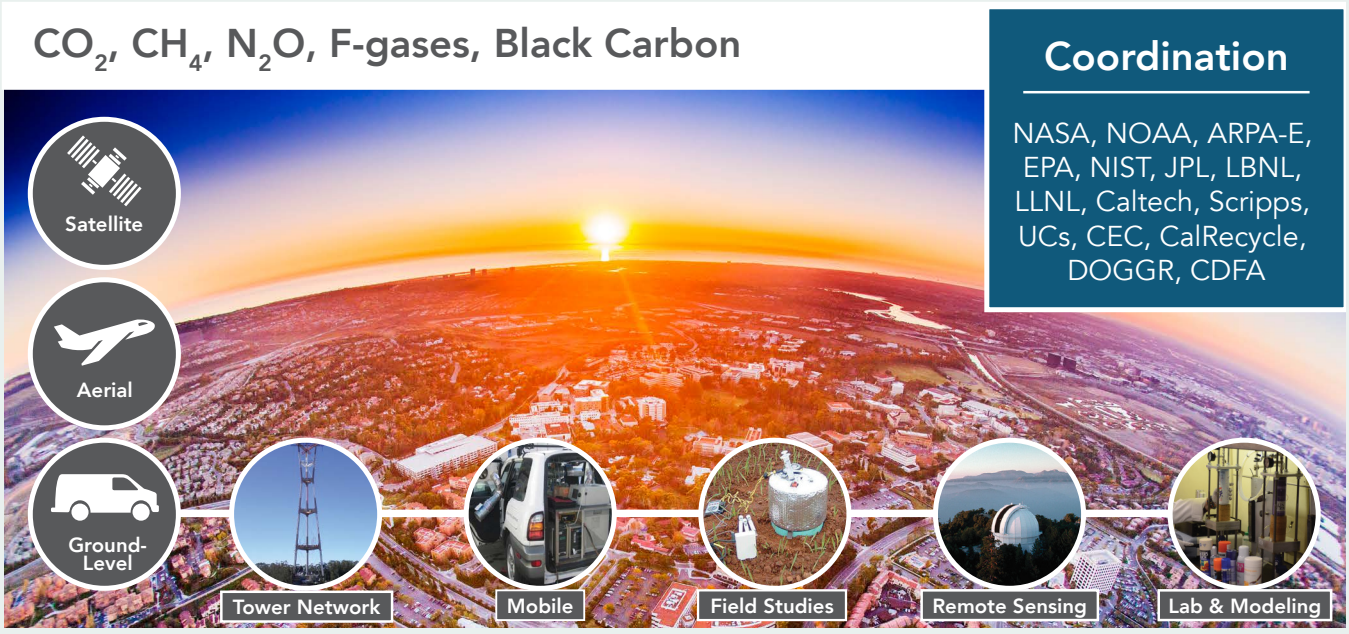
CARB staff disseminate new research results to the public through seminars, press releases, newsletters, final reports, and updates at Board Meetings. CARB also co-sponsors workshops with other state agencies on a variety of research topics. The workshops provide a public setting for researchers funded by multiple state agencies to showcase their efforts, provide an opportunity for an in-depth discussion of the implications of their results, and identify remaining research needs. Moving forward, CARB will consider new ways to make research results more accessible to the public. For example, by holding meetings at varied times to accommodate schedules and by providing reports in accessible formats and languages. This is especially important for projects involving priority communities, where community engagement will be critical in deciding how best to mitigate air quality issues in their communities. Legislation such as SB 375 and AB 617 require community involvement, and additionally programs are developing stronger guidance to prioritize community inclusion such as the Sustainable Transportation Equity Project.[23] This exemplifies CARB's commitment to help empower priority communities by providing the latest information on air pollutant emissions, exposures, and health impacts to enable them to engage in future policy and regulatory proceedings.

23 *https://ww3.arb.ca.gov/msprog/step/step_community_inclusion_guidance.pdf*

Leveraging Research Dollars

In recent years, CARB has increased efforts to leverage research dollars provided by other agencies to achieve research needs and continue to serve state air quality and climate goals. In assisting CARB's regulatory program in developing the *Short-Lived Climate Pollutant Reduction Strategy* (developed and adopted in response to *SB 605* and SB 1383, respectively), CARB's research program pulled from multiple sources and collaborated with multiple agencies to provide the needed data during rule development. Research efforts also helped to identify SLCP sources and evaluate their emissions, as well as develop new emissions reduction strategies for some pollutants and track progress in achieving State GHG reduction goals. CARB coordinated with NASA, NOAA, ARPA-E, EPA, NIST, JPL, LBNL, LLNL, Caltech, Scripss, UCs, CEC, BAR, CalRecycle, CalEPA, DOGGR CalGEM, OPR and CDFA in this massive research effort which included aerial measurements, ground-level measurements, and satellite data analysis. Moving forward, CARB intends to continue seeking out collaborative opportunities which pull in expertise, funds and innovation in order to tackle our agency's mission.

Figure 6: Scope of large scale research coordination effort to measure greenhouse gases on multiple platforms



Research Partners

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

Conclusion

The role of CARB's Research Program is to perform forward-thinking research that helps strengthen CARB's policies and regulatory programs and identifies new issues affecting air quality and related health issues, particularly for priority communities. CARB's Research Program will continue to address CARB program needs, such as achieving carbon neutrality and the equitable implementation of SB 375. Emerging topics, such as technology innovations, new transportation trends, and impacts from wildfires will continue to drive research priorities as well. Over time, CARB seeks to expand its work and in-house expertise to include new disciplines like behavioral economics, and to develop multidisciplinary projects with non-academic research partners. CARB is highly focused on incorporating equity considerations across programs and will ramp up efforts, as well as leverage existing efforts, to effectively engage with communities to get their input on the type of research that best serves their needs and builds on their expertise. The ideas and strategies presented here are a starting point for discussion. Determining the most effective processes and strategies will take time and engagement. This Plan is considered to be a work in progress, as the Research Program will continue to respond to emerging challenges and future legislation that may force the agency to shift or broaden its research priorities. CARB staff will report on updates and progress on the initiatives in the Triennial Plan annually to the Board. CARB staff will also report updates and progress on the proposed strategy for operationalizing equity in CARB research annually to the Board.

Research to Support CARB's Programs

Health

CARB's research on the health effects of air pollution has helped to set state and national air quality standards. It focuses on emerging issues of importance to protect California's communities. Improving the understanding of the health impacts of air pollution exposures through epidemiological research, and developing pollution and exposure reduction strategies continue to be high priorities. CARB's in-house health assessments are guided by the latest science and identify the potential human health benefits of CARB programs, plans, strategies, and regulations. The health program also funds external research on topics including the health effects from indoor and outdoor air pollution exposure, assessments of real-world exposures to pollutants – particularly among California's priority populations – and the identification and evaluation of exposure reduction strategies.

Exposure Impacts and Mitigation

Background and Past Research: CARB's mission is to promote and protect public health and is focused on reducing emissions and health effects from criteria pollutants, including $PM_{2.5}$ (particles up to 2.5 micrometers in diameter) and ozone, toxic pollutants and greenhouse gas pollution. CARB's health Research Program has provided the basis for many regulatory programs by investigating the connections between exposure to criteria pollutants and air toxics and negative health outcomes. Understanding exposure pathways helps uncover potential mitigation methods which improve air quality and help to avoid health burdens.

Over the years, CARB has sponsored landmark research on the additional risks faced by sensitive groups that are more susceptible to exposure impacts. Sensitive groups or receptors include individuals who are more susceptible to the health impacts of air pollution due to their age, other medical conditions, socioeconomic status, ethnicity, community factors and additional pollution burdens. One such study is the Children's Health Study, which revealed the extent to which ozone, nitrogen dioxide, acid vapors consisting of nitric acid and hydrogen chloride, and particulate matter affect children's lung development. The results of this study are evidence for classifying children in a sensitive group for air pollution health effects, and have shaped California legislation addressing children's microenvironments. CARB also funded a study of families in different neighborhoods in Los Angeles County. The researchers found that children more highly exposed to traffic pollution were 30-40 percent more likely to report wheeze symptoms.

Additional work on elderly people with cardiovascular disease in Los Angeles explored new ways to study vulnerability, such as examining the impact of genetic variability on health in populations exposed to different sources of air pollution, and provided information on the effects of air pollution exposures from different sources. Furthermore, traditional animal studies have focused almost entirely on male animals, so data on female health were limited. Although postmenopausal women have been shown to be more susceptible than men to PM-induced cardiovascular disease, it was not clear why. In response to this research gap, CARB funded an animal study examining both males and females, to allow for comparison between the sexes as well as testing the role of estrogen in cardiovascular outcomes (see research highlight below).

Current Research: CARB seeks to remain on the cutting edge of health research with tools that reflect changing exposures and related health risks and the understanding of those risks in order to mitigate impacts. For example, due to CARB's success at reducing ambient $PM_{2.5}$ levels, the relative proportion of particles arising from non-exhaust sources, such as tire and brake wear, is increasing. Given the high metal content and larger particle size, these non-exhaust sources are of concern since they may disperse differently, affecting populations living and working closer to major roadways. Realizing this, CARB has funded research on maternal exposure and pregnancy-related health

impacts from brake and tire wear PM. In addition, past CARB studies have examined joint pollutant exposures, such as the effects of combined ultrafine PM and ozone, on the heart and lung in animal models. More work and new tools will be needed to better understand how multiple environmental stressors and pollutants affect health, particularly for sensitive groups and priority communities.

The COVID-19 pandemic has brought unexpected health challenges that highlight disproportionate impacts in priority communities. CARB-funded research is investigating the health risks faced by California residents exposed jointly to ambient air pollution and the coronavirus SARS-CoV-2. A state-wide research project funded by CARB has been designed to examine whether long-term exposure to air pollutants (including $PM_{2.5}$, PM_{10}, NO_2 and ozone) increased COVID-19 case/death rates and severity in California using sub-county level data. Moreover, the study will investigate whether disparities in exposure to air pollution may explain a significant portion of the observed disparities in COVID-19 morbidity and mortality in the African American population and other priority communities in California.

Another research contract will investigate whether air pollution worsens the prognosis for patients infected with COVID-19 in Southern California where levels of air pollution often exceed California standards. This contract will utilize data from a patient base with in-depth patient history to allow for more analysis of individual and possibly community factors contributing to illness and deaths. The data will therefore be more detailed than the state-wide analysis and allow for more developed analysis. The contract will specifically examine the outcome of confirmed COVID-19 cases by examining admission to hospital, admission to the intensive care unit (ICU), advanced oxygen treatment or being put on a ventilator, and death in hospital. This may tell us how air pollution impacts the vulnerability of populations to ailments, such as COVID-19, underlining the importance of air pollution control measures to reduce illnesses beyond those previously linked to pollution exposures. The COVID-19 pandemic has revealed that disparities have real-life health outcomes, underlining the need to move as quickly as possible to reduce emissions across all communities to improve health and increase resiliency.

Future Research: Moving forward CARB's Research Program will expand understanding of exposure impacts that are strongly correlated with air pollution and air toxics emissions, and determine methods to better evaluate the health burdens experienced in priority communities and sensitive groups. The Research Program will continue to quantify the degree to which vulnerable groups are more sensitive to air pollution exposure and how their exposure may change as communities develop mitigation strategies. For more sensitive groups, more research is needed to determine how health outcomes may better inform more protective air quality standards, which should be inclusive and considerate of the cumulative health risk of the most vulnerable community members. CARB research will also continue to address the correlations between air pollution and health outcomes and how these correlations relate to sociodemographic characteristics. Emphasis will be placed on elucidating these correlations for vulnerable populations and designing mitigation options that address disproportionate exposure impacts on California populations of concern.

Research Question:

- To what extent are sensitive groups (e.g., children, the elderly, impacted communities) more affected by air pollution impacts, and how will these groups' exposure to pollutants change in future?

Evaluating health risks from less understood but important sources, such as tire and brake wear and multi-pollutant exposure, will continue to be a Research Program priority.

Research Questions:

- What additional pollutants need to be considered (e.g. toxics, non-tailpipe vehicle emissions)?
- How can we estimate the health effects that result from multipollutant exposures, particularly in communities near ports, railyards and other pollution hotspots?

- How do short and long-term ambient air pollution exposure affect people's resiliency and susceptibility to additional infections (e.g. COVID-19) as well as the severity and mortality of the resulting infections? Does this differ for priority communities?

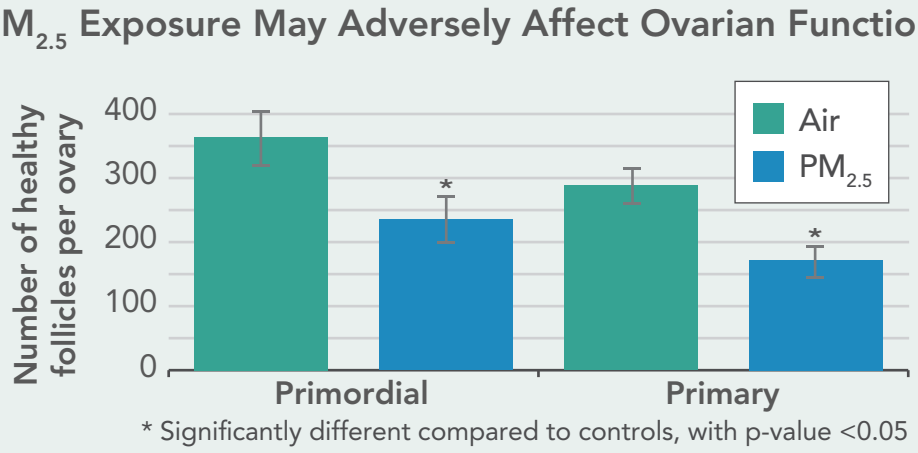
Health Analysis

Background: CARB estimates the impact of emissions on health endpoints as they relate to its programs, regulations, and policies, such as its Mobile Source Strategy, Climate Change Scoping Plan, and Short-Lived Climate Pollutant Reduction Strategy. In these health assessments, CARB has focused on quantifying health effects associated with exposure to $PM_{2.5}$ including premature deaths from pre-existing cardiopulmonary disease, hospitalizations related to heart and lung disease, and

Research Highlight: Older Women May Be at Greater Cardiovascular Risk from PM Exposure

CARB research helps ensure that California's air quality programs reflect the latest scientific knowledge of the human physiological response to air pollutant exposure. An up-to-date understanding of how the response to exposure varies across sensitive groups is needed to accurately estimate the benefits of air pollutant control policies and ensure that those benefits are equitably distributed. Recent epidemiological studies have found that older women may be more susceptible than men to cardiovascular damage from exposure to $PM_{2.5}$ because the cardioprotective effects of estrogen decline after menopause. To test this hypothesis, UC Irvine researchers performed a toxicology study that assessed the effects of $PM_{2.5}$ exposure on ovarian and cardiac health by exposing genetically modified mice to concentrated ambient $PM_{2.5}$. The research team's findings support the hypothesis that exposure to $PM_{2.5}$ may increase risk for cardiovascular disease in older women by accelerating the onset of ovarian senescence. Results showed clear evidence that $PM_{2.5}$ exposure impairs ovarian function (Figure 7). They also showed that multiple measures of heart rate variability – a positive indicator of cardiovascular health – decline more significantly in females than in males as a result of $PM_{2.5}$ exposure. Further analysis indicated that $PM_{2.5}$ exposure may have enlarged and thickened the left ventricle (the heart's main pump) in female mice, negatively affecting cardiac function. This research highlights the need for follow-up studies on the impacts of $PM_{2.5}$ exposure on reproductive toxicology to enhance CARB's understanding of the gender-differential damages caused by air pollutant exposure.

Figure 7: Primordial and primary follicle numbers per ovary were reduced in the female mice that had been exposed to $PM_{2.5}$ compared to control mice exposed to filtered air



emergency room visits for asthma. However, studies suggest strong associations between PM exposure and increased work loss days (when an individual is unable to attend work due to illness), restricted activity days, and even effects on the brain, such as brain degeneration that could potentially contribute to dementia and brain development concerns that can lead to learning disabilities in children. These findings underscore the need to expand understanding of exposure impacts from air pollutants, particularly in priority communities, and quantify these impacts in health assessments.

Evaluating and quantifying additional health endpoints will help CARB better understand the broader health benefits of CARB policies and programs, the economic costs of pollution related illnesses and health care, and disparate health outcomes experienced in different communities, particularly priority communities.

Current Research: In order to expand health analysis research, CARB research is currently investigating the effect of $PM_{2.5}$ exposure on several different health outcomes including work loss days in California. The study on work loss days will also examine days associated with wildfire smoke exposure. Another ongoing CARB funded study using GPS enabled inhalers will quantify the relationship between vehicle pollution, which includes non-exhaust pollutants, and sub-acute respiratory disease symptoms represented by medication use, for 2,870 patients in the major metropolitan areas of California. The results of this research will help CARB identify communities with disproportionate exposures and health impacts for possible mitigation strategies. In addition, the results will be used to support respiratory disease symptoms as a health endpoint in CARB's quantitative health impacts analysis.

In another project, CARB's contractors are developing a transparent and easily understandable tool to estimate and value health outcomes from reductions in exposure to pollutants including criteria pollutants and air toxics. This tool will include updating our understanding of health effects of pollutants in priority communities based on the most recent literature. In addition, CARB is developing a methodology to model health co-benefits of programs impacting the state's Natural and Working Lands (NWL). NWL include forests, woodlands, rangelands, farmlands, and urban green space. This project will create a scenario tool that quantifies human health impacts resulting from policies and programs that affect land use of NWL. A literature review will be performed to find existing NWL policies and models, as well as identifying direct effects to human health. It is anticipated that the resulting tool will fill critical knowledge gaps regarding potential human health impacts of various activities related to the conservation, management, and restoration of California's NWL and may help to identify the programs and policies that have the greatest health benefits.

Future Research: CARB is currently engaged in these on-going research topics to expand health analysis tools and fill knowledge gaps to better support our regulatory programs, but more work is needed. Moving forward, CARB research will focus on correlating a range of positive health impacts with decreases in criteria and toxics emissions and climate change. This will provide a more comprehensive understanding of health benefits and will be used for policy recommendations. In addition, CARB is focused on understanding the unique exposures and health effects experienced in priority communities, including multi-pollutant exposures, and finding ways to better incorporate these effects into the analysis of CARB regulations and strategies.

Research Questions:

- What additional health outcomes (beyond premature deaths, asthma ER visits and hospitalizations for respiratory causes) can CARB estimate and monetize (if feasible) and how can CARB ensure that the outcomes reflect the diversity of California and the existing health burdens for priority communities?
- Are there non-quantifiable metrics CARB can use to reflect adverse health impacts?
- How can CARB update its tools to estimate and monetize, where possible, the health outcomes from a broad range of air pollutants, including criteria pollutants and air toxics, for proposed rules, regulations and programs? How can CARB update and broaden its understanding of the benefits of policies to reduce climate change?

Indoor Pollution Sources, Exposure, and Mitigation

Past Research: The indoor microenvironment has been a continually impactful area of research for CARB over the past few decades. CARB's indoor air quality research improves Californians' health by identifying indoor air pollution exposures and effective exposure reduction approaches. A 2005 air-cleaning device survey, for example, found that while most people purchased air cleaners to help alleviate asthma and allergy symptoms, many devices emitted high ozone levels – some as high as a Stage-One smog alert. This finding led to state legislation authorizing CARB to regulate ozone emissions from indoor air cleaning devices. CARB's Indoor Air Cleaning Devices regulation, the only one of its kind, went into effect in 2010 and CARB has been implementing and updating the regulation to increase public health protection based on additional research. CARB-funded studies also spurred regulation of other indoor toxics, such as formaldehyde emissions from composite wood products. CARB's regulation limiting formaldehyde emissions from composite wood products was followed by federal legislation requiring national regulation of formaldehyde emissions from building materials. CARB's research on building materials and design also contributed to both state and national green building standards, building energy codes and certification criteria.

Recent CARB-funded research had important findings that have directly impacted California policies. The culmination of research found that: (1) high-efficiency filtration in homes can remove over 90 percent of particles from incoming outdoor air with low energy consumption, and (2) this high efficiency filtration can reduce asthmatic children's doctor's visits. These important findings fed into updated filtration requirements through the California Energy Commission's (CEC) building energy codes. These requirements started January 2020 and will have a clear benefit to protect Californians from exposures to $PM_{2.5}$, especially considering that Californians spend, on average, over 85% of their time indoors. Continued research on the effectiveness of different ventilation and filtration technologies will be needed to advance policies, such as the state building codes, as filtration technology advances and new sources of pollutants are found.

Current Research: CARB is examining emerging indoor air pollutants that are persistent and have health concerns, such as perfluoroalkyl and polyfluoroalkyl substances (PFAS). PFAS are widely used in consumer products and industrial applications, and have been classified as "possibly carcinogenic" to humans by the International Agency for Research on Cancer (IARC) and the US EPA. CARB has funded research to summarize the information about the sources of PFAS, both ambient and indoors, their potential health impacts, and available sampling and analysis methods. The study will provide recommendations for CARB on the best methods to measure PFAS in ambient and indoor air, soil, and indoor dust. This information will support research to determine the fate and transport of PFAS in key environmental media, Californians' exposures to these compounds, and their impacts on public health. This is vital knowledge to determine appropriate exposure mitigation across different media.

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

CARB is also working to assess exposure reduction methods in multifamily housing, which represents more than 50% of new residential housing in CA annually and often houses a disproportionate percentage of disadvantaged families. Compared to single-family homes, achieving healthful indoor air quality (IAQ) as well as significant energy use and GHG reductions is more challenging in multifamily buildings due to substantial differences in building construction. Results of this study will provide critical information to CARB and CEC in support of improving California's Title 24 Building Energy Efficiency Standards to meet California's climate, air quality, and energy efficiency goals and ensure co-benefits for health.

Future Research: Moving forward, CARB will continue to evaluate new technologies and materials that may present new exposures to harmful air contaminants, and existing and new strategies under development that will reduce exposure to air pollutants in California. Exposure in priority communities will continue to be a high research priority at CARB. Research is ongoing to characterize the exposure patterns of residents to air pollutants and noise both outdoors and indoors, and to identify sources that contribute to higher exposures in priority communities. Results from this research will be used to determine whether elevated risk from air pollutants necessitates additional measures for protection of residents in these communities and will guide future research needs.

Understanding exposures inside homes and buildings, especially in priority communities, to toxic air contaminants and other pollutants will continue to be a research priority. This includes the identification and evaluation of emerging indoor air pollutants of concern from sources such as building materials, consumer products and indoor appliances. Studies in this line of research will likely include evaluating the toxicity of PFAS and Californian's exposure to PFAS in indoor air and dust from both indoor and outdoor sources.

A new area of focus is on building decarbonization. CARB emissions data and additional research points to the fact that combustion pollutants from building appliances generate health concerns in indoor environments while also contributing significant levels of GHG emissions and criteria air pollution to outdoor air. CARB presented a research update on this topic to the board in November 2020 and the board adopted a resolution focused on expanding CARB's work to promote decarbonization in multiple ways and reaching out to priority communities to evaluate decarbonization strategies in different community contexts. CARB continues to evaluate research findings demonstrating the health benefits of reducing combustion emissions and utilizing building decarbonization strategies as well as assessing what additional research is needed to more fully understand health benefits. CARB is particularly focused on evaluating the health benefits from reducing exposures to combustion air pollutants from natural gas appliances in buildings, both indoors and outdoors. Additional research is needed on evaluating the impacts of wildfire emissions on indoor air quality, and assessing the efficacy of building cleanup practices after wildfire to provide science-based guidance for the public.

Research Questions:

- What are the most effective mitigation strategies beyond source reduction (e.g., filtration) to reduce air pollution exposure and improve health in indoor environments?
- Which sources of air pollutants indoors such as building materials, consumer products, and combustion appliances are responsible for the greatest amount of total (indoor and outdoor) exposures and health risks for residents and what are the best strategies for mitigating these impacts?
- What remaining information will further improve our understanding of the air quality and health benefits of building decarbonization?

Sustainable Communities and Health

Background and Current Research: California planners and policy makers face increasing demands for information on the health impacts of strategies to reduce GHG emissions from transportation. Senate Bill (SB) 375[24] requires metropolitan planning organizations to reduce GHG emissions through land use and other strategies. Studies world-wide, including several in California, have identified the potential for health co-benefits of active travel (walking, cycling, and transit) in significantly reducing the existing burden of chronic disease.

Several Metropolitan Planning Organizations (MPOs) have set voluntary health targets in their Sustainable Communities Strategies (SCS), and have used a spreadsheet version of the Integrated Transport and Health Impact Model (ITHIM) to estimate the health impacts of their preferred

24 Steinberg, Chapter 728, Statutes of 2008

scenarios. CARB staff working on SCSs create guidelines for MPOs and provide assistance with models like ITHIM. To complement this work, a project funded in fiscal year 2017-18 created an easy-to-use, open-source, updated version of the ITHIM branded as the Healthy Mobility Options tool. This tool helps MPOs set voluntary health targets in their SCSs, and helps MPOs and CARB calculate the health impacts of transportation strategies to reduce GHG that incorporate active transportation. When coupled with land use models, it may have additional applications to assess the health impacts of general plans. The insights gained from this research may lead to more sophisticated model versions that could be applied to project level and sub-county geographic scales.

CARB staff are also doing in-house work investigating commuters' exposures to traffic pollution for different transportation modes and analyzing the impacts that SB 375, and other policies reducing vehicle emissions, are likely to have on such exposures. To translate research into a form that planners and other stakeholders can use readily, staff developed a "Technical Advisory" to supplement the 2005 Land use Handbook. This Technical Advisory includes strategies that CARB staff has determined can effectively reduce air pollution exposure near high-volume roadways. These strategies are based on scientific literature and CARB studies, as well as discussions with various state and federal agencies, academic experts, and other stakeholders. The Technical Advisory's key strategies appear in the 2017 update of the General Plan Guidelines, and include direct links to CARB's Technical Advisory for planners and stakeholders seeking more information.

A current in-house project has evaluated associations between walkability, $PM_{2.5}$, and the prevalence of hypertension. Using adult participants (age 18 and older) from the California Health Interview Survey, this study found a beneficial association between hypertension and very walkable environments compared to car-dependent areas even after accounting for the potential adverse impacts of $PM_{2.5}$ and other factors such as age, sex, race/ethnicity, smoking, and education levels. In addition, similarly beneficial relationships were observed among males, Latino/Hispanic, non-Hispanic white, and younger age groups (<65 years old), those with low income (<$60,000), and participants from urban areas.

CARB exposure mitigation research is also focused on reducing exposure by altering the built environment. For example, previous CARB-funded research found that street designs and vegetation can both reduce community exposure to pollution. Streets designed with more open space and varied building heights can decrease near-street traffic pollution by up to 67 percent. Community and street designs can also encourage more walking, transit and active transportation.

An additional factor affecting health in the built environment is noise from traffic and other urban features. CARB currently has plans to use noise monitors and personal air pollution monitoring devices to collect data on commuters' exposure to noise and air pollution. This represents an important first step in improving our understanding of noise-related health effects and considerations of noise in the development of future compact, infill communities.

Future Research: CARB will continue to support research that will help organizations engage in better informed decision-making on issues related to transportation and health. Moving forward, it is a research priority to quantify health benefits and incorporate them into the equation for estimating the net health effects of SB 375 at the state and local level. This work will also help design future mitigation strategies, including land use changes that reduce VMT, built environment features that reduce air pollution in microenvironments where people live and work, including in priority communities.

Research Questions:

- What are the net health benefits associated with advanced technology vehicles, smart growth, active transportation, and other strategies to reduce vehicle miles traveled?
- How can we use the information from existing and new tools to support local and community strategies to maximize health benefits and reduce near-roadway air pollution exposure?

Environmental Justice

Environmental justice (EJ) refers to the the fair treatment and meaningful involvement of people of all races, cultures, incomes, and national origins with respect to the development, adoption, implementation, and enforcement of environmental laws, regulations, and policies.[25] Achieving EJ is one of the most important objectives of air quality management, and CARB is committed to reducing the disproportionate exposure to air pollutants and resulting health impacts in priority communities. Priority communities[26] include neighborhoods of California that disproportionately suffer from historic environmental, health, and other social burdens. These burdens include, but are not limited to, poverty, high unemployment, inadequate access to educational resources and training opportunities to secure high-road jobs, air and water pollution, presence of hazardous wastes, high incidence of asthma, heart disease, and other chronic illnesses. Due to historic discrimination, which includes discriminatory practices such as redlining,[27] these communities often include high levels of residents and households with people of color, low-income status, seniors, people with disabilities, non-English speakers, and those who have limited awareness of or access to clean transportation and mobility options. This definition recognizes the need to be inclusive and deliberate in acknowledging past and current policies resulting in the accrual of these burdens and minimizing further harms as paramount in meeting the State's equity goals and fostering actions that distribute community benefits intentionally and equitably.

Over the years, CARB has partnered with local and community organizations, carried out research projects and air monitoring studies to identify residual exposure risks, conducted health assessments of communities near ports and rail yards, studied health disparities, adopted regulations, and refocused enforcement efforts and incentive programs, all in support of EJ goals. These actions have resulted in encouraging improvements in air quality, especially in those communities where air pollution impacts have historically been the greatest. For several years, research projects have looked at health disparities in priority communities. CARB's past research on the Environmental Justice Screening Method led to the development of CalEnviroScreen[28] and further research on disparities. Previous in-house work on exposure disparities in priority communities has led to research focused on identifying the sources of these disparities so we can focus regulatory efforts on reducing exposures. And lastly, CARB's EJ research has broadened to include innovative methods to detect and monitor odors and toxics, including metals and PAHs.

Cumulative Impacts

Background and Past Research: There is a long history of research and population health studies demonstrating that priority communities and communities of color are exposed to higher levels of pollution due, in part, to their proximity to air pollution hot spots including air toxic emitting facilities, hazardous waste sites, busy roadways, ports, and railyards. Proximity to these high-polluting sources and other environmental and social stressors result in a range of health effects including exacerbation of asthma in children that results in missed school days. Studies demonstrating these higher impacts include the Los Angeles Family and Neighborhood Survey (L.A.FANS), the East Bay Children's Respiratory Health Study, and the California Health Interview Survey (CHIS). Findings from these studies have helped to inform policy decisions on motor vehicle emissions control and enforcement, as well as asthma prevention, control, and education in priority communities. For example, these results helped underscore the importance of siting sensitive sites

25 Assembly Bill 1628, Rivas, Chapter 360, 2019

26 Priority communities include disadvantaged communities (DACs), low-income communities, and underserved communities, which are specific terms used in many of the statutes and regulations in the Strategy (e.g., Senate Bill 535 (De León, 2012), Senate Bill 350 (De León, 2015), Assembly Bill 1550 (Gomez, 2016), Assembly Bill 841 (Ting, 2020)

27 *Pollution and Prejudice (arcgis.com)*

28 OEHHA's CalEnviroScreen tool is a cumulative impacts tool that uses over 20 pollution and population indicators to score community vulnerability and burdens by census tract, and rank communities across the state.

away from pollution sources. An example is California Senate Bill (SB) 352, which prohibits school siting within 500 feet of a freeway.

In response to these disparities, CARB funded the development of the Environmental Justice Screening Method (EJSM), an innovative tool to look at cumulative impacts that informed the development of the CalEnviroScreen tool by the Office of Health Hazard Assessment (OEHHA). OEHHA's CalEnviroScreen tool is an updated cumulative impacts tool that uses over 20 pollution and population indicators to score community vulnerability and burdens by census tract, and rank communities across the state. CARB has used research findings from the San Diego State study mentioned below and satellite-derived high resolution $PM_{2.5}$ information to help update air quality data in the CalEnviroScreen model (see Figure 8 in research highlight titled: Mexican Emission Sources Could Impact California's Border Communities). CalEnviroScreen has been used to guide allocation of Climate Investment Funds and decisions on enforcement priorities in priority communities and is increasingly considered in development of CARB's regulatory strategies.

Research Highlight: Comparing Source-Specific Pollution Burdens in Communities

California's air pollution control policies have successfully reduced emissions of particulate air pollutants under 2.5 microns in diameter ($PM_{2.5}$) statewide. But not all locations have seen equal improvement in air quality. Understanding the distribution of both air quality improvements and air pollutant exposure in communities throughout the state can aid CARB in policy development. CARB researchers developed a screening method that identifies pollution sources with potentially high impacts on exposure, and estimates the amounts of $PM_{2.5}$ from these sources inhaled by regional residents. Linking air pollution exposure data to demographic data about those same locations permits researchers to compare air pollution exposure burdens by income level, age and race/ethnicity. The study found that annual $PM_{2.5}$ exposure varies significantly by all these factors, with some of the widest variation across race/ethnicity. Combining these findings with the model's location-specific data on emission sources reveals the relative exposure burden imposed on each race/ethnicity by each emissions sector (Table 3). CARB's ongoing work to achieve environmental justice for priority communities can use these findings to help design regulatory programs that prioritize the most over-burdened locations and populations.

Table 3: Percent Difference in $PM_{2.5}$ exposure concentration by race-ethnicity and emission source. Units: $\mu g/m^3$, relative percent difference

Emission Source	Average	Δ White	Δ Hispanic	Δ Asian	Δ Black	Δ Other
Agriculture	1.37	-13%	16%	-4%	5%	-11%
Construction	0.28	-12%	11%	0%	21%	-6%
Cooking	0.15	-21%	14%	16%	30%	-8%
Elec. Gen	0.06	-15%	18%	-5%	9%	-11%
Fugitive Dust	0.21	-7%	10%	-13%	20%	-7%
Industrial	1.64	-25%	23%	12%	10%	-18%
Misc. Fuel Comb	0.12	-20%	18%	9%	13%	-12%
Nat. Gas and Petr.	0.22	-23%	19%	3%	42%	-8%
Off-road Mob. Srcs	0.50	-21%	14%	14%	30%	-9%
On-road Mob. Srcs	1.65	-19%	18%	5%	18%	-12%
Residential	0.58	-9%	3%	14%	12%	-3%
Total	**6.78**	**-18%**	**17%**	**6%**	**15%**	**-12%**

Current Research: Ongoing CARB research continues to support improvements to CalEnviroScreen to better capture patterns of cumulative exposures and impacts as well as social and health vulnerability. CARB is also carrying out research to better understand air pollution exposures in priority communities and sources that contribute to the highest exposure impacts. For example, a "total exposure project" is starting in fiscal year 2020-21 that will investigate exposures to both outdoor and indoor pollution sources in selected urban and rural priority communities. The impacts of noise may also be considered in this study, since it is a key, but little-studied, environmental stressor. Results from this work will be used to assess if stronger policies are needed for community protection.

CARB is also investigating impacts of oil and gas exploration activities in California and nationally. These activities have raised concerns about the potential health and equity impacts on local communities due to air pollution, water contamination, noise, and odors. A study that began in fiscal year 2018-19 is currently characterizing the potential health and equity impacts of oil and gas extraction activities at select locations in California to explore these concerns.

Future Research: For future projects in this research initiative, CARB is interested in investigating additional environmental stressors in communities, such as lack of access to healthy food, water quality, and air toxics sources. More research is needed to look at other measures of health burden such as psychosocial stress biomarkers, and to develop indicators to better track health conditions in priority communities. Investigating cumulative impacts is consistent with a recent CARB Board resolution directing staff to begin developing tools and methodologies to evaluate and mitigate the cumulative impacts of air toxics to inform the development of regulations and other strategies.

One important way to better understand the impacts of cumulative air pollution and environmental stressors and to evaluate progress in reducing those impacts is to identify and track health indicators in communities. CARB is planning to begin a new research project that will identify health indicators related to air pollution exposures in a number of Assembly Bill (AB) 617[29] communities and begin tracking progress on these indicators to determine where health improvements are occurring in response to regulatory progress.

Moving forward, investigating risk factors in vulnerable communities and potential methods for mitigating these risk factors will continue to be a priority.

Research Questions:

- What are the cumulative health impacts of multiple sources of air toxics and environmental stressors?
- What individual and community risk factors, individually or in combination, are most strongly associated with increased vulnerability to health effects associated with air pollution (e.g., asthma), particularly for sensitive populations?
- What health indicators can be used to track the progress of mitigation measures?
- How can information on the cumulative health burden in priority communities be used to guide the prioritization of resources for monitoring and mitigation strategies?

CARB is also interested in air quality projects led by people in impacted communities since they have first-hand knowledge of the pollution sources and exposures in their area. Resident-led science-based campaigns could be implemented to empower communities to better understand the monitoring process and help identify and track cumulative exposures. CARB is looking for opportunities to support these types of public-led projects. Various public and resident-led science programs across the country have shown that concerned community members can carry out successful monitoring. CARB also aims to improve access to data from community monitoring networks and on real-time exposures. Moving forward, CARB would like to investigate how data from crowd-sourced monitoring networks can best be collected, utilized, and disseminated to

29 C. Garcia, Chapter 136, Statutes of 2017

empower communities to determine the best path toward improved air quality and health outcomes.

Research Questions:

- How can the use of crowd-sourced real-time sensing networks, resident-led science campaigns, and community monitors be optimized to identify and track cumulative exposures?
- Can this monitoring be incorporated into other analysis to provide more spatial resolution?

Short-Term Exposures and Health

Background and Past Research: Short-term and acute exposure events can lead to adverse health effects. Measuring those effects has been facilitated by examining multiple data sets or using novel tools such as global positioning system (GPS) enabled asthma inhalers. Earlier, a study on high-efficiency air filtration in the homes of asthmatic children was described. That study found that although there was not a significant improvement in reported asthma symptoms, there were significant reductions in clinic visits, and a lesser decrease in emergency room visits and hospitalizations.

Current Research: Building upon that, a project beginning in fiscal year 2020-2021 will evaluate data from GPS-enabled rescue inhalers in Southern California communities. This new study will aim to identify when and where respiratory symptoms occur and to determine the air pollution exposures related to medication use. Ultimately, the results from this work will assist health analysis and help to identify areas with higher health impacts that could benefit from additional exposure mitigation.

Another consequence of short-term air pollution exposure is missing days of work due to health issues (work loss days). Investigators have recently begun a study to use the large CHIS dataset of health responses, along with air quality and meteorological data, to develop updated California data on the association between short-term $PM_{2.5}$ and work loss days. This project will also analyze the economic impact from the potential changes in work productivity.

Recent studies suggest traffic-related air pollutants (of which $PM_{2.5}$ is a major component) may produce health effects with exposure times as short as one hour. More research is needed.

Future Research: Two approaches to studying short-term exposures are being considered: One is to examine effects of exposures for periods less than 24 hours or even as short as an hour and the other is to examine the effects of spikes in sub-chronic exposures of days or weeks. Future research will consider which methods to utilize and which tools to leverage in these investigations. Future research will also consider how short-term exposures affect both health and economic productivity.

Research Questions:

- To what extent do acute smoke exposure incidents affect health vs. longer exposures?
- Which tools and metrics can be leveraged to discern both health and economic effects of acute exposures?

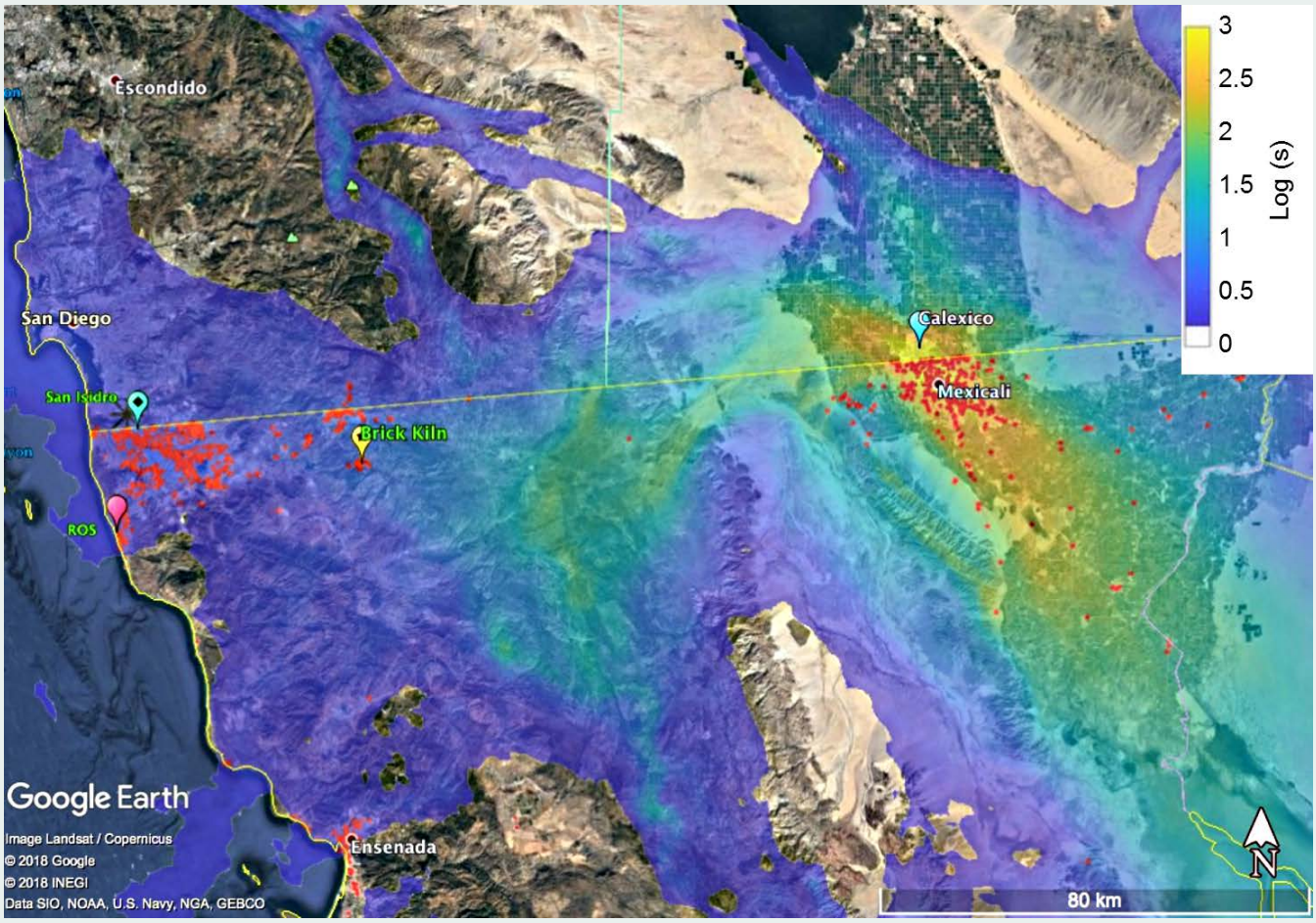
Short-term Exposures and Health: Focus on Wildfire Smoke

Background and Past Research: With Climate Change, wildfires are projected to become more frequent, longer in duration, and more intense over time. Indeed, in 2020, over 4 million acres were burned, more than double the amount within the past 20 years and millions of Californians were exposed to wildfire pollution. In 2018, the Camp Fire became the most destructive and deadliest fire in the state's history. Wildfire exposures can be at very high levels over a relatively short period of time. Much historical research on PM has focused on effects of long-term (e.g. annual) exposures. However, less is known about shorter-term exposures to wildfire smoke, or about the impacts on sensitive groups such as children and the elderly. CARB research has examined the persistent respiratory and pulmonary effects of early-life exposure to wildfire smoke in a non-human primate. A cohort of outdoor-living rhesus macaques was unintentionally exposed in infancy to high levels of wildfire-related PM. As they aged, the animals showed persistent immune dysregulation and deficits in lung function compared to age-matched animals that hadn't been exposed to smoke (see research highlight above).

Research Highlight: Mexican Emission Sources Could Impact California's Border Communities

Air pollutant emissions do not recognize international boundaries like the border between the United States and Mexico. But early versions of CalEnviroScreen, the tool CARB uses to identify California's most disadvantaged communities, didn't consider emission sources in Mexico that might impact California communities to the north. To help integrate their impacts in future versions of CalEnviroScreen, researchers from San Diego State University's School of Public Health identified over a thousand Mexican emission sources within 50 kilometers of the border and developed a method to estimate their potential impacts on California's border communities. Results indicate that areas immediately adjacent to the border and farther north in San Diego and Imperial counties are affected by emission sources in Mexico close to the border and further inland (Figure 13). But because California census tracts close to the border are large and sparsely populated, findings had little impact on environmental justice scores for these areas. Emissions from agricultural and urban burning newly identified by this study may affect environmental justice scores once integrated in future iterations of screening tools. Recommendations include using the methods and data developed by this study to assess border-specific approaches to incorporating Mexican emission sources in CalEnviroScreen scoring.

Figure 8: Exposure pathways of pollutant emissions from sources in Mexicali to Calexico, California. Yellow and blue correspond to higher and lower particle residence times, respectively. (Log scale)



Current Research: Short-term exposure to wildfire smoke is an active area of study for CARB. A white paper funded by CARB is examining how short (e.g. one-hour) $PM_{2.5}$ exposures affect health; a symposium discussing these short-term exposure impacts is anticipated in 2021. An on-going statewide study funded by CARB investigates the acute health effects from relatively short-term exposure to $PM_{2.5}$ (e.g., days and weeks) by studying associations between work loss days and ambient $PM_{2.5}$ exposures during normal times and exposures during and after wildfires. This study will provide the information needed for CARB to calculate the impacts of regulations and policies on these health outcomes, and can be used to estimate the benefits from regulations reducing $PM_{2.5}$ exposures. A new follow-up to the primate study will investigate whether the immune and lung deficits persist or even worsen as the animals continue to age. This study will also track the animals' activity levels, to determine whether motor activity is reduced due to compromised health.

Future Research: Many questions remain to better understand the health impacts of short-term exposures to fire smoke. With the recent proliferation of low-cost sensors that can provide near real-time measurements, communities and scientists alike are asking what short-term changes mean for public health. Two approaches to studying short-term exposures are being considered: One is to examine the effects of exposures for periods less than 24 hours or even as short as an hour and the other is to examine the effects of spikes in sub-chronic exposures of days or weeks. Future research will consider which methods to utilize and which tools to leverage in these investigations.

These fires have also underscored the need to better understand the toxicity and health effects of smoke at the wildland-urban interface. There is considerable concern that structures and vehicles burning could lead to increased toxicity.

Moving forward, more in-depth analysis of recent smoke events will be needed using high spatial resolution information and health impacts data to determine how short-term exposures are affecting community members. This information will also guide the development of updates to activity guidelines to mitigate health effects during smoke events.

Research Questions:

- What are the health impacts faced by vulnerable groups from short-term (sub-chronic) exposures to wildfire smoke?
- Which communities are more susceptible to sub-chronic exposure events and what mitigation options are available to abate them?
- What are the potential toxic and health implications of exposure to smoke from the wildland-urban interface?

With all the data that have been and continue to be gathered on short-term exposures and health effects, there is an increasing need to be able to communicate this material to the public. As seen with real-time pollution data, air quality conditions can change dramatically over a short period and this can immediately affect people's risk for asthma exacerbation, hospitalization, and other health

In-House Research Highlight: Cleaner Air Shelters and Cleaner Air Spaces

The increased frequency of large and high-intensity of wildfires and growing health information about the dangers of short-term exposure to wildfire smoke underscore the need to create clean air spaces where people can take refuge during wildfire episodes. In response to AB 836 (Wicks) CARB is working closely with air districts to administer a pilot clean air centers program in some regions of the state. The program includes $5 million in incentive funding to purchase filtration equipment for the centers. CARB is working with air districts and community stakeholders to develop guidelines for the program to ensure the funding is put to work as quickly as possible, and that clean air spaces funded by the program are equipped with updated filtration and air quality monitoring to protect residents during smoke events.

effects. Thus, it is especially important for sensitive subpopulations and vulnerable communities to be aware of the latest information in order to mitigate negative health outcomes. However, there are research needs regarding communicating real-time air quality data and short-term health effects, particularly using a wider variety of communication tools to maximize population coverage. CARB's programs would like to focus on investigating the most effective ways to reach the public with this information, and going further, determine effective methods to encourage behavioral change to reduce exposure during high-pollution events. These and other unknowns relating to outreach and communication will be research priorities moving forward.

Research Question:

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

Identifying Emission Sources

Background and Past Research: To address the issue of vulnerability of priority communities and communities of color to exposure to air pllution, CARB has supported and continues to support a variety of in-house and external research efforts on emission sources. Recent projects have focused on comparing the trends in pollutant concentrations in priority communities, especially from vehicles, and comparing them to state average concentrations. This work allows CARB to track the effectiveness of current rules and regulations to reduce traffic-related pollutants, as well as to quantify their impacts to ensure that California's priority communities benefit equitably from California's air pollution control programs.

Remote sensing devices are very useful tools for looking at traffic-related pollutants, as they obtain real-world emissions at the particular locations in which they are deployed. A recently completed study, conducted over multiple periods, utilized these instruments at a highly-trafficked I-10 on-ramp in West Los Angeles to measure on-road emissions from passing vehicles. Analysis of vehicle models and emissions revealed that despite reductions in carbon monoxide, hydrocarbons and nitric oxide between 1999 and 2018, emission disparities still remained, with higher emissions coming from vehicles registered in priority communities relative to those registered in other communities. To continue investigating these sorts of vehicular emission disparities, CARB is supporting a new project beginning in fiscal year 2020-21 to conduct remote sensing measurements at multiple locations throughout California.

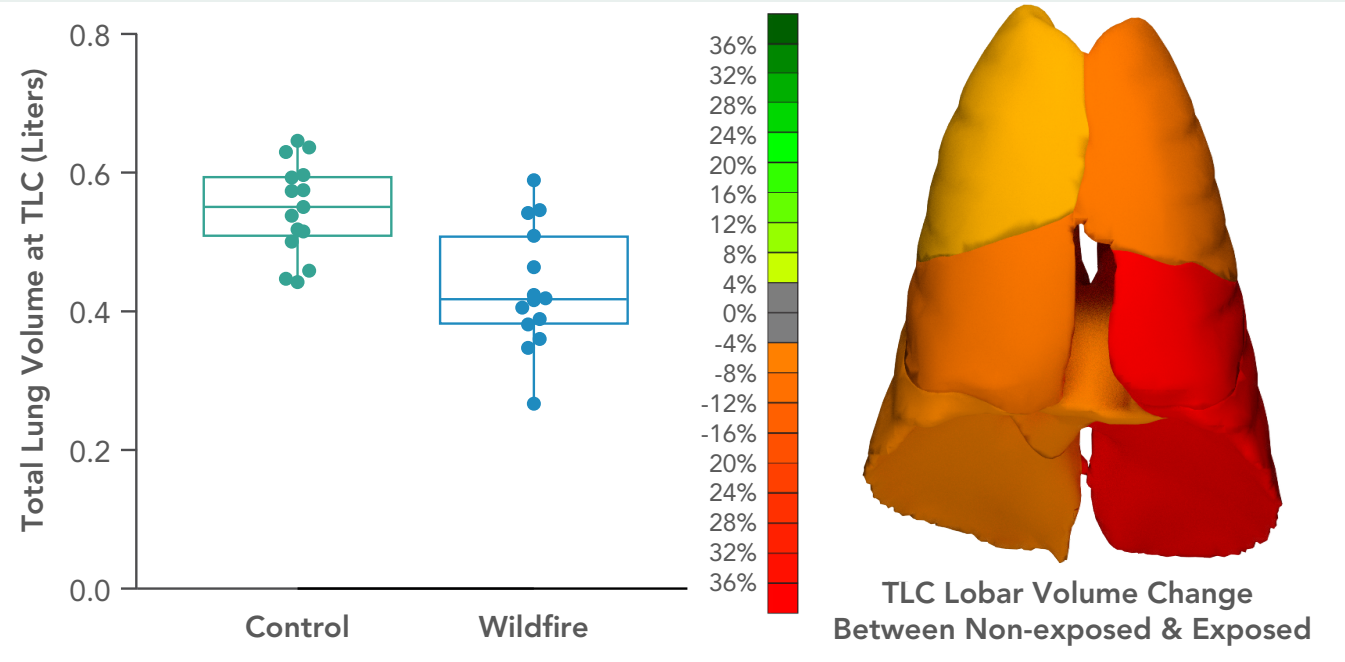
It is also vital to investigate understudied and emerging sources of pollution. As tailpipe emissions are declining, tire and brake-wear are becoming increasingly important sources of particulate emissions. It is estimated that in the near future the majority of $PM_{2.5}$ and PM_{10} mobile source emissions will be from non-exhaust sources such as tire and brake-wear. CARB is addressing this growing issue by developing methods of measuring non-exhaust particulate matter emissions from vehicles. A multi-institutional project that began in fiscal year 2018-19 is utilizing real-time instrumentation to measure brake and tire-wear emissions to monitor potential exposures of downwind communities. One of the sampling locations is near I-710 in Los Angeles County, a heavily trafficked highway upwind of a community of concern. The data from this work will be used to better understand the impact of non-exhaust emissions on communities and to develop methods to control them.

As mentioned earlier, CARB has also funded research that developed a screening method to help compare relative exposures to $PM_{2.5}$ sources among different areas and population groups in EJ communities. This study has constructed a spatial database of intake fractions for primary and secondary $PM_{2.5}$, calculated the resulting $PM_{2.5}$ intake for the total population and each demographic group, and derived exposure disparity metrics for different demographic groups including by race, age, income and other factors. Results of this study indicated that differences in per-capita $PM_{2.5}$ exposure concentration ranged up to 15% by income and 35% by race. The two top sources of $PM_{2.5}$ exposures for priority communities, on-road vehicles and industrial activity, contributed most to exposure disparity by race in absolute terms, while other sources, such as commercial cooking and

Research Highlight: Childhood Exposure to Wildfire Smoke Has Long-Term Adverse Health Impacts

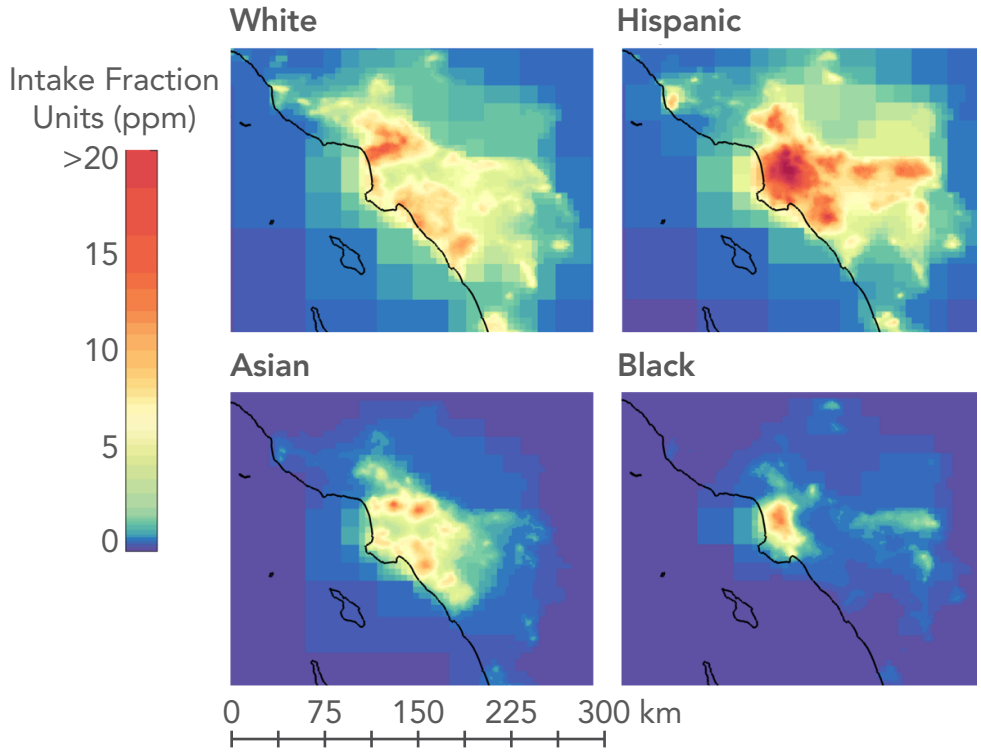
As the frequency and severity of wildfires increases, millions of Californians have become all too familiar with the immediate health effects of exposure to wildfire smoke - a toxic mix of particles and gases emitted by burning forests and buildings. Short-term effects range from irritation of the eyes and throat to exacerbation of life-threatening cardiovascular conditions. But little is known about the long-term impacts of early childhood exposure to an acute ambient air pollution event, such as wildfire smoke. To help fill this gap, CARB-funded researchers tracked the development of outdoor-dwelling infant monkeys at California's National Primate Research Center who were exposed to wildfire smoke $PM_{2.5}$ during the 2008 Trinity and Humboldt County wildfires. The decade-long investigation assessed the impact of early life $PM_{2.5}$ exposure from wildfire smoke on immune and respiratory health parameters that may influence responses to infectious disease and lung function in adulthood. Results showed that early-life exposure to ambient air pollution from wildfires was significantly associated with altered immune response and lung structure and function. CAT scans of adult female monkeys exposed to early-life wildfire smoke $PM_{2.5}$ showed significant reductions in lung volume, along with other respiratory changes, relative to unexposed monkeys, (Figure 9), while blood tests showed immune system dysregulation in adult monkeys that had been exposed to wildfire $PM_{2.5}$ as infants. The study also provides the first evidence of multigenerational transmission of immune dysregulation as a result of maternal wildfire smoke exposure: the mothers' exposure to wildfire smoke during infancy was associated with altered immune response in their unexposed offspring. Because the human genome is similar to that of the monkeys studied, the findings are likely to be applicable to humans who experience similar exposure.

Figure 9: Total lung volume at TLC in liters under different test conditions



petroleum refining, resulted in higher relative differences in $PM_{2.5}$ exposure (Figure 10). The results will help prioritize effective emission reduction targets to achieve CARB's EJ goals.

Figure 10: Example for Los Angeles of the intake fraction for ground-level emissions of primary $PM_{2.5}$

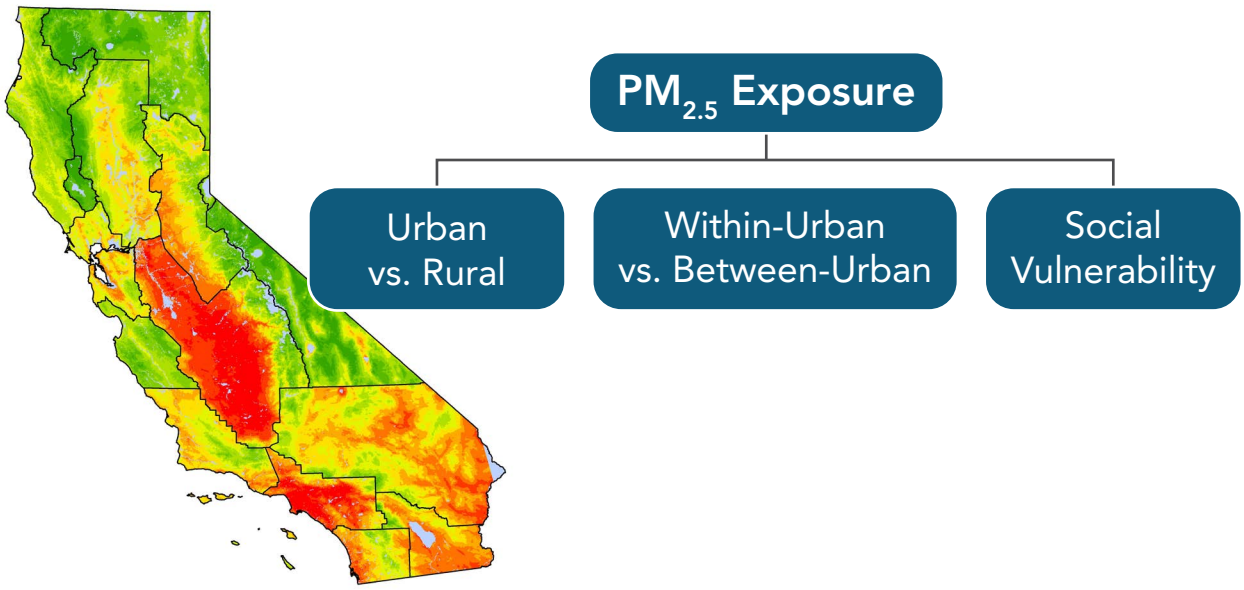


Current Research: Research to support new technology and analysis tools in order to detect pollutants and identify hotspots is critical for protecting priority communities. Of notable importance is the need to develop innovative methods to detect and monitor air toxics to support CARB's Air Toxics Program. Since fiscal year 2017-18, researchers from FluxSense Inc. and Chalmers University of Technology have been conducting a statewide survey of sources contributing to higher levels of the air toxics in priority communities. The results will be useful in identifying local air toxics risks, informing enforcement efforts and future monitoring efforts.

Another ongoing project initiated in fiscal year 2017-18 is focused on quantifying ambient toxic metals. Researchers are developing a portable instrument to measure ambient concentrations of toxic metals like chromium VI, lead and mercury, and other metallic elements in real-time. The researchers are also aiming to make this product available to the public at low cost. The resulting device will improve the ability to identify potential sources of a broad range of toxic metals, as well as the ability to prioritize efforts especially in priority communities close to industrial sources.

CARB staff are also developing novel applications of satellite remote sensing data to improve our understanding of various air pollution "hot-spots" in the state. Spatially comprehensive $PM_{2.5}$ data presents a tremendous opportunity for CARB to independently study areas where regulatory and community-based $PM_{2.5}$ monitors do not exist. The resulting data has the potential to advance efforts that would reduce air quality disparities among priority communities identified under AB 617 initiatives. This effort has thus far resulted in a research paper published in 2019, which generated $PM_{2.5}$ concentration estimates at a 1 km spatial resolution (Figure 11). The paper further describes how this work has been used to assess long-term $PM_{2.5}$ exposures for the state, including in rural and highly impacted populations. The results improved exposure classifications by accounting for land type, meteorology, and satellite remote sensing data. CARB will continue to track spatially resolved $PM_{2.5}$ levels over time and further assess sub-hourly $PM_{2.5}$ exposures during extreme events, such as wildfires.

Figure 11: The spatial distribution of $PM_{2.5}$ mass concentration in California in 2016, with a color scale from red (highest levels) to green (lowest levels). This work published in 2019 also focused on $PM_{2.5}$ exposure differences between populations



Future Research: Moving forward, long-term community monitoring systems for a broad suite of toxic air contaminants need to be established, especially in priority communities. Some of CARB's past and ongoing projects are a first step to developing this network, which will allow for the ability to identify hot spots. Future research will also aim to identify potential sources of nuisance odor complaints and determine if they are a result of air pollutant emissions that may result from a variety of sources such as foundries, dairies, industrial facilities, and fuel storage facilities. This work will evaluate the potential health impacts of odors from these sources, as well as methods to monitor identified pollutants.

Research Questions:

- What can new measurement and data analysis methods reveal about previously hard-to-detect sources of air pollution, particularly in priority communities?
- How can advanced screening tools that integrate meteorological data and real-time air quality monitoring data be used to identify air pollution hot spots for mitigation purposes?

Reducing Disparities

Background and Past Research: This research initiative is new for the Proposed 2021-2024 Triennial Strategic Research Plan. It is focused on investigating factors affecting disparities such as global events (COVID-19 and climate change) that impact air quality and health in California's priority communities, identifying options for cleaner technologies and programs to reduce pollution and related health effects, and evaluating trends and progress in improving health conditions in priority communities. Some research work is starting to address the aspects of this initiative, but many key questions remain.

CARB's emission and exposure research has found that priority communities are experiencing disproportionate air pollution exposures and health impacts compared to other communities. CARB continues to focus on ways to reduce disparities and increase air quality and health benefits in priority communities while continuing to study community and individual exposures. The ultimate goal is to provide Health Equity to priority communities who have experienced disproportionate exposure to pollutants. Health equity is the principle underlying a commitment to reduce—and, ultimately, eliminate—disparities in health and in its determinants, including social determinants. Pursuing health equity means striving for the highest possible standard of health for all people and giving special attention to the needs of those at greatest risk of poor health, based on social

conditions.[30] This goal is in line with CARB's commitment to racial equity and social justice as described in the recent Board resolution (20-33).[31]

Current and Future Research: CARB will continue to identify opportunities to reduce pollution sources, exposures and disparities in priority communities. For example, CARB has been pushing to increase clean mobility and transportation in all communities, including priority communities. However, this is more difficult in some areas. Additional strategies are needed, such as increased incentives as noted in the Senate Bill (SB) 350[32] Report "Overcoming Barriers to Clean Transportation Access for Low-Income Residents." A new study beginning in fiscal year 2019-20 will aim to identify barriers to adoption of clean mobility options in priority communities. This project will look at mobility adoption scenarios and analyze the impacts on transportation emissions. The research questions in the Program Assessment research initiative also stress the need to deploy transportation incentives equitably to better serve priority communities. CARB plans to continue to investigate ways to overcome barriers and increase clean transportation and mobility options for all communities.

CARB will continue to evaluate trends in disparities over time. CARB is also planning to begin a new research project in FY 21-22 to identify and assess air-pollution related health metrics in priority communities included in the AB 617 program. This will enable CARB to better evaluate health conditions in communities suffering from disproportionate impacts and to track community progress in improving health over time as clean air strategies are implemented.

Research Questions:

- How can CARB facilitate identification of exposure and health disparities among communities and find opportunities to further reduce those disparities related to criteria and toxics emissions?
- What health metrics should be considered and evaluated to better understand and evaluate progress in reducing exposure in priority communities?

The global COVID-19 pandemic has caused a staggering number of cases, hospitalizations, and deaths worldwide. Furthermore, this pandemic seems to be hitting already priority communities the hardest. In fact, studies have suggested that people who live in more polluted areas are more at risk for hospitalization and death due to COVID-19. Two new CARB-supported projects have just begun fiscal year 2020-21 to analyze these health impacts in California. One study led by UCSF will look at the relationship between air pollution levels and COVID-19 cases and deaths statewide, while another study led by UCLA will focus on southern California. As the world is continuing to learn more about COVID-19, there is no doubt that more research questions will arise, such as whether the long-term effects of infection are more severe in polluted communities.

Research Question:

- How, why, and what is the extent to which COVID-19 impacts different communities differently?

Climate change remains an ongoing concern for everyone but especially sensitive populations. Not only do greenhouse gas (GHG) emissions drive global warming, but the warming of the atmosphere itself could further worsen air quality, and less precipitation can increase the risk for wildfires and harmful smoke, among other meteorological changes and consequences. This brings forth questions about how climate change will affect priority communities and whether current disproportionate air pollution exposures and health outcomes will be exacerbated. Research looking at this will require sophisticated models and should consider different climate change scenarios, time periods, geographic areas in the state, health endpoints, and other factors.

30 *www.ncbi.nlm.nih.gov/pmc/articles/PMC3863701/*
31 *Resolution 20-33 A Commitment to Racial Equity and Social Justice (ca.gov)*
32 De Leon, Chapter 547, Statutes of 2015

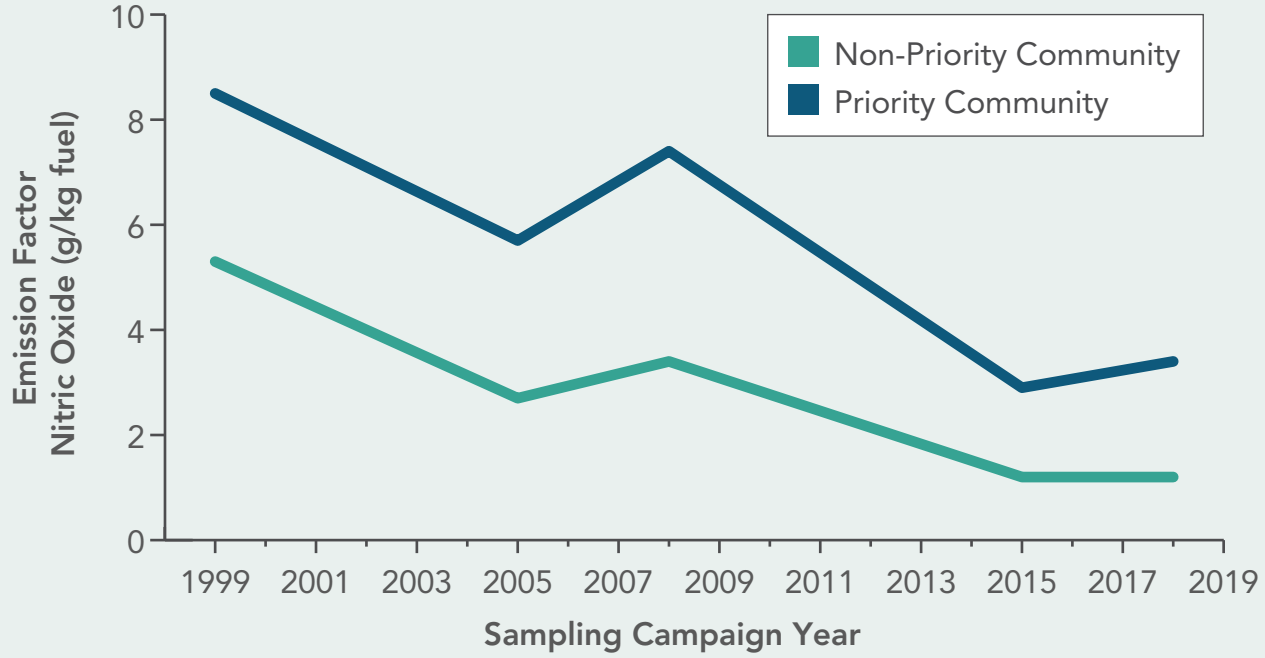
Research Question:

- What would future air quality disparities look like with changing meteorology due to climate change?

In-House Research Highlight: Differences in Vehicle Pollution Levels by Community

This project investigates how communities' socioeconomic status (SES) may have affected light-duty vehicles' exhaust emission characteristics. The in-house effort uses roadside exhaust emissions measurements from 1999-2018 at a a West Los Angeles location. Preliminary results suggest large emission rate disparities between vehicles registered in socioeconomically disadvantaged communities (DACs) and non-DACs, although the disparities have generally decreased during the last two decades (Figure 12). The disparities are partially attributable to the fact that the vehicles registered in DACs tended to be of older model years; but even when adjusted for model year distribution, DAC vehicles still had higher emission rates than their non-DAC counterparts. Findings of the project may be useful to inform community-level emissions inventory, to refine mobile source strategies that improve air quality at both community and regional levels, and to evaluate environmental justice status with respect to mobile source emissions. This information can also aid in designing incentive programs that can help accelerate fleet turnover toward zero emission vehicles.

Figure 12: NO emission rates from passenger vehicles registered in lower versus higher socioeconomic status communities



Economics

Financial incentives are a key part of California's efforts to ensure cleaner cars, trucks, equipment and facilities are operating in California neighborhoods. Incentives help drive the development of new, cleaner technologies and – by speeding up their sale and adoption – help clean up the air. To improve their effectiveness, CARB is prioritizing research to identify opportunities to accelerate new markets and develop metrics to track program benefits and ensure benefits in all communities. In fiscal year 2020-2021 CARB is initiating a new line of research on behavioral economics. This line of research aims to facilitate low-polluting consumer choices and improve regulatory compliance by improving the messaging of program benefits. The results of this research will enhance the performance of incentive programs to encourage purchases and decisions that support strategic development of markets for more sustainable products and services.

Market Transformation

Past and Current Research: CARB has sponsored research projects to help understand variables impacting the growth of the early zero-emission vehicle (ZEV) market, the health of the early secondary ZEV market, optimize our use of incentive funds for new and used clean light-duty vehicles, and to optimize incentives for low- and moderate-income households to retire highly polluting vehicles and acquire advanced-technology vehicles. CARB research is also investigating how to accomplish greater market transformation in the freight and off-road sectors, which have different challenges compared to the passenger vehicle market.

In the light-duty vehicle space, one study found that while consumers prefer conventional hybrid vehicles to plug-in hybrid electric vehicles (PHEVs) or battery electric vehicles (BEVs), incremental sales of cleaner vehicles can be maximized by appropriate weighting of purchase rebate incentives. A similarly weighted offering of guaranteed loans, by contrast, had little effect on the propensity to purchase. These projects have also found that carpool lane access and new-vehicle purchase rebates appear to be helping to expand the early electric car market, with an estimated 2.6 percent increase in sales for every 20 percent increase in miles of nearby carpool lanes, and an estimated 7 percent increase in PHEV sales as a result of rebates. In 2015, used plug-in hybrid cars were holding their value better than electric-only cars, typically selling for about 10 percent more compared to their MSRP than electric cars. An examination of the resale market for plug-in electric vehicles (PEVs), which include both plug-in hybrids and battery electric vehicles, found the mean household income of used PEV buyers to be 25% lower than the income of those buying new PEVs, and that high-occupancy vehicle (HOV) lane stickers added $1,430 to a used PEV's selling price. BEVs, meanwhile, were found to be more affordable in states incentivizing new PEV sales. These early research results are based on a nascent PHEV and BEV vehicle market. It is important to continue this line of research as new-technology vehicles improve and become more mainstream to continue the development of effective policies and incentive programs.

Heavy-duty and off-road equipment purchases are done by fleet operators who base their purchase decisions on total cost of ownership (TOC) and resale value. Many of these vehicles have a long lifetime and slow turnover rate, making it challenging to induce cleaner technology purchase decisions. Incentive programs have been targeted at these sectors both to adopt incremental technology changes and to test advanced vehicles still at the conceptual stage. These programs are meant to nudge the market to uptake advanced clean vehicles and lower TOC to further transform the market.

A project initiated in fiscal year 2016-17 has determined the costs, emissions, and impacts of multiple long-term scenarios to transition to advanced vehicle technologies and alternative fuels in the heavy-duty sector. Results from this project will inform the state on the best uses of electricity and combustion engines to power the heavy-duty sector, and identify the best policies and economic mechanisms to allow California to achieve its long-term goals.

Another current project was designed to assist in the development of cost-effective methods to reduce emissions from agricultural equipment in the San Joaquin Valley (SJV). The results from this work will provide CARB with data on agricultural-related businesses to enhance CARB's existing cost and economic impact methodologies. This information will be used to develop a program for mobile agricultural equipment in the SJV to transform their fleet to clean technologies at the lowest cost.

Researchers will also evaluate the cost-effectiveness and technological feasibility of reducing GHG and criteria pollutant emissions by electrifying or hybridizing equipment for a variety of off-road applications, including the cost of supporting infrastructure. A recently completed project on improved aftertreatment systems for small off-road engines identified comparatively cost-effective opportunities to reduce oxides of nitrogen (NO_X) emissions from these engines by up to 80% (see research highlight titled: Equipping small off-road diesel engines with advanced aftertreatment).

Future Research: Accelerating market transformation and identifying barriers to adoption of advanced technologies will continue to be research priorities as the state nears its 2045 carbon neutrality goal. Governor Newsom's Executive Order N-79-20, signed in September, 2020, mandates that all new passenger vehicles be zero-emission by 2035, and that all operations of medium- and heavy-duty vehicles be 100% zero-emission – where feasible – by 2045. A combination of incentives and regulatory and other complementary measures will be required to achieve these goals. Continued research on this topic will ensure that California achieves the greatest emission reductions possible per dollar of incentive funding spent, while also promoting the uptake of zero-emission technologies.

Research Question:

- What are the opportunities for incentive funds to encourage consumers, fleets, and sectors to accelerate conversion to advanced technology (e.g., zero-emission vehicles, equipment, etc.)?

The barriers to the sustainability of new markets also need to be assessed, particularly for low-emission vehicles, but also for appliances that use low-global-warming-potential refrigerants such as heat pumps, water heaters, and clothes dryers. Moving forward, CARB will investigate barriers to adopting cleaner, low emitting technologies and transportation modes with a focus on equity and access.

Research Question:

- What are the barriers to sustainability of new markets (e.g., for low-emission vehicles and appliances using low-GWP refrigerants) and transportation modes, and how can these be overcome?

Program Assessment

Background and Current Research: Identifying and quantifying the benefits of air quality improvements from policies and programs is at the core of CARB's economic research mission. The value of program benefits depends on the nature and the magnitude of health and environmental damages avoided by program implementation. A recently implemented project will create a user-friendly tool to evaluate program benefits. This project will examine the social cost of criteria and air toxic pollution that is not accounted for by conventional estimates of the social cost of carbon. This will include new health metrics for cancer risk. The tool will also calculate how the distribution of program benefits affects priority communities.

CARB's economic research is also supporting the implementation of sustainable community strategies (SCSs) adopted under Senate Bill (SB) 375.[33] Several CARB-sponsored studies include economic analyses that will help CARB assess the benefits of SCSs in reducing climate change emissions from housing and transportation. One major housing study will explore opportunities for housing development in transportation-efficient and healthy, high opportunity areas statewide

33 Steinberg, Chapter 728, Statutes of 2008

and will examine how pursuing these opportunities can equitably distribute benefits across socioeconomic cohorts.

A project that wrapped up in 2018 developed indicators that can be used in a future statewide monitoring system for tracking whether land use development patterns are moving in a direction consistent with SB 375 goals. One indicator in this project is residential proximity to the workplace. The project also focuses on identifying and communicating the local and regional economic benefits of increasing California's supply of affordable infill housing.

The economic, environmental, and social equity impacts of policies designed to relieve and manage traffic congestion were analyzed in a series of white papers recently completed. Their findings indicate that a variety of strategies currently exist and have the potential to reduce emissions, particularly when used in combination. However, many measures have the potential to lead to inequitable impacts. More empirical data are needed to quantify these impacts in order to implement strategies that benefit all communities.

Transitioning California's heavy-duty vehicles (HDV) and off-road equipment (ORE) to zero- or near-zero-emission technologies such as advanced-technology vehicles and alternative fuels is a strategic focus for CARB's research plan. A performance review of existing HDV/ORE incentive programs will guide the development of an incentive program evaluation tool that will be used to recommend clean technology incentives tailored to specific sectors, regions, and applications. This work will synthesize current low-carbon transportation incentive programs, and develop a performance evaluation tool that quantifies their emissions reductions, health and ancillary benefits, and cost-effectiveness. This research will identify potential policy and incentive strategies that promote greater adoption of low-carbon technologies in the heavy-duty and off-road sectors. Additionally, this research will forecast low-carbon transportation technologies' attainment of cost parity or market acceptance relative to conventional technologies without incentive program supports.

Because nearly 18 percent of NO_X emissions in the San Joaquin Valley come from agricultural equipment engines, CARB also studied the economic impacts of additional regulatory programs to reduce criteria pollutant emissions from agricultural equipment. This data-driven framework for modeling regulatory impacts on San Joaquin farms and farming communities found that small increases in regulatory compliance costs would have little effect on the regional economy, but also revealed important differences in production costs between small and large farms. Findings will guide adaptive management of CARB's incentive funding program for upgrading agricultural equipment.

Future Research: Past regulations and incentive funding have put California on the path towards meeting our GHG and air quality targets. However, additional research is needed to identify the best uses of incentive funding to meet stricter long-terms goals, ensure that economic prosperity and environmental sustainability can be achieved together, and that public incentive funds are used in an equitable manner. Research on the efficient deployment of incentives is needed to ensure emission reductions are optimized across vehicle and driver populations. Future research should also focus on deepening CARB's understanding of the economic, health, and environmental benefits of incentive funding and the Greenhouse Gas Reduction Fund investments (California Climate Investments) in priority communities, and how these benefits can be amplified to improve equity outcomes.

Research Question:

- What additional economic, health, and environmental metrics can be employed to understand the benefits of investments for priority communities?

As the transformation of California's vehicle fleet gains momentum, research continues to focus on transportation equity, new mobility options and evaluation of ongoing incentive programs. The benefits to air quality improvement and health will be substantial, but more work will be needed to quantify those co-benefits.

Research Question:

- What are the AQ, health, and GHG benefits of the incentive programs for advanced technology vehicles and what additional opportunities exist to improve AQ in priority communities?

Behavioral Economics

Background and Current Research: There are limits to what can be achieved through regulation. For California to meet its long-term air quality and climate goals, voluntary actions will be needed to reduce GHG and criteria pollutant emissions associated with waste, consumer product choices, and personal transportation. Examples of low-polluting voluntary practices that can reduce emissions from these sources include composting food waste, purchasing low-polluting consumer products, choosing to commute via public transportation, or purchasing a zero-emission vehicle.

Behavioral economics is a new tool employed by governments, academics, and the private sector. It evaluates decision environments and accounts for factors that affect what people choose or how they act. This information can be applied to make changes that result in better outcomes, such as by presenting information in a way that makes it easy for the consumer to compare the most important aspects of available options. For example, behavioral economists collaborated with private companies to make retirement decisions less complicated, which resulted in a large increase in the portion of employees who took advantage of the company's retirement matching program. CARB can likewise evaluate programs to determine if their decision environments unknowingly discourage Californians from taking actions that would benefit themselves and help the state to meet air quality and climate change goals. CARB is applying behavioral economics by studying what motivates Californians and testing those assumptions in real-world settings to ensure the validity of research findings and to obtain robust estimates of the impact of policy changes.

CARB is currently initiating a study to review how behavioral economics can be used to encourage and support low-polluting decisions, including the motivations and information that affect choices. This research will inform a pilot study conducted in collaboration with California Department of Resources Recycling and Recovery (CalRecycle) aiming to reduce waste. The waste sector makes up roughly 20% of methane emissions in the state, predominantly from methane that escapes landfill gas collection systems. Senate Bill (SB) 1383[34] has set a target to reduce organic waste to 25% of the 2014 level by 2025—an ambitious goal that will be challenging to achieve through mandates and penalties alone. The pilot in this study will use a communications campaign to encourage voluntary reductions in waste and carefully measure the campaign's effect. Reducing waste could save consumers money while helping CARB to meet regulatory goals.

Future Research: CARB staff hope to leverage the benefits of behavioral economics to achieve greater compliance with regulations and improve understanding of the barriers to compliance. In some cases, effective use of behavioral economics could encourage sufficient voluntary action to eliminate the need for regulation.

Research Questions:

- How can behavioral economics be used most effectively to support short and long-term goals?
- How can behavioral economics be leveraged to facilitate improved regulatory compliance for new and existing regulations?
- How can advanced analytical methods and behavioral science be harnessed to inform policies and streamline enforcement?

Effective communication is a key component of informing and motivating voluntary actions. CARB's in-house behavioral economics work has the potential to assist a wide variety of programs to

34 Lara, Chapter 395, Statutes of 2016

improve outreach and test which messages best inform consumers. Real-world tests are critical because they provide credible measurements of how well messages engage Californians that cannot be achieved through other means such as surveys or interviews. The results from this research will help inform how other CARB programs can more effectively encourage Californians to engage with information. There are many opportunities at CARB to improve the ease of compliance and communication of regulations. Better compliance tools and communication can help regulated entities meet compliance requirements, ultimately saving them money, while helping the state meet its air quality and climate goals.

Research Questions:

- How can we improve the dissemination of information on the benefits of low-polluting consumer options in order to facilitate voluntary adoption?
- How can educational campaigns best be utilized to encourage lower polluting choices (e.g. reduced waste)?
- How can CARB better communicate regulatory requirements to encourage compliance?

Air Quality – State Implementation Plans (SIP)

CARB's air quality research provides the technical and the scientific foundation that supports the development of the State Implementation Plans (SIPs). These plans describe the path by which an area will attain the National Ambient Air Quality Standards (NAAQS) set under the Clean Air Act. Research in this category has improved the robustness of the emission inventories, the understanding of atmospheric chemical mechanisms, and the performance of regional air quality models over the past decades. CARB continues to design and execute numerous laboratory, field, and modeling studies in coordination with external researchers and stakeholders to improve our understanding of the complex air pollution problems throughout the state. CARB will continue to evaluate air pollution control programs and the most viable air quality management strategies to meet region-specific air quality challenges. Future research will develop stronger connections between air quality and climate research to pursue co-benefit pathways to meeting California's multi-faceted goals.

Ozone Sensitivity and Transport

Precursor Sources

Background and Past Research: Tropospheric ozone is a criteria pollutant that has negative impacts on human health and the environment. Despite decades of air quality improvements, tropospheric ozone levels in regions like the San Joaquin Valley (SJV) and the South Coast Air Basin (SoCAB) continue to exceed the health-based ozone standards. Atmospheric ozone is produced by photooxidation of volatile organic compounds (VOCs) and NO_X. Therefore, effective mitigation of ozone pollution will require additional research on the sources of its precursor gases and updated knowledge on the complex atmospheric processes that form ozone. Photochemical modeling is a key tool used to develop SIPs for ozone. Modeling results are sensitive to the emission inventories as well as the spatial and the temporal distributions of ozone precusors: VOCs and NO_X.

Recent studies have demonstrated the growing importance of urban VOC sources as transportation-related emissions continue to decline rapidly in California. VOC sources like volatile chemical products (VCPs) are emerging as an important source of urban VOC emissions that can add to both regional ozone and aerosol burdens. The importance of biogenic VOCs is also growing in California because of their relative abundance in our atmosphere during the summer months. Identifying regionally- specific VOCs leading to ozone exceedances would support future SIP development particularly in densely urbanized areas within the SoCAB.

Previous field experiments evaluated ozone forming potential using a set of portable smog chambers in the greater Los Angeles region. The results showed good agreement between laboratory studies, field measurements, and a photooxidation model. With the goal of independently evaluating the quickest and the most effective path to ozone reduction in the SoCAB, CARB has funded a field project that began in fiscal year 2019-20 to directly measure the sensitivity of ozone to perturbation of precursor VOCs and NO_X. The project measures the response of ozone after addition of VOCs and NO_X into portable smog chambers filled with ambient air. The measurements will be conducted at three sites, each for four weeks, during the summer months in the SoCAB. The results will provide the first statistically significant direct ozone sensitivity measurements. These will be used to validate the predictions of chemical transport models used to develop optimal ozone control strategies.

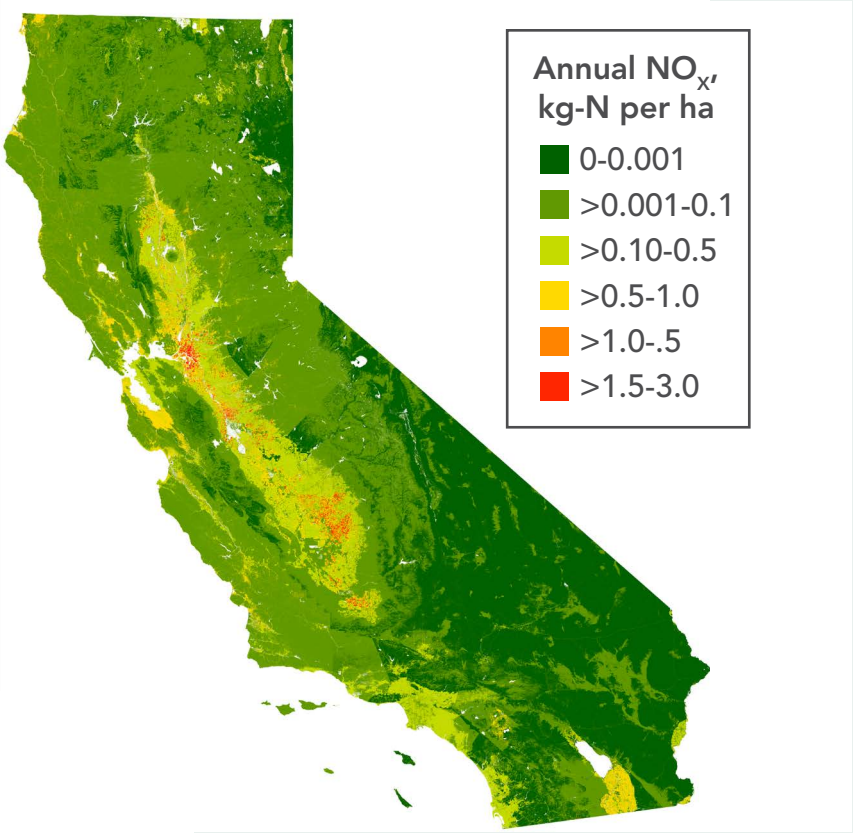
CARB has also funded a project that began in the 2019-20 fiscal year to map the spatial distribution of VOCs in the SoCAB and the SJV. The project used the NASA DC-8 aircraft to collect hundreds of air canister samples at or below 1500 meters above ground as it flew over the two air basins. These air canister samples were analyzed in a state-of-the-science laboratory to quantify a wide variety of VOCs captured during the airborne campaign. The measurements will provide information about the vertical and horizontal distribution of various VOCs, which will ultimately fill the knowledge gaps on the ozone forming potentials in these two regions.

Current Research: CARB is funding two field projects to study VOCs and NO_X in the SJV and the

SoCAB in the 2021-22 fiscal year. The first project will be conducted in partnership with the South Coast Air Quality Management District and will carry out high-precision airborne measurements of VOC and NO_x fluxes at a spatial resolution useful for CARB emission inventory evaluation. The second project will conduct detailed chemical speciation measurements of ambient VOCs at a ground site to evaluate the variety of species and their source contributions. These projects are

In-House Research Highlight: Evaluating the Impact of Soil NO_x in Air Quality:

Figure 13: Model derived soil NO_x emissions in California



Nitrogen oxides (NO_x) are criteria air pollutants that can react with other chemicals in the air to form particulate matter and ozone, both of which pose adverse impacts to human health and the environment. Control of NO_x emissions is critical to improving air quality in California. Soils are a known NO_x source, especially in agricultural areas where large amounts of nitrogen fertilizers are used to increase crop yields. The nitrogen chemicals in soil can be converted into various nitrogen gases, including NO_x, by soil microorganisms. The contribution of soil emissions to the total NO_x budget varies by region, depending on land uses and management activities. CARB has been conducting in-house research to study NO_x emissions from soils in California. The project combines biogeochemical modeling, air quality modeling, long-term measurements across California, and satellite observations to evaluate the contribution of agricultural sources to ambient NO_x. This study modeled soil NO_x emissions from different land covers in California and evaluated the impacts of soil NO_x emissions on the formation of ambient particulate nitrate in the San Joaquin Valley (SJV), where cropland is the dominant land use. Our results indicate that soil NO_x is a relatively minor fraction of the total NO_x budget in California and has a minor effect on atmospheric concentrations of particulate nitrate in the SJV. Additional ambient and satellite data analyses show traffic combustion being the dominant source of NO_x emissions in both urban and agricultural regions of the SJV.

designed to update the current inventory of VOCs and NO_X to improve the performance of the chemical transport models used for SIPs.

Future Research: Additional work is needed to enhance our understanding of the ozone exceedance events in California. The impacts of shifting VOC and NO_X emission sources, changing lifetime of NO_X, and changing particulate matter (PM) on ozone production efficiencies are yet to be explored. Based on existing knowledge and ongoing research and in consultation with experts and stakeholders, CARB staff have identified the following key research question:

Research Question:

- What are the dominant VOC emissions (e.g. VCPs and biogenics) leading to ozone formation during ozone exceedance events in the SoCAB?

Ozone Sensitivitiy and Transport: Transported Ozone

Background and Past Research: In addition to atmospheric ozone that photochemically forms within California, ozone transported from outside of the state's borders can also influence the surface air quality. This is also referred to as baseline or background ozone, which is defined by U.S. EPA as observed ozone that is uninfluenced by recent U.S. emissions. On the west coast, baseline ozone can be affected by stratospheric intrusions and long-range transport. The effect of baseline ozone on surface monitoring sites can be quite significant. It can directly force surface ozone levels to exceed NAAQS, which is 70 ppb, and or indirectly affect the surface ozone-NO_X-VOC chemistry, making attainment of the more stringent ozone standard increasingly difficult. Understanding the variability and the levels of baseline ozone is critical for attainment of future health-based ozone standards.

A large number of observations around the world have documented the presence of elevated ozone levels aloft that could potentially transport down toward the surface and 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.

CARB began addressing these pertinent questions in 2016 through partnerships with San Jose State University, NOAA, NASA, Bay Area Air Quality Management District (BAAQMD), and San Joaquin Air Pollution Control District (SJVAPCD) through the California Baseline Ozone Transport Study (CABOTS) (see Research Highlight: Novel Dataset Advances Study of San Joaquin Valley Ozone). The field measurements have provided detailed observations of ozone over California, and highlighted the importance of both surface ozone and ozone aloft in the context of increasing baseline ozone and more stringent air quality standards. Given the challenges in modeling ozone in the mountainous terrain of the western U.S., this study provided useful insight into the sources of elevated surface ozone observed in the rural western U.S.

Future Research: As CARB continues to implement various air pollutant emission control strategies, distinguishing the influences of regionally-produced ozone and transported ozone would lead to the development of effective policies addressing ozone attainment in California, especially as local and regional emissions are reduced. Moving forward, CARB research will continue to investigate the impacts of transported ozone on local and regional air quality.

Research Question:

- As regional emissions are reduced, how will baseline ozone and changing meteorology/ climate offset the air quality benefits expected from California's air regulations and policies?

Research Highlight: Novel Dataset Advances Study of San Joaquin Valley Ozone

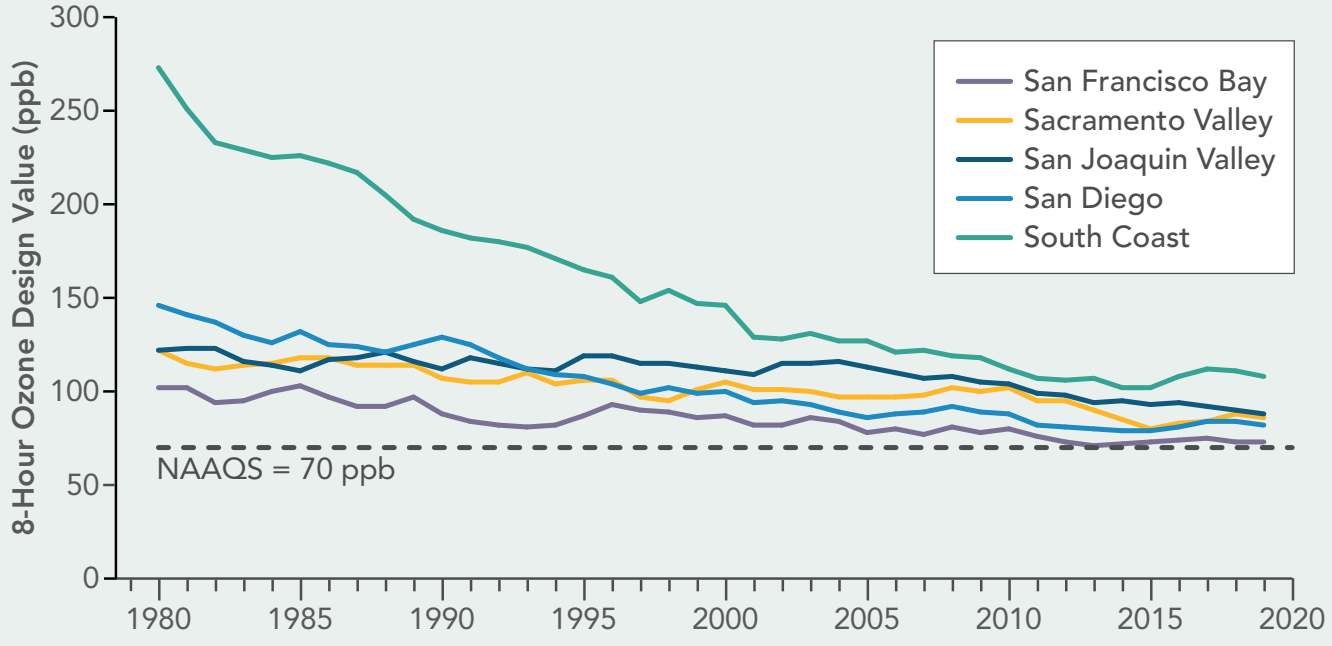
Ozone is one of the six pollutants identified by the U.S. Clean Air Act Amendment of 1970 as particularly harmful to human health. California emissions that worsen surface-level ozone have been reduced by a factor of five since 1980, but residents of the San Joaquin Valley and South Coast air basins remain exposed – especially in summer months -- to ozone levels that exceed national air quality standards (Figure 14). Among the challenges CARB faces as it develops emission control plans to meet those standards is the lack of detailed information about the influence of "baseline" ozone, transported aloft across the Pacific Ocean, on surface-level ozone in the state's non-attainment areas.

The main objective of the California Baseline Ozone Transport Study (CABOTS) was to gather data on daily changes in ozone layering at the coast (upwind of California) and in the Central Valley (downwind of the major emission sources and coastal mountains). This novel dataset will illuminate meteorological mechanisms that determine the vertical distribution of ozone and improve analysis of the impacts of background ozone and other pollutants transported from afar at high altitude on surface-level ozone in the San Joaquin Valley.

Initial review of over 100 coastal studies, 440 hours of vertical ozone profiles over Visalia, targeted airborne surveys and surface ozone data from May to August of 2016 (Figure 14) showed ozone levels in Pacific air masses crossing the California coast at Bodega Bay exceeded the national air quality standard on average once every five days. At Half Moon Bay, ozone levels observed within 1-2 km of the surface – where they are most likely to impact human health -- were consistently higher than those predicted by one commonly used analytic tool. The observation dataset also revealed layers of more concentrated ozone between 4 and 6 km above the surface, consistent with biomass burning and transport from Asia. Many of these higher layers most likely passed over the Sierra Nevada and into the Intermountain West.

In short, the unprecedented CABOTS dataset shows every sign of delivering on its promise of new insights into the transport and mixing processes contributing to the high surface ozone levels found in California.

Figure 14: Decadal trends in ozone concentrations from three different air basins in California compared to the national average and the current NAAQS



Identifying Sources of $PM_{2.5}$: Wildfires and Prescribed Fires

Identifying Sources of $PM_{2.5}$: San Joaquin Valley $PM_{2.5}$

Background: The number of large and destructive wildfires in California has been increasing because of a combination of past fire suppression and other land management practices, as well as a warming and drying climate. The pollutants emitted from wildfires degrade air quality and create health risks. Prescribed fire is used as one of the pathways to mitigate wildfires and to reduce catastrophic air pollution episodes. Quantifying the chemical composition and properties of emissions from wildfires and prescribed fires will help improve modeling of their impacts on human health and climate and also enable a better assessment of the benefits of prescribed fire over wildfire smoke impacts.

Current Research: CARB has funded a project in the 2019-20 fiscal year to study the emissions of prescribed fires. The measurements will be conducted via ground-based and airborne sampling platforms during controlled burn activities. This project will provide emission profiles from a representative set of controlled burns in a mixed conifer forest in California. Measured emission factors (EFs) will be used to improve the First Order Fire Effects Model estimates of short-lived climate pollutants (e.g., BC and CO_2) and other air pollutants (e.g., NO_X, CO, $PM_{2.5}$, selected VOCs and air toxics). Outcomes will include improved emission factors from controlled burns of managed and previously unmanaged forest; and comparison to emission factors from wildfires, including recently-measured and published values. The results of this research project, along with its unique database (i.e., chemical species and emission factors), will be a valuable resource for identifying specific chemicals in air masses impacted by biomass burning plumes and understanding the dominant source materials burned, fire characteristics, atmospheric transformations, and health implications. This project will also provide critical inputs for air quality modeling, and guidance for management efforts to reduce wildfires that are consistent with optimizing forest carbon storage, protecting public health, and promoting environmental justice.

CARB staff also began in-house research on wildfire and prescribed fire emissions using CARB's custom-built mobile measurement platform (MMP) in 2019. To date, CARB's MMP has been deployed during multiple wildfire events to estimate the emission factors of criteria and short-lived climate pollutants. The results will inform CARB's NWL program by improving the predictive understanding of how air pollutant emissions from wildfires and prescribed fires will change based on burning conditions (e.g. hot-burning, smoldering), meteorology, and fuel type (e.g. vegetation, human-made objects). See In-House Research Highlight: Understanding Wildfire Behavior and Emissions.

Future Research: More research is needed to constrain the emission factors and understand the chemical transformations of VOCs and organic aerosols emitted from wildfires and prescribed fires. The impacts of fires on ambient ozone require additional investigation to better inform CARB's NWL and air quality programs. In addition, improved parameterization of the plume injection height is critical for fire forecasting. Addressing these questions can enhance models to better predict the influence of fires on air quality. Forecasting when and where to expect air pollution exposure risks from wildfires and prescribed fires (if any) can support early warning systems that allow communities, and in particular vulnerable receptors, to mitigate exposure risk and protect public health.

Research Questions:

- What are the differences in air pollutants from wildfires and prescribed fires?
- How does exposure to emissions from various fires (e.g. prescribed burning vs. wildfires) affect health?
- Can we more clearly communicate the benefits of prescribed burning vs. wildfires?

Fires in the Wildland-Urban Interface

Background: The impacts of large wildfires on air quality and health have been studied in a number of research studies worldwide. However, the impact on air quality from wildfires in urbanized areas

has received less attention. Once wildfires extend into urbanized areas, a different mix of fuel is available. Combustible materials from house structures, house contents, vehicles, sheds, garages and other objects around a structure will burn and release potentially toxic chemicals into the air, which could increase the health risk to community members in the vicinity of the fire and to fire fighters. Tens of thousands of structures and more than 100 human lives have been lost in recent fire events throughout California. The 2018 Camp Fire was the deadliest and most destructive wildfire in California history, due in part to the large number of structures that were burned.

Existing methods for estimating emissions from structure and car fires are not as developed as they are for wildland fire. Modelers are motivated to include structures and vehicle emissions in models to examine the potential impacts on fire plume chemistry and downwind air quality when these sources are mixed with emissions from burning vegetation. There is major concern regarding post-fire air quality impacts, such as from wind transport of toxic materials from burned sites. Overall wildfire smoke composition produced from combustion of natural biomass and human-made materials is complex and dynamic, making characterization and modeling difficult.

Future Research: More research will be needed to understand how emissions due to fires are affected by different fuels, land management histories and incursion into the wildland-urban interface. In particular, more research is needed to understand how this complex mix of natural and human-made material emissions impact health, $PM_{2.5}$ concentrations and the climate.

Research Question:

- What are the health, air quality and climate impacts of emissions produced by wildfire incursions into populated areas?

San Joaquin Valley $PM_{2.5}$

Background and Past Research: Although air quality in the SJV has improved in recent years, the area still exceeds the $PM_{2.5}$ National Ambient Air Quality Standard. Conditions that have led to recent $PM_{2.5}$ exceedance events must be better understood to attain future $PM_{2.5}$ standards. A project that began in fiscal year 2017-18 deployed an advanced air quality analyzer in the SJV to collect measurements that will allow researchers to identify sources and chemical pathways that lead to $PM_{2.5}$ formation. This project measured concentrations of $PM_{2.5}$ species with sub-hourly time resolution, which can bridge the gaps between the long-term measurements and detailed observations from short-duration field campaigns. The results from this study will contribute to the development and refinement of effective and appropriate future $PM_{2.5}$ control strategies for the SJV.

Future Research: Building upon this work, CARB's Research Program will continue to focus on innovative methods to identify remaining precursors of $PM_{2.5}$ pollution and atmospheric processes that affect the air pollution levels in order to improve air quality, and thus health outcomes, for impacted communities.

Research Question:

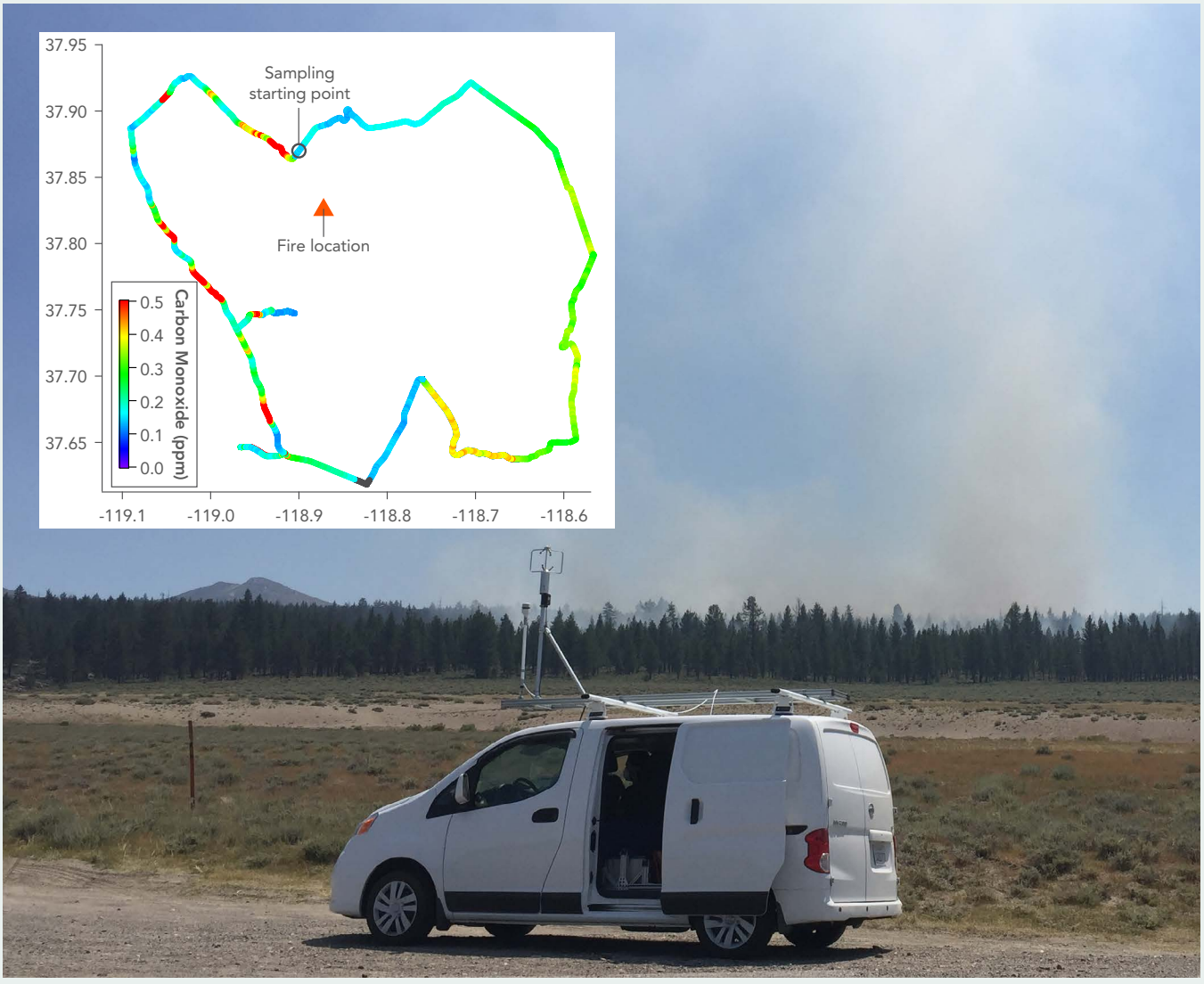
- What are the remaining sources of ammonia, $PM_{2.5}$, and $PM_{2.5}$ precursors in the San Joaquin Valley? How is the air quality in downwind communities affected?

CARB has funded several projects to improve the PM modeling for the SJV, which is needed to address the more stringent annual-average $PM_{2.5}$ standard adopted by the U. S. EPA in 2012. These projects have incorporated field observations into improved models for the stagnation events leading to $PM_{2.5}$ exceedances. These stagnation events occur under particular meteorological conditions, thus more work is needed to model these conditions appropriately. The identification and removal of biases in model inputs and the further development of new processes for $PM_{2.5}$ nitrate formation, in particular will allow regional chemical transport models to predict the effects of future emission control strategies to lower $PM_{2.5}$ concentrations that are expected in the coming decades.

In-House Research Highlight: Understanding Wildfire Behavior and Emissions

There is increasing interest in studying wildfires and their impact on air quality and climate. Wildfires emit pollutants like NO_X, carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter that can directly and indirectly affect health. Pollutants like CO_2 and black/brown carbon are also emitted from wildfires and can have lasting effects on global climate. The characteristics of wildfire emissions are complex and can vary by geography, meteorology, burning conditions, and materials being burned (e.g. vegetation, urban buildings). Meteorology also plays a critical role in how wildfire emissions are transported to population centers. As California experiences more intense wildfire events, it becomes imperative that the effects of wildfires on our air quality and climate are better understood to improve air management strategies. CARB staff began in-house research on wildfire emissions using CARB's custom-built mobile measurement platform (MMP) in 2019. The MMP was deployed to the vicinity of wildfires to quantify the emission factors for criteria and short-lived climate pollutants. The results will inform CARB's Natural and Working Lands (NWL) program by improving the predictive understanding of wildfire behavior and emissions.

Figure 15: Measuring air pollutants associated with wildfire plumes using CARB's mobile measurement platform



Research Question:

- How do meteorological conditions (temperature, humidity, planetary boundary layer height) influence the formation and seasonal cycle of $PM_{2.5}$ in the San Joaquin Valley? How can models better predict the conditions leading to National Ambient Air Quality Standard exceedances?

Studies also indicate that particulate nitrate is formed via distinct daytime and nighttime chemical pathways, the relative importance of which are not fully established. For the nocturnal pathway, nitrogen oxides react with ozone overnight, forming dinitrogen pentoxide (N_2O_5) that can react with preexisting PM to form new particulate nitrate. It has been suggested that this chemistry occurs efficiently in aloft layers decoupled from the surface. At sunrise, the rapid expansion of the boundary layer serves to entrain particulate nitrate formed aloft at night, increasing the surface PM concentration. Because this nitrate production occurs above the surface, it is difficult to characterize. Further research is needed to improve the characterization of the evolving near-surface vertical distribution and the chemical composition of PM in the San Joaquin Valley.

Research Question:

- How can we directly measure the vertical chemical composition of PM in the San Joaquin Valley to refine the regional air quality model(s)?

Identifying Sources of $PM_{2.5}$: South Coast Air Basin $PM_{2.5}$

Background and Past Research: CARB research has specifically addressed the complex problem of modeling secondary organic aerosol (SOA) formation. Organic aerosols are a significant component of $PM_{2.5}$ in California. As emissions from more dominant air pollution sources continue to decrease, less prominent SOA precursor sources become more important for future attainment of the $PM_{2.5}$ standard. Hence, the sources, impacts of existing controls, precursors, and processes that form SOA are the focus of several ongoing research projects. Increasing our knowledge of the processes associated with SOA formation can further refine the performance of regional air quality models and support the development of air quality improvement strategies.

CARB has funded projects to address questions concerning organic compounds used in consumer products. These projects have answered questions about the environmental fate of currently-exempt low-vapor-pressure volatile organic compounds (LVP-VOCs) and the actual impact of these compounds on ozone and SOA formation. While the results of these experiments are useful to calibrate models and provide SOA formation relative to chemical structure of the compounds, it is noted that real atmospheric conditions vary widely and the results of this work only represent SOA formation under certain environmental conditions. Hence, further detailed studies are required to determine functional relationships of other LVP-VOC compounds to improve future $PM_{2.5}$ modeling.

A current project is evaluating, compiling, and conducting SOA chamber experiments as a supplement to an existing SOA database being compiled for UCR and Caltech. This will improve understanding and modeling of SOA mechanisms to address inconsistencies between the experimental results from various environmental chamber studies and the chemical mechanisms that take place in the real atmosphere. Data compared between the two chambers and input into models provide the basis to understand the atmospheric chemistry and aerosol formation occurring in the SoCAB.

Future Research: Secondary organic aerosol responds differently to emission controls depending on the atmospheric ratios of NO_X and VOCs. The abundance of these chemical compounds in our complex atmosphere determines how SOA and $PM_{2.5}$ are formed. A future research project will help determine the $PM_{2.5}$ SOA response to NO_X and VOC perturbations to further inform and optimize CARB's emissions control programs.

Moving forward, research will have to address the uncertainties surrounding the fate of VCPs under atmospheric conditions. This will be crucial for the refinement of information used in regional air

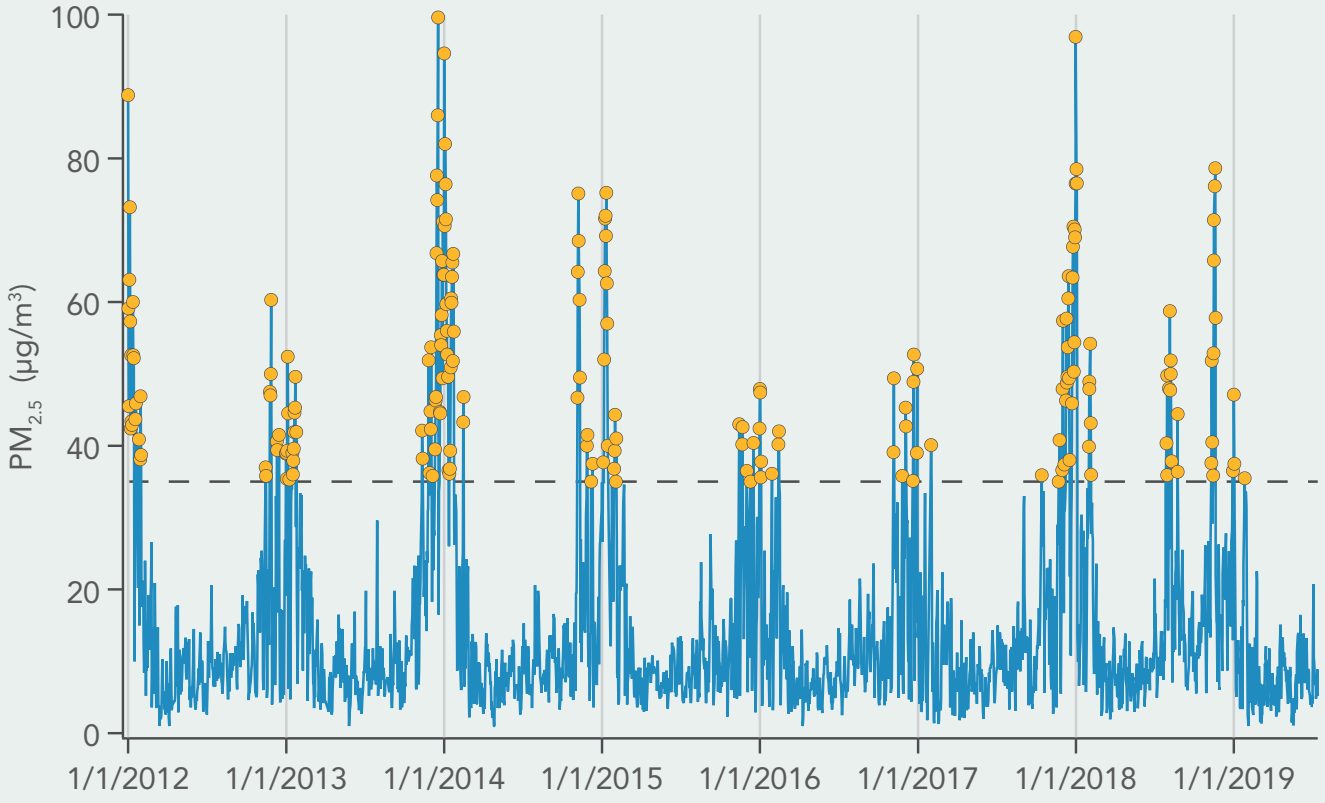
Research Highlight: San Joaquin Valley Deep Dive Exposes Drivers of Wintertime Pollution Episodes

Hemmed in by mountains to the east, west and south and blanketed by warmer air aloft, polluted air stagnates on the San Joaquin Valley (SJV) floor during winter periods of calm, sunny weather. Despite persistent efforts to control it, wintertime particulate matter (PM) air pollution in the San Joaquin Valley (SJV) of California remains the worst in the state, often exceeding the national air quality standard for fine PM ($PM_{2.5}$) (Figure 17). To help solve this intractable problem, regulators need to understand the sources and atmospheric processes that contribute to the Valley's high PM levels.

Aerial and ground measurements made in and around Fresno during two severe pollution episodes in January and February 2013 were analyzed by UC Davis researchers to refine and update CARB's understanding of wintertime particle pollution in the SJV. Isolating specific pollutants and tracking them day and night, researchers found two types of particle pollutants were primarily responsible for elevated levels of $PM_{2.5}$ pollution in the SJV during calm winter weather: organic aerosols and nitrate.

While the concentration of total particle pollution remained more or less constant around the clock, surface level pollution at night was found to be primarily driven by organic aerosols (from wood burning, cooking and vehicle emissions, e.g.). Daytime particle pollution, meanwhile, was found to be driven by nitrate formed aloft during the night and mixed down to the surface as the next morning's sun warmed the valley. Researchers recommended that measures to further reduce wintertime particulate pollution at the surface of the SJV should focus on controlling emissions of nitrogen oxides and organic aerosols.

Figure 16: Wintertime $PM_{2.5}$ in the San Joaquin Valley. Yellow dots show $PM_{2.5}$ exceedance days



quality models, which in turn help predict the outcome of mitigation methods. More work is needed to improve the understanding of SOA precursor sources, atmospheric chemistry, and potential control strategies to improve the regional air quality.

Research Question:

- What are the opportunities for controlling sources of VOCs (e.g. VCPs and biogenics) in the South Coast?

Emission Reduction Strategies

Emission Reduction Strategies: Imperial Valley $PM_{2.5}$

Background: The Imperial Valley, a NAAQS non-attainment area for particulate matter (PM), is the second largest agricultural region in California and is home to the Salton Sea. The communities surrounding the Salton Sea, with predominantly Hispanic/Latino roots, disproportionately suffer from environmental pollution, health disparities, and poverty. Dust emissions from agricultural activities, dried Salton Sea lakebed, and arid lands are suspected to contribute to the PM burden in the valley. Studies have projected that given a combination of climate change and other circumstances the Salton Sea water levels are likely to be further reduced in the future. This will potentially impact air quality due to fugitive dust from wind erosion of the exposed lakebed playa. What is currently unknown is the chemical composition of the dust and the relative contributions from pesticides and other sources, variability of emissivity of dust due to soil variability on the playa, whether this can be determined and predicted, and how it can best be controlled or mitigated. There are also concerns over hydrogen sulfide emissions and how they are impacting communities in the area. Air quality concerns over PM_{10}/$PM_{2.5}$ levels, chemical composition of fugitive dust, impacts of fugitive dust on human health, and methods for suppressing fugitive dust are major research topics of discussion.

Future Research: Improving the characterization of other sources of air pollutant emissions such as traffic at the California-Mexico border, atmospheric transport of air pollutants from Mexico, unpaved roads, industrial operations, and biomass and waste burning will be critical when prioritizing air pollution control strategies in the Imperial Valley. The heterogeneity of the air pollutant sources and their varying influences on local and regional air quality highlight the challenges in developing a comprehensive air pollution reduction strategy for the Imperial Valley that is effective at reducing adverse health outcomes equitably across all communities. Priority should be given to investigating reduction strategies for each of the sub-regions/communities within the Imperial Valley by consolidating region-specific information on air pollutant sources, atmospheric processes, air quality monitoring data, and air pollution exposure studies.

Research Question:

- What air pollution reduction, mitigation and health improvement strategies will most effectively and efficiently improve air quality and health in all Imperial Valley communities as quickly as possible?

Emission Reduction Strategies: Greenhouse Gas Mitigation and Air Quality Co-Benefits

CARB is researching the influence of climate-oriented emission reduction strategies on regional air quality to ensure that California's air quality and climate objectives are achieved simultaneously. This is especially important when addressing sources that co-emit both types of air pollutants.

CARB funded a project that utilizes ambient measurements and chemical transport modeling to evaluate the greenhouse gas (GHG) emissions and the air quality impacts of California dairies upon implementation of various alternative manure management practices. The results from this project will help determine which mitigation strategies are most effective in reducing GHG emissions while improving regional air quality, and how these co-benefits can be maximized.

CARB is also conducting in-house research that supplements this effort by utilizing satellite remote sensing and ground-level mobile measurement data to study the emission sources and the ambient

levels of ammonia (NH_3) in the SJV. Although $PM_{2.5}$ formation in the SJV is limited by the availability of NO_X, atmospheric NH_3 plays an important role in the formation of $PM_{2.5}$. CARB will continue to leverage in-house expertise to identify and mitigate emission sources.

Although there are significant numbers of in-house, sponsored, and leveraged research activities that support air quality improvement strategies and GHG emission reduction efforts, additional research may be able to further accelerate California's progress towards its climate and air quality goals.

Research Question:

- What new opportunities are there for controlling sources of ammonia, $PM_{2.5}$, and $PM_{2.5}$ precursors?

Mobile Sources

Mobile sources include light-duty vehicles, heavy-duty vehicles and off-road equipment. Together these sectors comprise the largest single source of greenhouse gases (GHGs) in the state and remain a large source of criteria pollutants. CARB's mobile-source emissions Research Program supports California's effort to meet National Ambient Air Quality Standards (NAAQS), reduce health risk from toxic air contaminants, and meet GHG and air pollution reduction goals. The results of these research efforts support the development and implementation of regulations and incentive programs to reduce transportation related emissions.

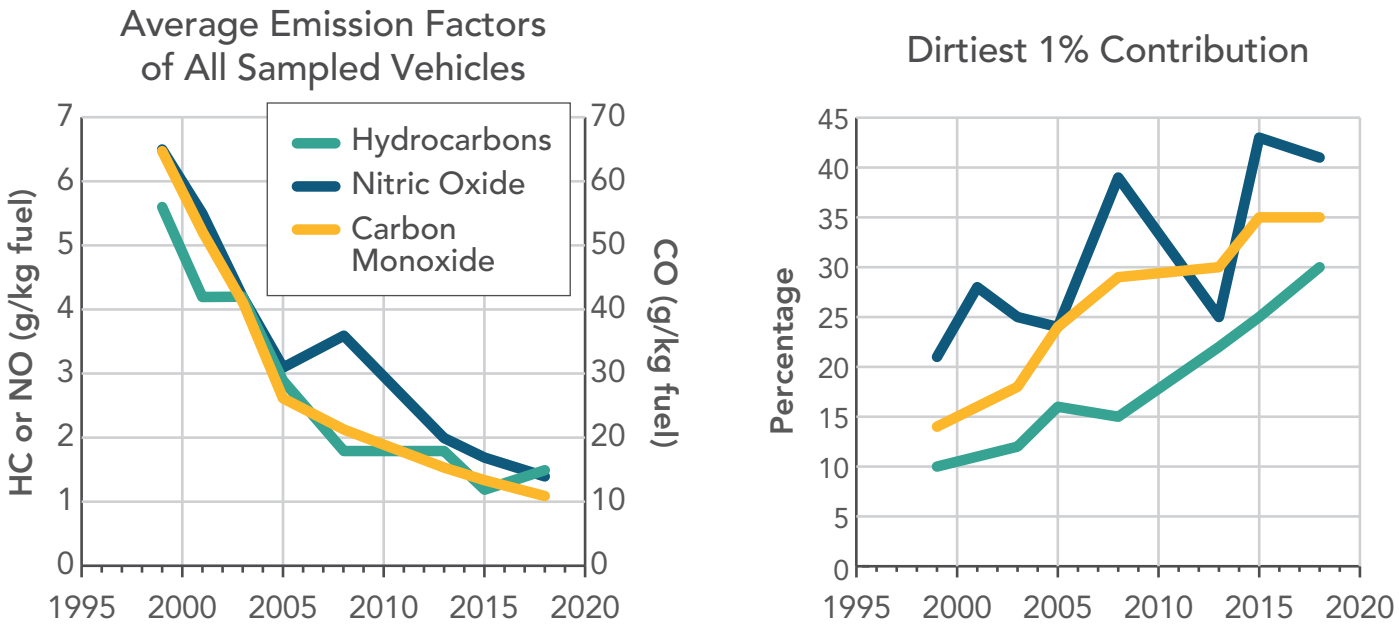
In the heavy-duty sector, research to reduce criteria pollutants has focused on the durability of emission control technologies and tracking the results of regulatory efforts. Research supported the development of low-NO_x emission standards for heavy-duty vehicles of model year 2024 through 2026, as well as for model year 2027 and beyond. A new priority for heavy-duty research will focus on reducing emissions from off-road equipment and identifying strategies to improve efficiencies in the freight sector. A major priority is identifying barriers to adoption of advanced, low- and zero carbon technology in the light-duty, heavy-duty and off-road sectors. The research in this area often evaluates advanced emission reduction technologies and monitors the effectiveness of emission reduction strategies to ensure that the expected air quality and public health benefits are achieved. The results from this suite of projects are also used to ensure that emission reduction programs provide information for future policy development and have co-benefits for the economy, environment, and health in all communities.

Light-Duty Fleet Deterioration and High Emitter Tracking

Background and Past Research: CARB has implemented increasingly stringent emissions standards as well as vehicle scrappage incentive programs. This has transformed the California on-road fleet significantly. To track how well these programs are reducing emissions, various research projects have been funded using varying techniques to take detailed measurements at representative sites.

To address the question of how decades of evolving emissions standards have affected real-world

Figure 17: Summary of long-term LDV emissions record in West Los Angeles. (a) Fuel-based emission factors for hydrocarbons (HC), nitric oxide (NO), and carbon monoxide (CO). (b) Portion of these polutants emitted by the dirtiest 1% of sampled LDVs



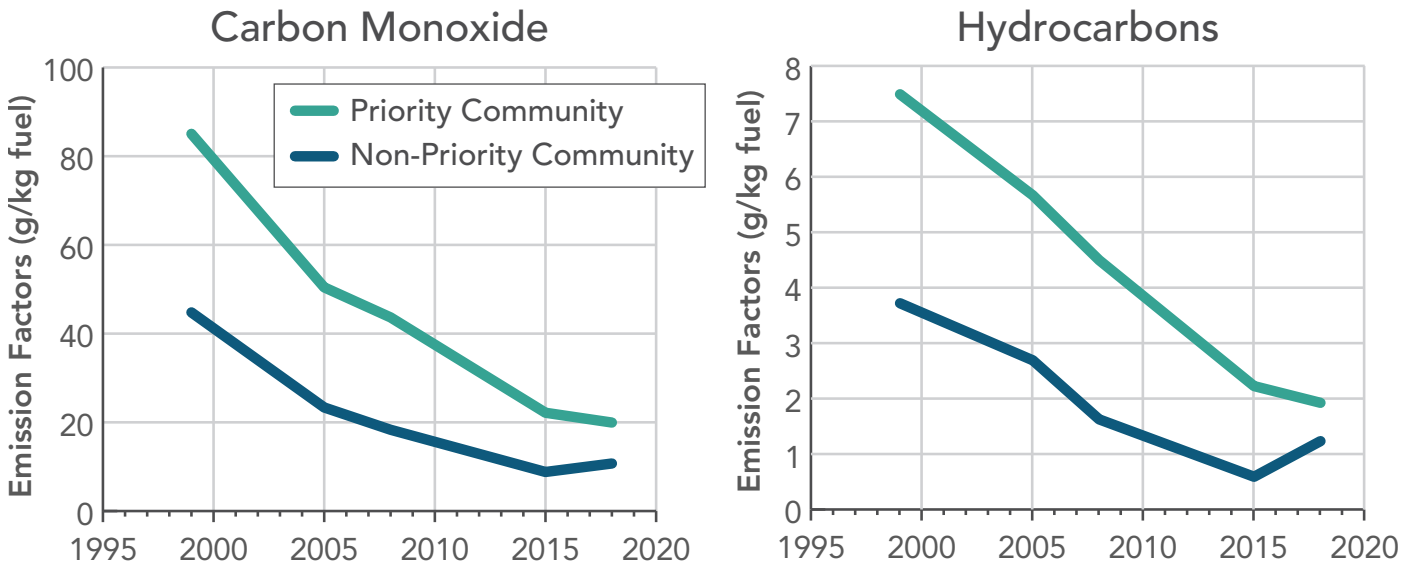
emissions from California's light-duty vehicle (LDV) fleet, CARB initiated a project in fiscal year 2017-18 with University of Denver researchers to sample passenger vehicle emissions at a West Los Angeles freeway on-ramp. These measurements were made in May of 2018, and continued a long-term record at this site that began in 1999 and now includes eight sampling campaigns (Figure 17). Dramatic reductions in fleetwide mean fuel-based emissions have been observed over this period, with carbon monoxide (CO), nitric oxide (NO), and hydrocarbons (HC) per kilogram of fuel used decreasing by 84, 76, and 79%, respectively (Figure 17a). At the same time, the distributions of these emissions have become more skewed, meaning that a relatively small number of "high emitting" vehicles are emitting an increasing share of these pollutants. In 1999, the dirtiest 1% of all LDVs emitted 15% of CO and 7% of NO. By 2018, these proportions had risen to 38 and 27% (Figure 17b). This implies that vehicle scrappage programs continue to be important, and that this type of research needs to be continued to evaluate if these trends continue as the model years of the oldest vehicles change.

CARB staff matched the vehicles observed in the University of Denver program to vehicle registration records to evaluate the geographic distribution of the vehicles sampled. It was found that passenger vehicle emissions are highly correlated with community socioeconomic status (SES). Fleet turnover, however, has reduced emissions in all communities, and reduced the disparity among communities (Figure 18). Emissions from vehicles registered in priority communities remain higher, largely because these vehicles are older on average than they are in other communities. This finding underscores the need for CARB to continue to focus on addressing air quality disparities and provide incentives for fleet turnover.

CARB staff also examined the deterioration of emissions control systems by determining how emissions from LDVs from a given model year (MY) changed over time. It was found that MY 1993 and older vehicles did not show a consistent trend in CO or HC with time. However, NO from these vehicles, as well as all three pollutants from MY 1994-2003 LDVs, showed consistent increases with vehicle age.

To gain further insight into high-emitting vehicles, CARB initiated a contract in fiscal year 2017-18 with Eastern Research Group, Inc., to obtain and analyze a set of over 50 million observations of LDV emissions in the Greater Denver area. These measurements were collected as part of the "Rapid Screen" program in Colorado. It was determined that LDV NO emissions are still dominated by Volkswagen/Audi/Porsche diesel vehicles with model years from 2009 to 2016. In more recent years, no similar high-emitting diesel vehicles were observed.

Figure 18: Comparison of emissions by LDVs registered in priority and non-priority communities in the Los Angeles area



Future Research: Over the next several years, CARB will continue to sponsor the measurement of real-world emissions from light-duty vehicles via remote sensing, and this effort will be scaled up to include additional sites. The long-term site in West Los Angeles will be revisited, along with seven other locations. This will shed light on how fleet emissions change as LEV II vehicles continue to age. The additional sites will be in or near priority communities, to evaluate vehicle emission disparities between these communities and the general population; and two will be along the U.S.-Mexico border to gauge the air pollution impact of vehicles from Mexico. These campaigns will measure fuel-based emissions of carbon monoxide, hydrocarbons, and nitrogen oxides (NO_x). Each will last for approximately a week, and sample approximately 25,000 vehicles.

Research Questions:

- Are there specific makes and models of light-duty vehicles that are high emitters, and are high emitters disproportionately impacting specific communities?
- Do we continue to see fleetwide emission reductions as more of the fleet are LEV II and LEV III vehicles, and are the reductions distributed equitably?

Real-World and Laboratory Emission Discrepancies

Building upon the research initiatives on fleet deterioration and high emitters, further research is being prioritized to understand real-world vehicle emissions and how these compare to laboratory testing emissions. Laboratory testing is designed to be as representative as possible of real-world driving, but because it has to be implemented in a practical way, it cannot cover all possible driving behaviors. New research performed at CARB is leveraging on-board diagnostic (OBD) information recorded from hundreds of vehicles in every-day usage to better understand real-world driving and emissions patterns including energy consumption and typical on-road speeds and accelerations. The number of vehicles upon which this analysis is performed continues to be expanded. This is improving our understanding of real-world emissions and activity patterns, and may inform new laboratory test cycles and regulatory options for in-use compliance. At the same time, more work is needed to understand the relationship between OBD parameters, which are primarily provided by on-board sensors, and more sophisticated measurement techniques, such as in laboratory settings and from portable emissions measurement systems .

Research Questions:

- How can on-board diagnostic data be effectively collected and used to evaluate activity and engine performance to assess real-world emissions, energy use, operating patterns, and compliance with in-use requirements for light-duty vehicles
- What additional data could complement the OBD data?

Potential of Advanced Technology

Background and Past Research: In 2012, CARB adopted the Advanced Clean Cars program to reduce emissions from passenger vehicles in accordance with California's long-term air quality and climate goals. This regulation led to the widespread use of hybrid and electric vehicles, and CARB-funded research on light-duty vehicles expanded beyond emissions measurements to include market forces, consumer acceptance, and driving and fueling behavior associated with new vehicle technologies. Results from these projects informed the "Midterm Review" of the Advanced Clean Cars program, and continue to support the state's efforts to attain zero-emission vehicle targets and greenhouse gas and PM standards.

As part of the 2017 midterm review of Advanced Clean Cars, CARB conducted in-house emission testing to evaluate the cold start performance of several blended plug-in hybrid electric vehicle (PHEV) models. The testing confirmed that cold-start emissions under high power-demand conditions experienced while running can be significantly higher than cold starts in traditional vehicles (typically the first engine start of the day). However, the cumulative impact on emissions

from this fraction of starts had not yet been determined. In order to address this issue, a project initiated in fiscal year 2017-18 characterized the activity profiles of cold-start emissions produced by blended PHEV models in order to understand the real-world scale of the increased emissions previously measured in the lab. Results indicated that blended PHEVs with smaller electric range are much more likely to have high-power cold-starts than those with larger range. The results of this study are being used to improve the emission inventory estimates of PHEV start emissions in CARB's Emission Factor (EMFAC) Model and guide the development of the next clean car standards.

The projects above are examples of benefits and unintended impacts of advanced technologies in the transportation sector. Additional research is needed to ensure that these technologies evolve in a way that allows California to accelerate towards its air quality and climate goals.

Current and Future Research: An important goal for CARB is to increase the adoption of Zero-Emission Vehicles to reduce both criteria pollutants and GHGs. This goal became even more necessary with Executive Order N-79-20, which sets a goal that 100% of in-state sales of passenger cars and trucks be zero-emission by 2035.

Current research is evaluating the performance of these advanced vehicles in fulfilling typical transportation needs to better understand how quickly this technology is likely to be adopted. The OBD measurements from a large number of light-duty vehicles (see in-house research highlight titled: Transportation Network Company data collection in support of Clean Miles Standard development) are also being used by in-house researchers to evaluate real-world energy use, from both gasoline and advanced technology vehicles and determine how energy use is influenced by operating conditions and vehicle characteristics. Findings from this study will advance understanding of real-world vehicle activity and energy use patterns and examine the range and fueling infrastructure requirements for advanced-technology vehicles to meet the transportation needs of every day Californians. Additional research will evaluate the effect of road grade, parasitic energy use, and regenerative braking on total energy use in advanced-technology vehicles, as well as compare real-world driving cycles with certification cycles and the fit between zero-emission vehicles and TNC driving needs.

Emerging mobility services have also significantly impacted the transportation sector and led to unintended consequences on transit use and other low-carbon transportation options. A project initiated in fiscal year 2019-20 is assessing equity barriers to making ride-hailing more sustainable by exploring links to transit and active transportation, increasing passenger occupancy and, vehicle electrification. This project is also examining the impact of the COVID-19 pandemic on transportation behavior specifically on shared mobility, other modes, and delivery services. Results from research on these topics will help to inform the Clean Miles Standard rulemaking, investments in charging infrastructure, and strategies to maximize the benefits of emerging mobility services.

Connected and automated vehicle technology is an important innovation that is projected to have wide-ranging impacts on travel behavior, the energy grid, the economy, and emissions. As the penetration of electrified, connected, automated, and shared vehicles into California's light-duty fleet accelerates, information will be needed on their real-world use, charging needs and the emission benefits of their integration into the grid. A project initiated in fiscal year 2017-18 has begun to quantify the projected impacts of varying penetration levels of light-duty connected and automated vehicles on GHG and criteria pollutant emissions, and on vehicle miles traveled.

The impacts of advanced transportation technologies – such as the use of connected and automated vehicles, shared vehicle fleets, and electric vehicles – will be priority research areas for CARB over the next three years. Future research should focus on providing the data and tools necessary to assist policy makers and local governments in their efforts to ensure that connected, shared and electrified vehicles do not have the unintended consequence of increasing vehicle miles traveled and degrading air quality.

Research Questions:

- How is the energy in advanced-technology vehicles used for motion vs parasitic loads; how is this affected by outside factors such as road grade and temperature; and what are the energy and refueling needs to create a functional advanced technology mobility system?
- As advanced-technology vehicles replace internal-combustion engines, how significant will the remaining emissions, such as from cold start emissions in hybrids and PM from brake and tire systems be and will they need to be addressed to ensure clean air and low exposures in priority communities?
- As we move towards zero-emission vehicles (ZEV) in all sectors how can we encourage their use, maximize emission reductions equitably, and achieve reductions in vehicle miles traveled?

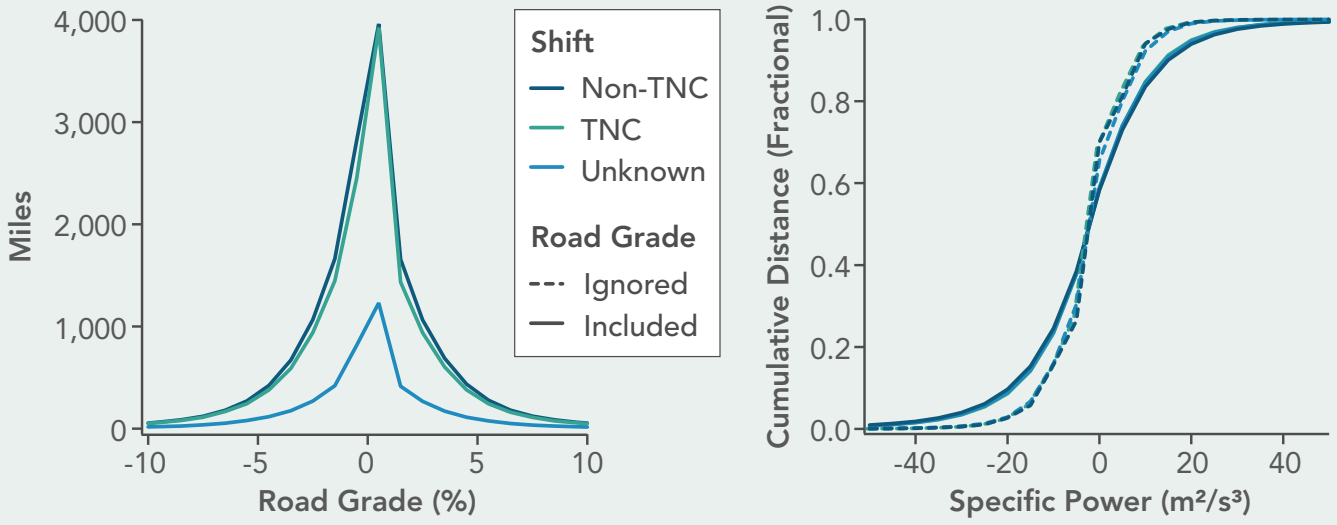
Heavy-Duty Real-World and Certification Emission Discrepancies

Background: CARB's research has focused on monitoring emissions from on-road heavy-duty vehicles to improve understanding of trends in real-world emissions. This research has tracked the effectiveness of in-use fleet rules, (e.g., Drayage and Truck and Bus Rules) and programs (e.g., the

In-House Research Highlight: Transportation Network Company Data Collection in Support of Clean Miles Standard Development

CARB staff have been deploying dataloggers in light-duty vehicles to collect real-world on-road engine and/or motor activity information, and records of real-world energy consumption. These loggers have been deployed in Transportation Network Company vehicles, and have been used by CARB staff to support the Clean Miles Standard (CMS). Staff have also investigated the road grade distribution of this driving, and how grade might impact engine/motor output and energy consumption. Results from this study have been used to derive speed correction factors for CARB's CMS emissions baseline inventory. They also suggest that accounting for road grade increases the prevalence of strong deceleration events, which may exceed the regenerative braking capacity of most capable LDVs and also be associated with brake-wear PM emissions.

Figure 19: Statistical analysis of vehicle data logger information showing prevalence of road grade percentage and specific power use

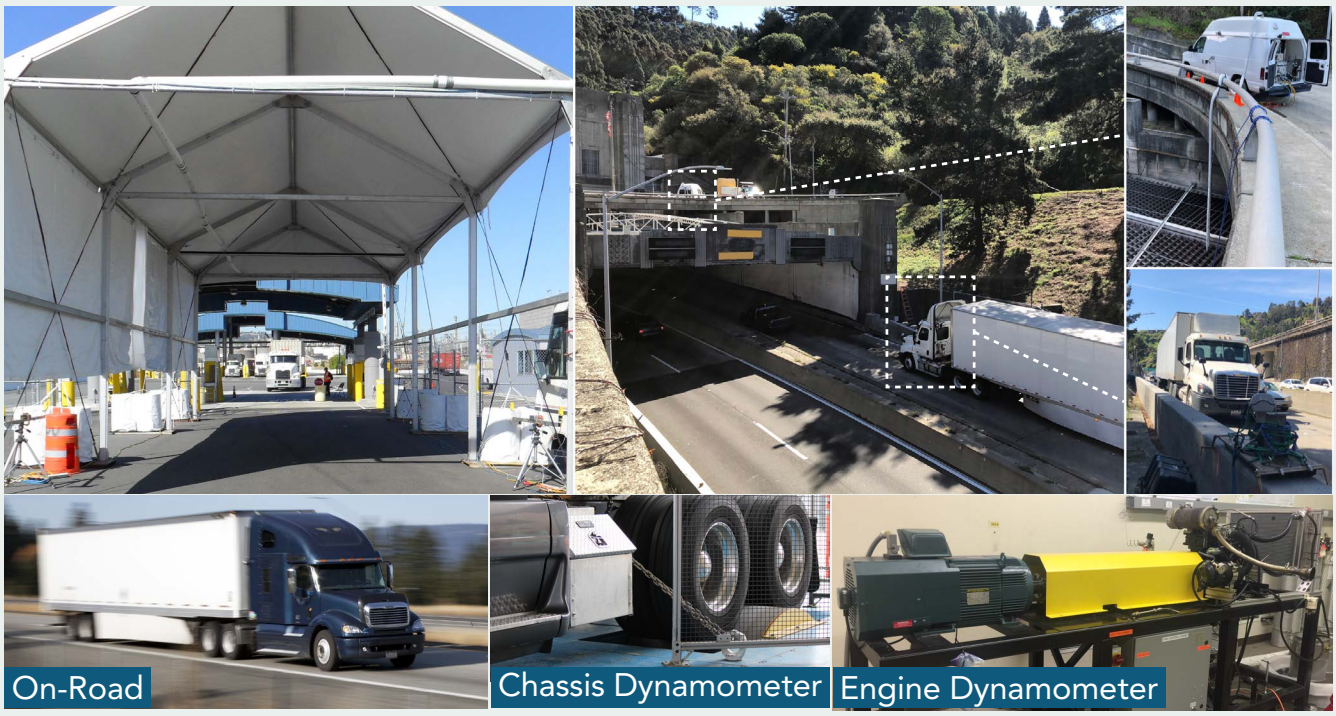


Research Highlight: Real-world Emissions of Heavy-Duty Trucks

Heavy-duty on-road vehicles are an integral part of California's transportation system and economy, moving a majority of goods across the state. However, they are also a large source of oxides of nitrogen (NO_X) and particulate matter (PM) emissions that must be reduced to meet national air quality standards and protect priority communities in areas such as the San Joaquin Valley and Southern California from the health effects of diesel PM (DPM). Over the years, CARB has implemented strict certification standards to reduce NO_X and DPM, as well as regulations that promote fleet turnover. Engine emissions are certified in a laboratory setting, but mounting evidence of discrepancies between certification emissions and in-use emissions led CARB to investigate the causes of the discrepancies, the nature of in-use emissions, and the durability of aftertreatment devices. A series of research projects (Figure 20) sampled heavy-duty exhaust emissions at ports and highway locations. By testing a large number of trucks over a decade, researchers found that fleet vehicle aging and aftertreatment device wear caused in-use emissions to increase. By contrast, where higher turnover reduced average vehicle age and more older trucks were retrofitted, emissions decreased on average. While total heavy-duty fleet emissions are declining in California, high-emitting trucks continue to be an issue because their in-use emissions are much higher than estimated by engine certification tests. This is partly because on-road performance varies significantly from certification test assumptions, and the selective catalytic reduction (SCR) technology used to reduce NO_X does not operate effectively under all on-road conditions.

A related project tested two heavy-duty vehicles on an engine dynamometer (as during certification), on a full chassis dynamometer, and on-road. The emissions differences between laboratory and on-road testing were attributed to factors that impact engine-out NO_X and SCR catalyst performance. These projects confirm that in-use emissions can be significantly higher than certification emissions and may warrant a different approach to emissions control and certification in the future. This could include new SCR thermal management techniques, improved on-board emission control sensors and more varied certification cycles to better replicate on-road driving conditions.

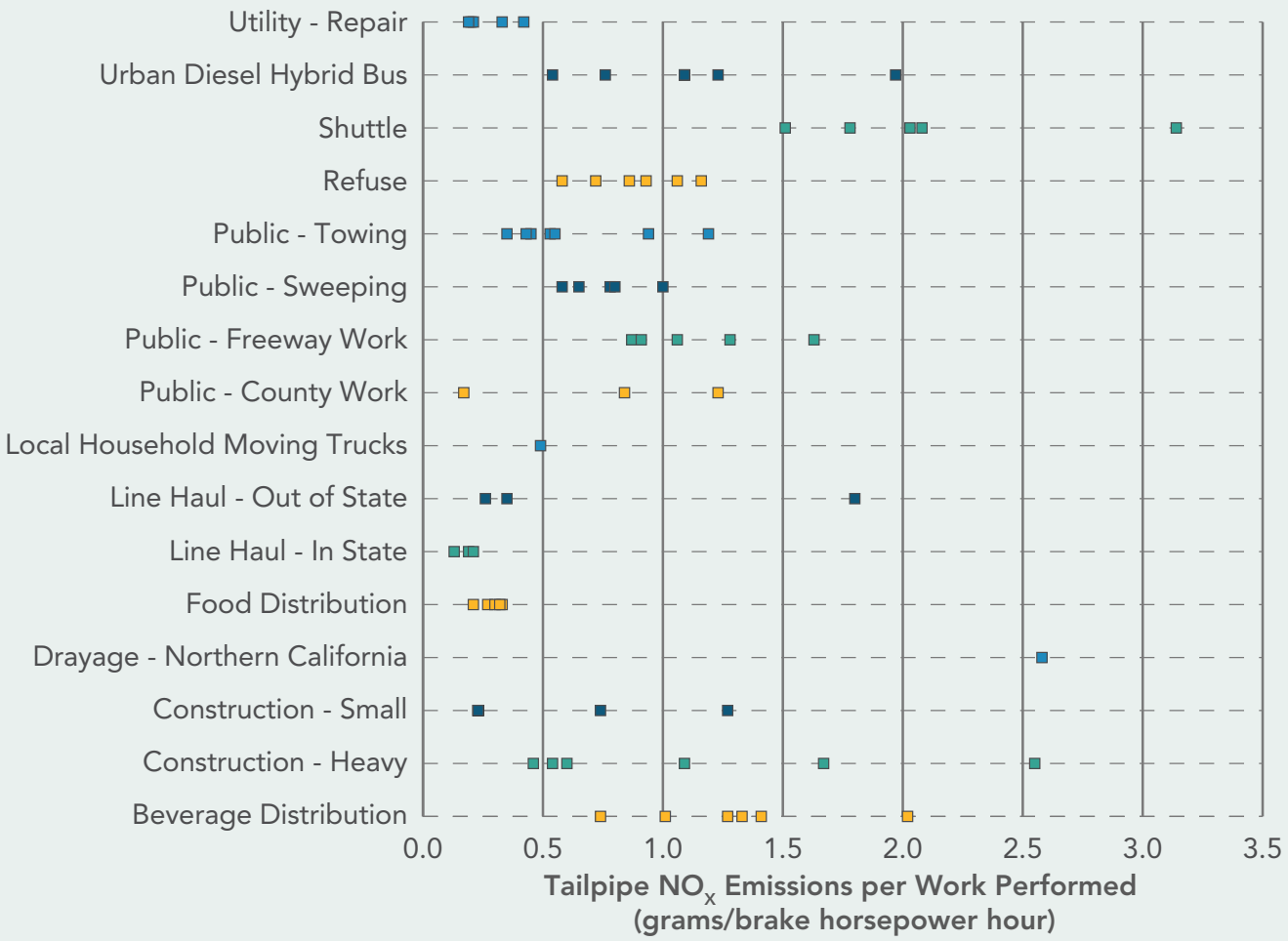
Figure 20: Various measurement platforms utilized to measure heavy-duty vehicle emissions



In-House Research Highlight: Analyzing Large Data Sets on Heavy-Duty Vehicles in Support of CARB Regulations

In-use NO_x emissions from Heavy-Duty Diesel Vehicles (HDDVs) can in some cases be unexpectedly high due to tampering, mal-maintenance, and malfunction of the emission control systems. CARB has made significant progress in reducing NO_x emissions from HDDVs through a series of regulations, such as the heavy-duty omnibus regulation. This work has been evaluating the in-use NO_x emissions from HDDVs using various data sources, including Portable Activity Measurement Systems (PAMS), Portable Emission Measurement Systems (PEMS) and chassis dynamometers, to support the development of these regulations. The analysis found that the overall NO_x conversion efficiencies of the Selective Catalytic Reduction (SCR) system on many HDDVs were well below the 90% threshold that is expected for an efficient SCR system, even when the SCR system was above the optimum operating temperature threshold of 250°C. While most trucks appeared to fit an increasing emissions rate with vehicle mileage, there were a few trucks that showed extraordinarily high emission rates – reaching several multiples of the standard – within the first 15,000 miles of operation (Figure 21). This work also examined the distribution of vehicle activities and NO_x emissions across different operating conditions, and the impact of vehicle driving history on NO_x emissions. The results have provided a thorough evaluation of the challenges in controlling in-use NO_x emissions from current HDDVs.

Figure 21: Tailpipe NO_x emissions normalized by work performed for various vocational trucks



Heavy-Duty Vehicle Inspection Program and the Periodic Smoke Inspection Program) in reducing in-use emissions. To estimate the effectiveness of in-use rules and programs, diesel emissions research has examined the durability, degradation, and failure rates of aftertreatment devices that reduce NO_X and diesel particulate matter (DPM), and the real-world efficacy of NO_X controls. This has been accomplished by measuring emissions from the in-use fleet using laboratory dynamometers, Portable Emission Measurement Systems (PEMS), on-board sensors, remote sensing, and plume capture devices (see research highlight titled: Real-world emissions of heavy-duty trucks and see research highlight titled: Analyzing large data sets on heavy-duty vehicles in support of CARB regulations).

Real-world emission monitoring can also inform CARB's work in priority communities. CARB is highly focused on equity and improving air quality in priority communities as mandated by Assembly Bill 617.[35] Many priority communities are located near ports or other sources of emissions highly influenced by freight or off-road equipment. Additional monitoring and testing near these communities could help to design better mitigation strategies.

Future Research: In the future, CARB will continue to support the measurement of HD emissions at long-term sites. This will allow a continuous record of real-world PM and NO_X emissions over the entire (multi-decade) course of implementation of the Truck and Bus Rule, which will be essential for accurate quantification of its benefits. Also, recent and future regulations, such as Heavy-Duty Omnibus and Inspection and Maintenance (HD I/M) rules, will be evaluated using these long-term records. CARB will also demonstrate the feasibility of using state-of-the-art sensors in the Heavy-Duty On-Board Diagnostic (HD OBD), Heavy-Duty Omnibus and HD I/M regulations. This will be especially important for monitoring NO_X under real-world conditions where a wide range of operational conditions can lead to higher emissions than expected. Results of this research will help determine technological development strategies to control NO_X emissions under all operating conditions. Moving forward, advanced screening tools should also be developed to identify high-emitting vehicles or vehicles with persistently malfunctioning aftertreatment devices.

Research Questions:

- What are the fleetwide emissions trends and what new mitigation opportunities exist to help achieve emission reduction goals?
- How can we develop more accurate sensors and tools to identify high emitters? How will high emitters affect fleetwide emissions? As emission rates decrease, will high emitters cause community exposures to remain unacceptably high?
- What are the capabilities of advanced on-board sensors and telematics to monitor real-world emissions of future heavy-duty vehicles?

Reductions from Off-Road Equipment

Background and Current Research: Off-road equipment is a highly diverse part of the transportation sector comprising multiple engine sizes, applications, duty cycles and activity profiles. CARB's research has focused on informing the emission inventory by mining activity profile data and emission rate measurements of off-road equipment and vehicles in use. According to inventory projections, off-road equipment will be the largest emitter of NO_X in the state of California by 2022, underscoring the importance of this sector to air quality.

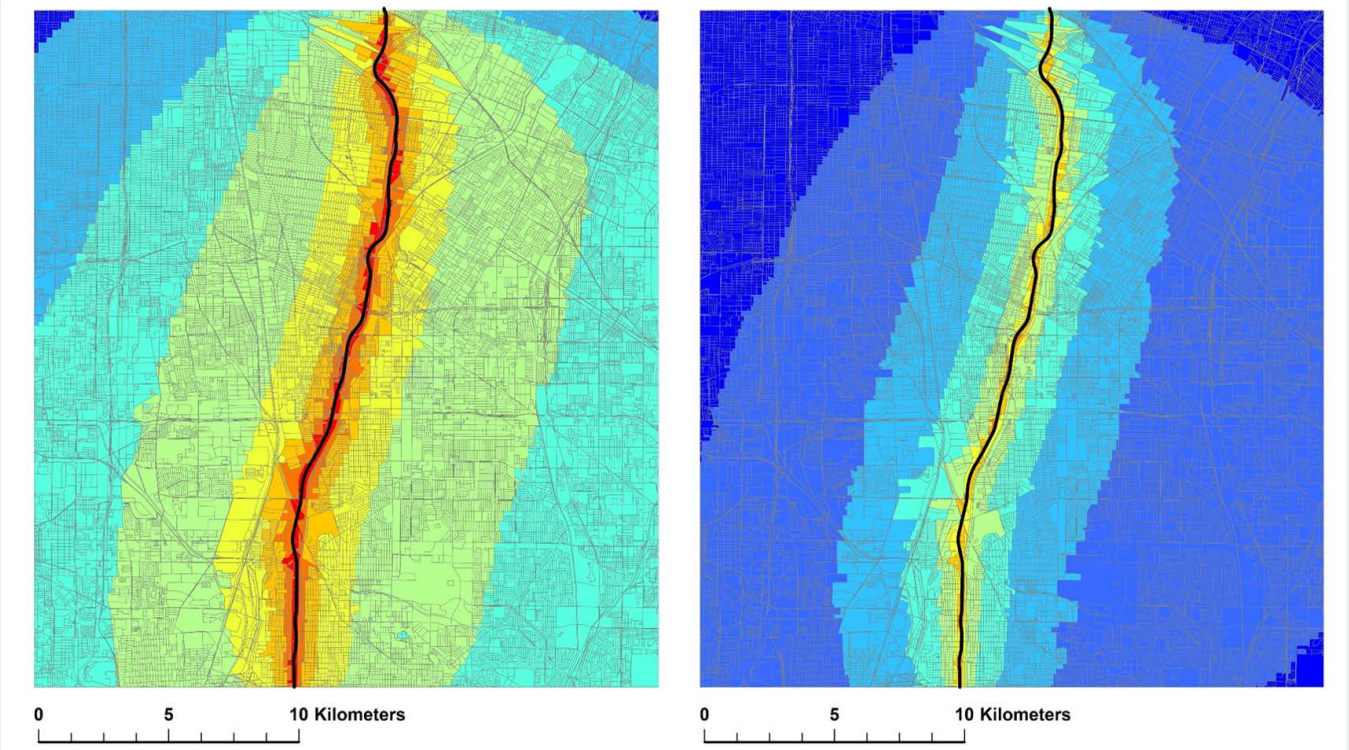
To inform emission inventories and emission control programs for off-road equipment and vehicles and to gain a better understanding of toxic emissions, current CARB research is measuring the emission rates of a suite of criteria and non-criteria pollutants from two off-road diesel engines with different aftertreatment configurations. The findings from this project will increase the understanding of the characteristics of emissions from engines that meet the Tier 4 final off-road regulation with and without a diesel particulate filter. Building on this work and to inform future

35 C. Garcia, Chapter 136, Statutes of 2017

In-House Research Highlight: Tracking Real-World Program Effectiveness of Truck and Bus Regulation, and Studying Pollution Transport and Impacts from Freeways into Neighboring Communities

CARB has conducted a long-term research study to measure the real-world air quality benefits from California's Diesel Risk Reduction (DRR) program in an important diesel corridor – the I-710 freeway in Los Angeles. The study continues to track the real-world fleet-wide emissions of diesel particulate matter (DPM) and nitrogen oxides (NO_X) from heavy-duty trucks, and compares the trends against expected emissions from the truck fleets as a result of the DRR program. The study is also analyzing the potential reduction in excess cancer risk from DPM exposure using advanced air quality modeling. Results indicate that from 2009 to 2016, the unit per-mile emission rates of black carbon (BC, a surrogate for DPM) and NO_X were reduced by 83% and 70%, respectively. This agreed with the expected reductions due to reduction from the Drayage Truck Regulation and Truck and Bus Regulation. As a result, the additional cancer risk from DPM emissions from the I-710 freeway has been reduced significantly, with average population weighted cancer risk reducing from 201 chances per million in 2009 to 34 chances per million in 2016 (Figure 22). In addition to evaluating the effectiveness of CARB programs, the study has also tracked the impact of these programs in reducing community exposures to air pollution in the historically-disadvantaged portside communities in Southern California.

Figure 22: Estimated cancer risk by heavy-duty vehicle diesel particulate matter emissions in I-710 neighborhood over different time periods



Tier 5 standards, CARB has recently initiated a research project on the fabrication and optimization of next-tier off-road diesel NO_X aftertreatment technology. The project will design, procure, age, and optimize advanced NO_X and PM aftertreatment technologies for incorporation on a new Tier 4 off-road diesel engine with the goal of reducing NO_X emissions by 90 percent and PM emissions by 75 percent below Tier 4 final standards. CARB's research is also examining the technical and economic feasibility of electrification and hybridization of off-road equipment. This work will help advance the development and deployment of low-emission off-road equipment.

Two projects are characterizing in-use activity data for typical off-road equipment to inform the emission inventory and provide accurate real-world data to inform policies, incentive programs, and the development of future emission standards. One project, begun in fiscal year 2017-18, is characterizing 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 in construction. The research will evaluate the representativeness of current certification cycles, and inform the development of duty cycles that better represent equipment activities by vocational use. The collection of activity profiles has been extended to agricultural equipment with a new project from fiscal year 2019-20. This research will characterize how agricultural engines in the San Joaquin Valley operate under actual working conditions, including their activity parameters (e.g., engine speed, torque and fuel rate) and maintenance frequency, type and cost.

Future Research: Moving forward, more work is needed to characterize the emissions and activity profiles covering a wide variety of off-road equipment types. This will likely entail the use of large datasets collected from OBD data loggers, which collect large amounts of data at low cost. Future work may also include development of more standardized OBD protocols for off-road equipment.

Research Question:

- How do we effectively monitor in-use emissions from off-road engines with on-board diagnostic or other tools?

Since the market of off-road diesel engines is expanding, and off-road emissions are becoming a larger portion of the inventory due to better control of emissions from on-road vehicles, development of emission reduction strategies for the off-road sector will be essential for the state to achieve its stringent air quality goals. Going forward, additional research will be needed to support the development and implementation of a suite of strategies to lower emissions from existing and new off-road equipment. Additional work is needed to identify how off-road equipment emissions impact community exposure. This work will be essential to guide CARB's future incentive, regulatory and voucher programs aimed at reducing the climatic and air quality impacts of off-road equipment.

Research Question:

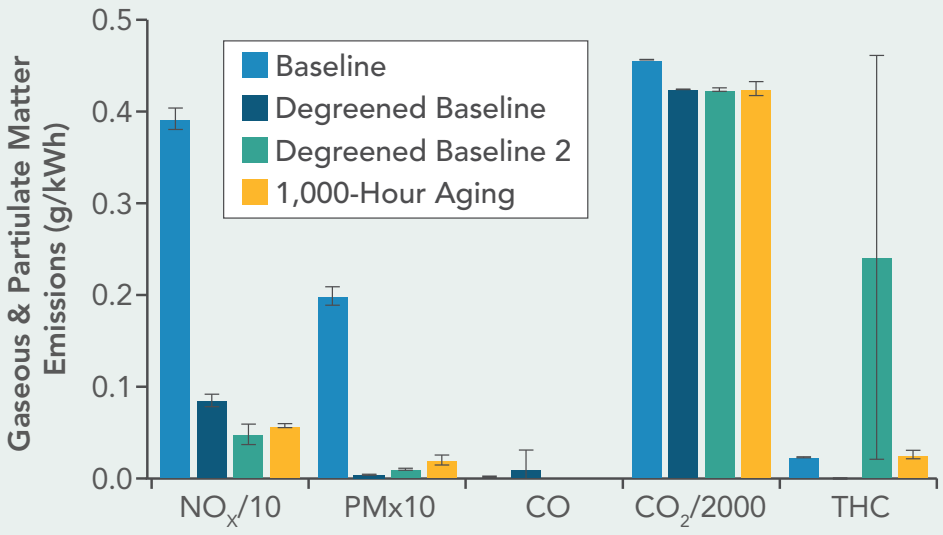
- What are the optimal pathways to control criteria pollutants from off-road diesel engines, particularly in priority communities?

Finally, on the lower end of the power spectrum, small off-road engines tend to be used for lawn and garden care and other maintenance vocations within communities. These small off-road equipment types have less stringent emissions standards because it has been deemed infeasible to add aftertreatment devices. However, there is concern that these equipment types are leading to higher pollutant exposure in residential areas and for people working with the equipment itself. Electrification may be a viable option, if the infrastructure to recharge can be implemented effectively. It's also possible some engines in the smaller size range can accommodate aftertreatment devices. Recently completed research demonstrating the feasibility of equipping small off-road equipment with aftertreatment devices showed that significant emissions reductions could be achieved (see research highlight titled: Equipping small off-road diesel engines with advanced aftertreatment). Moving forward, more research will be needed to determine the best mitigation methods in order to lower emissions and reduce community exposure impacts.

Research Highlight: Equipping Small Off-Road Diesel Engines with Advanced Aftertreatment

Off-road equipment represents one of the largest sources of NO_X and PM emissions in California. Existing standards do not effectively require small off-road diesel engines (SORDEs) (<75 horsepower) to be equipped with aftertreatment devices, partially because it was believed to be too costly or technically difficult for the smaller engines. Aftertreatment control devices for diesel vehicles and engines are considerably more common now, and the use of these devices on SORDEs may be more viable and thus warrant renewed consideration. CARB researchers worked with aftertreatment device manufacturers to add custom devices to commercially-available off-road equipment, then deployed these in the field to accumulate realistic work hours. The engines from the equipment were tested at baseline, before aftertreament devices were added, once modified, and after aging in the field to better understand the durability of these devices after typical use. The researchers also performed emissions inventory, economic and market impact analyses to determine the implications of added emission control strategies. The results showed that the various aftertreatment devices led to substantial reductions of their respective target pollutants and that they were durable after significant field use. For instance, diesel particulate filters (DPFs) led to very large decreases in PM and selective catalytic reducers (SCR) led to significant decreases in NO_X. When combining results to determine the impact of adding these devices to SORDEs, the researchers found that DPFs could reduce statewide PM from engines less than 25 hp from .214 tons/day to 0.01 tons/day and SCR could reduce statewide NO_X emissions from engines 25-75 hp from 27.13 tons/day to between 12.23 and 4.07 tons/day. Over half of these reductions would occur in the San Joaquin Valley and Southern California, areas with frequent non-attainment of air quality standards. The costs are estimated at $29k/ton for PM and about $700-1000/ton for NO_X, which compare favorably with costs for previous regulatory measures.

Figure 23: Picture on the left of the skid steer with SCRT added and on the right, of emissions results



Research Question:

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

Increased Freight Efficiency

Background and Current Research: The freight system is a vital part of California's economy and must respond to growing demand for e-commerce. California's freight system is also a major source of emissions of both criteria pollutants and greenhouse gases. New regulations, technological change, and shifting market forces triggered by the COVID-19 pandemic are re-shaping the demand and supply sides of California's freight industry in unforeseen ways. Vehicles, fuels, logistical systems, and fleet management technologies are in flux, creating new challenges and opportunities for improving freight system efficiency.

Increased system efficiency is needed to enable California's freight industry to meet these combined challenges. Governor Jerry Brown's Executive Order B-32-15 (July 2015) directed an interagency task force to develop an action plan to improve California's freight system efficiency while increasing competitiveness and reducing environmental impacts. The action plan was accompanied by a series of white papers focusing on freight efficiency strategies.

CARB will review these and all similar research efforts, both recent and ongoing, to identify potential strategies for improving California freight system efficiency, as well as additional research needed to evaluate those strategies. A white paper initiated in fiscal year 2020-2021 will review the papers developed for the 2016 Sustainable Freight Action plan, as well as recent freight system literature and practices in order to identify remaining research needs and new technologies that can improve California freight system efficiency and competitiveness while reducing GHG and criteria-pollutant emissions. Focusing primarily on freight system sectors and technologies, operational adaptations and regulatory policies within CARB's regulatory authority, the paper will provide a research roadmap for future projects on this topic.

Future Research: Going forward, CARB will continue to coordinate with academics, stakeholders, and state and Federal agencies to ensure that freight research efforts are efficiently leveraged and avoid duplication of effort. Stakeholder engagement during research planning and execution will be essential to identify real-world needs and provide input on the feasibility of implementing potential efficiency strategies. The inherently complex and evolving system will require an equally complex and visionary set of solutions.

Research Questions:

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

New transportation trends and methods in goods delivery services are leading to new possibilities for reducing overall emissions. Particularly due to the pandemic, e-commerce and on-demand delivery services have seen a boost as more and more people avoid driving personal vehicles to purchase goods and services. This trend of increasing goods delivery needs to be monitored and made as efficient as possible in order to derive the greatest emission benefits. Various projects are tracking the rise in e-commerce and its impacts on vehicle miles traveled. Moving forward, CARB will investigate how these trends are potentially affecting emissions and where efficiency can be maximized for lower congestion and reduced personal vehicle travel. There may also be potential for blending transportation modes: allowing transit, automated vehicle travel and other modes of moving people to also carry goods to their final destinations. Innovative ideas for new efficiencies will be of interest moving forward. Finally, there may be potential to optimize the health benefits from increased freight efficiency, therefore the co-benefits of proposed interventions should be evaluated – particularly in communities highly impacted by freight emissions.

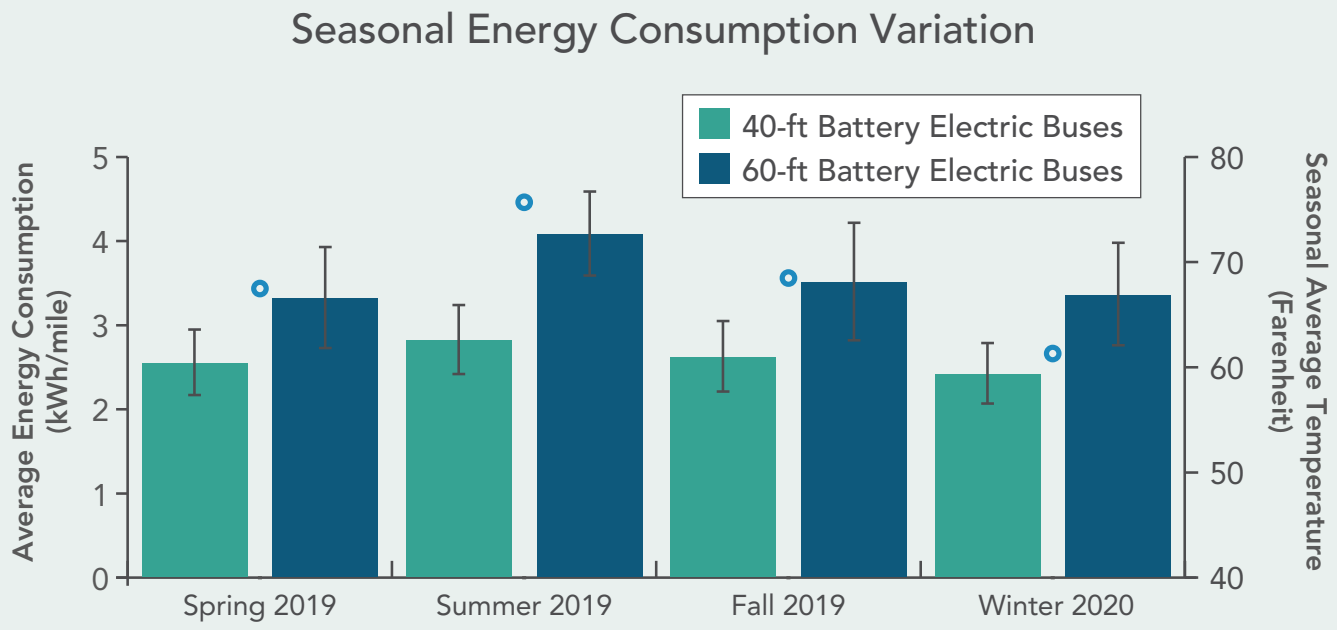
Research Questions:

- How can we leverage economic data, survey and other analysis tools to quantify displacement of personal vehicle VMT by e-commerce? How can e-commerce with high VMT displacement potential be incentivized and promoted?

In-House Research Highlight: Characterizing the Energy Demand of Transit Battery Electric Buses

As part of the Innovative Clean Transit regulation, policymakers and program management are required to track the progress of converting conventional transit fleets to zero-emission transit fleets. Converting whole bus fleets from compressed natural gas or diesel to 100% battery-electric buses is challenging and costly. Thus identifying the operational barriers and lessons learned from pioneering fleets is critical for ensuring future victories in cleaning up transit across the state. CARB staff has worked with a pioneering bus fleet leapfrogging from diesel to battery-electric buses (BEBs) to answer questions on operational limitations and variability in energy demand. BEB activity data was collected using HEM® data loggers for more than a year. The 1-Hz data included powertrain control parameters as well as global positioning system (GPS) data. The data is being analyzed to elucidate typical activity changes as functions of route type, propulsion type, time of day, and season. From this analysis, it was found that 40-ft buses consume 2.43-2.83 kWh/mile depending on the season (Figure 24), and the 60-ft buses consistently consume 30-41% more energy. The energy consumption of buses, based on the evidence, is dependent on the state-of-charge of the battery. Overall, the buses are charged less frequently during peak periods, and charging time is higher during off-peak periods. Using these research findings, program management and fleet operators can anticipate the variability in BEB energy economy to account and plan for operational limitations during different seasons. Transit operators and program staff can also use this data to deploy BEBs in a more cost-efficient manner by optimizing the BEB charging frequency/time and transit schedule together.

Figure 24: Energy consumption of battery electric buses operated in Lancaster, CA over different seasons



- What potential methods are feasible in the near and long-term future for increasing freight efficiency by leveraging other innovative transport technologies such as automated vehicles, personalized and shared mobility services, and mass transit?
- How can we incentivize less personal VMT and provide benefits to priority communities through better understanding and analysis of consumer behavior trends?

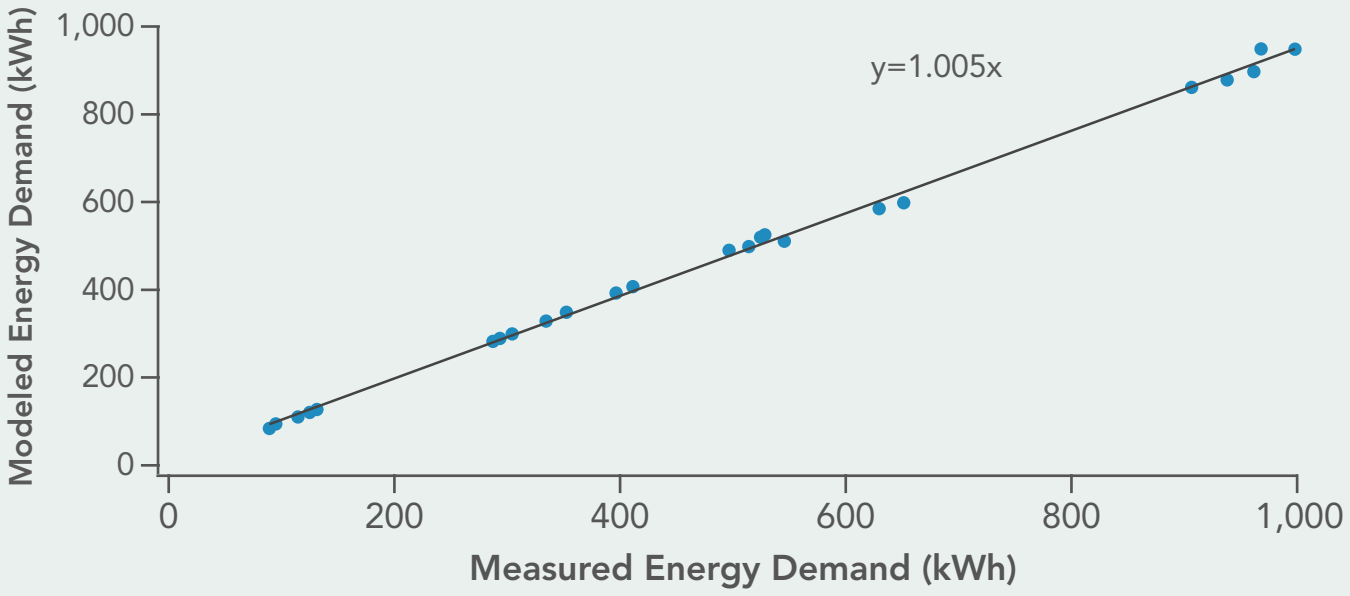
Potential of Advanced Heavy-Duty Technology

Background: CARB funds research on the use of advanced technologies in the heavy-duty and off-road sectors to guide CARB's incentive, regulatory and voucher programs aimed at reducing

In-House Research Highlight: A Tool to Model Energy Use by Zero Emission Vehicles

One of the major goals of CARB's low carbon transportation programs is to encourage the adoption of zero-emission vehicles. Programs such as the Innovative Clean Transit and Advanced Clean Truck regulations need more reliable energy economy estimates for different types of vehicles. These estimates should include parameters such as auxiliary energy consumption and efficiency of regenerative braking. Building on the data collection and analysis work done on BEBs described earlier, CARB staff have developed a model to inform programs. Instead of collecting huge datasets to answer these questions, a robust modeling methodology has been created that uses both backward modeling principles (from wheel to engine) and forward calculation (from the engine to wheel) methods to calculate event-specific— i.e. running, idling, braking, transmission loss, and auxiliary energy demand. This model, ITEM-Tools (Integrated Transportation Energy Modeling Tools), can take latitude, longitude, and speed data to calculate the aforementioned event-specific energy consumption for different technology vehicles. This model has different modules for transit bus-diesel, diesel-hybrid and electric, drayage trucks-diesel, and long-haul trucks-diesel. These modules were calibrated and validated with real-world data and they have predicted real behavior well for different modules (Figure 25). This modeling suite can be useful for estimating the impact of critical parameters such as road grade and passenger occupancy on energy demand. Further, it can be used to identify possible limitations for the deployment of certain battery capacity buses on specific routes. The model can potentially provide reliable technical statistics such as energy efficiency ratios used in future ZEV regulations.

Figure 25: Measured versus modeled energy requirements of battery electric buses



their climatic and air quality impacts. Near-term exposure mitigation strategies are being addressed by real-world clean transportation projects, such as the Low Carbon Transportation program, Air Quality Improvement Program (AQIP), VW 3.0-Liter Settlement, Carl Moyer Program, and Prop 1B. CARB has funded several research projects that informed the best use of these funds to minimize criteria pollutant, air toxic and greenhouse gas emissions and incentive strategies for technology adoption to spur the market toward a zero-emission future.

Current Research: Achieving California's climate and air quality goals will require significant transformation of the heavy-duty sector. While electrification will be required to decarbonize vehicle energy demands, new sales and turnover of existing heavy-duty vehicles will take time. In the meantime, biofuels can also reduce greenhouse gas (GHG) emissions and provide a drop-in fuel substitute; however, they do not reduce criteria pollutant emissions as much as zero-emission vehicles (ZEVs). This is of particular concern for EJ advocates and where possible, zero emission propulsion technologies should be prioritized where freight operations impact priority communities.

A recent project has done a comprehensive analysis of the fuel pathways that will lead to rapid decarbonization of fuel stocks for heavy-duty vehicles. This study developed long-term scenarios for least-cost uses of renewable fuel feedstocks, fuel production technologies, and powertrains for the heavy-duty sector, given technology and emission constraints. These scenarios will inform investments and policy development so that California can achieve air quality and climate goals. Results from the techno-economic optimization showed that electricity and biomass-derived renewable diesel, natural gas, and hydrogen were viable pathways toward fleet mixes that can meet climate and air quality goals, but increasing ZEV adoption yielded lower GHG emissions in the long-term at nearly the same cost. Additionally, constraints on biomass availability and uncertainty regarding competing demands from other sectors may require electrolytic fuel pathways play a prominent role long-term if hydrogen and renewable natural gas meet a substantial portion of fleet fuel demands.

Fleet barriers to achieving these future scenarios were investigated to create a guidance document incorporating strategies that help overcome identified constraints. The most effective policies and economic mechanisms to encourage zero and near-zero pathways were identified through analyzing existing policies and potential barriers to using advanced technologies.

As mentioned above, models tend to predict that ZEV adoption yields lower GHG emissions in the long-term. But significant barriers exist for electrification of heavy-duty engines, particularly for off-road equipment. The off-road sector is complex, with varying equipment chassis, variable duty cycles and differing refueling needs. Converting off-road equipment such that it functions on battery power will be challenging due to the various niches in this category. However, there is an urgent need to find the best technology pathways to rapidly transform the market.

An ongoing project is examining the barriers to adoption of battery electric technology to power off-road equipment, with an emphasis on construction and agricultural equipment. That project is prioritizing equipment types that comprise the largest emitters of criteria pollutants and GHGs to establish which of these equipment types may be suitable for electrification. As battery technology improves, and charging infrastructure becomes more prevalent, the barriers to adopting this technology will diminish. A modeling exercise is examining which equipment types could electrify with today's battery technology by simulating real-world duty cycle data collected from in-use equipment.

Future Research: Future work in this area will continue to examine technology interventions, advances in efficiency and optimization of charging infrastructure to meet the energy needs of freight and off-road equipment. Going forward, CARB will continue to prioritize research to support the use of advanced technologies to reduce emissions in the heavy-duty and off-road sectors.

Research Question:

- What are the policy opportunities to promote and shape the deployment of clean and equitable passenger mobility, goods delivery, and ZEVs to meet community needs, prevent congestion, reduce VMT, promote electrification, and support other state goals?

Moving forward, CARB will continue to evaluate the barriers to electrification across all heavy-duty and off-road vocations, and to determine the most effective placement for charging infrastructure to meet power demands and integrate efficiently with the electric grid. There are also many research questions regarding vehicle-grid integration. Hydrogen and battery electric vehicles may play a role in helping the grid to decarbonize as more refueling and recharging infrastructure is built.

Research Questions:

- What is the feasibility and cost of the hybridization and electrification of certain heavy-duty vehicle and off-road vehicle fleets?
- What is the potential for vehicle-grid integration and how could it play a role in electric grid decarbonization?

In the medium- and heavy-duty sector, advanced technologies have the potential to reduce vehicle emissions, improve freight system efficiency, and improve the health of communities adjacent to freeways and freight hubs such as ports, railyards, and distribution centers. A recently completed project assessed geofencing as a strategy to lower emissions from heavy-duty vehicles in urban areas that are also environmental justice communities. Geofencing was defined as using a virtual boundary for a specific area within a broader geographic area where strategies can be triggered to reduce air pollutant emissions to minimize adverse public health and environmental impacts. Such strategies can be triggered temporally and spatially.

The project used models to show the reduction in exposure if certain geofencing strategies were implemented in select environmental justice communities in California; and provided policy recommendations to establish a more formal role for geofencing strategies in some of California's premier efforts to reduce community exposure. CARB's Research Program hopes to build on this work by continuing to evaluate the direct and indirect benefits of geofencing strategies and other advanced-technology applications in modeled and real-world demonstration projects. This research will be crucial for reducing emissions in priority communities disproportionately impacted by freight emissions.

Research Question:

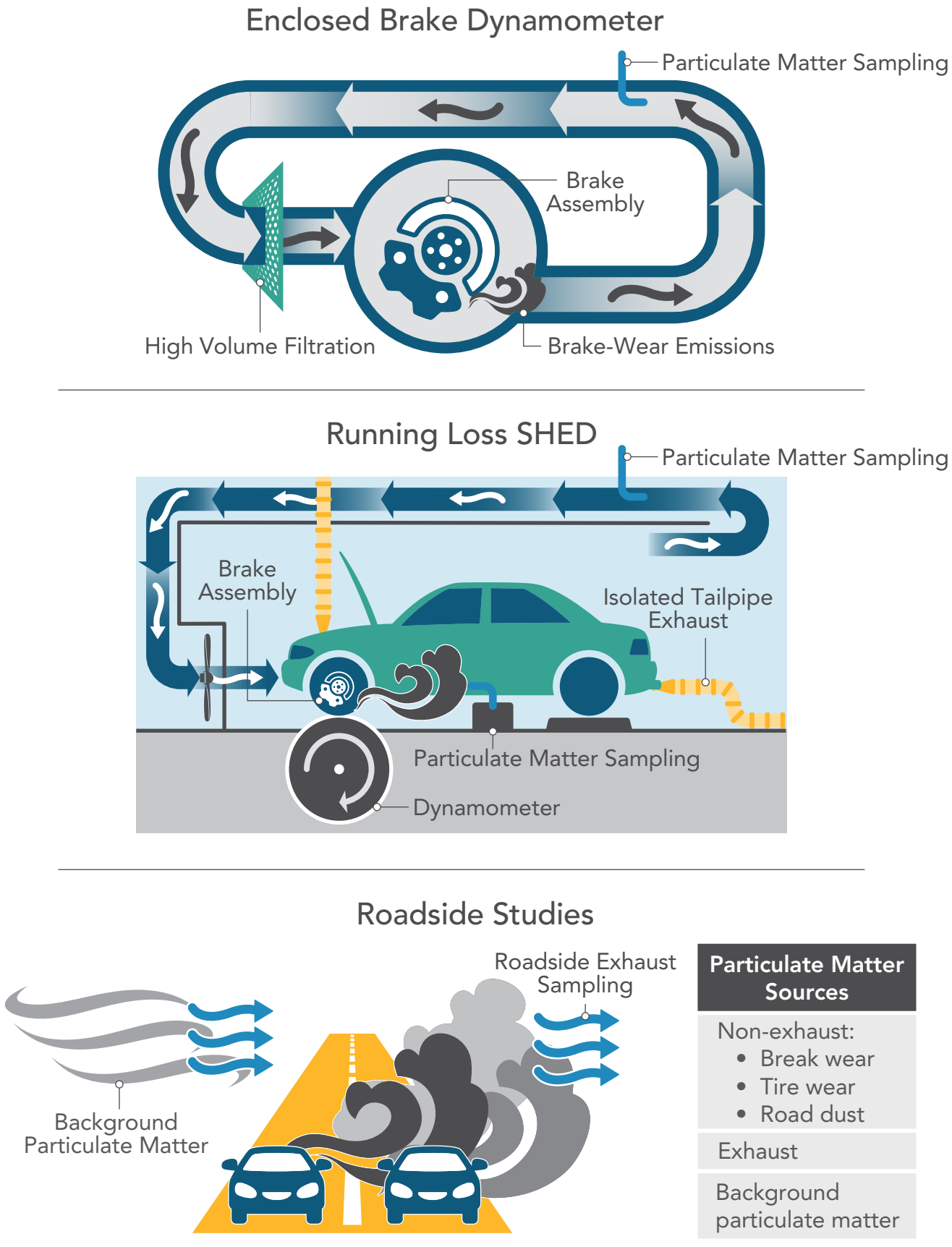
- How can the deployment of geofencing and automation be shaped to meet mobility needs, minimize exposure to mobile source emissions (especially in priority communities), as well as minimize VMT?

Non-Tailpipe Emission Sources

Background: Recently CARB has significantly ramped up its research efforts to improve understanding of non-exhaust emissions from vehicles; and their effects on air quality and public health. The new effort comes in response to various research needs. The current emission inventory shows vehicle non-exhaust PM to be a substantially larger fraction of vehicle primary PM emissions than PM from exhaust. However, new technologies, such as fully- or partially-electrified vehicles, will become more prevalent, particularly with the Advanced Clean Car Regulation. These vehicles have regenerative braking and low-rolling-resistance tires to maximize battery capacity, so their non-exhaust emissions are likely to be affected. Brake-wear emissions are also likely to change over time as copper removal laws for brake-pads are adopted. These technology changes signal a likely change in emissions.

Most inventory values today rely on tests performed almost 20 years ago, and are due for an update. Brake- and tire-wear emissions are likely to depend on driving behavior. The inventory should also account for this to better model how emissions may impact different regions based on typical driving patterns. What is clear from previous studies is that brake- and tire-wear emissions consist of relatively large inhalable particles. This suggests they can still impact health but may not remain suspended or dispersed in the same way that exhaust PM does. This has

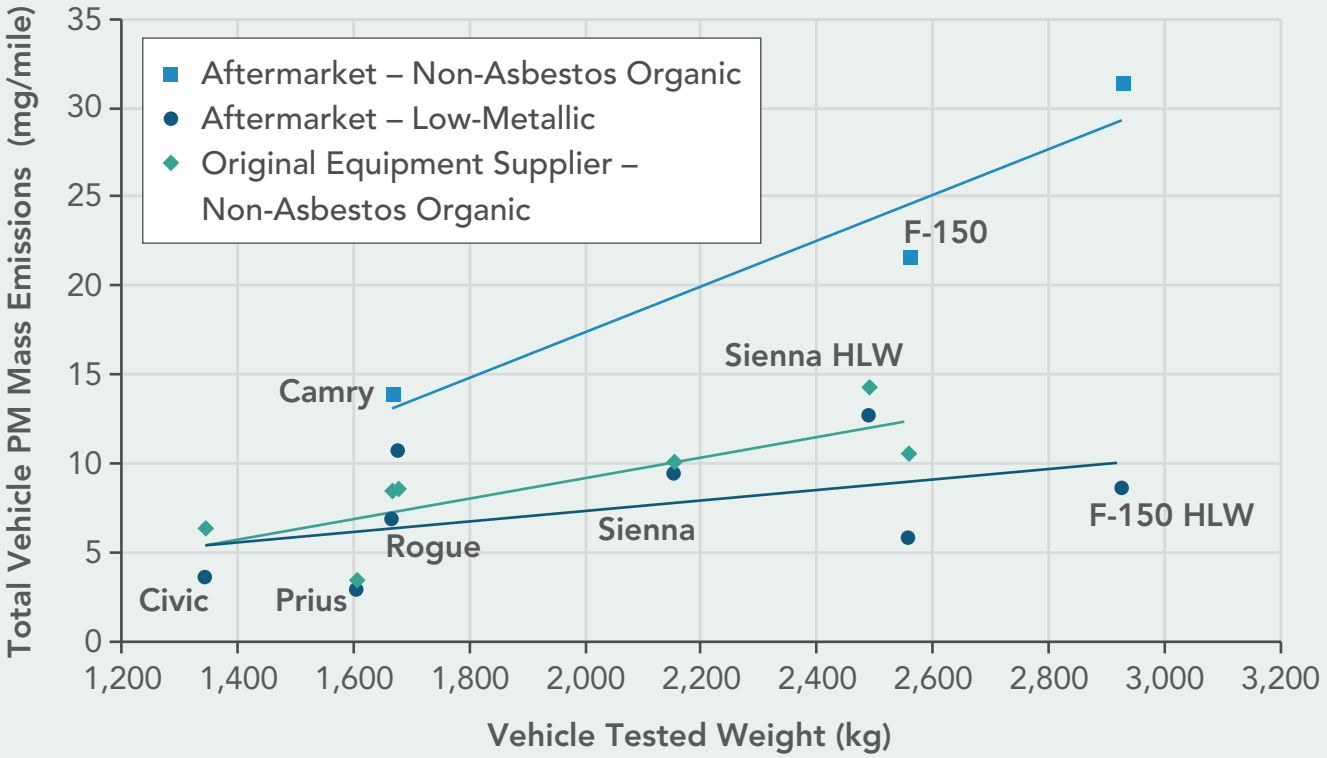
Figure 26: Diagram comparing various methods for characterizing brake-wear emissions: a) enclosed brake-dynamometer, b) sealed RL-SHED, leveraging full vehicle chassis dynamometers, and c) roadside studies



Research Highlight: Measuring Brake-wear Emissions from Passenger Vehicles

California's vehicle emission inventory model, EMFAC, helps CARB keep track of important sources of pollution and is a critical tool for air quality planning on both regional and local levels. Updates to the inventory are necessary to continue meeting air quality goals and understanding how regulatory measures may impact air quality. Models like EMFAC predict that non-exhaust sources, such as brake and tire-wear, are the main source of primary particulate matter (PM) from on-road vehicles and this has raised concerns around the world to better understand this source of emissions. CARB researchers measured and characterized PM emissions from a variety of brake components under various operating conditions. Brake PM emissions were generated using an enclosed brake dynamometer and measured using state-of-the-art measurement techniques. The results show that PM emissions are sensitive to braking materials, braking force, and simulated vehicle weight. The investigators also simulated regenerative braking, a typical feature of advanced clean cars, and found that this technology led to lower overall PM emissions. The test results will be used to create new emission factors for the EMFAC model and provide the most comprehensive data set on light-duty vehicle brake emissions to date. Given that brake-wear is currently estimated to be the largest source of primary PM from on-road vehicles, updates to the model that include current materials and advanced technologies will help CARB better assess how these emissions will impact air quality on a regional level, but more importantly on a local scale, particularly for populations living near major roadways. This source of emissions has become a major concern recently, and this project is an important first step in better understanding its potential impacts on air quality and exposure.

Figure 27: Total vehicle PM mass emissions for all vehicle tests and as a function of vehicle weight and brake pad material



implications for exposure. One concern is that these emissions may impact communities living very near major roadways while having a less dramatic impact on regional air quality. This is a major concern for priority communities. Another important difference between exhaust and non-exhaust PM relates to their composition. There is a concern that non-exhaust PM contains higher concentrations of metals and other toxic compounds that could have negative health effects.

The non-exhaust emissions Research Program recently developed at CARB is designed to fill many of these research needs. Extramural contracts designed to generate new emission factors began in early 2017. In-house projects designed to complement the extramural contracts are on-going. A roadside project designed to better understand non-exhaust emissions at the roadside and their impacts on exposure is also on-going.

Non-Tailpipe Emission Sources: Brake-Wear

Background and Current Research: CARB has invested in research efforts to modernize its emission inventory for brake-wear PM, which is currently the largest source of primary PM from on-road vehicles and is predicted to increase over time. Currently EMFAC relies on older data that was limited in scope and did not focus on California-relevant vehicles or driving behavior. The most widely accepted method for testing brake-wear PM to derive emission factors is the enclosed brake dynamometer. This method isolates brake-wear from other sources and thus removes a large uncertainty compared to on-road or full vehicle tests. Although this method has been used since the 1980s, a standardized and recommended protocol was not established until recently. Currently, the European Joint Research Centre (JRC) is leading the effort to establish a standard protocol so that experimental results around the world can be more easily compared. A recent study used this method to collect brake-wear PM from various on-road vehicles under various conditions. Likewise, the California Department of Transportation (Caltrans), in collaboration with CARB, is funding a similar project focused on heavy-duty vehicles. Both projects will provide new emission factors based on common vehicles operating in California. Thus far, results have demonstrated that higher vehicle loading and aftermarket parts lead to higher emission factors (see research highlight titled: Measuring brake-wear emissions from passenger vehicles). Brake-wear emissions are lowest in higher speed driving due to less-frequent braking as a function of distance driven. Regenerative braking does lead to lower emissions overall.

In addition to the enclosed brake dynamometer method, other complementary laboratory methods can investigate the shortcomings of the enclosed brake dynamometer and link its results to the on-road situation. Since the enclosed brake dynamometer is designed to capture all emissions with minimal losses, it may overestimate emissions. In-house research efforts are currently underway at CARB using full-size vehicle testing methods that will still simulate brake-wear while minimizing other sources of pollution.

Going forward it will be important for CARB to continue testing vehicles as the fleet make-up changes and as brake part materials change. Additionally, the inventory should be updated as more regenerative braking capable vehicles enter the fleet. This line of research will continue to inform inventory estimates and guide potential regulatory programs.

Non-Tailpipe Emission Sources: Tire-Wear

Background and Current Research: In addition to brake-wear, tire-wear is an important component of the emission inventory. Like brake-wear, the tire industry is changing and evolving in response to calls for more efficient vehicles to reduce greenhouse gases. This has led to wider adoption of low-rolling-resistance tires. These shifts in materials and vehicles suggest the need to create new tests and modernize emission factors. Increasing interest in this topic, as with brake-wear, has led to new methodologies for testing and better understanding the factors affecting tire-wear PM. As with brake-wear, tire-wear emissions depend on driving behavior, materials and vehicle type. The issue with tire-wear is that it is more challenging to test because emissions are highly dependent

on the road surface as well. Few laboratory methods thus far can recreate real road conditions with high fidelity. The literature also suggests that aggressive driving, side slip and hard braking lead to significantly higher tire-wear emissions. This suggests that certain road segments with higher turning radius, or off-ramps requiring harder decelerations, could lead to higher tire-wear. These roadway facilities could be hotspots for this type of emission. More information is needed on the prevalence of aggressive driving maneuvers leading to higher tire-wear emissions, and whether recurring emissions could lead to exposure concerns for people living near those hot spots.

As part of the on-going research plan to update our understanding of non-exhaust emissions, an in-house white paper project is currently underway to explore different testing methodologies and to define the most important parameters affecting tire-wear (see research highlight titled: Brake and tire-wear white paper in support of developing local and regional air quality policies). Leveraging industry knowledge will be critical in determining the direction tire-wear technology is heading and which materials and tire types dominate the market share today and in the future. Updates to the emission inventory are critical for predicting which sources of pollution dominate certain environments and help CARB properly plan to mitigate the worst effects of toxic air pollutants. Future laboratory or on-road testing will be informed based on the analysis in this white paper.

Real-World Non-Exhaust Emissions and Exposure

Background and Current Research: A current study is analyzing emissions collected at two monitoring sites in Southern California using a comprehensive suite of instruments. The instrumentation has been chosen to probe PM chemical and physical characteristics to understand how traffic patterns and fleet mix contribute to PM. Meteorological information has also been recorded. The project is leveraging Southern California Air Quality Management District air quality data as well as weigh-in-motion sensor data to determine fleet mix. Additional sampling of PM has been performed to probe the toxicity of different PM sizes. The data collected from this research will be analyzed to derive the relative impact of exhaust and non-exhaust PM emission, and will be input into a dispersion model to determine the potential exposure impacts downwind. The results of this research will be critical in providing a real-world comparison with the laboratory generated brake-wear data. One of the sampling sites chosen was near the 710 freeway, considered a major pollution source in a nearby environmental justice community, thus this project will also provide invaluable information for the AB 617 program.

This research will help refine emissions estimates by using a top-down approach. In coordinating with the lab projects, which are a bottom-up approach, the results of this project will help support

In-House Research Highlight: Brake and Tire-Wear White Paper in Support of Developing Local and Regional Air Quality Policies

One of the main targets for regulatory measures adopted and implemented by the Board has been to decrease pollutant levels from tailpipe exhaust emissions of on-road vehicles. Non-exhaust PM emissions, including inhalable dust from brake and tire-wear, have raised concerns due to their predicted significant emissions compared to tailpipe exhaust PM. However, until recently, no commonly accepted brake-wear emission test method had been established, and as of yet there is no commonly accepted test for tire-wear emissions. CARB is currently investigating different approaches and methodologies to better understand and measure brake- and tire-wear PM emissions. An in-house white paper will summarize the current state of knowledge on brake- and tire-wear emissions measurement methods, emission factors, PM characteristics, health effects, potential mitigation options and remaining unknowns. This paper will allow CARB to determine future directions for investigating these sources of pollution, which raise exposure and health concerns for communities living near major roadways.

emission reduction strategies. The design and execution was informed by results and methods tried in the past. This project is establishing a new precedent for monitoring non-exhaust emissions that can be replicated in the future to track how exhaust and non-exhaust emissions change with fleet turnover and land use changes brought about by the Advanced Clean Car and Advanced Clean Truck programs as well as SB 375. In addition, the toxicity and PM characterization information will be invaluable to our Health Research Program.

Future Research: Going forward, more information will be needed regarding non-exhaust emissions on other road types. Surface streets may present important hot spots for non-exhaust emissions impacting vulnerable populations. More granular information would elucidate potential exposure hot spots that could be modified to induce different driving behavior. In the future, vehicle automation may present opportunities to minimize driving behavior that leads to higher non-exhaust emissions. More work will be needed on how driving behavior affects the emission of brake and tire-wear particles to determine how to mitigate their effects on the surface street level, where there may be the highest potential for exposure.

Research Question:

- What are the real-world emissions associated with brake and tire wear and what are the best methods for monitoring these sources?

Climate Pollutant Inventories and Mitigation

California's seminal Global Warming Solutions Act, Assembly Bill (AB) 32,[36] charged CARB with developing a Scoping Plan that describes the approach California will take to achieve the goal of reducing GHG emissions to 1990 levels by 2020. Senate Bill (SB) 32[37] codified a new GHG emissions target of 40 percent below 1990 levels by 2030. Governor Brown's Executive Order B-55-18 (2018) commits California to total, economy-wide carbon neutrality by 2045.

Short-lived climate pollutants (SLCPs) and nitrous oxide (N_2O) emission reductions are critical to achieving California's GHG emissions reduction goals. SLCPs include methane (CH_4), fluorinated gases (including hydrofluorocarbons, or HFCs), and black carbon (BC). These air contaminants are powerful climate forcers that have an outsized impact on climate change in the near term compared to longer-lived GHGs such as carbon dioxide (CO_2). Senate Bill (SB) 1383,[38] also requires a 40 percent reduction in methane and HFC emissions and 50 percent reduction in anthropogenic black carbon emissions, all relative to 2013 baseline levels, by 2030.

CARB's Research Program has sponsored external research and developed in-house research initiatives to support the agency's efforts to inventory, monitor, and mitigate the emissions of these SLCPs. In addition, CARB's climate research quantifies co-benefits and supports mitigation opportunities and pathways to help reach climate goals.

Evaluating Trends and Refining Emissions Estimates

CARB is currently engaged in several research efforts to better understand GHG emission behavior both regionally and from individual sources. This work relies mainly on ambient measurements of greenhouse gases. The statewide GHG monitoring network can provide insights at regional levels through a host of ambient measurements (e.g., CH_4, isotopic CH_4, CO_2, N_2O, BC, and F-gases). CARB has two mobile platforms, with research-grade GHG, air quality, and trace chemical measurement capabilities; and flux towers, which can evaluate emissions at the source level to supplement regional-level information. Mobile platforms provide snapshots but can be deployed at more sources while flux towers can provide longer-term information and provide insights on emission characteristics but are not easily moved between locations. CARB is also collaborating with others on a variety of ambient observations, including satellite, aerial, and ground-level measurements, and with a new focus on remote sensing. Collectively, these efforts are helping us gain a better understanding of GHG sources, their emissions, and mitigation options in California.

Evaluating Trends and Refining Emissions Estimates: Methane

Background and Past Research: California has made significant progress on understanding methane emissions in the state, and the results help inform California's climate change mitigation program under the requirements of AB 32 and SB 32, among other pieces of legislation. The Methane Research Program at CARB uses a variety of scientific approaches to understand source profiles and characteristics of methane emissions at regional and local scales as well as for different source sectors. Major research efforts include CARB in-house studies, CARB-funded research contracts, collaboration with local and federal organizations, national labs and leveraged research outcomes from other state agencies, such as the California Energy Commission (CEC), California Department of Food and Agriculture (CDFA) and California Department of Resources Recycling and Recovery (CalRecycle). Leveraging findings from research projects funded by other state agencies allows for a comprehensive and integrated understanding of California methane emissions and mitigation measures.

At the statewide level, CARB has supported both extramural and in-house research to develop top-down estimates of California methane emissions using inverse modeling approaches based

36 Nuñez, Chapter 488, Statutes of 2006
37 Pavley, Chapter 249, Statutes of 2016
38 Lara, Chapter 395, Statutes of 2016

on data from the statewide GHG monitoring network, airplanes and satellites. Current work in this vein includes reducing the uncertainty of the modeling estimates and investigating the reasons for discrepancies with the inventory. CARB also has a long-standing research collaboration with the *Megacities Carbon Project* in Southern California to study regional methane emissions in the Los Angeles area and is funding multiple data-collection projects in support of the effort.

To better understand the occurrence and emission rates of point-source leaks of methane in California, CARB and the CEC, along with NASA, commissioned the California Methane Survey (CMS); using imaging spectrometers mounted on airplanes to identify and show on a map the location of methane point sources to within several meters. Such point sources, if identified, could potentially be easy targets for mitigation. The airplanes surveyed the main methane-emitting sources in California – agriculture, the oil and gas industry, and landfills – scanning 272,000 distinct facilities and infrastructure components across the state. These scans identified 564 large methane plumes with emissions above the detection limit of 10 kgCH_4/hr. These could contribute significantly to statewide methane emissions. To evaluate the extent to which these plumes are mitigable, CARB worked with industry partners during a similar field campaign in 2020 to put boots on the ground whenever a plume was identified in the partner's operation or infrastructure. The results from this latest study show that a significant portion of the plumes identified can be mitigated, and that, in aggregate, they are an important fraction of the methane inventory. Satellites with this type of technology would enable important mitigation for methane worldwide, and are one of the potential outcomes of the Bloomberg – Planet – California 'Satellites for Climate Action' collaboration (see research highlight titled: Launching satellites to detect methane leak sources).

CARB is further expanding methane measurement and analysis efforts by initiating facility-level emission quantification with aircraft-based emission estimation, ground-based mobile monitoring, and flux tower measurements. The airborne technique was successfully applied to quantify methane emissions during the Aliso Canyon leak incident, and has continued for all natural gas storage facilities in the state. The ongoing project extends these measurements to include dairies, landfills, oil and gas fields, and refineries.

In the agriculture sector, CARB has supported various projects to understand the emissions and activities of California dairy farms, develop a California Specific Dairy Emission Model to quantify GHG and air pollutant emissions from enteric fermentation and manure management, and evaluate the effectiveness of multiple mitigation strategies such as alternative manure management practices, dairy digesters, and feed additives. In the waste management sector, CARB has conducted a long-term study of methane emissions at a large California landfill using a comprehensive, multi-scale measurement approach. Results show that emissions at this particular landfill vary both temporally and spatially due to meteorological factors and landfill operations, and that the active portion of the landfill may emit a disproportionate fraction of the total emissions. Additional work is needed to understand if these results are generally representative of landfills. In the energy sector, CARB has funded projects to estimate fugitive emissions from natural gas well heads, distribution pipelines, and customer gas meters.

Future Research: While CARB has made progress in understanding methane emissions, there are still knowledge gaps that need to be addressed. Moving forward, the focus of CARB's research efforts on methane is to improve our understanding of methane emissions from major sectors, identify and evaluate certain sector-specific mitigation strategies where possible, and better understand the occurrence and mitigation potential of point sources. Future research on methane emissions will need to translate source-level emissions snapshots to relevant emission factors and/or process-based models that are able to estimate emissions based on source specific environmental factors, considering temporal and spatial variations. A more systematic understanding is needed for both source-specific activity patterns and emission rates to better understand these emission sources.

Moving forward, CARB will continue to address questions related to further improving knowledge on the major sources of GHGs discussed above. The various tools and methods leveraged across multiple efforts will also be used to identify any new, understudied or emerging sources of GHGs across the state.

Research Questions:

- What are the GHG emission trends for specific sources and how can they inform future GHG policies?
- How can new technologies, such as remote sensing that can pinpoint individual leaks, be used to achieve further methane mitigation?

In-House Research Highlight: New Techniques for Emission Measurements

In the last three years, CARB staff have integrated the use of eddy covariance flux systems that allow comprehensive and continuous assessments of carbon emissions from a variety of complex sources (Figure 28), and have successfully deployed these systems to measure methane emissions from major sources in California. Staff have deployed these systems at a series of dairies across the state to study the emission reduction potential of alternative manure management practices. In another study, staff deployed a series of flux towers at one of the largest landfills in the state, and collected data over a two-year period to study the various methane emission sources, such as the cover itself, the gas collection system, and the landfill active zones, as well as the influence of short-term meteorological factors and longer-term seasonal changes on emissions. These new research efforts are improving CARB's capabilities and tools to study these source behaviors, and are laying the groundwork to improve emission estimates, and help identify effective mitigation strategies to reduce their emissions.

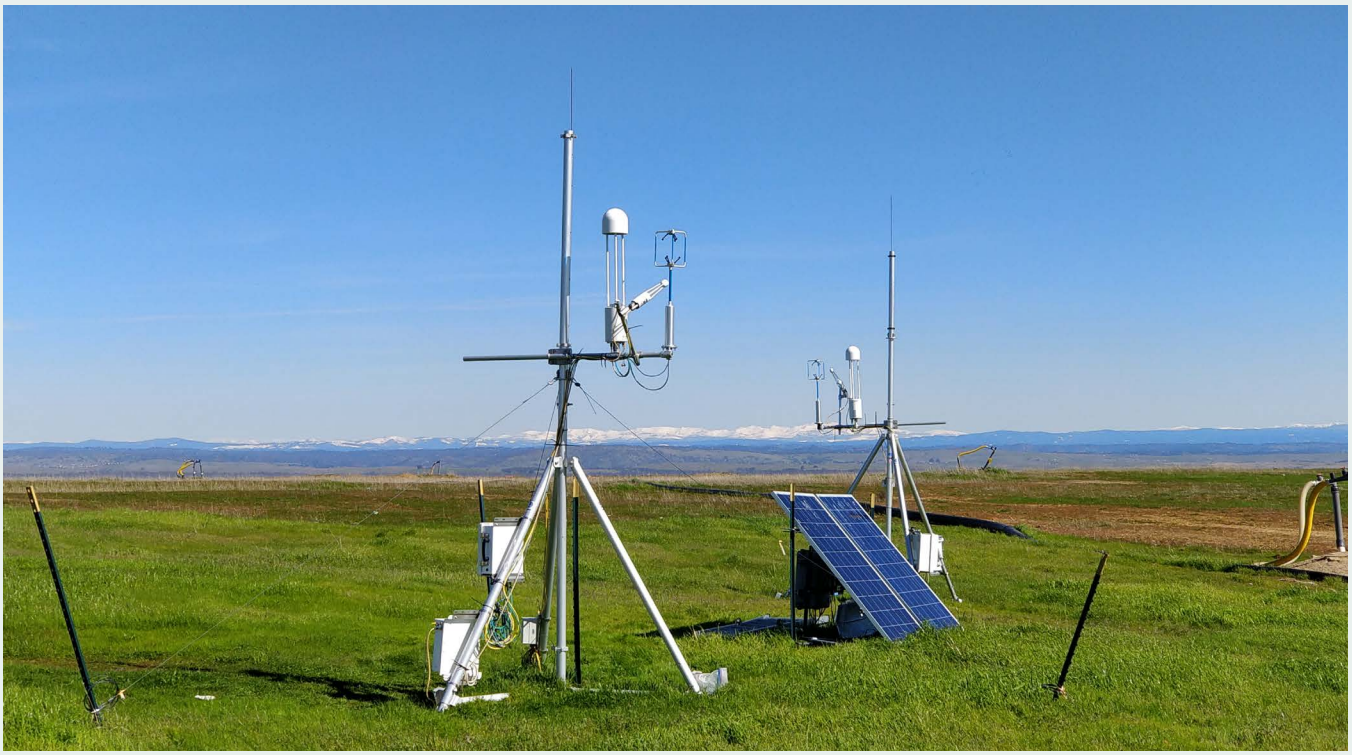
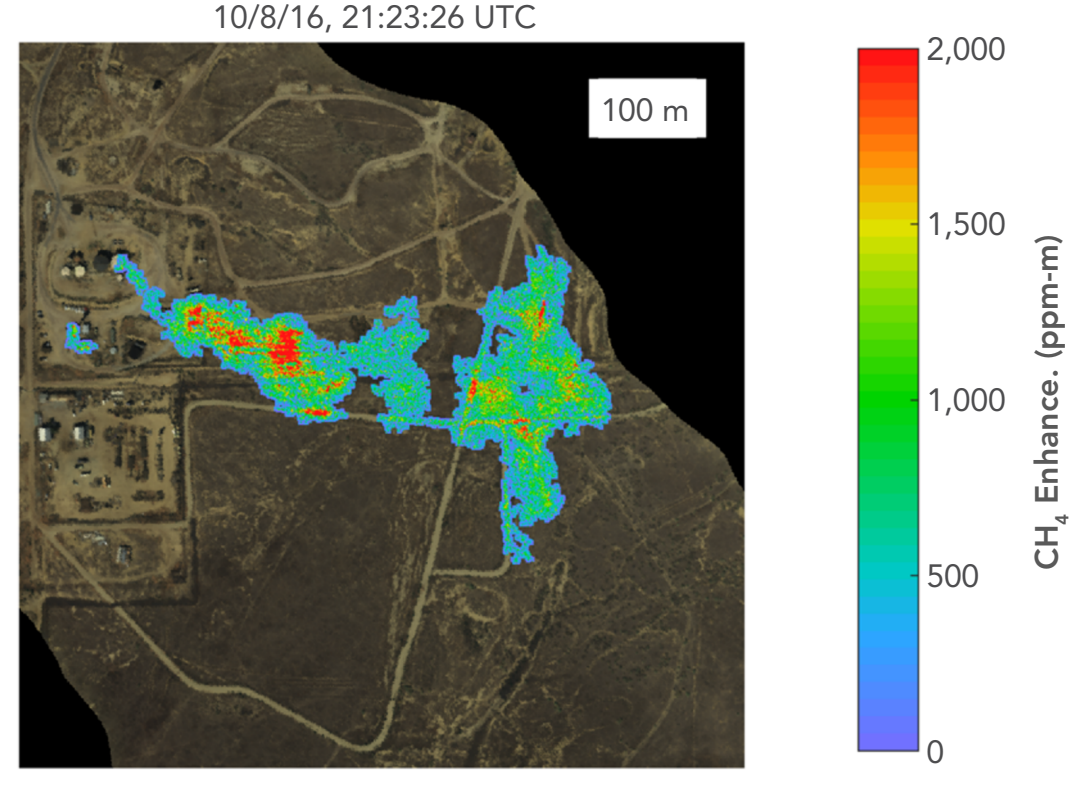


Figure 28: Flux tower deployed in the field

In-House Research Highlight: Launching Satellites to Detect Methane Leak Sources

CARB has funded a series of research projects to test and deploy state-of-the-art NASA methane plume imaging technology to survey California's methane infrastructure. This approach can find large methane emitting sources and equipment quickly and efficiently. CARB, along with the California Energy Commission (CEC) and NASA, funded the 2016-2018 California Methane Survey, which successfully deployed this technology using aircraft campaigns, and found over 550 large sources of methane emissions and leaks. CARB has also worked with the research team and various stakeholders to integrate, evaluate, and demonstrate the utility of these products using quick-look methane plume data. This can notify the operators and stakeholders within 24-48 hours of observing an emission source so that it can be quickly mitigated. However, aircraft are costly in the long run and impractical for the long-term routine monitoring required to achieve effective mitigation across California and the globe. The state of California has therefore entered into a "Satellites for Climate Action" partnership with partners like PLANET, Inc., the High Tide Foundation and Bloomberg Philanthropies, amongst others, to launch spaceborne versions of these sensors on satellites in the coming years. Concurrently, CARB is working with JPL to bring the source and data visualization platform (JPL's Methane Source Finder: *methane.jpl.nasa.gov/*) in-house. This project will develop the data pipeline and notification system needed for effective mitigation for future satellites and will take place in collaboration with stakeholders and operators on the ground. Once an operational constellation of multiple satellites is available, California would have the ability to track methane plumes from point sources in time and space with sufficient resolution and accuracy to potentially inform its programs and regulations.

Figure 29: Airborne methane source mapping example in California



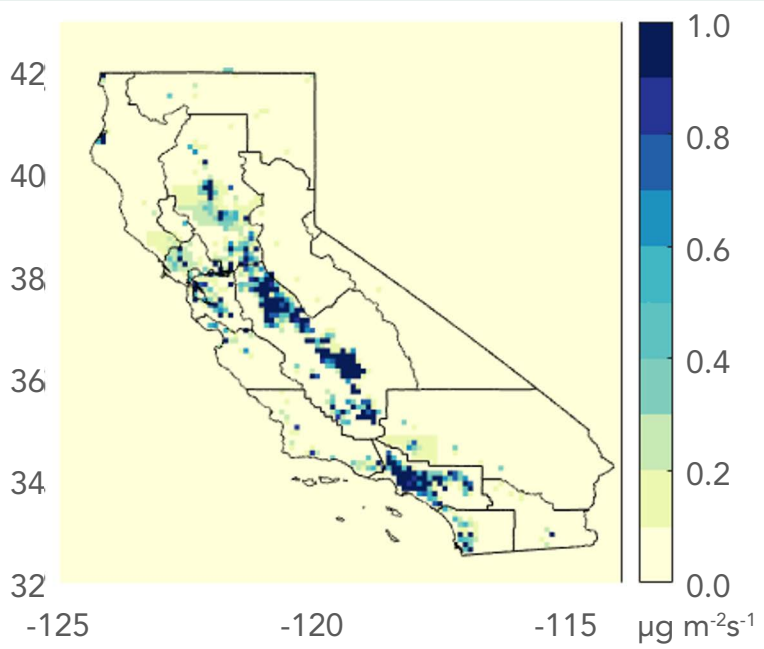
Evaluating Trends and Refining Emissions Estimates: Nitrous Oxide

Past and Current Research: CARB's N_2O Research Program has focused on agricultural soil management, the largest source of N_2O emissions in the state. N_2O emissions from soil are mediated by soil microorganisms and are therefore sensitive to soil environmental factors, leading to extraordinary spatial and temporal variability in N_2O emissions. CARB has collaborated with CEC, CDFA, and CalRecycle in funding both field and modeling studies of N_2O emissions from California croplands. This Research Program measured N_2O emissions from major California cropping systems, evaluated alternative management options that are potentially effective in curbing N_2O emissions, and developed a California-specific biogeochemical model: DeNitrification DeComposition (DNDC), that can be used to quantify N_2O emissions under a wide range of cropping scenarios under California conditions. The DNDC model is currently being used by CARB. Work is ongoing to

In-House Research Highlight: GHG Monitoring and Analysis Framework

In the last decade, CARB staff have implemented a GHG emissions monitoring and analysis research program that uses statewide GHG monitoring network data coupled with inverse dispersion modeling and analysis techniques for evaluating regional GHG emissions. These research efforts use data collected by CARB's Statewide GHG Monitoring Network, a first-of-its-kind state-operated network designed to support CARB's programs and to provide additional information that can be used in CARB inventories. Staff have completed a variety of regional emissions analyses, including two multi-year inverse analyses of statewide methane and nitrous oxide emissions, and a series of regional studies of methane, nitrous oxide, and fluorinated gases in the South Coast Air Basin using emission modeling and source apportionment techniques. CARB is also expanding the GHG monitoring network to add additional monitoring sites in the San Joaquin Valley where methane emissions are highest and complex due to a multitude of sources, adding boundary layer measurements using ceilometers, and real-time F-gas and VOC measurements (which can help with source attribution). These measurements and analytical methods shed additional light on GHG emissions in the state and help inform our inventory and programs.

Figure 30: Statewide methane emissions map generated using statewide GHG monitoring network data and inverse modeling



incorporate the DNDC-based N_2O emissions into the state inventory, and by CDFA for information for the Healthy Soils program. That program implements mitigation measures on the ground to cut N_2O emissions and increase carbon sequestration in California agricultural soils.

Future Research: This research initiative has been fruitful over the past few years, and while CARB staff will continue to provide foundational information and investigate the discrepancies between atmospheric measurements and modeling, there is not a priority research question for this Triennal Plan. As additional knowledge is gained, Staff may recommend a future question.

Evaluating Trends and Refining Emissions Estimates: F-Gases

Past Research: CARB's Research Program on F-gases has inventoried California's sources of these high-GWP gases. Past CARB-funded research on HFCs and other high-GWP GHGs found that these gases are emitted by a variety of sources, and are the fastest growing GHGs in California. These studies also assisted with the development of the Short-Lived Climate Pollutant Reduction Strategy.

Current Research: Current research on F-gases aims to improve the inventory of small stationary refrigeration and air conditioning equipment that use either HFCs or alternative high-GWP refrigerants. Through this current effort, CARB will have a better understanding of the number of systems in use, their leak rates determined by practices in the field, and the age of these systems. CARB will continue to prioritize research to refine F-gas emission inventory estimates, including updating with potential new sources such as heat pumps, which have potential to increase in numbers with electrification over the coming years. The results will be used to improve F-gas emissions estimates, and will also be used to inform policy decisions to reduce GHG emissions.

Evaluating Trends and Refining Emissions Estimates: Black Carbon (BC) and Brown Carbon (BrC)

Past Research: CARB research on BC began with the creation of a California inventory for BC. A CARB-funded study observed a 50 percent reduction in BC measured at monitoring sites throughout California over the past twenty years, and a 90 percent reduction over the past 45 years. The 50 percent reduction in BC accounted for a 25 percent decrease in atmospheric heating in California. Through a collaborative research effort with NOAA, CARB was able to produce direct measurements of this forcing in the atmosphere. These results agree with the expected emission reductions associated with California's diesel emissions control program. While the scope of this work was limited to determining the impact of BC, this study discovered that brown carbon (a form of organic carbon aerosols) is also an absorber of radiation, particularly at short wavelengths, and may serve as an extra warming agent due to its typically higher concentrations.

CARB conducted a study that applied multi-wavelength ambient BC and carbon monoxide (CO) measurements made at the Mount Wilson Observatory (MWO) to produce BC emission estimates for Los Angeles County within the South Coast Air Basin (SCLA) from 2013 to 2020. The annual measurement-based BC emissions showed a reduction of 28% between 2013 and 2018. Subsequent analysis of multi-wavelength ambient BC data determined that biomass burning contributed 20% of the annual average BC concentrations observed at MWO. This study highlights the successful implementation of past PM emission control strategies in reducing ambient BC, and the need to further evaluate BC emission sources and their spatial variabilities in SCLA to aid in the development of air pollution control and management policies.

Current Research: Recent studies show that BrC (light-absorbing organic carbon) particles can also absorb solar radiation efficiently, although they differ from typical BC particles. BrC emissions from residential, agricultural, and wildfire burning are a highly seasonal, episodic, and poorly characterized fraction of $PM_{2.5}$ in California. A multi-institution collaboration identified and characterized the contribution of BrC to climate forcing in California. The results indicate that BrC is important for surface-level absorption in wintertime Fresno, although BC is still the largest fraction of surface-level absorption. A combination of source-oriented regional modeling and global plus regional modeling showed that diesel engines make a larger contribution than biomass burning to total-column absorption in California. The results of this project provide valuable insights regarding the

fundamental processes that govern BrC formation and its evolution in the atmosphere, and help determine the potential climate benefits of mitigating emissions of BrC in California. This study also presents a number of new questions related to the contribution of residential burning to wintertime air quality. For example, the role of fog in affecting aerosol composition and concentration needs to be better understood, as well as the implications of fog-related particle production for predicted changes in California climate.

Future Research: CARB will continue efforts to refine the BC emission inventory.

Mitigation Options

California is working to reduce GHG emissions across all sectors of the economy under the framework of AB 32, SB 32, SB 1383, and Executive Order B-55-18. Although CO_2 emissions constitute the largest share of California's GHG inventory, nitrous oxide and SLCPs are also significant contributors. New strategies to monitor and reduce emissions of SLCPs and nitrous oxide thus offer tremendous potential for climate benefits, and have therefore been a research priority for CARB. CARB's GHG emissions measurement efforts help to identify sources, evaluate the emissions from these sources, identify new emission reduction strategies, and track progress in reducing emissions. CARB complements this research with studies to examine GHG mitigation strategies.

California's goal of Carbon Neutrality by 2045 will require both reductions in GHG emissions and as carbon sequestration, such that there are net zero GHG emissions by mid-century. To achieve carbon neutrality by mid-century, we must minimize emissions from our fossil energy and industrial sources, and transition our natural and working lands from a source to a sink so that the net negative GHG emissions from NWL offset the remaining GHG emissions from other sources.

Mitigation Options: Carbon Dioxide

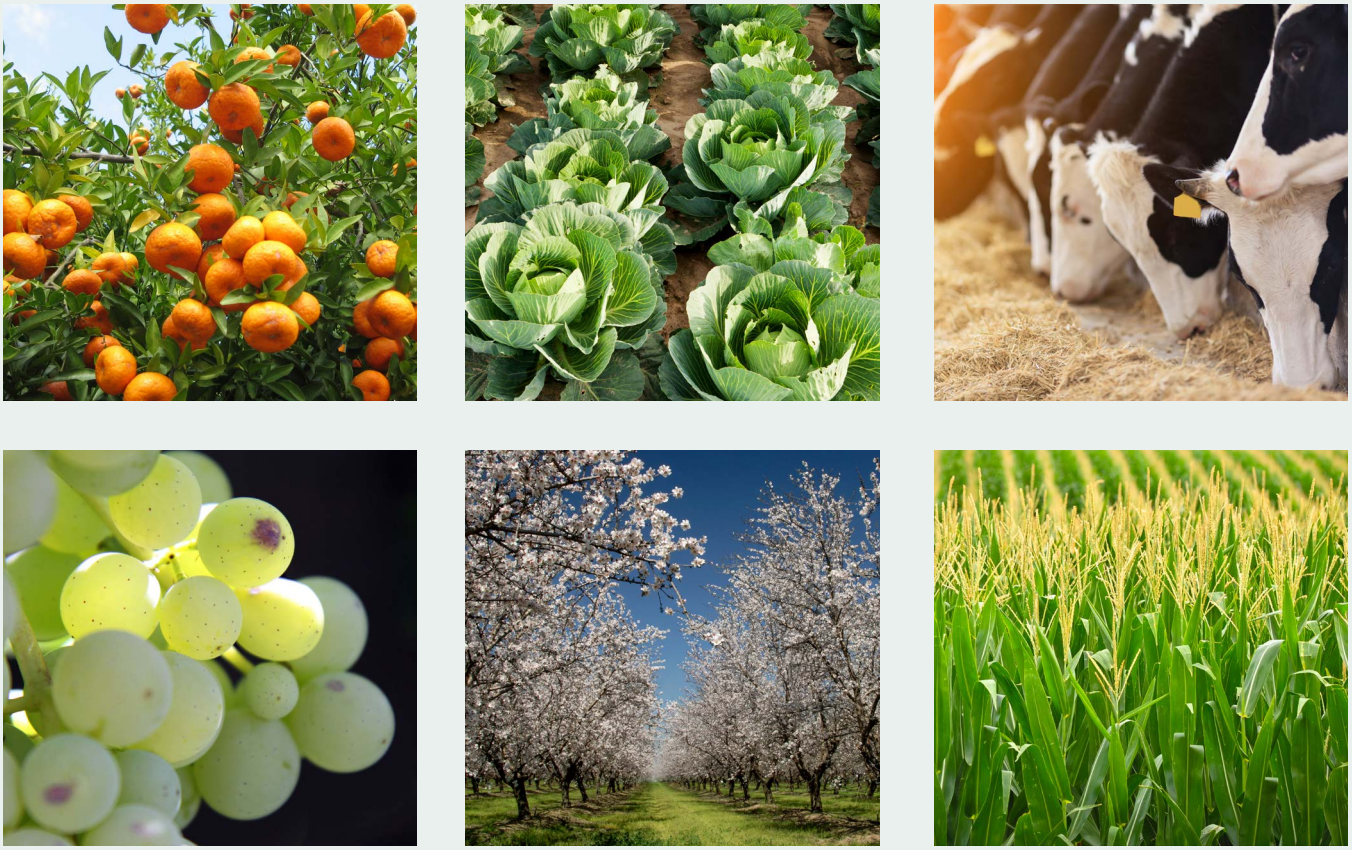
Background: California's natural and working lands play a key role in carbon neutrality, and have the potential to become a valuable emissions sink despite currently being a source of GHG emissions. CARB's Research Program will continue to measure and model the carbon sequestration potential of land management practices in natural and working lands (NWL). This work will support CARB's NWL GHG inventory, Scoping Plan NWL strategies, and quantification methods for incentive programs. Work on the potential for sequestration strategies in NWL will continue to identify management practices, or combinations of practices, to maximize carbon sequestration with co-benefits for the economy and the environment. The Research Program will also prioritize research that assesses the viability of these strategies in future climates, and estimates how climate change may impact the long-term sequestration potential of these practices.

Current and Future Research: In 2018, the Board adopted a Carbon Capture and Sequestration Protocol for low carbon fuel standard projects that capture CO_2 and sequester it in geologic formations. The Research Program will prioritize research to assess policy instruments and incentive programs to motivate investments in carbon-negative technologies, and will support the development of tools to assess the health, economic, equity, and environmental outcomes of strategies to achieve carbon neutrality.

Research Highlight: Solving Dairy Emissions While Maintaining Productivity

California's climate change mitigation goals can't be achieved without reducing GHG emissions from livestock, which account for more than 50% of statewide methane emissions -- the majority from cattle operations. Enteric fermentation in the animals' digestion process and manure management are the primary sources of methane from cattle operations. Cutting methane emissions from these sources is crucial to achieving California's climate goals. In recent years, CARB has funded several projects to study dairy methane emission sources. CARB's research has improved enteric emission estimates by accounting for the California-specific animal ration, diet composition, animal breeds, and production stages and types. These projects have also characterized the emissions from California's dairy facilities and manure management practices, while evaluating the feasibility of using feed and manure additives to reduce enteric and manure methane emissions. Drawing on the literature, statistical and life cycle analyses, researchers examined over 90 feed additives and 13 manure additives, and found only one that they deemed safe and effective - 3-nitrooxypropanol (3NOP). The study estimates that 3NOP could reduce enteric methane emissions by as much as 11.7%, or 2.5 MT CO2e annually if used statewide for dairy and beef. The manufacturers of 3NOP are currently pursuing FDA approval for the product. More research is required before any manure additives can be recommended for use. Ongoing research will integrate California-specific information into process-based models used to quantify the methane and air pollutant mitigation potential of feed additives and alternative manure management practices at California dairies and their impacts on climate and local and regional air quality. These research investments will yield comprehensive information needed to guide SLCP strategies targeting California's largest source of methane emissions.

Figure 31: Dairy and agriculture ecosystem in California



Research Questions

- What land management practices can be used individually and in combination to advance carbon sequestration methods in geologic formations and natural working lands in California?
- Can ambient measurements and remote sensing be used to inform the exchange of CO_2 between the atmosphere and biosphere?

Mitigation Options: A Multipollutant Evaluation of Dairies

Background: California is already implementing methane reduction strategies in all anthropogenic source sectors, as required by SB 1383. SB 1383 requires CARB and CDFA to work with a broad range of stakeholders to identify and address technical, market, regulatory, and other challenges and barriers to the development of dairy methane emission reduction projects. In keeping with this requirement, CARB, CDFA, CEC, and the California Public Utilities Commission convened a Dairy and Livestock Working Group in May 2017. This Working Group established three subgroups that focused on policy recommendations in specific areas: fostering markets for digester projects, fostering markets for non-digester projects, and research needs – including enteric fermentation. The research subcommittee developed a comprehensive Dairy Air Research Prospectus. The Prospectus outlines various research concepts, and addresses the knowledge gaps for both enteric fermentation and manure management practices.

So far, CDFA has created two incentive programs for dairy operations to reduce GHG emissions from manure management practices. One program incentivizes the installation and the use of digester systems on dairy farms as a strategy to capture and use the methane gas as a source of energy. The other focuses on the implementation of alternative manure management practices to reduce the amount of anaerobic manure treatment and storage, resulting in methane emissions reductions.

Current Research: Beginning in 2018, CARB, in coordination with CDFA, initiated a series of research projects to study the influence of alternative manure management practices on GHG emissions and regional air quality. CARB supplements this effort by analyzing satellite remote sensing data and periodically deploying its ground-level mobile measurement platform to evaluate the methane emissions from hundreds of California dairies that employ conventional and alternative manure management practices as well as digester systems. CARB also initiated a study examining the economic and logistical feasibility of strategies to inhibit CH_4 production from enteric fermentation and anaerobic manure storage lagoons at California dairy operations. The project evaluated a list of feed additives such as seaweed, nitrate, and 3NOP, and manure additives such as biochar and acidification agents (see the research highlight titled: Solving Dairy Emissions while Maintaining Productivity).

Future Research: Future research will reflect the priorities outlined in the Prospectus: addressing the knowledge gaps in dairy air research for both manure management practices and enteric fermentation. These include: assessing the localized air pollution issues associated with dairies near priority communities; developing a long-term air monitoring program to track the reduction of methane and other pollutants (e.g., NH_3 and N_2O) from California dairies; and improving the dairy emission inventory using California-specific data, among others. The Prospectus will help guide California's funding agencies and prioritize future research projects.

Research Questions:

- How can we best address the knowledge gaps outlined in the Prospectus for dairies?
- What additional strategies can the state adopt to effectively and cost-efficiently reduce methane emissions from the dairy and livestock operations (from both enteric and manure)?

Identification and Mitigation of Methane Point Sources

Current and Future Research: CARB's ongoing and future research effort will consider opportunities to gather more refined data on large emissions of methane – including those from oil

and gas facilities – as methane regulations take effect.

CARB will continue to support research to evaluate the opportunities and effectiveness of source-specific methane reduction strategies. Such research will improve the understanding of source characteristics, identify unintended or accidental methane emissions, inform best management practices, and evaluate the source-specific trends of methane emissions as various mitigation strategies are implemented.

Research Question:

- Will emerging technologies such as remote sensing provide an opportunity for identification and quicker mitigation of large methane leaks from point sources?

Mitigation Options: Nitrous Oxide

CARB's N_2O research projects collected field flux data, calibrated the DNDC biogeochemical model, and used the model to quantify the mitigation potential of specific management practices. This research has been well coordinated with external stakeholders, CEC, and CDFA. Recent improvements to the model included expanding the range of California cropping systems represented and the refinement of model parameters related to manure management and irrigation methods. These have greatly enhanced its capacity to identify effective mitigation strategies. Modeled emission scenarios indicate that the use of nitrification inhibitors, cover cropping, and water-efficient irrigation consistently reduce N_2O emissions.

CARB's N_2O research projects have informed the CDFA's Healthy Soils Program, which built the DNDC results into its GHG estimating tool to estimate the benefits of on-ground mitigation efforts by growers across the state. Moving forward, CARB will investigate methods for improving understanding of the GHG emission impacts and ecosystem benefits of improving management practices of natural and working lands.

Research Question:

- How can the modeling of the GHG emission impacts and ecosystem benefits of management practices and interventions in the natural and working land sectors be improved?

Mitigation Options: F-Gases

Past and Current Research: Reducing emissions of F-gases is one of the most effective near-term actions for reducing the impacts of climate change in California and the globe. CARB's F-gas research has resulted in the successful development and implementation of multiple regulations and programs to reduce F-gas emissions. These programs have led directly to the adoption of national rules to reduce HFCs from commercial refrigeration, motor vehicle air conditioning systems, and other sources. Based on this research, CARB also adopted a protocol to provide incentives to recover and destroy F-gases (specifically, ozone-depleting substances) as part of the Cap-and-Trade Program. A new regulation to prohibit the use of certain HFCs with high global warming potential in stationary refrigeration equipment and foams was approved by the Board in March 2018. Prior to 2018, California was the only state that regulated HFCs. Seventeen other states have now passed legislation based on California's rules, or are in the process of doing so. In December 2020, the Board approved additional high-GWP HFC prohibitions in stationary refrigeration and – for the very first time – in stationary air conditioning equipment.

Future Research: Continued research on this topic will be necessary to guide and inform the HFC reduction measures required by SB 1383, which requires a 40 percent reduction in HFC emissions below 2013 baseline levels by 2030. Rules and regulations supporting these goals are expected to spur technology innovation. Changes and growth in the technologies that utilize refrigerants have already been observed, although this is still a burgeoning field. To reach carbon neutrality, continued innovation and industry research on technologies with very low or zero GWP will be key. In order to get all necessary approvals, refrigerant manufacturers will need to consider the full environmental fate and transport of alternatives and their by-products.

An unexamined area relevant to F-gases is the use of alternatives to sulfuryl fluoride (SO_2F_2) in termite fumigation. This is a very high-GWP compound that is currently regulated as a pesticide and toxic air contaminant in California, but is not regulated as a greenhouse gas. Current understanding of promising alternatives is limited, and research is needed for the development of effective low-GWP alternatives.

Continuing research related to F-gas mitigation is essential to guide future investments and ensure that SLCP mitigation strategies are successful and cost-effective. Ensuring rapid technology turnover may require additional research in behavioral economics, incentive strategies and communication methods.

Research Question:

- How can the adoption of low-GWP and reduced-GWP technologies be accelerated?

Mitigation Options: Black Carbon

California has made extraordinary progress in reducing PM and black carbon (BC) emissions, especially from on-road mobile sources. This record of success makes California an international leader in reducing harmful $PM_{2.5}$ pollution, including BC and other constituents, to protect health, the environment, and climate. The strategies and technologies developed in California can also be applied to other regions to yield additional emission reductions. According to CARB's research, if California's efforts in reducing BC were replicated globally, global warming could be slowed down by about 15 percent in the coming decades. There would also be large benefits to human health. Globally, exposure to outdoor $PM_{2.5}$ is estimated to result in between four million and nine million premature deaths per year.[39]

CARB will continue to develop mitigation strategies for mobile sources, as well as strategies to reduce biomass burning. Efforts to reduce specific sources of GHGs, such as BC, will have clear co-benefits for health since $PM_{2.5}$ and diesel PM in particular, are associated with negative health outcomes. With the drive to zero-emission vehicles, 100% renewable energy as well as carbon neutrality, various co-benefits will also be achieved. While some interim options still have emissions, these will decrease overall as California moves forward with its climate goals.

39 Burnett et al., Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter, PNAS September 18, 2018 115 (38) 9592-9597; *doi.org/10.1073/pnas.1803222115*

Sustainable Communities Program Support

Sustainable communities are neighborhoods with safe, reliable, and affordable transportation choices, equitable and affordable housing options, and access to quality employment, education, and other services. CARB's Sustainable Communities Research program supports the fostering of these communities statewide, the implementation of Senate Bill (SB) 375[40] (the Sustainable Communities and Climate Protection Act of 2008), and the construction of new environmentally-friendly and health-protective buildings.

CARB's Sustainable Communities and Climate Protection Program encourages regional planning that integrates transportation and land use to reduce vehicle miles traveled (VMT) and thereby greenhouse gas (GHG) emissions from passenger vehicle use via its role in implementing SB 375. SB 375 requires that California's metropolitan planning organizations (MPOs) develop sustainable community strategies (SCSs) containing land use, housing, and transportation strategies that, when implemented, meet per-capita passenger vehicle GHG emission reduction targets set by CARB. The goals of an SCS are: to align regional land use and transportation planning to focus housing and job growth in existing urbanized areas, giving people greater accessibility to job opportunities and transportation options; to expand transit and active transportation networks and infrastructure to reduce VMT and foster healthier and more equitable communities; and to conserve natural resources and farmland.

Community sustainability also relies on the sustainability of individual buildings that house and serve the community. CARB plays a role in influencing building construction standards and practices by collaborating with other state agencies on the development of the Green Building Standards (CalGreen) Code. This code establishes requirements to improve the environmental and health impacts of new residential and commercial construction in California.

Research themes that have emerged from the needs identified by CARB's Sustainable Communities and Climate Protection Program and its CalGreen Code efforts include: investigating strategies that reduce VMT and GHG emissions from the built environment, evaluating the co-benefits and potential impacts of those strategies, including developing best practices to implement these strategies equitably, creating metrics to track the impact of strategies on equity, and tracking progress toward SB 375 goals. These projects have identified strategies to maximize the benefits of sustainable planning (including reduced air pollution, greater energy efficiency, and cost savings), and developed tools to monitor, evaluate 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 maximizing health and social equity, and to guide future policies.

Going forward, CARB will continue research to support the implementation of SB 375 while maximizing co-benefits across the state, especially in priority communities, and evaluating GHG reductions associated with VMT, land use, and buildings.

Tracking Progress and Co-Benefits

Background: CARB's Research Program supports the implementation of the Sustainable Communities and Climate Protection Act of 2008 (SB 375) and thereby helps pave the way for California's achievement of the 2050 climate goal. Senate Bill 150[41] requires CARB to prepare a report to the Legislature starting in 2018, and every four years thereafter, to evaluate progress in meeting the goals of SB 375. Based on the first SB 150 report released in 2018, metro areas in the state are falling short of the VMT reduction goals stipulated by SB 375. Although transportation planning efforts across the state have identified strategies intended to reduce VMT, real-world implementation of these strategies is not yielding the anticipated reductions. This further suggests that health and air quality goals, and their benefits, are not being fully realized, particularly in priority communities.

Current Research: The findings from the SB 150 report described above are echoed by the findings

40 Steinberg, Chapter 728, Statutes of 2008
41 Allen, Chapter 646, Statutes of 2017

of a separate research project. CARB has funded research, in collaboration with Caltrans, to lay the foundation for a future statewide monitoring system that will evaluate whether changes in the built environment are consistent with SB 375 goals. Results from a study in LA County suggest that while new housing is not sprawling into the suburbs, there is room for improvement to better align with SB 375 goals. Future research will continue to evaluate whether "on the ground" changes, planned land use, and transportation investments align with regional SCSs and state climate goals.

CARB continues to conduct research that evaluates the potential co-benefits of SB 375 implementation and assesses whether communities are benefiting equitably from the transition toward greater sustainability. Past case studies indicate that re-zoning for higher-density development, reducing parking requirements, and requiring pedestrian-friendly design, if implemented in combination, can result in up to $1 million in benefits to cities and over $100 million in benefits to the region. Another recent study showed that "complete streets" – designed for walking, biking, and transit, as well as cars – are sometimes associated with lower vehicle traffic volumes, less exposure to traffic pollution, and more use by pedestrians and cyclists, but complete streets are much more successful in downtown business districts than in other types of neighborhoods.

Research Highlight: New Housing Is Built in Less Sustainable Neighborhoods

Under SB 375, CARB sets regional targets for reducing miles traveled and greenhouse gases emitted by light-duty vehicles, and metropolitan planning organizations (MPOs) include Sustainable Community Strategies (SCS) in their regional transportation plans. Each SCS contains integrated land use, housing, and transportation strategies that, if implemented, would allow the region to meet the CARB-set target. CARB reviews each adopted SCS to evaluate the MPO's determination that the strategy will meet the target and – as of 2017 – must also report to California legislators every four years on the progress of SB 375 implementation. Without a way to directly measure how many miles passenger cars drive, CARB needed a system of data-supported metrics to assess how effective transportation, housing, and land use strategies have been in meeting SB375 goals.

To address this need for SB 375-related data, metrics, and indicators, CARB joined with Caltrans to sponsor research at the University of California at Los Angeles (UCLA) to develop a data-driven Statewide Monitoring System to measure on-the-ground changes at the community scale to shed light on SCS implementation and progress toward SB 375 goals. The research team used an array of indicators to gauge real-world changes in regional land use between 2010 and 2014. The indicators show whether:

- New housing was more concentrated in higher-density neighborhoods.
- New housing was more concentrated in neighborhoods with greater access to job opportunities.
- New affordable housing was more concentrated in neighborhoods with more job opportunities for low-income residents (jobs-housing fit).
- New housing and new jobs were more concentrated in neighborhoods better served by high-quality public transit.
- New jobs were concentrated in areas where workers would travel fewer miles to reach their workplaces.

Relative to baseline 2010 values, researchers found that real-world land use changes from 2010 to 2014 had moved California further away from achieving four of these proxy indicators for VMT reductions (Table 4). The exception was jobs-housing fit, which was unchanged. On the strength of these findings, CARB determined that California's lack of progress put at risk important public health, equity, economic, mobility and housing benefits expected from SB 375. These results will help shape recommendations for future incentive and equity policies and provide useful information to regional and local government agencies.

Over the past several decades, discriminatory practices such as redlining[42] that placed public services and funding sources out of reach for residents of certain areas based on race or ethnicity have been outlawed. Current policies are still not providing sufficient investments to adequately develop clean, healthy, and resilient communities, or reverse the impacts of historical and sustained racial, economic, and pollution burdens experienced in some of California's historically disinvested priority communities. This has resulted in priority communities having inadequate access to transportation infrastructure, mobility options, economic upward mobility, and housing, among other social determinants of health. As California identifies areas for new, affordable, transportation efficient housing developments, reciprocal effort needs to go towards identifying investments for priority communities to avoid exacerbating existing inequities. Research illustrates the challenges of ensuring that transit-oriented developments remain equally accessible to priority communities. Displacement is occurring in many neighborhoods near rail stations in California's major metropolitan areas, especially older neighborhoods near downtowns. CARB research has developed tools to help communities identify neighborhoods at risk of gentrification and displacement, and has identified

42 Pollution and Prejudice (arcgis.com)

Table 4: Short-term effects of various policy interventions on VMT

Baseline	New Housing Units	Changes in Subsidized Affordable Housing[1]	Net Change in Jobs
Occupied Housing Unit Density	Compared to the baseline, new housing units are relatively less concentrated in the higher-density tracts, which is inconsistent with SB 375 goals	-	-
Jobs-Housing Fit	-	The distribution of new/changes in subsidized affordable housing is similar to the baseline, thus reproducing the preexisting imbalance of low-earning jobs and affordable housing	-
Access to Jobs from Residential Location	New housing units are relatively less concentrated in high job access tracts, which is inconsistent with SB 375 goals	-	-
Access to High Quality Transit Locations (HQTLs)	New housing units are relatively less concentrated in HQTL areas, which is inconsistent with SB	-	Net increases jobs are relatively less concentrated in HQTL areas, which are inconsistent with SB 375 goals
Average (Mean) Person Miles Traveled (PMT) at Job Site	-	-	Net increases jobs are less concentrated in job sites with lower average PMT, which is inconsistent with SB 375 goals

1 Low-income housing tax credits and housing choice vouchers

policies that local governments can adopt to help prevent displacement. CARB currently funds a white paper that examines the effectiveness of different anti-displacement strategies and policies and outlines a research agenda for the future. This effort provides both local governments and the state with more information on policies and strategies that prevent or mitigate displacement.

A recent study set out to assess both the VMT implications and co-benefits of affordable transit-oriented housing developments. Results showed a significant association between affordable transit-oriented developments (TOD) and vehicle trip frequency, but not VMT. Focus groups with residents highlighted the many benefits of living in affordable TODs, especially those in highly accessible areas and in close proximity to many services and opportunities. Another current study focused on housing is assessing the legal, planning practice, and political barriers to advancing equitable infill development in California by providing insights into real-world greenfield development policy and by examining the impact of specific laws on both infill and greenfield residential development entitlement.

Ongoing research is also developing tools that will help public agencies identify, analyze, and visualize transportation access across the state in an effort to better understand current clean transportation access disparities and pinpoint areas that would most benefit from new policies, strategies, or investments.

CARB research has also focused on the potential health impacts from exposure to pollutants during active travel, including updating the Integrated Transport and Health Impact Model (ITHIM) in a tool called the Healthy Mobility Options Tool. The updated model is available online now to help policy makers and planners calculate the health impacts of reductions in vehicle miles travelled through modeling the expected increase in physical activity and related health benefits.

Future Research: Future research will continue to assess and quantify the co-benefits of SB 375 implementation, and evaluate whether priority communities are benefiting equitably.

Research Questions:

- What are the comprehensive impacts of sustainable communities policies, programs, and strategies, and what are the opportunities to increase the benefits, especially in priority communities?
- Are there best practices that can serve as models to assist different regions and community contexts to boost VMT reduction and public health benefits while avoiding displacement?

Evaluating Reductions in GHGs from VMT, Land Use and Buildings

Background and Current Research: Sustainable communities can yield GHG reductions as a result of declining VMT, but also from more sustainable land use patterns and from buildings themselves. CARB funded a series of white papers on the VMT impacts associated with various transportation and land use strategies (Table 5), and has funded other studies to verify VMT benefits in the real-world. One study analyzed travel survey data to quantify how much Californians will change the amount that they drive in response to changes in land use and transport system variables. The results of this research are embedded in the VMT Impact Spreadsheet Tool, which allows users to easily see the implications of this work for any census tract, city, or region in California.

Another study examining the VMT impacts of transportation investments in California is focusing on the VMT implications of adding "managed" lanes (such as high-occupancy and high-occupancy toll lanes). There is a large body of research showing that adding freeway lane capacity can lead to increases in VMT—a phenomenon called "induced demand." Little is known, however, about the potential induced-demand impacts of non-general purpose lanes.

COVID-related changes have led to wider adoption of telework in some industries, significantly reducing commute VMT for people working in those industries. This has forced CARB and its researchers to remain responsive to shifting mode choices and transportation patterns while trying to achieve state goals to reduce emissions. A timely question is: what policy levers could be used to

encourage telework to become a more permanent solution for reducing VMT? A project initiated in 2019-2020 is conducting surveys and focus groups to identify barriers to adopting high occupancy transportation, active transportation, and mass transit, with an emphasis on preferences based on socioeconomic status and sociodemographic characteristics. Since the project began prior to the pandemic, project priorities have shifted slightly to capture these new transportation patterns. Preference questions regarding telework will be included in the survey study as a result. Results from the survey instrument will be input into a land use and activity model to test different policy levers to determine which policy interventions significantly impact VMT.

Sustainable land use encompasses a variety of built-environment strategies that reduce GHGs and improve air quality. CARB has funded research exploring the climate and air quality implications of cool roofs and cool pavements, confirming that these strategies can reduce urban heat islands and reduce the need for energy to cool buildings in some climate zones. An ongoing study is investigating the potential to zero out GHG emissions from energy, transportation, waste, and water and is leveraging an existing zero net energy community project in an environmental justice community. 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 environmental justice communities. The results of this study will be useful in the development of a GHG baseline to quantify additional non-energy GHG reductions from California ZNE communities that are needed to achieve the 2050 target.

Buildings also play a key role in creating more sustainable communities. Past CARB-funded research shows that certified green office buildings have significantly lower GHG emissions than their conventional counterparts, and other studies have highlighted large potential to reduce building energy use. Accounting for emission reductions associated with zero carbon buildings (encompassing waste, water and transportation, in addition to energy savings) will be essential as we continue to pursue an integrated approach to reduce the GHG impact of new and existing buildings while improving indoor air quality. An ongoing research project is evaluating the technical feasibility of achieving zero or near-zero carbon for both residential and commercial buildings, focused on transportation, water, and waste strategies that can be implemented at the building level by owners, property managers, and occupants. The results of this study will be used to assess the practicality and appropriate timeframe for a zero or near-zero carbon building state policy or program, and to help keep California on track to reach its mid-term and long-term climate goals. Future research will shed light on the GHG, criteria pollutant, and toxic air contaminant co-benefits of retrofitting, operating, and maintaining existing homes as certified green homes.

Future Research: The results from the current projects described above will help CARB refine its reviews of SCSs and help other state agencies and MPOs to refine their transportation demand and land use planning models to ensure that they align with real-world success in meeting VMT reduction goals. As more methods are implemented and their benefits quantified, CARB will compile this information and make it available to MPOs to help them fulfill and succeed in their use of SCSs outlined in the Regional Transportation Plans.

Table 5: VMT impacts associated with various transportation and land use strategies

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

Research Question:

- What is the potential of built environment changes to reduce VMT and GHGs, and to improve air quality and reduce air pollution exposure?

Reducing VMT is one of the major targets for reducing GHGs across the state and achieving climate change goals. Strategies and policy levers need to be identified that serve state goals in reducing VMT and GHG emissions. CARB research has illustrated that more compact housing development results in energy savings, and that local governments can facilitate VMT reductions through a variety of land use and transportation decisions (including land conservation, zoning for higher density and mixed-use development, increasing transit service frequency, and requiring pedestrian-friendly design) many of which have been shown to result in financial savings as well. Future work will continue to support studies that identify strategies to reduce VMT at various levels, including pilot studies and policy implementation.

Research Question:

- What are the most effective strategies to reduce VMT at various levels (policy- through project-level)—including land conservation, housing and infill development, and transportation strategies—and how can the state support these strategies?

Future research will continue to investigate the potential of built environment changes to reduce VMT and GHGs, and to improve air quality and reduce air pollution exposure.

New research should also evaluate the net emission reduction potential of building-level strategies (e.g., cool roofs, solar photovoltaic, EV charging, and energy storage), and consider the life-cycle performance of energy efficiency technologies (e.g., low-GWP refrigeration equipment).

Research Question:

- In addition to converting building appliances to zero-emission electricity sources, what additional strategies can reduce the emissions generated by the existing building stock? (including advanced energy efficiency technologies such as low-GWP appliances, and combinations of strategies such as renewables, energy storage, and electric vehicle charging, etc.), and what are the associated GHG and air quality co-benefits?

As transportation patterns have changed due to COVID, a major unknown identified is whether permanent changes will impact land use. For example, will workers able to access telework also choose to move farther from city centers? How will this impact land use, and will it negatively impact housing and transportation options for essential workers unable to telework? Priority communities tend to be unable to telework and thus are subject to more inequitable outcomes as land use patterns shift. These consequences of the pandemic must be closely monitored and studied to

ensure SB 375 goals are met in the future. Additional research will be needed to identify innovative strategies combining land use changes, behavioral changes, and policy levers to reduce VMT and decrease emissions while ensuring benefits are distributed equitably.

Research Question:

- What strategies or policy levers could be used to encourage present changes in commute behaviors to become a more permanent solution for reducing VMT? How can these changes be implemented to address potential land use and equity priorities?

Next Steps

Each fiscal year, CARB staff will present research projects that fulfill the stated research initiatives in the Triennial Plan. The proposed projects for each fiscal year guided by this plan are listed in the appendices below. Following Board approval of the research projects presented every fiscal year, CARB staff will proceed to work with researchers to develop these projects into complete proposals. These will be reviewed by CARB's Research Screening Committee, and then brought to CARB's Executive Officer for final funding approval. Results, including data, analysis, lessons learned, policy and equity implications, and final reports, are anticipated three to five years after a project commences.

Abbreviations and Glossary of Terms

Common Abbreviations

Acronym	Definition	Extended Definition	Reference
AQI	Air Quality Index	-	-
BEB	Battery Electric Bus	-	-
COVID-19	Coronavirus Disease (2019), also known as SARS-CoV-2	Severe Acute Respiratory Syndrome, Coronavirus Disease (2019)	-
DPM	Diesel Particulate Matter	-	-
EJ	Environmental Justice	-	-
FY	Funding Year	-	-
GHG	Greenhouse Gas(es)	-	-
GPS	Global Positioning Satellite	-	-
HFC	Hydrofluorocarbons	-	-
IAQ	Indoor Air Quality	-	-
MERV	Minimum Efficiency Reporting Value	Minimum Efficiency Reporting Values, or MERVs, report a filter's ability to capture larger particles between 0.3 and 10 microns (µm).	*U.S. EPA*
MPO	Metropolitan Planning Organization	-	-
NAAQS	National Ambient Air Quality Standards	-	-
NO_X	Oxides of Nitrogen	-	-
NWL	Natural and Working Lands	-	-
O_3	Ozone	-	-
PHEV	Plug-in Hybrid Electric Vehicle	-	-
$PM_{2.5}$	Fine inhalable particulate matter	Particles with diameters that are generally 2.5 micrometers and smaller.	*U.S. EPA*
PM_{10}	Inhalable particulate matter	Particles with diameters that are generally 10 micrometers and smaller.	-
RSC	Research Screening Committee	-	-
SCS	Sustainable Community Strategies	-	-
SLCP	Short-lived climate pollutants	-	-
TNC	Transportation Network Company	An organization whether a coporation, partnership, sole propriertor, or other form, operating in California that provides prearranged transportation services for compensation using an online-enabled application (app) or platform to connect passengers with drivers using their personal devices	*CPUC Decision 13-09-045*
UC/CSU	University of California/ California State University	-	-

Acronym	Definition	Extended Definition	Reference
UFPM	Ultra-fine particulate matter	Particles less than 0.1 micrometers or 100 nanometers in diameter	*U.S. EPA*
VCP	Volatile chemical products	-	-
VMT	Vehicle Miles Travelled	-	-
VOC	Volatile organic compounds	-	-
WUI	Wildland-Urban Interface	-	-
ZEV	Zero-Emission Vehicle	-	-

Government Agency Acronyms

Acronym	Definition
ARPA-E	The Advanced Research Projects Agency-Energy
CalEPA	California Environmental Protection Agency
CalGEM	California Geologic Energy Management Division
CalRecycle	California Department of Resources Recycling and Recovery
Caltech	California Institute of Technology
Caltrans	California Department of Transportation
CDFA	California Department of Food and Agriculture
CEC	California Energy Commission
CPUC	California Public Utilities Commission
JPL	Jet Propulsion Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
OPR	California Office of Planning and Research
U.S. EPA	United States Environmental Protection Agency

Appendix A –Proposed Research Projects

Fiscal Year 2021-2022

The projects proposed for Fiscal Year 2021-22 are designed to support attainment of upcoming air quality and greenhouse gas targets, track implementation of existing programs, ensure the benefits of longer-term strategies and will advance the state of the science in the areas of health and exposure, environmental justice, air quality and climate. Some of these studies are long-term, and build on unique data sets, while others address specific implementation or knowledge gaps. Together, they will provide essential data and tools to support actions to meet California's air quality and climate goals and protect public health, the economy, and priority populations. A research budget of approximately $4.2 million is anticipated to fund 11 new projects in fiscal year 2021-2022.

Table 6: Summary table of proposed projects for FY21-22

Health Projects	Cost
P1: Expanding Health Analysis - Identify additional health endpoints (brain, cancer, respiratory, etc.) needed for our analysis and benefit quantification. Consider additional exposure routes, such as fires, additional burdens due to proximity to both mobile and stationary sources in priority communities	$1M
P2: Short-Term Exposure - Update science to better inform public on the impacts and mitigation of short-term exposure including wildfire smoke events and remediation	$500K
P3: Tracking Health Impacts - Investigate baseline health indicators in highly impacted communities including asthma incidence; investigate health metrics to track health progress	$500K
P4: Framework for Imperial Valley Research (White Paper)	$50K
P5: Framework for Time-Activity Data Collection (White paper)	$25K
Air Quality and Mobile Sources Projects	**Cost**
P6: Sensor Technology Demonstration for durability, measurement accuracy at low NO_X concentration, operability at low temperature, and light-off time from cold starts. Include economic impact of implementation	$750K
P7: $PM_{2.5}$ Satellite Data Dashboard - Estimating ambient concentrations of $PM_{2.5}$ composition using satellite remote sensing to refine mitigation strategies; develop a tool to process satellite data.	$300K
P8: $PM_{2.5}$ Sources and Formation Regimes - Understanding the sources and formation regimes of present-day $PM_{2.5}$ to mitigate particulate pollution in California; develop a detailed understanding of VOC and SOA, and the roles they played in the recent O_3 and $PM_{2.5}$ trends. Understanding the influences of non-mobile sources.	$500K
Sustainable Communities and Transportation Projects	**Cost**
P9: Address Past Inequity - Define and identify marginalized communities that have the potential to become location-efficient and high-opportunity areas, and identify what policies and place-based investments could assist in fostering more equitable and sustainable outcomes in those communities.	$300K
P10: Align Investments with Climate and Equity Goals - What is the potential to better align planned transportation investments in SCSs with climate, VMT reduction, and equity goals?	$200K
P11: Pathways to Improve Freight Efficiency - focus on the disruption due to pandemic and long-term system changes, leverage results from recent studies, provide input on how to achieve deep CO_2 reductions	$25K
TOTAL	$4.2M

Project Descriptions

Project 1: Expanding Health Analysis

CARB has launched an expanded health analysis project in response to Board resolution 17-46 to evaluate a broader range of health impacts than those routinely analyzed and monetized in the regulatory review process. Currently, CARB analyzes three specific health endpoints for $PM_{2.5}$. However, emerging research findings provide evidence for additional air pollution-related health outcomes beyond what CARB currently quantifies. As part of our expanded health analysis project, the objective of this project is to provide a broader scientific basis for evaluation and quantification, where possible, of California-relevant associations between air pollutants (e.g. criteria pollutants, air toxics, and greenhouse gases) and additional health outcomes. Priority areas of interest include but are not limited to: nervous system effects (e.g. neurodegenerative disease, such as dementia, Alzheimer's disease, and Parkinson's disease, or learning impairments in children and young adults), and adverse birth outcomes (e.g. preterm birth, low birth weight, and decreased fetal growth). Additionally, results should help us better understand air pollution's impacts on priority communities: how health impacts may be amplified due to proximity to pollution sources, and how socioeconomic and environmental factors increase community vulnerability. The project will identify concentration-response functions between air pollutants and a variety of health endpoints, monetized values (actual financial costs and/or valuations, such as willingness to pay) for those health impacts, and associated uncertainties or provide other ways to measure impacts and benefits of air pollution control efforts on health outcomes. The results of this project will allow for expanded evaluation and quantification of public health impacts and their associated economic values, as well as identification of potential qualitative outcomes. This will in turn promote better understanding of the full scope of health and welfare protections arising from air pollution reductions brought about by California's programs and policies. Researchers should understand the equity implications of the research and data limitations due to potential for structural data collection or study bias. We encourage multidisciplinary teams and multi-university teams to apply.

Project 2: Updating the Science to Better Inform the Public on the Impacts and Mitigation of Short-Term Exposure Including Wildfire Smoke Events

Extreme fires are a growing threat to public health and safety in California with longer seasons and higher exposures. Smoke from extreme fires can emit large amounts of air pollutants in a short time and travel long distances to affect the health of Californians. In the 2020 fire season, vast areas of the state experienced unhealthful air for days or weeks at a time. Our current knowledge of wildfire smoke health effects is based largely on two different streams of research: 1) $PM_{2.5}$ effects determined from epidemiological research on the short- and long-term health effects of chronic $PM_{2.5}$ exposure and 2) recent studies that found increased respiratory and cardiac symptoms in people living near wildfire events. However, there has been insufficient attention to studying the effects of repeated exposures to short but intense levels of wildfire smoke as California residents experienced in the 2020 fire season. Therefore, the objective of this project is to estimate the sub-chronic effects (e.g., respiratory and cardiovascular diseases) of short-term exposures (e.g., hourly or daily variations, smoke wave[43]) over days to weeks to wildfire-specific air pollution and to use this information to help educate communities and mitigate health risks in extreme events like wildfires. While there are recent studies of health effects linked to individual wildfire events, this study is envisioned to be a larger-scale (statewide) and multi-year study that will evaluate respiratory and cardiac symptoms across different events and different durations of smoke exposure in the sub-chronic category. State-of-the-art techniques (e.g., GEOS-Chem) should be applied to model wildfire-specific air pollution concentrations with fine spatial-temporal resolution. The expected

43 Smoke wave was defined as a period (e.g., two consecutive days) with high air pollution concentrations due to an episodic extreme fire event by Liu JC, Wilson A, Mickley LJ, et al. in "Wildfire-specific Fine Particulate Matter and Risk of Hospital Admissions in Urban and Rural Counties." Epidemiology. 2017;28(1):77-85. doi:10.1097/EDE.0000000000000556

health outcomes include (but are not limited to) asthma exacerbations, hospitalizations and emergency department visits for respiratory and cardiovascular diseases, although other health effects such as total hospitalizations and emergency department visits and adverse birth outcomes are possible. The study should specifically include impacts in priority communities and populations (e.g., children, elderly populations, pregnant women, different racial and ethnic groups and those living in poverty). It is preferable for the study to consider both urban and rural locations, and to also include tribal communities. Updated estimates of health effects of sub-chronic exposure to wildfires will better inform CARB's analysis of the health burdens from extreme events like wildfires which negatively impact public health and degrade quality of life in California.

Project 3: Improved Assessment and Tracking of Health Impacts for California Communities Most Burdened by Pollution

To fulfill the mission of California Assembly Bill (AB) 617 and continue leadership on public health improvements in the communities that also experience disproportionate pollution exposures, it is critical that CARB develop ways to assess, measure, track, and communicate the multifaceted health benefits that derive from an expanding list of air pollution control measures. CARB regularly estimates the expected statewide health benefits that can result from implementation of proposed air pollution rules and regulations -- and is now looking to develop a methodological framework for assessing and tracking the actual health impacts from air pollution reductions in AB 617 communities, as a way of monitoring progress toward health and equity goals for all priority communities. The first phase of this project will be to compile and/or develop health metrics or indicators, ideally in collaboration with community partners and for as many AB 617 communities as possible. The second project phase will be to determine which metrics or indicators are most effective at meaningfully reflecting real-world health progress over time in these communities. Especially informative community health indicators will be those that meet several criteria, including: sensitivity to health improvements from reductions in air pollution emissions/exposures, insightfulness regarding unique health impacts within AB 617 communities, timeliness for short-term tracking, and neighborhood-level geographic scale. Potential health metrics may include: prevalence of asthma symptoms or attacks, asthma medication use, hospitalizations or emergency room visits for respiratory or cardiac conditions or other metrics. In the project's final phase, researchers will bring together the datasets best indicative of overall community health and develop a summary health dashboard. This dashboard will be visually communicative, for semi-annual tracking of changes in community health conditions linked to air pollution control strategies, for most of the individual AB 617 neighborhoods. In summary, the project will provide a new, scientifically robust, and user-friendly mechanism for CARB, local air districts, communities, and other stakeholders to observe and assess – and also to better communicate – the health-based effectiveness of CARB's work. Such improved tracking of health impacts within California's most pollution-exposed communities will support CARB's Community Air Protection Program Blueprint. Because priority communities are more impacted by pollution and socioeconomic inequities, this project will additionally contribute to CARB's work toward mitigating health disparities for AB 617 communities.

Project 4: Partnering on a Collaborative Community-Focused Research Path in the Imperial Valley

Communities in California's Imperial Valley are subject to numerous environmental concerns due to the variety of air pollutant sources that exist in and around the region (e.g., dust from the Salton Sea, agricultural activities, traffic at the California-Mexico border, unpaved roads, industrial operations, and biomass and waste burning). The heterogeneity of the air pollutant sources and their varying influences on local and regional air quality highlight the challenges in developing a comprehensive air pollution reduction strategy for the Imperial Valley that is effective at improving health outcomes equitably.

Many Imperial County communities have been designated by CalEPA as being "disadvantaged" under SB 535, scoring among the 25% highest scoring census tracts in California in terms of the

high amount of pollution people are exposed to. People living in Imperial Valley understand the history, impacts, current efforts, community needs and concerns, and have unique perspectives and ideas for meeting those needs. The objective of this research is to create a community-based and participatory project establishing research priorities and designs to address air pollution impacts and solutions in the Imperial County region. Partnering with communities in the Imperial Valley, including both community members and community organizations, will lead to developing a research path that is reflective of those voices and brings on-the-ground knowledge. CARB will also fund a review of research in the area to serve as a resource for the discussions. The review will consolidate region-specific information on air pollutant sources, atmospheric processes, air quality monitoring data, and air pollution exposure studies and include information from the most recent peer-reviewed publications, ongoing CARB outreach efforts to foster collaboration between communities and area researchers, community-led air monitoring data, and satellite remote sensing. This review will also incorporate the experience and perspectives of local residents.

The final product of this project will be a focused research plan with strategies to optimize the use of available resources and fast-track actions that will improve public health and the environment. The project will develop a comprehensive, well justified, and transparent document that describes the findings and summarizes recommendations for both short- and long-term air pollution reduction strategies that encompasses all communities in the Imperial Valley. The project will inform CARB of potential gaps in data and research needed to refine such recommendations.

Project 5: Summary and Update of Time Activity Pattern Data to Improve the Understanding of the Exposure to Air Pollution

Time activity patterns (TAPs) are important for estimating exposure to outdoor and indoor air pollutants emitted from a wide range of sources such as vehicle exhaust, cooking, cleaning solvents, and sources near other activities in Californians' everyday life. However, TAPs used by health and exposure efforts are outdated, typically lack key components including priority communities, social economic status (SES), or environmental justice (EJ), and are often too general, resulting in a bias or misclassification in the estimation of exposure in the population being studied. There is an urgent need to develop an up-to-date and more comprehensive set of TAP data for researchers to refine exposure assessment in health and exposure studies. The objective of this project is to create 1) a white paper that summarizes a one-stop-shop for time activity methods, models, and uses, including how these techniques can help regulations, improve exposure estimates by including the activity pattern data in health and exposure studies and 2) a framework for a follow-on study to update TAP data to modern life activities throughout the diverse regions and socio economic strata in California using a combination of modern data information including big data, low cost sensors, modeling, and traditional personal monitoring with a multi-regional and multi-community emphasis. The results of the two-fold effort will first yield a compendium of knowledge about how activities effect exposure to sources, both indoor and outdoor, that determine the real exposure to air pollution among Californians. This information will be used to refine exposure estimate benefits from regulations and avoid exposure misclassification in published results from population studies. Secondly this work will create a framework for a follow-on effort to develop an updated modern, multi-racial, multi-regional activity pattern data set which will improve the efficacy of future regulations, health, and exposure studies.

Project 6: Demonstration of Sensor Technologies for On-Road and Off-Road Heavy-Duty Diesel Vehicles

On-road and off-road heavy-duty (HD) diesel vehicles are major sources of NO_X and CO_2 emissions. A suite of regulatory programs have been developed and are in development to help the state achieve air quality improvement and greenhouse gas (GHG) reduction goals by reducing NO_X and CO_2 emissions, respectively, from HD diesel vehicles. Accurate, stable, and durable on-board sensors are necessary for implementing the programs effectively. The objective of this research

is to demonstrate the feasibility of using state-of-the-art NO_X and on-board sensor technology to assist in the successful implementation of on-road HD on-board diagnostic (OBD), inspection and maintenance and in-use compliance programs, and developing off-road low NO_X and OBD programs. HD diesel vehicles will be equipped with the latest technology sensors for laboratory and in-use vehicle testing to ascertain their accuracy, stability, durability, and operation limitations, and explore if higher aftertreatment efficacy rates can be achieved with better sensors. The results will be used to enhance HDV NO_X and CO_2 emission reduction programs and ensure the programs achieve the state's air quality improvement and GHG reduction goals.

Project 7: Estimating Ambient Concentrations of $PM_{2.5}$ Composition Using Satellite Remote Sensing to Refine Mitigation Strategies

Ambient fine particulate matter ($PM_{2.5}$) concentrations often exceed the National Ambient Air Quality Standards (NAAQS) in many parts of California. CARB conducts regional air quality modeling to understand the spatial and temporal variabilities of $PM_{2.5}$ composition in the regulatory decision-making process. The model outputs are evaluated using limited ground-level air quality monitoring data that primarily describes the air quality over populated urban centers. Recent advancement in satellite remote sensing technology and data processing algorithms have demonstrated their ability in describing surface-level air quality at the relatively high spatial resolution, providing opportunities for the regional air quality models to be evaluated using an independent dataset. Taking advantage of such data resources is valuable for building additional confidence in the spatial and temporal representativeness of the regional air quality models where ground-level air quality monitoring data is lacking.

The objectives of this project are to (1) quantify California's local and regional $PM_{2.5}$ composition (e.g. nitrate, sulfate, organic carbon, elemental carbon, and dust) using satellite remote sensing data collected over the last two decades, (2) track the long-term progress of $PM_{2.5}$ reductions in regions underrepresented by ground-level air quality monitors and evaluate the spatial disparities in these regions, and (3) recommend pathways that refine existing $PM_{2.5}$ mitigation strategies with considerations for social equity. The project will estimate daily ambient concentrations of each $PM_{2.5}$ composition using satellite remote sensing data from Multi-angle Imaging SpectroRadiometer (MISR) operated by NASA Jet Propulsion Laboratory (JPL). Furthermore, the project will incorporate the regional air quality modeling to impute ambient concentrations that are missing due to unavailable satellite data on cloudy days. The project will deliver both finalized satellite data products (i.e., $PM_{2.5}$ composition) and a tool that can be used by CARB staff to further process the MISR data. The project will also process the data just beyond California's borders to understand the influence of interregional air pollution transport and its influences on California's local and regional air quality.

Project 8: Understanding the Sources and Formation Regimes of Present-Day $PM_{2.5}$ to Mitigate Particulate Pollution in California

Ambient fine particulate matter ($PM_{2.5}$) levels continue to exceed the 24-hour National Ambient Air Quality Standards (NAAQS) in many regions across California despite the decades of multifaceted air pollution management strategies. Achieving concurrent reduction of $PM_{2.5}$ along with other criteria pollutants such as ozone (O_3) require coordinated understanding of various emission control measures and their influences on atmospheric chemical composition. Recent plateauing of average ambient $PM_{2.5}$ and O_3 levels pose additional challenges for California's air quality improvement pathways that has been developed to reduce the design values. The objective of this study is to consider strategies that optimize reductions of both $PM_{2.5}$ and O_3. This will be realized by advancing CARB's understanding of the current sources and formation regimes of $PM_{2.5}$, which will be synergistically analyzed with the formation regimes of O_3. The project will measure and analyze sub-hourly speciated $PM_{2.5}$ in several California cities where $PM_{2.5}$ is a major problem. Source apportionment of highly resolved $PM_{2.5}$ will identify local and regional sources of relative importance. In addition, the sensitivity of $PM_{2.5}$ formation (e.g. secondary organic aerosols) to perturbations

in Oxides of Nitrogen (NO_X) and Volatile Organic Compounds (VOCs) will be measured directly and compared with that of O_3. This project will provide observational constraints on the present-day sources and production mechanisms of $PM_{2.5}$, which will enable CARB to refine the modeling framework for State Implementation Plans (SIPs) for joint $PM_{2.5}$ and O_3 mitigation.

Project 9: Transportation and Land Use Policies and Practices: Opportunities to Address Past Inequity to Build Healthier, More Sustainable Communities

Historically, racial discriminatory practices placed public services and funding sources out of reach for many residents based on race or ethnicity. Although many of these practices have been outlawed in the past several decades, current policies are still not providing sufficient investments to adequately develop clean, healthy, and resilient communities, or reverse the impacts of historical and sustained racial, economic, and pollution burdens experienced in some of California's historically disinvested priority communities. This has resulted in priority communities having inadequate access to transportation infrastructure, mobility options, economic upward mobility, and housing, among other social determinants of health. As California works to identify new areas for affordable, transportation-efficient housing developments as potential solutions to address the housing crisis, it will be equally important to identify additional investments for existing priority communities to avoid exacerbating inequities. The objective of this project is to examine the policies, along with systemic precedents, that have contributed to the inequitable distribution of resources and resulting disparities in California's priority communities. In addition, the project will identify strategies to address these inequities, in transportation and land use policies, strategies, and funding practices. The project may also identify other needed systemic changes. This project will recommend existing and new place-based investments along with policies intended to yield economic, environmental, and social returns to support healthy, sustainable community development. Researchers will use spatial and policy analyses to characterize the role of historical land use, housing, and transportation-related funding programs in creating and exacerbating resource and access inequities. This project will also leverage the results of a companion project aimed at identifying areas across the state that are transportation-efficient, healthy, and where residents have access to economic and educational opportunities—high-opportunity places to live. The results of this project will help propose strategies and policies that state, regional, and local governments can use to identify and address inequitable planning and funding policies. Results will also help to establish planning-related policies along with place-based investments that can begin to reduce inequities in resources and opportunities experienced by priority communities, and help the state achieve its climate goals.

Project 10: Strategies to Improve the Alignment of Planned Transportation Investments with Climate and Equity Goals

In accordance with the Sustainable Communities and Climate Protection Act, or SB 375 (Chapter 728, Statutes of 2008), California Metropolitan Planning Organizations (MPOs) are required to create and adopt Sustainable Communities Strategies (SCS) that demonstrate how each region will meet greenhouse gas (GHG) emission reduction targets from light-duty vehicle travel in support of the state's climate goals. In 2018, CARB assessed statewide progress toward achieving the goals of SB 375—as mandated by SB 150 (Allen, Chapter 646, Statutes of 2017)—and published a report on its findings. The report revealed that California is not on track to meet the GHG emission reductions needed to achieve the goals set by SB 375. Per this finding, CARB is committed to finding solutions to reverse this trend. Also, illuminated by the SB 150 Report, is the opportunity to shift transportation investments toward more sustainable transportation projects that provide Californians with more and better mobility options. Many MPOs have existing practices, tools, and measures to help them select and prioritize projects and these could inform best practices for other regions. The objective of this project is to identify and analyze the methods, project performance assessments (PPA), and SCS decision-making frameworks that MPOs currently use. Further, the project seeks to recommend methods to assess projects beyond standard, transportation-based metrics for mobility

and accessibility, to examine project performance related to climate protection, equity, affordable housing, safety, and other important outcomes. To achieve the project objectives, the researchers will review PPAs, tools, and other practices used by MPOs across the state. This project will also use interviews, focus groups, surveys, or other qualitative methods to develop a deep understanding of project selection and SCS implementation. The project results will provide recommendations on best practices to select, evaluate, and strengthen SCS development. In addition, the results will make recommendations for practices and metrics that effectively evaluate equity and strategies for how MPOs can achieve the most equity and climate co-benefits. The results will be shared publicly and will help accelerate progress toward meeting SB 375 goals with equitable outcomes.

Project 11: Pathways to Increasing California Freight System Efficiency – White Paper

California's freight transportation system faces surging demand, intensifying competition, regulations, and accelerating technological change. A major source of pollutant emissions as well as a vital part of the state's economy, California's freight industry must rapidly identify and implement substantial improvements in system efficiency to meet these combined challenges. This project reviews recent freight system literature and practices and identifies research and operational opportunities to further improve freight system efficiency (FSE) and competitiveness. Focusing on freight system sectors and technologies within CARB's regulatory jurisdiction, the contractor will inventory research needs, operational adaptations and regulatory policies with the greatest potential to improve FSE in California. Project findings will include research recommendations and policy implications for future regulatory and incentive programs.

Fiscal Year 2020-2021

For Fiscal Year 2020-2021 a series of projects have been proposed and accepted by the Board for execution. These projects will commence in early 2021. Start and end dates are approximate and subject to change.

Contract #	Title	Start	End
20RD004	Plume Capture Measurement of Vehicle Emissions at the Caldecott Tunnel for Heavy-Duty Emission Program Development and Verification	2/1/2021	1/31/2025
20RD005	A Data Science Framework to Measure VMT by Mode and Purpose	4/1/2021	3/31/2023
20RD006	Measuring, Analyzing, and Identifying Small-Area Vehicle Miles Traveled Reduction	3/1/2021	2/28/2023
20RD007	Developing a Comprehensive Framework for Estimating the Social Costs of Emissions of Criteria Pollutants and Air Toxics in California, and Identifying Other Direct and Indirect Benefits of California's Climate and Air Quality Programs	1/15/2021	7/14/2023
20RD012	Total Exposures to Air Pollutants and Noise in Disadvantaged Communities	2/1/2021	1/31/2023
20RD013	An Integrated Framework to Guide Improvements in Air Quality at Community, Urban, and Regional Scales	3/1/2021	8/30/2022
20RD015	HIFIVE - Health Impacts of Filtration in Imperial Valley Elementary Schools	2/15/2021	2/14/2023
20RD016	Impacts of Train and Port Pollution and Air Toxics on Respiratory Symptoms and Emergency Department Visits within Vulnerable Communities in Southern California	4/15/2021	4/15/2021-4/14/2023
20STC008	Post-COVID Transportation Scenarios: Evaluating the Impact of Policies	5/1/2021	11/1/2022
20STC009	Evaluating the Potential for Housing Development in Transportation-Efficient and Healthy, High-Opportunity Areas in California	5/1/2021	5/1/2024

Appendix B – Current Projects

Health and Exposure

Exposure Impacts and Mitigation

Contract #	Title	Start	End
In-House	Personal exposure: Estimating exposure impacts from daily activities which correspond to highest pollution exposures (commute trips, cooking, restaurant visits), and identifying potential personal choices to reduce personal exposures to air pollution	1/1/2015	On-Going
16RD005	Women's Cardiovascular Risk from PM Exposure	7/1/2016	4/30/2020
17RD011	Combined Exposures to Ultrafine Particulate Matter and Ozone: Characterization of Particular Deposition, Pulmonary Oxidant Stress and Myocardial Injury	1/30/2018	1/28/2021
19RD004	Sources of On-Road Vehicle Emissions and their Impacts on Respiratory Disease Symptoms in California	4/1/2020	3/31/2022
19RD006	Particulate Matter 2.5 Acute Health Impacts on Work Loss Days	2/1/2020	1/31/2022
In-House	Characterization of Cleaner Air Shelters and Cleaner Air Spaces	7/1/2020	6/31/2021

Indoor Exposure and Mitigation

Contract #	Title	Start	End
19RD013	Improving Indoor Air Quality, Energy Efficiency, and Greenhouse Gas Reductions through Multifamily Unit Compartmentalization	3/15/2020	8/31/2022
19RD019	Assessment of Methods to Collect and Analyze Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS)	2/1/2020	1/31/2021

Emerging Health Challenges

Contract #	Title	Start	End
19RD005	Health Impacts of California Wildfire $PM_{2.5}$ Across the Lifespan: Wildfire Exposure to Rhesus Monkeys	4/1/2019	3/31/2021
17RD012	Effects of Brake and Tire Wear on Particulate Matter Composition, Reactive Oxygen Species, Placental Development and Birth Outcomes in Los Angeles	5/1/2018	4/1/2022
19RD029	Impact of Air Pollution on COVID-19 Case and Death Risk in California	6/1/2020	4/15/2022
19RD030	Ambient Air Pollution and COVID-19 Disease Severity or Death among Confirmed Cases in Southern California	6/15/2020	4/14/2022

Sustainable Communities and Health

Contract #	Title	Start	End
18RD018	Characterizing the Potential Health and Equity Impacts of Oil and Gas Extraction and Production Activities in California	2/1/2019	1/31/2022

Environmental Justice

Identifying Sources

Contract #	Title	Start	End
In-House	Developing new mobile monitoring systems and analytical frameworks for air pollution mapping and hotspot identification in communities	1/1/2015	On-Going
17RD006	A Tool to Prioritize Sources for Reducing High $PM_{2.5}$ Exposures in Environmental Justice Communities in California	6/1/2018	11/30/2019
17RD021	Characterization of Air Toxics and GHG Emission Sources and Their Impacts on Community-Scale Air Quality Levels in Disadvantaged Communities	6/6/2018	3/30/2021
In-House	Source apportionment of ambient air monitoring data collected at Lost Hills, CA in support of SNAPS program	10/1/2019	11/30/2020

Reducing Disparities

Contract #	Title	Start	End
In-House	Quantifying community-scale pollution contribution from regional and local sources, and identifying community sources and land use characteristics which correspond to highest pollution exposures in communities	1/1/2015	On-Going
In-House	Understanding the influence of reduced anthropogenic activities during COVID-19 on air quality disparities in CA	4/1/2020	12/31/2021
20RD001	Remote Sensing Measurements of Light-Duty Vehicle Emissions at Multiple California Locations	11/1/2020	4/30/2024

Economics

Market Transformation

Contract #	Title	Start	End
18RD016	Hybridization of Full Electrification Potential in Off-Road Applications	3/1/2019	2/28/2021
19RD010	Determinants of Medium and Heavy-Duty Fleet Turnover	2/15/2020	2/14/2022
20RD009	White Paper: Economic Benefits of Affordable Infill Housing	10/1/2020	6/30/2021

Program Assessment

Contract #	Title	Start	End
19RD026	Low-Carbon Transportation Incentive Strategies Using Performance Evaluation Tools for Heavy-Duty Trucks and Off-Road Equipment	6/1/2020	11/30/2022

Behavioral Economics

Contract #	Title	Start	End
20RD008	Decision Drivers to Facilitate Lower-Polluting Products Choices by Consumers	11/1/2020	10/31/2022

Air Quality – State Implementation Plans

Ozone Sensitivity and Transport

Contract #	Title	Start	End
17RD004	Spatial Variation of Vertical Ozone Distribution over California	4/15/2018	4/14/2020
18RD031	Trinidad Head, CA: Continued Ozone-Sonde and Surface Ozone Measurements	3/1/2019	2/27/2021
In-House	Understanding the effectiveness of ozone reduction pathway in California	7/1/2019	4/1/2021
In-House	Assessing temporally comprehensive vertical ozone measurements to evaluate AQ influence of changing global anthropogenic emissions during COVID-19 pandemic	10/1/2019	4/1/2021
In-House	Understanding the spatiotemporal influence of wildfires on California's ozone sensitivity	1/1/2020	4/1/2021

Identifying Sources of $PM_{2.5}$

Contract #	Title	Start	End
In-House	Tracking real-world emissions from ocean going vessels and evaluating ship sulfur regulations use of a remote plume detection and emissions measurement system	1/1/2015	On-Going
In-House	Evaluating Black Carbon Emissions and its Spatiotemporal Variabilities in Southern California, including COVID-19 impacts	1/1/2017	1/1/2021
17RD008	Long-term Characterization of Fine Particulate Matter Chemical Composition in the San Joaquin Valley	2/1/2018	1/31/2021
17RD022	Design and Development of an Instrument for Toxic-metal Aerosol Real Time Analysis	5/15/2018	4/13/2022
In-House	Spatially comprehensive evaluation of satellite-based NO_2 trends and their associated emission sources	4/1/2018	6/30/2021
In-House	Developing and utilizing MODIS 1 km $PM_{2.5}$ derivative for AQ assessment in CA	10/1/2018	On-Going
In-House	Evaluation of long-term Boundary Layer Height and Atmospheric Optical Depth monitoring data in the SJV to improving AQ modeling and understand residual layer influences	10/1/2018	On-Going
In-House	Operating Fresno-Supersite: real-time air monitors (HCHO, NH_3, BC, MiniMPL)	10/1/2018	On-Going
In-House	Meteorologically adjusted urban air quality trends in major air basin in California	1/1/2019	1/1/2021
In-House	Evaluating the spatial variabilities of NH_3 sources in the SJV using satellite and CMAQ	7/1/2019	1/1/2022
18RD009	Environmental Chamber Experiments to Improve Secondary Organic Aerosol Model Prediction	4/1/2019	3/31/2022
In-House	Long-term trend and diurnal pattern of high-resolution speciated $PM_{2.5}$ to evaluate sources and improve AQ modeling (Fresno Supersite)	10/1/2019	On-Going
In-House	Evaluation of multi-wavelength attinuation data at Fresno, CA to understand the $PM_{2.5}$ BC source categories	10/1/2019	On-Going
19RD008	Understanding and Mitigating Wildfire Risk in California	1/1/2020	6/30/2022

Contract #	Title	Start	End
In-House	High spatiotemporal $PM_{2.5}$ from newly released geostationary satellites	1/1/2020	On-Going
In-House	Understanding the distribution of VOC species in the SJV and the SoCAB	4/1/2020	7/1/2022
20RD003	Airborne Flux Measurement of Volatile Organic Compounds and Oxides of Nitrogen in California	10/1/2020	3/1/2023

Emission Reduction Strategies

Contract #	Title	Start	End
In-House	Intensive analysis of statewide monitoring data and comparison to previously published air quality models to evaluate pollution reduction due to COVID-19 restrictions	4/1/2020	3/1/2021

Air Quality – Mobile Sources

Light-Duty Vehicle Research

Contract #	Title	Start	End
16RD009	Emerging Technology Zero-Emission Vehicle Household Travel and Refueling Behavior	6/1/2017	4/30/2021
In-House	Vehicular emissions disparities between disadvantaged and non-disadvantaged communities	7/1/2017	6/30/2021
In-House	Examine real-world fuel economy, characterize braking activity, and evaluate energy use patterns	2/1/2018	On-Going
17RD003	Emission Impacts of Connected and Automated Vehicle Deployment in California	5/1/2018	4/29/2021
18RD027	White Papers on California's Changing Transportation Landscape	4/1/2019	3/30/2021

Heavy-Duty Vehicle Research

Contract #	Title	Start	End
14-300	Evaluation of the Feasibility, Cost-Effectiveness, and Necessity of Equipping Small Off-Road Diesel Engines with Advanced PM and/or NO_x Aftertreatment	8/20/2014	4/15/2020
In-House	Tracking real-world program effectiveness of Truck and Bus regulation, and studying pollution transport and impacts from freeways into neighboring communities	1/1/2015	On-Going
16RD011	The Optimal Route for a Clean Heavy-Duty Sector in California	6/15/2017	12/14/2020
17RD009	Geofencing as a Strategy to Lower Emissions in Disadvantaged Communities	1/1/2018	12/30/2020
17RD013	Activity Data of Off-Road Engines in Construction	2/1/2018	1/30/2021
18RD016	Hybridization of Full Electrification Potential in Off-Road Applications	3/1/2019	2/28/2021
In-House	Characteristics of Battery Electric Bus activity and energy use in support of the Innovative Clean Transit rule and the Advanced Clean Transit programs	3/1/2019	12/31/2021

Contract #	Title	Start	End
In-House	Large in-use emissions data analysis in support of on-road and off-road heavy-duty regulations and policies	On-Going	On-Going
18RD006	Off-Road Diesel Low-Emission Demo for Nitrogen (NO_x), Particulate Matter, (PM) and Toxics	4/22/2019	4/21/2021

Non-Tailpipe Emission Sources

Contract #	Title	Start	End
17RD016	Brake and Tire Wear Emissions	4/15/2018	3/13/2021
18RD017	Real-World Tire and Brake-Wear Emissions	2/1/2019	1/31/2021
In-House	White paper: Update on Non-exhaust Emissions Research at the California Air Resources Board	4/1/2019	On-Going

Climate

Tracking Progress and Refining Emissions Estimates

Contract #	Title	Start	End
In-House	Evaluation of regional black carbon emissions in South Coast LA	1/1/2016	6/30/2021
In-House	Cropland emissions of N_2O from fertilizer applications in California	1/1/2016	6/1/2020
In-House	Statewide evaluation of landfill methane fugtivite emissions using CARB sponsored measurements (JPL, SciAv, Mobile, Flux Tower data) and landfill model improvements	1/1/2016	On-Going
In-House	Real-world evaluation and tracking of statewide and regional GHG emissions (CH_4, N_2O) using atmospheric measurements, inverse modeling, and other analytical tools	1/1/2016	On-Going
In-House	Application of a mobile monitoring system for methane leak detection and quantification from oil, gas and landfill sources	1/1/2016	On-Going
In-House	Evaluating N_2O emission in South Coast LA; drought effect	1/1/2017	7/1/2020
In-House	Landfills: Comprehensive long-term studies of spatial and temporal emission behavior of landfills using Eddy Covariance (EC) flux towers, mobile platforms, airborne measurements, and other advanced measurement systems	1/1/2017	On-Going
In-House	Comprehensive long-term studies of spatial and temporal emission behavior of landfills using Eddy Covariance flux towers, mobile platforms, airborne measurements, and other advanced measurement systems	1/1/2017	On-Going
In-House	Analysis and tracking of dairy emissions using EC flux towers	1/1/2017	On-Going
In-House	Coordination and expansion of CARB GHG Research Monitoring Network with additional sites, and advanced measurements for meteorological and chemical speciation data	1/1/2017	On-Going
In-House	Soil emissions of NO_x from California land covers	1/1/2018	1/1/2020
In-House	New collaboration for launching a California Satellite, onboarding source and data visualization platform (Methane Source Finder), and partnerships with operators for testing data to action pipelines for identifying and fixing methane leaks	1/1/2018	On-Going
18RD008	Fluorinated Gases (F-gas) Inventory Update for Small Refrigeration and Air Conditioning Systems	1/14/2018	On-Going

Contract #	Title	Start	End
In-House	Evaluating CH_4 emissions from California dairies through MMP and dispersion modeling approach	4/1/2018	1/31/2021
In-House	Development of California-specific dairy database (CADD) and visuilization platform	4/1/2019	
In-House	Understanding the seasonal variabilities of CH_4 emissions from CA dairies	4/1/2018	1/1/2022
In-House	Soil emissions of NH_3 from California land covers	1/1/2020	1/1/2021
In-House	Investigating the impact of recent wildfires on climate and air quality in California	7/1/2020	On-Going

Mitigation Options

Contract #	Title	Start	End
17RD017	Benchmarking of Post-Alternative Manure Management Program (AMMP) Dairy Emissions and Prediction of Related Long-Term Airshed Effect	5/1/2018	4/30/2021
17RD018	Strategies to Reduce Methane Emissions from Enteric and Lagoon Sources	4/27/2018	4/25/2021
19RD015	A Scenario Tool for Assessing the Health Benefits of Conserving, Restoring and Managing Natural and Working Lands in California	3/1/2020	2/28/2022
In-House	Evaluating the effectiveness of dairy digester technology in reducing CH_4 and NH_3 emissions using satellite remote sensing	4/1/2018	On-Going
19RD017	White Paper: A Review of Emerging Technologies and Methods for Carbon Sequestration	3/1/2020	2/25/2021

Sustainable Communities Program Support

Tracking Progress and Co-Benefits

Contract #	Title	Start	End
18RD021	Screening Method and Map for Evaluating Transportation Access Disparities and other Built Environment-related Social Determinants of Health	2/1/2019	1/31/2021
19RD018	White Paper on Anti-Displacement Strategy Effectiveness	1/1/2020	2/28/2021
19STC005	Examining Entitlement to Inform Policy and Process in California: Advancing Social Equity in Housing	3/16/2020	9/14/2021

Evaluation and Mitigating GHG Emissions from VMT, Land Use and Buildings

Contract #	Title	Start	End
16RD004	Zero-Carbon Buildings in California: A Feasibility Study	9/1/2016	2/28/2021
18RD022	Estimating Induced Travel from Capacity Expansions on Congested Corridors	4/1/2019	3/31/2021
19RD009	Strategies for Incentivizing High-Occupancy, Zero-Emission, New Mobility Options	2/1/2020	7/31/2022
19STC006	Barriers to Reducing the Carbon Footprint of Transportation	6/1/2020	12/31/2022

Appendix C – Recent Research Final Reports: March 2019 – October 2020

Health and Exposure

Contract Number 14-314. Kleeman, Michael. *Association between long-term ultrafine particulate matter exposure and premature death.* (April 2019)

Contract Number 16RD010. Quintana, Penelope. *Improving the CalEnviroScreen Score at the US-Mexico Border.* (November 2019)

Contract Number 15-303. Miller, Lisa. *Are Adverse Health Effects from Air Pollution Exposure Passed on from Mother to Child?* (November 2019)

Contract Number 18RD010. Suffett, Irwin (Mel). *White Paper: Odor Complaints, Health Impacts, and Monitoring Methods.* (2019)

Environmental Justice

Contract Number 17RD006. Apte, Joshua. *A Tool to Prioritize Sources for Reducing High $PM_{2.5}$ Exposures in Environmental Justice Communities in California.* (November 2019)

Air Quality – State Implementation Plans

Contract Number 15RD007. Chiao, Sen. *A characterization of California ozone baseline using ozonesonde measurements at two coastal sites.* (April 2019)

Contract Number 17RD004. Iraci, Laura. Spatial Variation of Vertical Ozone Distribution over California. (April 2020)

Mobile Sources

Contract Number 12-315. Kirchstetter, Thomas. *Measuring real-world emissions from the on-road heavy-duty truck fleet.* (March 2019)

Contract Number 12-319. Turrentine, Tom. Advanced Plug-In Electric Vehicle Usage and Charging Behavior. (April 2020)

Contract Number 17RD014. Kishan, Sandeep. *Identify Outlier Makes and Models of Light Duty Vehicles Using Remote Sensing Data.* (November 2019)

Contract Number 17RD015. Bishop, Gary. *Measuring Emissions from the On-Road Vehicle Fleet in West Los Angeles.* (November 2019)

Contract Number 14-300. Durbin, Thomas. Evaluation of the feasibility, cost-effectiveness, and necessity of equipping small off-road diesel engines with advanced PM and/or NO_X aftertreatment. (January 2020)

Contract Number 16RD009. Tal, Gil. *Emerging Technology Zero-Emission Vehicle Household Travel and Refueling Behavior.* (September 2020)

Contract Number 16RD011. Samuelsen, Scott. *The Optimal Route for a Clean Heavy-Duty Sector in California.* (September 2020)

Contract Number 17RD009. Boriboonsomsin, Kanok. *Geofencing as a Strategy to Lower Emissions in Disadvantaged Communities.* (September 2020)

Contract Number 18RD011. Kavaralakis, George. *White Paper: A Review of Polycyclic Aromatic*

Hydrocarbon and Polycyclic Aromatic Hydrocarbon Derivative Emissions from Off-Road, Light-Duty, Heavy-Duty, and Stationary Sources. (2020)

Climate

Contract Number 16RD002. Meyer, Deanna. Characterize physical and chemical properties of manure in California dairy systems to improve greenhouse gas emission estimates. (June 2019)

Contract Number 16RD015. Hunter, George. Benchmarking Risk by Whole Room Scale Leaks and Ignitions Testing of A3 Refrigerants. (July 2019)

Contract Number 17RD018. Kebreab, Ermias. *Strategies to Reduce Methane Emissions from Enteric and Lagoon 23 Sources* (September 2020)

Sustainable Communities and Transportation

Contract Number 16RD003. Chapple, Karen. *Assessing the Travel Demand and Co-Benefit Impacts of Affordable Transit Oriented Developments.* (March 2019)

Contract Number 18RD029. Shaheen, Susan. *White Paper: Social Equity Impacts of Congestion Management Strategies.* (2019)

Contract Number 18RD028. Skabardonis, Alexander. *White Paper: Environmental Impacts of Congestion Management Strategies.* (2019)

Contract Number 16RD004. Mozingo, Louise A. *Zero-Carbon Buildings in California: A Feasibility Study.* (September 2020)

Appendix D – Impact of CARB Research Program Work in the Literature: Research Division Staff Peer-Reviewed Publications

CARB-Funded Research in World Class Publications

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

CARB's Research Staff Produce High-Impact Publications

During the past 20 years, CARB Research Division staff has authored or co-authored 150 peer-reviewed scientific articles (Figure 42) published in widely-read, prestigious journals. The wide range of topics (Figure 43) is indicative of the range of CARB's air quality and climate priorities as well as the complexities of the challenges CARB is working to address across disciplines to meet air quality, climate and equity goals. In the last Triennial Strategic Research Plan for 2018-2021, a comprehensive list of peer reviewed journal articles was provided. Recent publications are provided below.

Collier, S., **Ruehl, C.**, **Yoon, S.**, Boriboonsomsin, K., Durbin, T.D., Scora, G., Johnson, K. and **Herner, J.**, 2019. Impact of Heavy-Duty Diesel Truck Activity on Fuel Consumption and Its Implication for the Reduction of Greenhouse Gas Emissions. Transportation Research Record, 2673(3), pp.125-135, ISSN 0361-1981

Faloona, I.C., Chiao, S., Eiserloh, A.J., Alvarez, R.J., Kirgis, G., Langford, A.O., Senff, C.J., Caputi, D., Hu, A., Iraci, L.T., Yates, E.L., Marrero, J.E., Ryoo. J, Conley, S., Tanrikulu, S., **Xu, J.**, and **Kuwayama, T.**, 2020. The California Baseline Ozone Transport Study (CABOTS). Bulletin of the American Meteorological Society, 101(4), pp.E427-E445.

Guo, L., Chen, J., Luo, D., Liu, S., Lee, H.J., Motallebi, N., Fong, A., Deng, J., Rasool, Q.Z., Avise, J.C. and **Kuwayama, T.**, 2020. Assessment of Nitrogen Oxide Emissions and San Joaquin Valley PM2. 5 Impacts from Soils in California. Journal of Geophysical Research: Atmospheres, p.e2020JD033304.

Ho, P., Quiros, D., Robertson, W., Ruehl, C., Sobieralski, W., Ianni, R., Chernich, D., Littaua, R., Evaluation of Greenhouse Gas Emission Benefits of Vehicle Speed Limiters on On-Road Heavy-Duty Line-Haul Vehicles. Emiss. Control Sci. Technol. 4, 279–288 (2018).

Kuwayama, T., Charrier-Klobas, J.G., Chen, Y., Vizenor, N.M., Blake, D.R., Pongetti, T., Conley, S.A., Sander, S.P., **Croes, B.** and **Herner, J.D.**, 2019. Source apportionment of ambient methane enhancements in Los Angeles, California, to evaluate emission inventory estimates. Environmental science and technology, 53(6), pp.2961-2970.

Lee, H.J. 2019. Benefits of high resolution $PM_{2.5}$ prediction using satellite MAIAC AOD and land use regression for exposure assessment: California examples. Environmental Science and Technology 53:12774-12783.

Lee, H.J., Park, H.-Y. 2020. Prioritizing the control of emission sources to mitigate $PM_{2.5}$ disparity in California. Atmospheric Environment. 224, 117316.

Misra, C; Ruehl, C; Collins, J; Chernich, D; and Herner, J: In-use NO_X emissions from diesel and liquefied natural gas refuse trucks equipped with SCR and TWC respectively, Environ. Sci. Technol. (2017).

Ruehl, C., Misra, C., Yoon, S., Smith, J., Burnitzki, M., Hu, S., Collins, J., Tan, Y., Huai. T., and Herner, J.; Evaluation of Heavy-Duty Vehicle Emission Controls with a Decade of California Real-World Observations; Journal Air and Waste Management Association; Accepted, 2020

Ruehl, C; Smith JD; Ma Y; Shields J; Burnitzki M; Sobieralski W; Ianni R; Chernich, D; Chang M-C; Collins, J; Yoon S; Quiros D; Hu S; and Dwyer H: Emissions During and Real-world Frequency of Heavy-duty Diesel Particulate Filter Regeneration, Environ. Sci. Technol. (2018).

Schwarzman M, Schildroth S, **Bhetraratana M, Alvarado A**, Balmes J (2021). "Raising standards to lower diesel emissions." Science 371(6536): 1314-1316.

Smith, JD; Ruehl, C; Burnitzki, M; Sobieralski, W; Ianni, R; Quiros, D; Hua, S; Chernich, D; Collins, J; Huai, T; Dwyer, H: Real-time particulate emissions rates from active and passive heavy-duty diesel particulate filter regeneration, Sci. Total Environ. (2019).

Stauffer, R.M., Thompson, A.M., Johnson, B.J., Kollonige, D.E., Carlson, A.J., Particla, J.S., **Amini, S.**, and **Kuwayama, T.**, 2020. Linking the Trinidad Head, CA, Ozonesonde Profile Record to Surface Ozone Pollution. The Magezine for Environmental Managers. A&WMA.

Tan, Y.; Henderick, P.; **Yoon, S.; Herner, J.; Montes, T.**; Boriboonsomsin, K.; Johnson, K.; Scora, G.; Sandez, D.; Durbin, T. D., On-Board Sensor-Based NO_X Emissions from Heavy-Duty Diesel Vehicles. Environmental Science and Technology 2019, 53, (9), 5504-5511.

Yadav, V., Duren, R., Mueller, K., Verhulst, K.R., Nehrkorn, T., Kim, J., Weiss, R.F., Keeling, R., Sander, S., Fischer, M.L., Newman, S., **Falk, M., Kuwayama, T.**, Hopkins, F., Rafiq, T., Whetstone, J., and Miller, C., 2019. Spatio-temporally resolved methane fluxes from the Los Angeles Megacity. *Journal of Geophysical Research: Atmospheres, 124*(9), pp.5131-5148.

Yang, J; Roth, P; **Ruehl, CR**; Shafer, MM; Antkiewicz, DS; Durbin, TD; Cocker, D; Asa-Awuku, A; Karavalakis, G: Physical, chemical, and toxicological characteristics of particulate emissions from current technology gasoline direct injection vehicles, Sci. Total Environ. (2019).

Zhan, T; Ruehl, C; Bishop, G; **Hosseini, S; Collins, J; Yoon, S; Herner, J:** An analysis of real-world exhaust emission control deterioration in the California light-duty gasoline vehicle fleet, Atmos. Environ. (2019).

Zhou, X., Yoon, S., Mara, S., Falk, M., Kuwayama, T., Tran, T., Cheadle, L., Nyarady, J., **Croes, B., Scheehle, E., Herner, J.D., and Vijayan, A.**, 2021 Mobile sampling of methane emissions from natural gas well pads in California. *Atmospheric Environment, 244,* p.117930.

Figure 32: Publications from CARB authors sorted topically

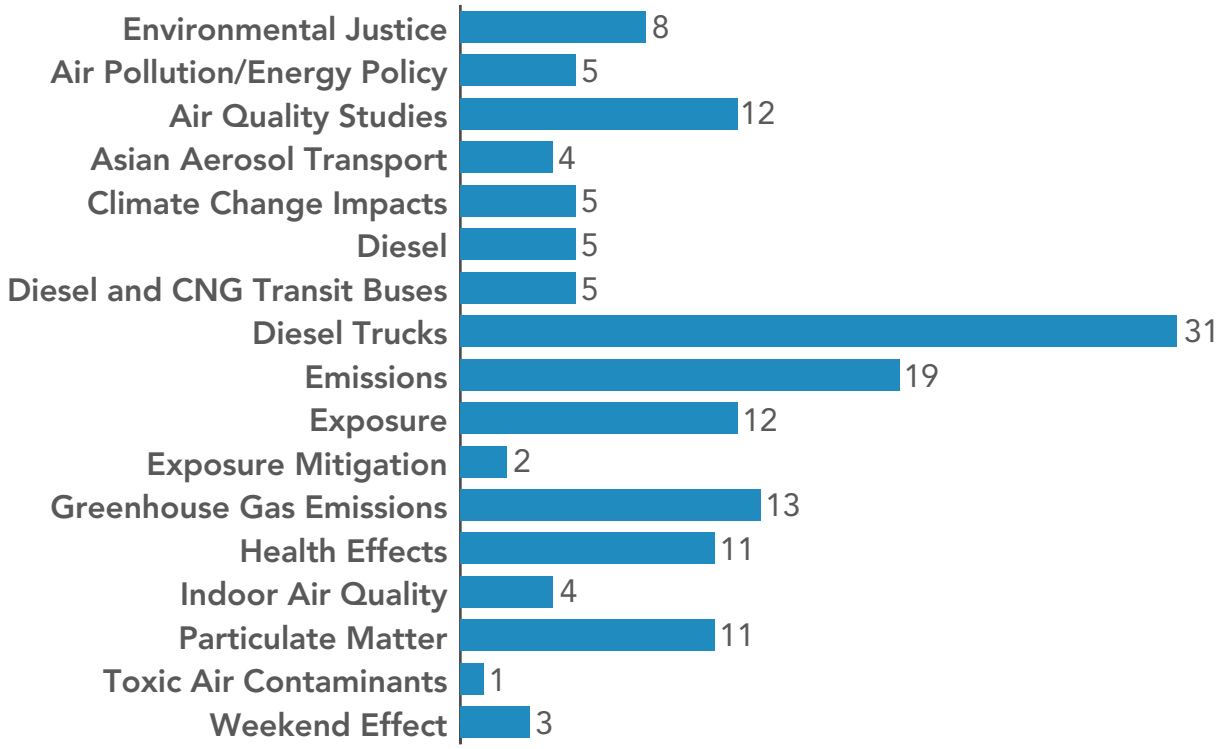
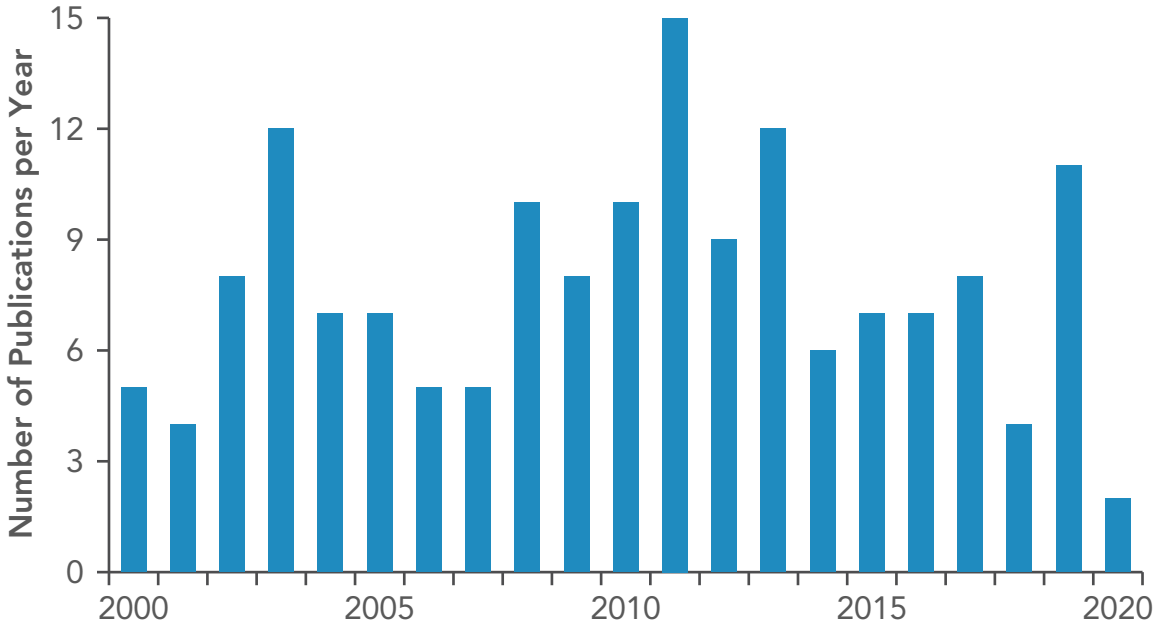


Figure 33: Total number of CARB authored publications by year



Appendix E – Research Roundtable Public Docket Summary

On Wednesday September 16, 2020, CARB hosted two online research roundtables to gather public comments on the proposed research initiatives for the Proposed 2021-2024 Triennial Strategic Research Plan. Community members and academic stakeholders were invited to both meetings and a total of 110 non-CARB attendees logged in. Two meetings were set up for flexibility and Spanish translation services were provided. Public engagement on the Research Program is a critical element to addressing community needs and hearing from subject matter experts on the direction CARB research is going. Each meeting began with a presentation briefly outlining the research planning process and then presenting on each category covered in the draft Triennial Strategic Research Plan. CARB also solicited input on our engagement efforts. During the meeting CARB heard a wide-range of comments, including resident concerns over persistent air pollution issues in their communities and suggestions on how CARB does research and how CARB could engage with communities better. A public docket was also set up to collect written comments. A summary of the public docket comments is provided below. The full docket can be accessed *here*. Below that is a summary of comments collected during the Research Roundtables.

Summary of Public Docket Comments

Suggestions for Better Outreach and Collaboration

- CARB should support partnerships between universities and municipalities to address local sustainability-related goals
- CARB should undertake research that is action-oriented and equity centered, such that communities are engaged early on in the design and planning process and leverage existing efforts; further, CARB should partner with communities, rather than doing research "on" them
- CARB needs to better address equity in its Research Program. The following recommendations are being made to improve how it collaborates with community groups:
    - Understand the context of racism in research in the past and present
    - Review the challenges, best practices, and opportunities for centering racial equity in research
    - Conduct an internal equity assessment of your research institution, department, or team
    - Partner with and pay a community partner to conduct research
    - Co-create the research questions and scope of work with a community partner
- CARB should coordinate with other state agencies who provide research funding to accelerate new scientific and technological solutions by hosting research roundtables and forums which promote greater dialogue on priorities and efficient use of research funds
- CARB should improve its research planning process by soliciting more robust research concepts and ensure that publicly submitted concepts more closely address CARB needs; this can be achieved by asking for more detailed concepts including budgetary needs and capabilities and putting them through a thorough screening process

Air Quality Issues

- Fog water may be a vector to transfer chemicals from agricultural activities to regional communities, can fog water be collected to better understand air quality issues in the central valley and other agricultural communities?

- The Eastern Coachella Valley is frequently in non-attainment for ozone; what can CARB do to better understand pollutant transport from Southern California to the Coachella Valley communities, many of which are priority communities and highly impacted by pollution
- Air quality issues are severe in the Eastern Coachella Valley and other surrounding areas with multiple sources impacting communities; despite this, one air quality index (AQI) value is reported for the entire region. Can CARB invest in integrating the various low-cost sensors that currently exist to provide higher spatial resolution AQI values, particularly for highly impacted regions with multiple sources of pollutants?
- The Salton Sea produces various types of air contaminants. Can CARB fund research that explores health risks from biological components of the Salton Sea?
- Fragrances are an understudied yet persistent environmental stressor that can cause severe migraines in sensitive groups; what research can CARB do regarding regulatory interventions to alleviate the health concerns of people experiencing negative health impacts from pervasive fragrances and odors?
- CARB should continue to focus on air quality disparities and leverage new tools to provide more fine-grained estimates of how pollution impacts various communities and how costs and benefits of regulating air pollutants impact communities differently

Technological Innovations and Proposed Solutions to Air Quality and Climate Issues

- CARB should consider utilizing small wind turbines to reduce carbon emissions
- To tackle the climate crisis, CARB should radically reimagine proposed interventions and consider major land use changes and including lifestyle and behavioral changes; additional interventions could include pricing carbon to change consumer behavior
- CARB should consider investigating retraining of certain workers who will have to shift tools and methods used in their work to instead gain skills in methods that would lower carbon; for example, retraining landscapers to implement permaculture
- CARB should engage with researchers to develop behavioral economics projects to improve regulatory compliance

Summary of Research Roundtable Verbal Public Comments

Community Concerns

Community members expressed concern over the following needed interventions and air pollution issues:

- Improvements to AQI reporting and increasing spatial resolution, particularly in areas where local sources create hot spots for unhealthy air
- Increased community engagement on air quality siting monitors, air toxics and community exposure
- Exposure to fragrances impacting health with no viable recourse to be heard
- Access to list of toxics for reporting
- Salton Sea community concerns including agricultural burning and hydrogen sulfide exposures, even inside homes
- Imperial Valley air quality concerns
- More granular GHG inventories for school districts

Collaboration

Community members brought up the following ideas to improve CARB's engagement with communities and other government agencies:

- Create a forum for researchers to collaborate on CARB research initiatives
- Improve how CARB is working with MPOs and local governments to implement best evidence based policies
- Collaborate with CPUC to improve overlap of standards for indoor air quality and refrigerants

Emerging Issues

Community members brought to CARB's attention emerging issues that may require further investigation in the future:

- Cannabis industry emissions and impacts on communities are unregulated and understudied
- Conversion of ports for helicopter commuting may be generating high emissions

Technology

Community members brought various recommendations to the Research Roundtable regarding new technological interventions to solve air quality and climate issues moving forward:

- CARB should jump to the next technology rather than investing in interim technologies which may continue to contribute to unhealthy air
- Health benefits of climate change mitigation should be investigated
- Technological innovation on reducing border emissions should be investigated, various interesting ideas have been proposed recently
- CARB should optimize incentives to introduce clean technologies at ports
- CARB should focus on improving energy density of batteries

Continuing Concerns

Some comments related to phenomena that is somewhat understood, but needs further study:

- Better understanding of the impacts of meteorology on central valley pollution is needed

Wildfires

Various attendees brought up concerns over wildfire smoke and its health impacts:

- Health concerns particularly due to smoke from burning structures as well as wildland fuels
- Greater land management interventions are needed to reduce fire risk
- Disparities in building codes for reducing infiltration of smoke are an issue, particularly for sensitive groups and more vulnerable populations

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