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Maximizing the Air Quality and Environmental Justice Benefits of Zero Emission Off-Road Vehicles and Equipment in California

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16. Abstract

Diesel fuel powered off-road vehicles and equipment used in agriculture, construction, mining, and industry have significant air quality and public health impacts due to high levels of pollutant emissions. Replacing these with zero emission powertrains represents a key strategy for reducing the harmful environmental impacts. However, the air quality impacts of zero emission off-road vehicles have not been assessed. Using the CMAQ model, we find that fully converting the off-road sector to zero emission equipment can decrease annual $PM_{2.5}$ up to 0.9 μg/m^3 and reduce daily maximum 8-hr average (MDA8) ozone as much as 6 ppb in Southern California. Statewide, these improvements yield benefits to public health potentially ranging up to $22.0 billion annually. The results further demonstrate the ability of zero emission off-road equipment to achieve health benefits within socially and economically disadvantaged communities.

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List of Abbreviations

CARB	California Air Resources Board
CMAQ	Community Multiscale Air Quality
DACs	Disadvantaged communities
MDA8	Maximum Daily Average 8-hour ozone
NAAQS	National Ambient Air Quality Standards
NOx	Oxides of nitrogen
$PM_{2.5}$	Fine Particulate Matter
SoCAB	South Coast Air Basin
ZE	Zero emission

Executive Summary

Executive Summary

Off-road vehicles and equipment play a significant role in air pollution and public health concerns due to their reliance on diesel-fueled engines, which emit high levels of pollutants including nitrogen oxides (NO_x) and fine particulate matter ($PM_{2.5}$). These pollutants are harmful in and of themselves, and further contribute to degraded air quality through the formation of even more pollution including ground-level ozone (i.e., smog). Replacing these engines with zero-emission (ZE) powertrains, including hydrogen fuel cell and battery electric technologies, represents a key strategy for reducing the harmful environmental impacts from the off-road sector. However, quantifying these benefits, particularly from an environmental justice perspective, has not been done before. This study evaluates the air quality and health benefits of transitioning to ZE off-road vehicles and equipment across California, with a particular focus on disadvantaged communities that bear a disproportionate burden of air pollution.

Reflecting the importance of transitioning to ZE off-road vehicles and equipment, California has established a range of policies and incentive programs to accelerate the transition to ZE off-road technologies, anchored by Executive Order N-79-20, which targets 100% ZE adoption by 2035 where feasible. While the definition of "feasibility" and enforcement remain uncertain, the transition is expected to be driven by regulations, incentives, and infrastructure investment. Existing regulations mandate fleet reductions in pollutants including $PM_{2.5}$ and NO_x from existing off-road vehicles and cover a wide range of vocations and technologies including (but not limited to) agriculture, construction, commercial buildings, air travel, manufacturing, landscaping, and other industrial needs. Key initiatives include CARB's Off-Road ZE Targeted Manufacturer Rule**,** In-Use Off-Road Diesel-Fueled Fleets Regulation, and the CORE voucher program, which subsidizes ZE equipment and related fueling infrastructure. Additional funding is available through the FARMER and Carl Moyer programs to support cleaner technologies in agriculture, construction, mining, and industrial sectors. For smaller engines, the SORE Program regulates emissions, and in 2021 CARB mandated that all new small off-road equipment ($\leq$25 hp) sold from 2024 onward must be zero-emission.

The California Air Resources Board (CARB) 2022 Scoping Plan update outlines a bold and aggressive transition towards a carbon-neutral economy by 2045, including wide-spread deployment of ZE off-road technologies in accordance with Executive Order N-79-20. However, feasibility limits prevent the attainment of a completely zero emission off-sector by 2045. Therefore, there is still the potential for increasing the level of ZE off-road technologies up to the complete replacement of ICE (although attaining this will be a major challenge and require significant development and advancement of ZE off-road equipment and vehicles).

In this study, the potential improvements in atmospheric pollutant concentrations, including NO_x, $PM_{2.5}$, and ground-level ozone, are assessed for 1) a reference scenario consisting primarily of the continued use of internal combustion equipment, 2) higher levels of ZE vehicles and equipment in line with the Scoping Plan, and 3) full deployment of ZE off-road equipment. The results of the air quality modeling are then used to determine benefits to public health from cleaner air in exposed California populations. Finally, the health benefits are analyzed from an environmental justice perspective to consider how the benefits impact overburdened communities, which should be the prioritized for benefits.

Results

The widespread deployment of ZE off-road equipment in the Scoping Plan substantially improves statewide air quality through reductions in NO_x, $PM_{2.5}$ and ozone, and these improvements can be further maximized if California transitions to a complete ZE off-road sector. As shown in **Figure ES1**, improvements are most pronounced in the South Coast Air Basin in Southern California, but also benefit other populated regions in California including the Central Valley, the San Francisco Bay area, and greater San Diego. Fully decarbonizing the off-road sector in Southern California would reduce ambient concentrations of up to 2.4 parts per billion (ppb) NO_x, 0.9 microgram per cubic meter (μg/m^3), of $PM_{2.5}$, and reduce maximum daily average eight-hour (MDA8) ozone levels by 6 ppb.

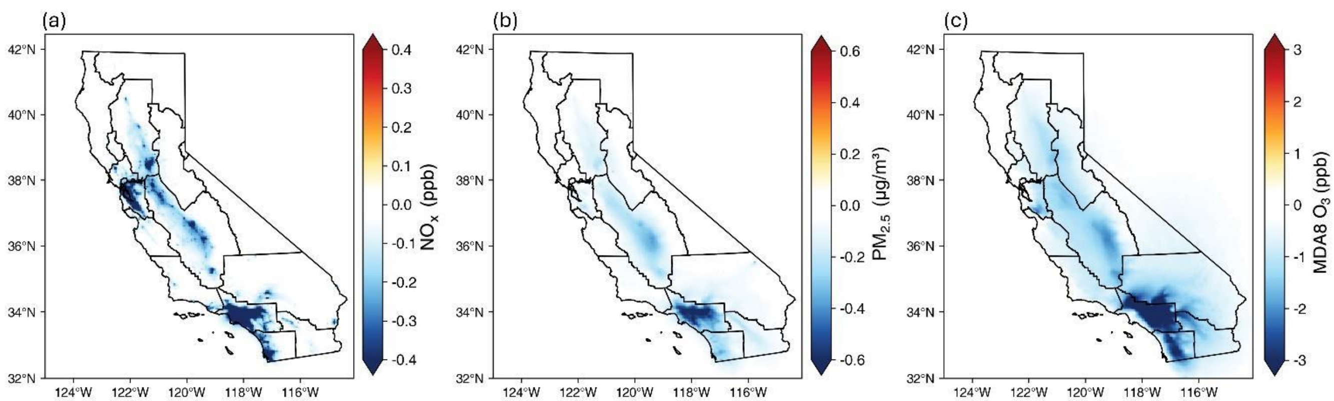

Figure ES1. Changes in annual (a) NO_x, (b) $PM_{2.5}$, and (c) MDA8 ozone concentrations from fully decarbonized off-road sector.

The monetary value of the health benefits associated with these changes is then quantified with a focus on socially and economically disadvantaged communities (DACs) which currently experience an unfair burden from air pollution. These improvements yield statewide avoided incidence of mortality potentially up to 1,800 and further lead to benefits to public health in 2045 of up to $22.1 billion annually (although the upper bound represents a completely ZE off-road sector which represents a major challenge to attain by 2045). **A key finding is that the Scoping Plan achieves benefits of $4.5 billion from the off-road sector relative to the Reference scenario, demonstrating the co-benefits of reducing off-road GHG emissions.** The results provide insight into how ZE off-road equipment can attain maximum air quality health benefits, particularly in minority and low-income areas where improvements are needed most. The largest contribution to the total health benefits occurs from the 1,800 avoided incidences of mortality from reduced exposure to $PM_{2.5}$. Three-quarters of the health benefits occur in the South Coast Air Basin due to its large, dense urban population. Additional benefits occur in the Central Valley, San Francisco Bay area, and San Diego region.

Furthermore, the health benefits from air quality improvements specifically within socially and economically disadvantaged communities (DAC) are substantial, reaching nearly $7 billion annually. The results demonstrate that, in total, approximately 37 percent of public health savings occur within these communities, which make up 29 percent of the population in California, indicating that a higher ratio of benefits occurs within DAC relative to the general population. Benefits in DAC are significantly higher in the South Coast Air Basin, which includes Los Angeles, Orange, Riverside, and San Bernardino counties, than any other region of California, **Figure ES2** shows a detailed overview of the benefits for this area with the DAC outlined in red. As can be seen in **Figure ES2(a)**, areas with some of the highest benefits include those surrounding the ports of Los Angeles and Long Beach, specifically the communities of Wilmington, Carson, West Long Beach (**Figure ES2(b)**), parts of metropolitan Los Angeles, and the eastern portion of the South Coast Air Basin.

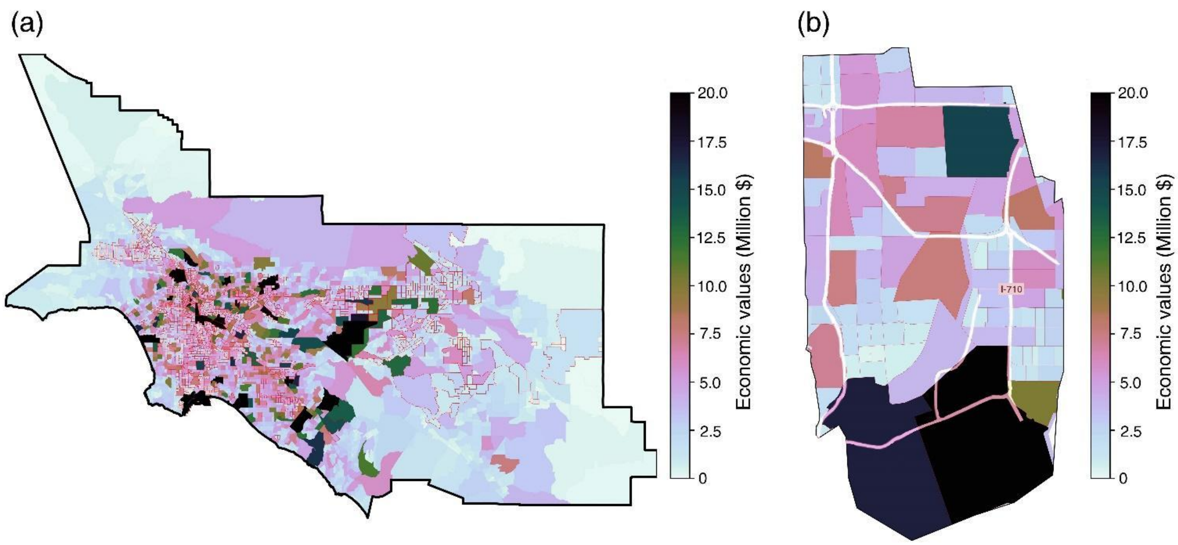

Figure ES2. Monetized health benefits from decarbonizing the off-road sector across (a) the South Coast Air Basin and (b) the Wilmington, Carson, West Long Beach communities.

Conclusions

This report provides data-driven insights to inform regulatory and investment decisions to maximize the benefits of off-road emission reductions. The goals of this effort are primarily directed to answer two questions. First, **what are the benefits attained in the Scoping Plan specifically from the off-road sector?** Second, **what additional benefits are potentially attainable if the levels of ZE equipment and vehicles are expanded even further?** This structured approach enables the comparison of the air quality and environmental justice outcomes of different strategies, identifies potential gaps in achieving reduction targets, and design policies that maximize health and equity benefits. By illustrating the potential for air quality improvements and significant health benefits, this research supports policy measures that accelerate the transition to ZE off-road equipment, ensuring cleaner air and healthier communities statewide. Major sources of off-road emissions include construction vehicles and equipment, commercial equipment, and cargo handling equipment at the ports of Los Angeles and Long Beach, and represent important targets for ZE technology deployment, especially within low-income and marginalized communities.

Current California policies and programs targeting off-road sector emission reductions achieve significant air quality improvements and the potential exists to increase these benefits. Under the policy assumptions made for the CARB Scoping Plan, aggressive shifts to ZE off-road equipment and vehicles are assumed which achieve significant reductions in NO_x, $PM_{2.5}$, and ground-level ozone (i.e., smog). In all cases, the air quality improvements are important in terms of both magnitude and location. The regions with the most pronounced benefits have elevated importance for air quality improvements due to 1) pre-existing degraded air quality, 2) large populations, and 3) the presence of disadvantaged communities.

Transitions to ZE off-road technologies results in thousands of fewer deaths each year and billions in economic savings. Air quality improvements associated with ZE off-road emission reductions achieve large benefits to public health through avoided incidence of premature death and many other health consequences including heart attacks, strokes, and respiratory illness. For example, the Scoping Plan achieves approximately ~400 fewer premature deaths and the total health benefits are valued at $4.5 billion *annually* in 2045 relative to a future where internal combustion engine technologies (primarily diesel) continue to dominate. Benefits of fully eliminating off-road sector emissions could attain up to nearly 2,000 fewer deaths and far less injuries with the total economic value of $22.1 billion.

The benefits of ZE off-road equipment can increase even further if a complete ZE sector is achieved, particularly within DAC. The Scoping Plan scenario already delivers large benefits, but the complete removal of internal combustion engines in the off-road sector approximately doubles the emission reductions, health gains, and economic value, while significantly advancing environmental justice outcomes. For example, complete elimination of off-road sector emissions prevents ~25 percent more premature deaths and illnesses compared to the Scoping Plan. Additionally, 37 percent of the total health benefits, nearly $7 billion annually, that can be achieved are within disadvantaged communities, as defined by California' CalEnviroScreen 4.0. These communities constitute about twenty nine percent of the state's population. Thus, greater benefits are attained with DAC populations relative to non-DAC populations. Overall, the highest DAC benefits occur within the Southern California Air Basin, particularly the communities surrounding the port areas, and parts of metropolitan Los Angeles.

However, it is important to note that achieving a full zero emission off-road sector represents a major challenge and may not be feasible in the 2045 timeframe used in this study. Barriers include the high energy demand and duty cycles of large equipment, which require batteries that are currently too heavy, costly, or unable to provide sufficient runtime for continuous operation. This is particularly problematic in some vocations including construction and agriculture, where equipment often operates for long shifts in remote or infrastructure-poor areas. Charging and hydrogen refueling infrastructure is another critical limitation, as fast-charging systems are scarce on job sites and farms, and grid access may be inadequate to support high-power charging needs. The durability and ruggedness of ZE technologies under harsh conditions (dust, vibration, temperature extremes) raises concerns for many vocations, while equipment downtime for charging reduces productivity compared to rapid refueling with diesel. Finally, capital costs remain high relative to conventional engines, and uncertainties about battery lifetimes, recycling, and replacement costs add to the risk for fleet operators. These challenges mean that although ZE technologies may be well-suited for smaller equipment and certain controlled environments, scaling to heavy, long-duty off-road applications will require advances in energy density, charging solutions, cost reduction, and supportive infrastructure.

The targeted deployment of ZE equipment and vehicles in high impact areas can maximize benefits. This report further highlights the critical importance of prioritizing ZE deployment in regions with pre-existing poor air quality and high population density, particularly in the South Coast Air Basin. Benefits of ZE off-road technologies are most pronounced in the South Coast Air Basin, which includes the counties of Los Angeles, Orange, Riverside, and San Bernardino with annual reductions up to 2.4 parts per billion (ppb) in nitrogen oxides (NOx), 0.9 micrograms per meter squared ($\mu g/m^3$) in $PM_{2.5}$, and 6 ppb in maximum daily average 8-hour (MDA8) ozone as shown in **Figure ES1**. Major sources of off-road emissions in the basin include construction vehicles and equipment, commercial equipment, and cargo handling equipment at the ports of Los Angeles and Long Beach, and represent important targets for ZE technology deployment, especially within low-income and marginalized communities. This is critical since the region is currently in non-compliance with federal standards for both ozone and $PM_{2.5}$, which could put federal transportation funding dollars in jeopardy. Other populated regions in California, including the Central Valley, the San Francisco Bay area, and greater San Diego would also benefit.

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Introduction

California is a world leader in climate change mitigation spearheaded by the state's target of economy-wide carbon neutrality by 2045. Specifically, the state has established statutory goals for reducing statewide greenhouse gas (GHG) emissions down to at least 40 percent below 1990s level by 2030, and to at least 85 percent below by 2045. However, while the state has made some progress in reducing GHGs those gains will need to be accelerated to reach these goals. In support of this, the California Air Resources Board (CARB) 2022 Scoping Plan outlines a bold and aggressive transition towards a carbon-neutral economy including wide-spread deployment of ZE technologies, sustainable and low carbon fuels, carbon sequestration, and other actions. California further aims to lead the world in climate action while ensuring economic resilience and environmental justice. Off-road equipment and vehicles, including those used for construction, mining, agriculture, port operations, industry, and other activities, are dominated by the use of fossil fuel combustion engines that emit GHGs including carbon dioxide. Therefore, additional carbon mitigation strategies will be required within the off-road sector as part of California's broader climate change efforts.

In addition to GHGs, off-road equipment produces oxides of nitrogen (NO_x), which are precursors to ground-level ozone (O_3), and fine particle matter ($PM_{2.5}$), all components of smog which contribute to California's degraded air quality and lead to health problems in exposed populations. Reducing the air pollution impacts of off-road equipment will be more difficult than on-road vehicles and other economic sectors. Moreover, air pollution from the off-road sector disproportionately impacts socially and economically disadvantaged populations, including low-income and/or minority communities [1]. Therefore, deploying strategies to reduce pollutant emissions from off-road equipment is an important and necessary step to meet California's clean air mandates and goals.

Figure 1 shows the current and projected emissions from off-road equipment if no further action is taken other than the policies and programs in place in 2019, which is the most current year for CARB's baseline emissions projection tool [2]. For example, CARB's In-Use Off-Road Diesel Regulation mandates fleet reductions in PM and NO_x emissions from existing off-road heavy-duty diesel vehicles and covers a wide range of vehicle types used in (but not limited to) construction, air travel, manufacturing, landscaping, and ski resorts. As can be seen, reductions are predicted in 2035 and 2045 from current (i.e., 2020) levels, but the off-road sector is still expected to be a major contributor to pollutant emissions. Indeed, it is projected to contribute approximately 15 percent to statewide NO_x in 2035 and 2045 [2].

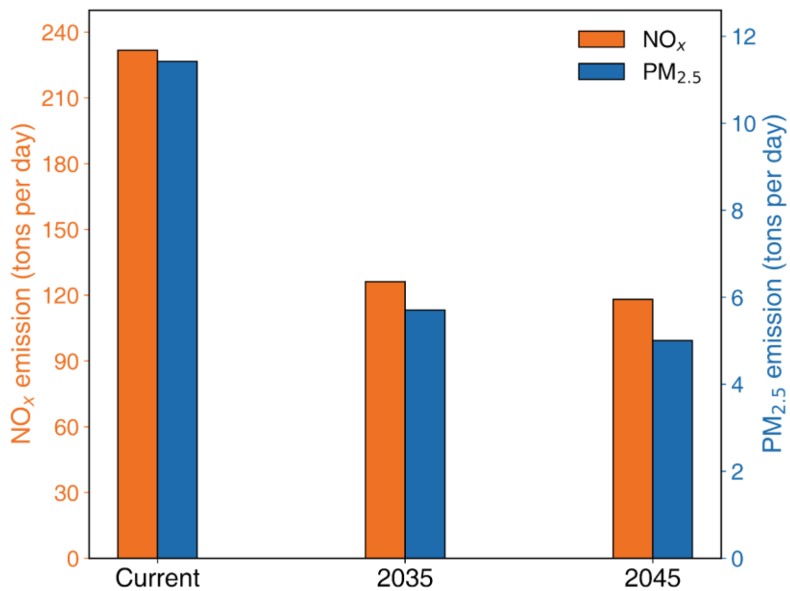

Figure 1. Current and projected emissions of NO_x and $PM_{2.5}$ from off-road equipment and vehicles under present policies.

ZE options, including battery electric and hydrogen fuel cell electric vehicles, are increasingly being developed for off-road applications in response to environmental policy and other drivers. Replacing current, largely diesel-powered equipment and vehicles with either option will reduce pollutant emissions, improve air quality, and provide health benefits. The electrification of construction equipment, including excavators, loaders, and compact equipment, is being led by manufacturers like Volvo, Caterpillar, and Komatsu. In the mining sector, battery-electric haul trucks and loaders are being developed by Epiroc and Sandvik, and hydrogen fuel cell mining trucks are being demonstrated by Anglo American and Komatsu. In the ports and material handling sector, ZE terminal tractors, forklifts, and cranes are already being deployed in ports and logistics hubs. Indeed, in Southern California, the Ports of Los Angeles and the Port of Long Beach are planning for 100 percent ZE cargo handling equipment by 2030. Therefore, in the coming decades, there will be a shift to ZE off-road equipment in many different economic sectors in California.

Reflecting the importance of deploying ZE off-road equipment, the state has a variety of policies and programs in place beginning with Executive Order N-79-20, which sets a goal of 100 percent transition to ZE off-road vehicles and equipment by 2035 where feasible. However, it should be noted that there is uncertainty in defining feasibility and how the goal will actually be enforced. This transition is assumed to be supported by regulations, incentives, and infrastructure build-out including CARB programs such as the Off-Road ZE Targeted Manufacturer Rule, the In-Use Off-Road Diesel-Fueled Fleets Regulation, and the Clean Off-Road Equipment Voucher Incentive Project (CORE) which offers a streamlined incentive process to encourage the purchase or lease of ZE off-road equipment with additional funding for charging and hydrogen fueling infrastructure [3]. Additional funding mechanisms include the Funding Agricultural Replacement Measures for Emission Reductions (FARMER) [4] and Carl Moyer [5] programs which provide incentive funds for replacing off-road equipment for construction, mining, industrial, cargo handling, and agricultural uses with cleaner technologies. The Small Off-Road Engine (SORE) Program regulates emissions from small engines (at or below 25 hp) including equipment such as lawn and garden tools, industrial machinery, and small construction equipment. In 2021, CARB adopted a rule requiring manufacturers to produce only ZE small off-road equipment by 2024.

Exposure to elevated concentrations of air pollutants including $PM_{2.5}$ are prominent risk factors for illness and death. Improved air quality will reduce the burden of several major diseases leading to healthier and longer lives, fewer patients requiring hospital admission and other treatments while decreasing the burden on health systems statewide. California has experienced significant air quality improvements in the past few decades, largely due to the successful regulation of on-road air pollutant emissions [7]. However, many regions of California continue to experience levels of $PM_{2.5}$ that exceed state and federal health standards and significant reductions in pollutant emissions are required to achieve compliance and ensure healthy air for all California communities.

This study evaluates the air quality and health benefits of fully transitioning to ZE off-road vehicles and equipment across California, with a particular focus on socially and economically disadvantaged communities (DACs) that bear disproportionate burdens from air pollution. We also present a high-resolution assessment of regions identified as being particularly vulnerable to the impacts of air pollution from the off-road sector, including the South Coast Air Basin of Southern California which encompasses Los Angeles, Orange, and non-desert portions of Riverside and San Bernardino counties. The South Coast Air Basin experiences some of the worst air quality in the United States and is home to a large, dense, urban population which heightens the importance of pollution effects on health. Therefore, improvements in $PM_{2.5}$ and ozone are badly needed as the region is currently in non-attainment for the National Ambient Air Quality Standards (NAAQS) for these pollutants. This study further assesses a key sub-region within the basin, including the communities of Wilmington, Carson, and West Long Beach adjacent to the ports of Los Angeles and Long Beach, as they are some of the most polluted communities in California from emissions associated with significant activity from refineries, port operations, rail yards, warehouses, and major highways [8].

While it is clear that ZE off-road equipment will reduce pollutant emissions, quantifying these benefits in specific locations is no simple matter and requires the use of advanced air quality modeling tools to account for both primary emissions (e.g., NOx, emitted particulate matter) and secondary (formed) pollutant concentrations (e.g., ozone, secondary $PM_{2.5}$). In this report, our approach to quantifying the air pollution health benefits of increasing the deployment of ZE off-road equipment consisted of four major steps. First, we projected the emission reductions from deploying ZE off-road equipment on NO_x, and fine particulate matter over time and geographic locations. Emissions are projected using output from an economy-wide tool used extensively in state planning efforts called the PATHWAYS model [9] applied to a detailed CARB pollutant emissions inventory processed by the Sparse Matrix Operator Kernels Emissions (SMOKE) v4.9 model [10]. Using this approach, we projected emissions of NO_x for different scenarios representing 1) existing state policies regarding the continued use of internal combustion equipment in the off-road sector, 2) higher levels of ZE off-road vehicles and equipment in line with the 2020 Scoping Plan, and 3) full deployment of ZE off-road vehicles and equipment. Second, we determined ground-level concentrations of NOx, ozone, and $PM_{2.5}$ using a photochemical air quality model called the Community Multiscale Air Quality (CMAQ) v5.5 model that accounts for atmospheric chemistry and pollutant transport [11]. Third, we produced a health impact assessment of each scenario using the Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP) v1.5.8 which provides a quantitative estimate of the incidence and monetary value of avoided harmful health outcomes associated with air pollution [12]. Fourth, we analyzed the results through an environmental justice framework to quantify and evaluate the benefits that occur specifically within socially and economically disadvantaged communities identified using CalEnviroScreen 4.0 [13], a model that identifies areas highly burdened by air pollution. The results provide insight into how the roll-out of ZE off-road equipment can be designed to attain maximum benefits in disadvantaged communities and can be used to guide investments that best improve public health in vulnerable segments of the population including minorities and low-income individuals.

Methodology

Scenario Development

First, scenario development is required for assessing the air pollution impacts of reducing emissions from off-road equipment that reflect varying levels of technology adoption and account for important parameters such as equipment turnover rates, differences in technological feasibility across subsectors (e.g., construction, agriculture, mining, cargo handling), and the timing and scale of policy measures. Projections of sector-specific equipment activity, fuel consumption, and emissions must be linked to assumptions about ZE technology penetration and the supporting buildout of charging and hydrogen fueling infrastructure. Spatial and temporal variations in off-road activity must be represented to capture localized air quality and health impacts, especially within disadvantaged and AB 617 communities where burdens from diesel emissions remain high.

In this work, the basis for the scenario development is the 2022 CARB Scoping Plan which included. In the 2022 Scoping Plan Scenario, the off-road sector is assumed to undergo a complete transition to ZE equipment ***where technologically feasible***, in alignment with Executive Order. Still, feasibility constraints mean that a full transition will not be achieved across all subsectors by 2045. Energy use and emissions from internal combustion engines (ICE) are projected to decline significantly, replaced by ZE technologies in agriculture, construction, and other sectors. Nevertheless, ICE equipment persists for some vocations in 2045. For example, in the construction sector, electricity use increases sharply but diesel and gasoline are projected to meet 36% of total energy demand as shown in **Figure 2**.

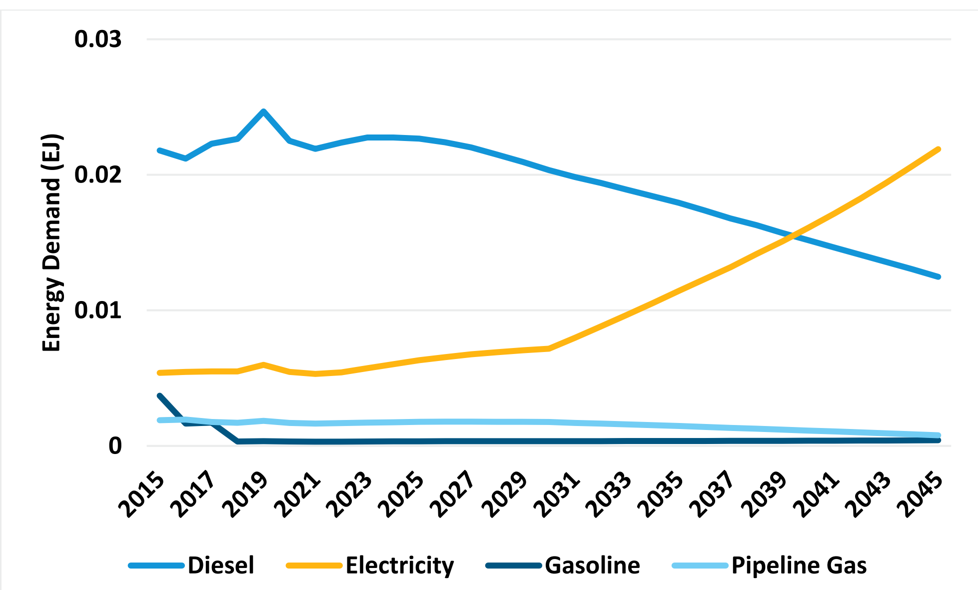

Figure 2. Energy demand by fuel for the construction sector in the Scoping Plan.

Given the goals of 1) quantifying the benefits specifically for off-road equipment in the Scoping Plan and 2) identifying any additional benefits that could result from completely eliminating off-road sector emissions, this study uses four overarching scenarios. Two scenarios are taken directly from the 2022 CARB Scoping Plan update [13] including a business-as-usual Reference scenario that reflects what future emissions would be under current state practices and policies, and the Scoping Plan scenario which is characterized by the actions required to achieve the state's goals for achieving a carbon neutral economy by 2045. Further, scenarios of complete replacement of ICE with ZE off-road vehicles and equipment are developed for both the Reference scenario (i.e., all other sectors are held constant with the Reference scenario and the off-road sector emissions are eliminated) and the Scoping Plan scenario (i.e., all other sectors are held constant with the Scoping Plan scenario and the off-road sector emissions are eliminated) to provide the maximum benefits that could be attained for each baseline, called the 100 ZE Reference and 100 ZE Scoping Plan scenarios. Additional descriptions of the assumptions within the off-road sector scenarios are detailed in **Table 1** and additional descriptions of the assumptions within other sectors can be found in the 2022 CARB Scoping Plan [13].

Table 1. Configuration and detailed description of scenarios.

Scenario	Off-road Sector Assumptions
Reference	Continuing current policies in place (2019)
Scoping Plan	Higher levels of ZE vehicles and equipment are deployed including: **Port Operations:** 100% of cargo handling equipment (CHE) is ZE by 2037 **Oil and Gas Extraction:** Reduced in line with petroleum demand by 2045 **Construction Equipment:** 25% of energy demand electrified by 2030 and 75% by 2045 **Other Industrial Manufacturing:** 50% energy demand electrified by 2045 **Agriculture:** 25% energy demand electrified by 2030 and 75% by 2045
100 ZE Reference	100% deployment of ZE vehicles and equipment in the off-road sector by 2045. **Achieves a ZE off-road sector based on the Reference scenario.**
100 ZE Scoping Plan	100% deployment of ZE vehicles and equipment in the off-road sector by 2045. **Achieves a ZE off-road sector based on the Scoping Plan scenario.**

By comparing the air quality impacts that occur across the four scenarios, the following questions can be answered. First, what are the air quality and health benefits achieved in the Scoping Plan ***specifically from the off-road*** **sector**. For example, the air quality and health benefits of the Scoping Plan overall were assessed and included in the Scoping Plan. However, those were estimates of the benefits of reducing emissions in all sectors combined and it was not possible to determine those from the adoption of ZE technologies in the off-road sector. Second, what ***additional benefits*** can be achieved if the deployment of ZE off-road vehicles exceeds that assumed in the Scoping Plan up to complete adoption of ZE technologies by 2045.

Emissions and Air Quality Modeling

For each scenario, we quantified the pollutant emissions by location for pollutant source in California. The baseline pollutant emissions are from a highly detailed 2020 inventory developed by CARB (CARB 2020, v0018) including total emissions by sector and source as well as by time and location. The emissions were then extrapolated to 2045 using output from the PATHWAYS model [9] for technologies, fuels, and energy demand by Assembly Bill 32 GHG Inventory sector. Additionally, data from various sources including EMission FACtor (EMFAC) 2021 v1.0.1 [14] for on-road vehicles, OFFROAD2021 [15] for other transportation sectors, and the CARB California Emissions Projection Analysis Model (CEPAM) 2019 v1.03 for stationary sources [16] were used to account for changes in emission rates, control factors, and other variables. The pollutant emissions inventory was then processed into air quality model-ready format using the Sparse Matrix Operator Kernel Emissions model (SMOKE) v4.9 including the location and timing of off-road equipment activity responsible for specific emissions [10].

Next, the formatted emissions served as input for the Community Multi-scale Air Quality (CMAQ) model v5.5 [17] which provides a comprehensive assessment of changes in both primary (e.g., NO_x, emitted particulate matter) and secondary (e.g., ozone, secondary $PM_{2.5}$) pollutant concentrations. The use of the CMAQ model is important as a significant fraction of the pollution impacting California's population is secondary, with ozone and secondary $PM_{2.5}$ being particularly important from a human health perspective [18]. Both $PM_{2.5}$ and ozone have well-known health impacts, and several regions of California are in non-attainment for these pollutants under the NAAQS [19]. CMAQ simulations were validated using measurement data from the air monitoring networks operated by CARB [20] confirming acceptable performance with appropriate statistical metrics [21].

The CMAQ model domain is configured as two nested grids with resolutions of 4 kilometers (km) and 1 km, respectively, as shown in **Figure 3**. The outer domain covers all of California and the inner domain focuses on metropolitan Southern California including the South Coast Air Basin. Meteorological fields were taken from Weather Research and Forecasting (WRF) v4.1.1 model simulations [22]. The initial and boundary conditions for these simulations were acquired from the North American Regional Reanalysis dataset which has 45 vertical layers with a grid resolution of 32 km [23]. The physical parameterization schemes used in the WRF model are detailed in Wu et al. [24]. The gas-phase chemical mechanism SAPRC07TIC and aerosol-phase chemical mechanism AERO7 were used for calculating gas-phase chemistry and aerosol dynamics [25], [26], [27]. Chemical initial and boundary fields for the outer domain of CMAQ are taken from the CAM-chem model [27]. For the inner domain, initial and boundary conditions are extracted from the 4 km domain CMAQ output. For on-road mobile emissions, the Emissions Spatial and Temporal Allocator model [28] developed by CARB was used to allocate light-duty and heavy-duty vehicle emissions from the EMFAC emissions inventory [29] to 1 km × 1 km grid spaces using spatial surrogates and California Vehicle Activity Database (CalVAD) temporal surrogates. For other source emissions, the CARB emissions are scaled to 2045 by using the CEPAM growth and control data [2]. Biogenic emissions (including those from vegetation and soil) are based on the Model of Emissions of Gases and Aerosols from Nature (MEGAN) v2.1 [30]. For each scenario, we employed an annual modeling period to achieve a thorough assessment of the health benefits.

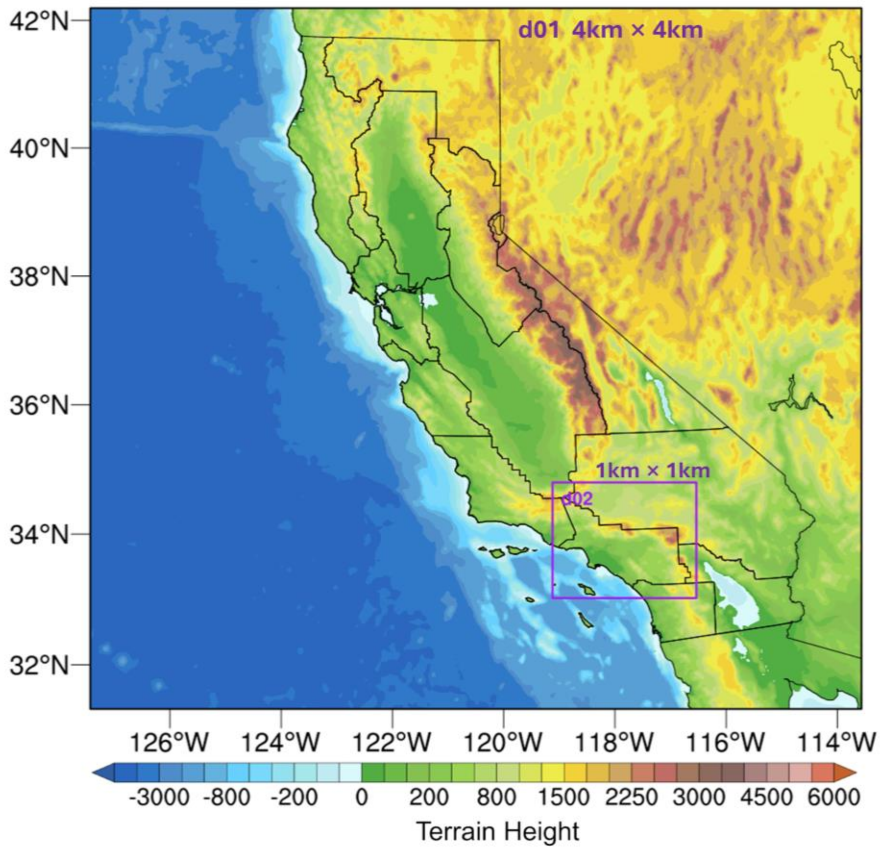

Figure 3. Nested WRF-CMAQ model domains.

Health Impact Assessment

We used the Benefits Mapping and Analysis Program—Community Edition v1.5.8 (BenMAP) from the U.S. Environmental Protection Agency to estimate health impacts associated with changes in $PM_{2.5}$ and ozone levels for each scenario [31]. BenMAP is based on extensive epidemiological studies of exposure and has been widely used in prior studies to quantify air pollution health effects and quantify damages [32], [33]. The population data for BenMAP was derived from demographic information at the census tract level and projected to 2045 [34]. Baseline rates of mortality and morbidity are provided in BenMAP. The selection of concentration-response functions and the value of a statistical life ($9.7 million) was the same as in Zhu et al. [35], which is based on a systematic review of the epidemiological literature and suggested criteria. The impacts reported in this study are the number of avoided incidences of mortality and morbidity associated with annual exposure to $PM_{2.5}$ and ozone.

Finally, the results were analyzed from an environmental justice perspective through an established framework used in Zhu et al. [36] which provides the magnitude and distribution of the air quality and health benefits within disadvantaged communities that have been identified as socially and economically disadvantaged using the CalEnviroScreen 4.0 tool [13] by downscaling the modeling results from the 4 km and 1 km modeling grids to the census tract level.

Results

Criteria Pollutant Emission Results

This section provides an overview of the emissions of NO_x associated with the different scenarios quantified by the SMOKE model. **Figure 4** provides the total emissions of NO_x in tons per day (tpd) for the modeled scenarios both statewide and within the South Coast Air Basin.

Implementing the Scoping Plan would eliminate a total of 598 tpd of NO_x statewide from all sources and sectors (i.e., on-road transportation, industry, commercial and residential sources, etc.) compared to current policies (Reference scenario), of which 49 tpd would come specifically from the off-road sector.[1] Statewide, a 100 percent ZE off-road sector would remove an additional 40 tpd from the atmosphere by 2045. Altogether, a fully decarbonized off-road sector can contribute a total of 89 tpd in NO_x reductions due to the enhanced levels of ZE equipment. PM_{10} reductions range from 2.8 tpd with the Scoping Plan to 7.1 tpd from full conversion to ZE equipment in the off-road sector.

In the South Coast Air Basin, NO_x emissions from the off-road sector are reduced by 18 tpd in the Scoping Plan relative to current policies (Reference scenario) and an additional 14 tpd reduction is possible with 100 percent ZE vehicle adoption. Thus, fully decarbonizing the off-road sector would reduce NOx emissions by a total of 32 tpd in the basin. Furthermore, the importance of achieving additional emissions reductions from the off-road sector is clear as they contribute approximately 10 percent of the total NO_x in California and the South Coast Air Basin in both the Reference and Scoping Plan scenarios in 2045.

[1]Existing policies (2045 Reference scenario) will remove 330 tpd of NO_x statewide from the 2020 baseline. The Scoping Plan reduces emissions by 928 tpd. Thus, the Scoping Plan would reduce an additional 598 tpd compared to the Reference scenario. A 100 percent ZE off-road sector would remove an additional 89 tpd from the 2045 Reference scenario and 40 tpd from the 2045 Scoping Plan scenario. By comparing these two results it can be determined that the Scoping Plan scenario removes 49 tpd of NO_x from the off-road sector relative to the Reference scenario.

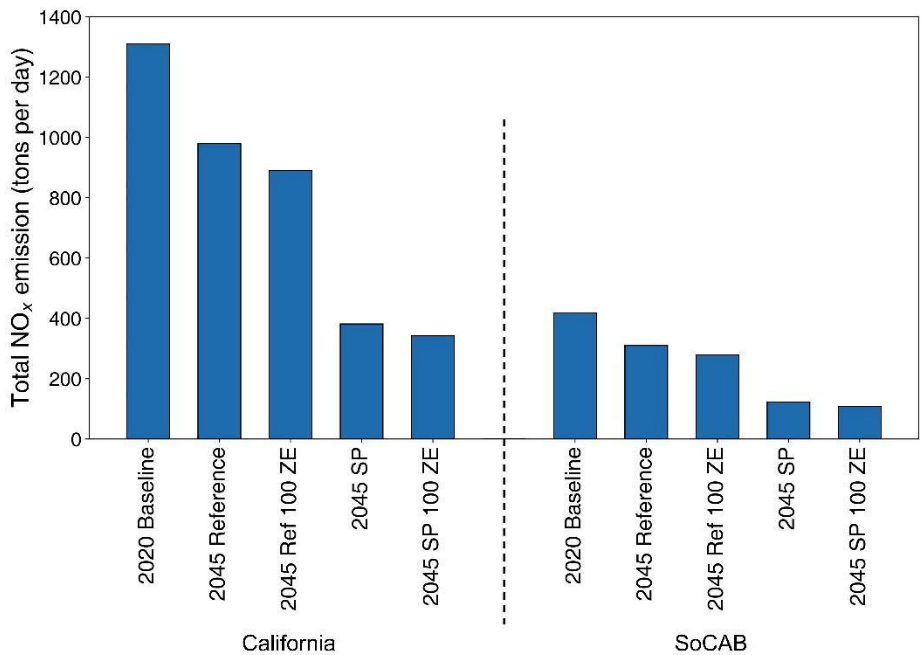

Figure 4. Total NO_x emission (tons per day) in California and the South Coast Air Basin (SoCAB) for all scenarios.

Air Quality Results

The following section presents the results for the air quality analysis using CMAQ including annual changes in NO_x, $PM_{2.5}$, and maximum daily average 8h (MDA8) ozone concentrations. Results are shown for two sets of scenario comparisons: (1) between the 100 ZE Reference and Reference scenarios, and (2) between the 100 ZE Scoping Plan and Scoping Plan scenarios.

First, the difference between the Reference scenario and a scenario of 100% ZE off-road using the Reference scenario for all other sources is presented. **This provides an upper bound for the potential benefits of ZE off-road equipment by showing the improvement potential if significant progress is not made in California in terms of deploying carbon mitigation measures.** Recall that the Reference scenario is a business-as-usual scenario which does not include significant progress in terms of ZE equipment and renewable fuels. Therefore, in the Reference scenario the emissions from the off-road sector are higher in 2045 than those in the Scoping Plan scenario so the air quality health benefits are also higher when the emissions are removed.

Next, we present the difference between the Scoping Plan scenario and a scenario of 100% ZE off-road using the Scoping Plan scenario for all other sources. **This comparison is made to demonstrate the additional benefits that can be attained by increasing the levels of ZE off-road equipment over and above the levels projected in the Scoping Plan.**

These comparisons ultimately provide important quantitative insight regarding the potential of ZE off-road equipment to improve air quality and public health across a range of futures with varying levels of clean energy technologies and fuels.

Impact of 100% ZE Off-road on Air Quality in the Reference Scenario

Figure 5 displays the differences in annual pollutant concentrations between the Reference and the Reference 100 ZE scenario in California. The results present the improvements in annual NO_x, $PM_{2.5}$, and MDA8 ozone concentrations that result from complete removal of the off-road sector emissions while emissions from all other sources in the Reference scenario remain the same.

Reductions in NO_x reach 2.41 parts per billion (ppb) with peak improvement in Southern California because of the high activity associated with construction, lawn and garden, industrial, commercial off-road sectors. Reductions are also important in the Central Valley, San Diego metropolitan area (San Diego), and the San Francisco Bay metropolitan area (S.F. Bay). In the Central Valley, agricultural and commercial activity are important contributors to NO_x emissions.

In terms of $PM_{2.5}$, Southern California is the location of the largest and most widespread improvements with annual average reductions reaching nearly 1 $\mu g/m^3$. The Central Valley experiences notable improvements as well. While the $PM_{2.5}$ reductions generally follow the spatial pattern of those for NO_x, it is interesting to note that $PM_{2.5}$ reductions in the S.F. Bay and San Diego are not extensive, despite notable NO_x reductions in those regions. This highlights the complex nature of the formation and fate of secondary $PM_{2.5}$ in relation to precursor emissions of NO_x. For example, the conditions in the Central Valley are conducive to $PM_{2.5}$ formation and accumulation due to geographical location, meteorological patterns, and human activities. The area is surrounded by mountains which prevent pollutant dispersal. The region experiences frequent temperature inversions in winter which trap pollution at ground level, and there are extensive sources of emissions including farm equipment, agricultural burning, and ammonia emissions from livestock and fertilizer.

The largest improvements in ground level MDA8 ozone also occur in Southern California with a peak of 6 ppb in the eastern portion of the SoCAB. The conditions for the formation of photochemical air pollution in SoCAB result in the region experiencing the worst ozone air quality in the entire U.S. The basin is surrounded by several mountain ranges, experiences abundant sunshine and warm temperatures, and experiences frequent temperature inversions. Furthermore, it is a large, dense urban region that encompasses a tremendous amount of emission sources from nearly every economic sector. Ozone pollution also improves in the Central Valley which further emphasizes the importance of ZE off-road equipment being deployed in the region.

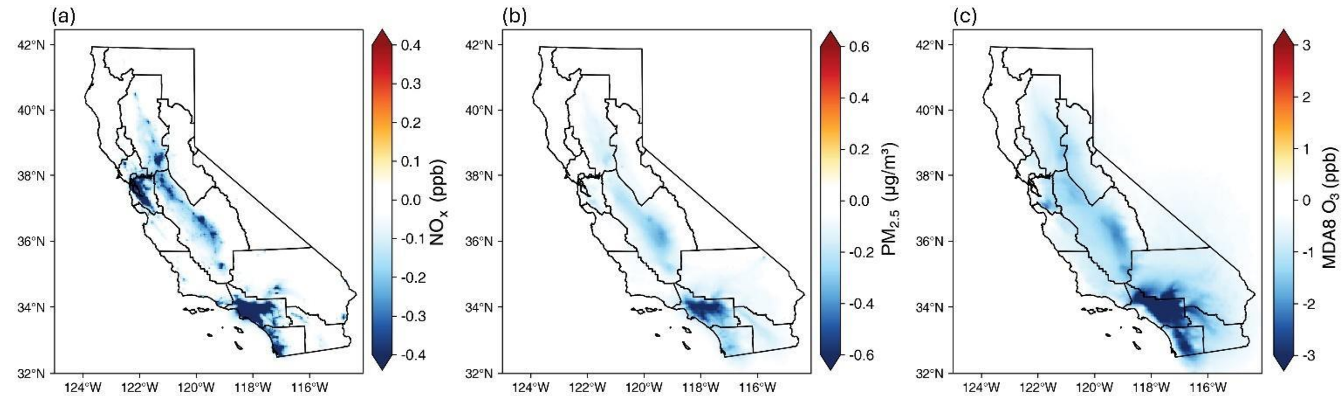

Figure 5. Changes in annual (a) NO_x, (b) $PM_{2.5}$, and (c) MDA8 ozone concentrations between the 100 ZE Reference and Reference scenarios across California.

Figure 6 shows the results of the 1 km modeling for Southern California for NO_x, $PM_{2.5}$, and MDA8 ozone. The largest changes in NO_x concentrations occur in the southeastern portion of metropolitan Los Angeles. Notable sources of emissions in this area include the Ports of Los Angeles and Long Beach, refineries and other sources of industry, rail yards, and warehouses. Changes in $PM_{2.5}$ reach -0.93 μg/m^3 with peak impacts downwind of the peak NO_x changes over central Los Angeles. Reductions in ozone reach 5.5 ppb and the largest impacts occur in the eastern portion of the SoCAB over San Bernardino and Riverside counties. The progression of the pollutant concentrations clearly shows the prevailing wind conditions in the SoCAB, which are characterized by weak onshore winds blowing from the ocean inland. This pushes atmospheric pollution inland as the chemical reactions that produce secondary $PM_{2.5}$ and ozone occur, leading to the pattern of impact for both pollutants.

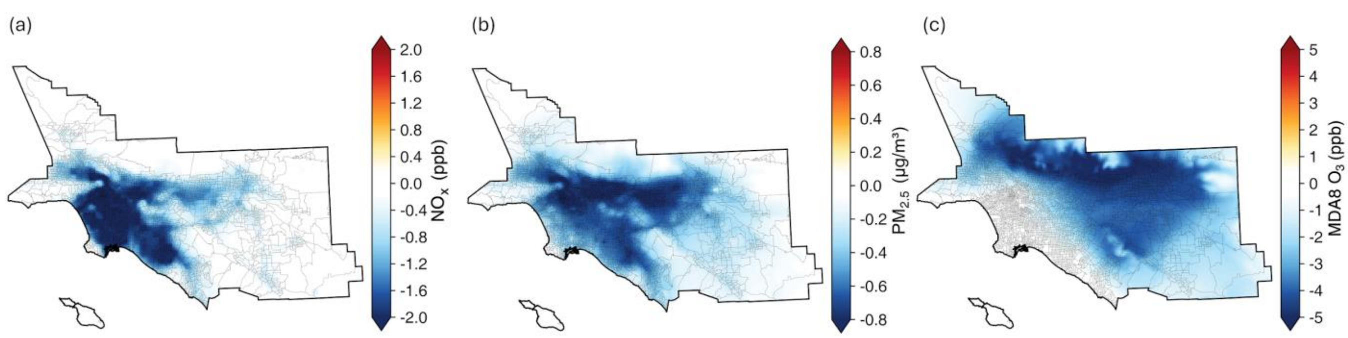

Figure 6. Changes in annual (a) NO_x, (b) $PM_{2.5}$, and (c) MDA8 ozone concentrations between the 100 ZE Reference and Reference scenarios in Southern California.

Impact of 100% ZE Off-road on Air Quality in the Scoping Plan Scenario

To quantify the potential for additional improvements in air quality over and above the Scoping Plan, **Figure 7** displays the differences in annual pollutant concentrations between the Scoping Plan and the Scoping Plan 100 ZE scenario in California. The spatial patterns of impact are essentially equivalent to those from the 100 ZE Reference scenario shown in the previous section, but the magnitude of the improvements is reduced due to the implementation of a cleaner off-road sector assumed in the Scoping Plan. That is, the total emissions from off-road equipment in the Scoping Plan scenario are much lower than the Reference so the removal of those emissions has a smaller impact on pollutant concentrations.

The largest decreases in NO_x occur in the SoCAB, specifically metropolitan Los Angeles, with a peak reduction of 1.9 ppb. Reductions in NO_x levels are also notable in S.F. Bay, exceeding 0.4 ppb annually. Reductions in annual $PM_{2.5}$ reach 0.59 μg/m^3 in SoCAB with basin-wide average decreases of 0.38 μg/m^3 and decreases in $PM_{2.5}$ in the Central Valley of California are reduced by up to 0.15 μg/m^3. The results demonstrate that higher levels of ZE off-road vehicles than what is assumed in the Scoping Plan can still achieve additional $PM_{2.5}$ reductions with the largest improvements in Southern California, and moderate improvements in the S.F. Bay area and the Central Valley.

Statewide decreases in annual MDA8 ozone concentrations for the 100 ZE Scoping Plan are shown in **Figure 7(c)**. Despite being lower than those for the Reference scenario, improvements in ozone are still considerable with the largest decreases of 3.65 ppb in eastern portions of the SoCAB due to the significant reductions in precursor emissions. It is interesting to note that the San Diego Air Basin (SDAB) and S.F. Bay Area experienced the second-highest decreases in ozone reaching 1.4 ppb, suggesting that off-road emissions are important to ground-level ozone formation in those regions as well.

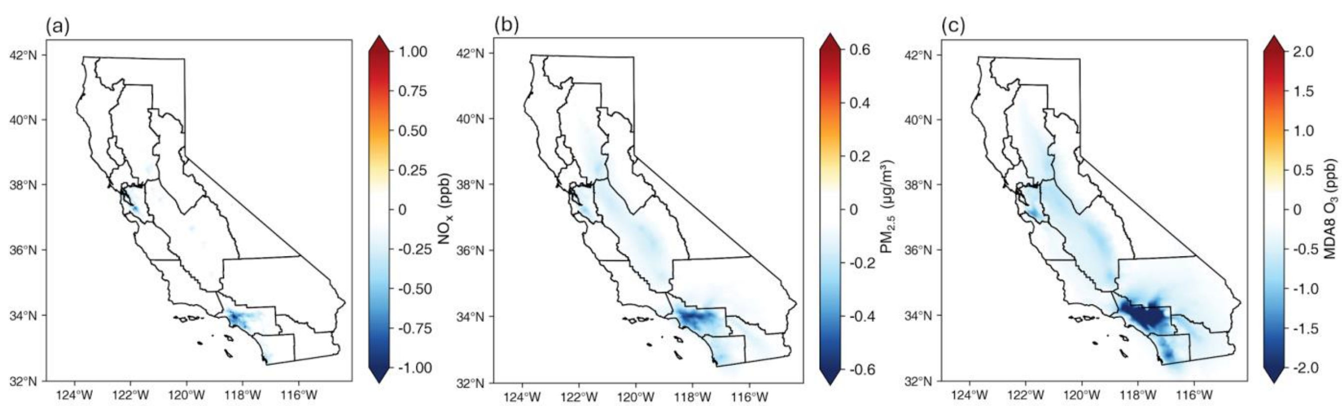

Figure 7. Changes in annual (a) NO_x, (b) $PM_{2.5}$, and (c) MDA8 ozone concentrations between the 100 ZE Scoping Plan and Scoping Plan scenarios.

Figure 8 presents the air pollutant changes at 1 km using the high-resolution nested CMAQ model across Southern California. The largest changes in NOx concentrations occur in the southeastern portion of metropolitan Los Angeles. Notable sources of emissions in this area include the ports of Los Angeles and Long

Beach, refineries, other heavy industries, rail yards, and warehouses. The peak improvements in $PM_{2.5}$ occur downwind of the peak NOx changes over central Los Angeles as weak onshore ocean winds push atmospheric pollution inland as the chemical reactions that produce secondary $PM_{2.5}$ and ozone occur. The largest reductions in ozone occur in the eastern portion of the South Coast Air Basin over San Bernardino and Riverside counties.

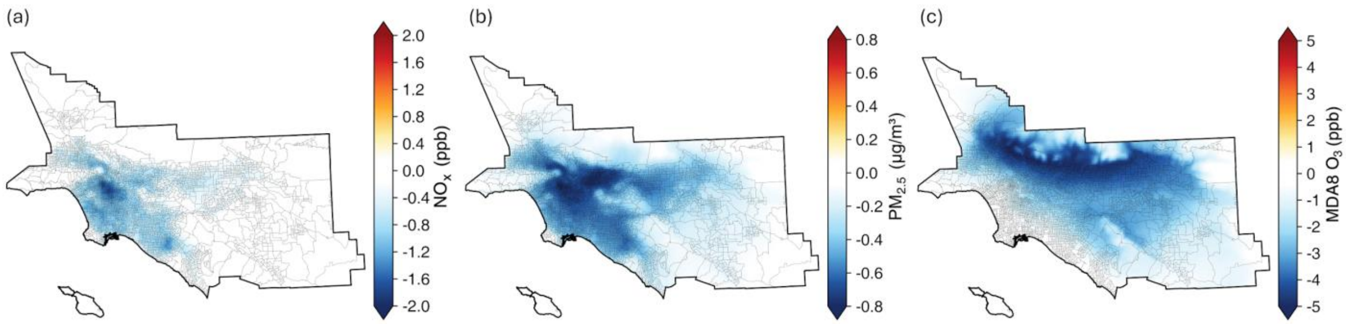

Figure 8. Changes in annual (a) NO_x, (b) $PM_{2.5}$, and (c) MDA8 ozone concentrations between the 100 ZE Scoping Plan and Scoping Plan scenarios in Southern California.

Health Impacts

This section presents the health benefits associated with the potential air quality improvements shown in the previous section. The complete implementation of ZE off-road equipment results in substantial health benefits in California, including annual avoided mortality incidences from $PM_{2.5}$ and ozone exposure. Avoided mortality and morbidity incidences summarized in **Table 2** are estimated using BenMAP based on the annual changes in ozone and $PM_{2.5}$ concentrations. Compared to existing policies, full decarbonization of the off-road sector in the 100 ZE Scoping Plan results in 1,450 fewer deaths from reduced $PM_{2.5}$ and 136 fewer deaths from improvement in ozone levels in 2045. The incidence of avoided mortality increases to 1,821 attributed to $PM_{2.5}$ decreases and 173 attributed to ozone decreases in the 100 ZE Reference scenario, given the larger benefits in air quality that scenario achieves. In addition, 100 percent ZE in the off-road sector also results in numerous avoided incidences of morbidity, as also shown in **Table 2**.

Table 2. Avoided annual mortality and morbidity incidences from reduced annual exposure to $PM_{2.5}$ and ozone (2045).

Health endpoints	Pollutant	100 ZE Reference v. Reference (Avoided Incidence)	100 ZE Scoping Plan v. Scoping Plan (Avoided Incidence)
Avoided Mortality, All Causes	$PM_{2.5}$	1,821	1,450
Hospital Admissions, Alzheimer's Disease	$PM_{2.5}$	886	724
Hospital Admissions, Parkinson's Disease	$PM_{2.5}$	70	57
Incidence, Lung Cancer	$PM_{2.5}$	109	87
Incidence, Asthma Onset	$PM_{2.5}$	2,572	1,960
Acute Myocardial Infarction, Nonfatal	$PM_{2.5}$	68	55
Asthma Symptoms	$PM_{2.5}$	176,159	140,062
Hospital Admissions, Cardiovascular	$PM_{2.5}$	123	101
Hospital Admissions, Respiratory	$PM_{2.5}$	19	16
Emergency Room Visits, Cardiovascular	$PM_{2.5}$	197	160
Emergency Room Visits, Respiratory	$PM_{2.5}$	302	241
Avoided Mortality, Respiratory	Ozone	173	136
Incidence, Asthma Onset	Ozone	1,874	1,875
Emergency Room Visits, Respiratory	Ozone	857	746
Asthma Symptoms	Ozone	835,655	753,301
Hospital Admissions, Respiratory	Ozone	106	79

It is important to interpret these results within the framework of the scenario development as shown in **Table 3**. The comparison of the 100 ZE Reference with the Reference demonstrates that the potential exists for approximately $22 billion in public health benefits from ZE off-road sources in 2045 if no major actions are taken to advance ZE off-road equipment. Next, the comparison of the 100 ZE Scoping Plan with the actual Scoping Plan demonstrates that there are approximately $18 billion potential health benefits still remaining for the off-road sector after the aggressive ZE adoption measures that are assumed in the Scoping Plan. By comparing the results of these two steps, the total benefits that are achieved strictly from the Scoping Plan off-road measures can be identified as $4.5 billion in total. While the Scoping Plan achieves approximately $4.5 billion in savings from the off-road sector, the further deployment of ZE technologies can advance these benefits up to an upper limit of $17.6 billion in 2045, suggesting that it would be highly advantageous to implement additional restrictions on conventional diesel engines in the off-road sector.

Table 3. Economic Valuation of avoided mortality and morbidity incidences from reduced annual exposure to $PM_{2.5}$ and ozone (2045).

Health endpoints	Pollutant	100 ZE Reference v. Reference (2020$)	100 ZE Scoping Plan v. Scoping Plan (2020$)
Avoided Mortality, All Cause	$PM_{2.5}$	19,417,991,168	15,459,510,272
Hospital Admissions, Alzheimer's Disease	$PM_{2.5}$	217,013,952	177,442,752
Hospital Admissions, Parkinson's Disease	$PM_{2.5}$	62,374,472	50,433,608
Incidence, Lung Cancer	$PM_{2.5}$	26,123,378	20,903,744
Incidence, Asthma Onset	$PM_{2.5}$	139,728,784	106,480,432
Acute Myocardial Infarction, Nonfatal	$PM_{2.5}$	35,703,676	28,945,402
Asthma Symptoms	$PM_{2.5}$	95,035	75,561
Hospital Admissions, Cardiovascular	$PM_{2.5}$	8,314,459	6,792,188
Hospital Admissions, Respiratory	$PM_{2.5}$	286,844	232,694
Emergency Room Visits, Cardiovascular	$PM_{2.5}$	356,522	289,749
Emergency Room Visits, Respiratory	$PM_{2.5}$	411,755	329,360
Avoided Mortality, Respiratory	Ozone	1,840,150,400	1,446,351,104
Incidence, Asthma Onset	Ozone	101,839,440	91,462,096
Emergency Room Visits, Respiratory	Ozone	1,169,856	1,018,999
Asthma Symptoms	Ozone	218,469,968	196,499,584
Hospital Admissions, Respiratory	Ozone	5,942,999	4,421,465
Total Health Benefits		***22,075,972,708***	***17,591,189,011***

Here, we focus on the additional benefits by region from fully decarbonizing the entire off-road sector beyond what should be achieved as the state carries out CARB's Scoping Plan. As would be expected given the results from the air quality analysis, the most incidences of avoided negative health effects and the greatest corresponding additional economic benefits are found in the South Coast Air Basin, which comprises $13.6 billion of the total or 75 percent of the nearly $18 billion estimated statewide benefits (see **Figure 9**). Further, San Diego and the San Francisco Bay Area experience the second-highest additional health benefits with economic savings of $1.3 billion, which corresponds well to air quality improvements in off-road emissions. The benefits in these three locations are primarily attributed to urban off-road sources, including commercial, lawn and garden, industry, and construction and mining equipment.

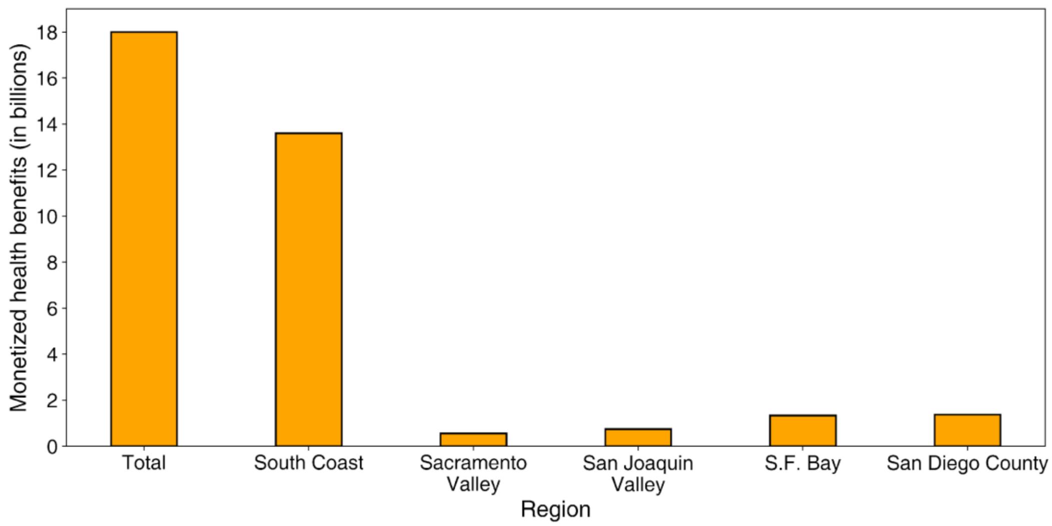

Figure 9. Potential benefits from expanding the use of ZE off-road technologies by region annually in 2045.

Next, the additional health benefits that would occur specifically within socially and economically DACs was quantified due to the importance of achieving improvements for those disadvantaged communities. The total added health benefits that occur within communities identified as disadvantaged using CalEnviroScreen 4.0 are presented in **Figure 10**, as well as a breakdown of DAC benefits by region. The results demonstrate that approximately 37.3 percent of all public health savings occur within DACs, which make up just 28.6 percent of census tracts across California, suggesting that implementing policies to support the transition to ZE off-road equipment will significantly benefit these vulnerable populations.

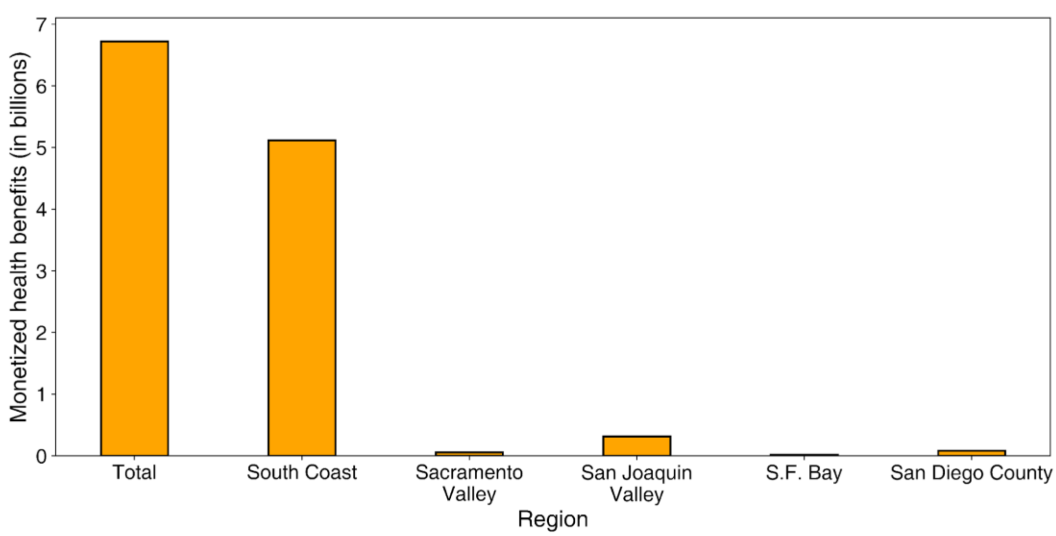

Figure 10. Estimated health benefits from air quality improvements between the 100 ZE Scoping Plan and Scoping Plan scenarios specifically within disadvantaged communities (2045).

As the air quality benefits in DACs are significantly higher in the South Coast Air Basin than in any other region of California, a more detailed overview of the benefits is provided in **Figure 11**, with the DAC communities outlined in red. As can be seen, several DACs experience some of the highest benefits, including the Wilmington, Carson, and West Long Beach communities surrounding the ports (see **Figure 11(b)**), in parts of metropolitan Los Angeles, and in the eastern portion of the South Coast Air Basin. These areas are associated with some of the largest $PM_{2.5}$ (ports, Los Angeles) and ozone (eastern air basin) reductions. Again, this demonstrates the value of adopting ZE off-road vehicles and equipment beyond levels in the 2022 Scoping Plan.

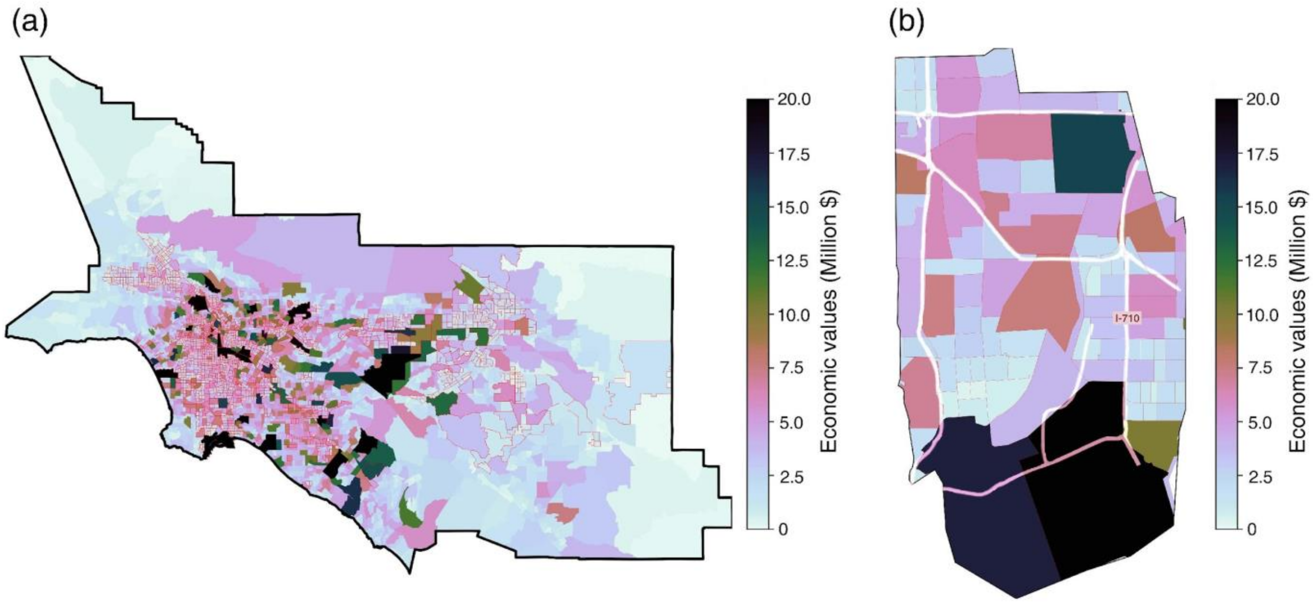

Figure 11. Monetized health benefits across (a) the South Coast Air Basin and (b) the Wilmington, Carson, and West Long Beach communities between the 100 ZE Scoping Plan and Scoping Plan scenarios (2045).

Conclusions

This report provides data-driven insights to inform regulatory and investment decisions to maximize the benefits of off-road emission reductions. The goals of this effort are primarily directed to answer two questions. First, **what are the benefits attained in the Scoping Plan specifically from the off-road sector?** Second, **what additional benefits are potentially attainable if the levels of ZE equipment and vehicles are expanded even further?** This structured approach enables the comparison of the air quality and environmental justice outcomes of different strategies, identifies potential gaps in achieving reduction targets, and design policies that maximize health and equity benefits. By illustrating the potential for air quality improvements and significant health benefits, this research supports policy measures that accelerate the transition to ZE off-road equipment, ensuring cleaner air and healthier communities statewide. Major sources of off-road emissions include construction vehicles and equipment, commercial equipment, and cargo handling equipment at the ports of Los Angeles and Long Beach, and represent important targets for ZE technology deployment, especially within low-income and marginalized communities.

Current California policies and programs targeting off-road sector emission reductions achieve significant air quality improvements and the potential exists to increase these benefits. Under the policy assumptions made for the CARB Scoping Plan, aggressive shifts to ZE off-road equipment and vehicles are assumed which achieve significant reductions in NO_x, $PM_{2.5}$, and ground-level ozone (i.e., Smog). In all cases, the air quality improvements are important in terms of both magnitude and location. The regions with the most pronounced benefits have elevated importance for air quality improvements due to 1) pre-existing degraded air quality, 2) large populations, and 3) the presence of disadvantaged communities.

Transitions to ZE off-road technologies results in thousands of fewer deaths each year and billions in economic savings. Air quality improvements associated with ZE off-road emission reductions achieve large benefits to public health through avoided incidence of premature death and many other health consequences including heart attacks, strokes, and respiratory illness. For example, the Scoping Plan achieves approximately ~400 fewer premature deaths and the total health benefits are valued at $4.5 billion *annually* in 2045 relative to a future where internal combustion engine technologies (primarily diesel) continue to dominate. Benefits of fully eliminating off-road sector emissions could attain up to nearly 2,000 fewer deaths and far less injuries with the total economic value of $22.1 billion.

The benefits of ZE off-road equipment can increase even further if a complete ZE sector is achieved. The Scoping Plan scenario already delivers large benefits, but the complete removal of internal combustion engines in the off-road sector approximately doubles the emission reductions, health gains, and economic value, while significantly advancing environmental justice outcomes. For example, complete elimination of off-road sector emissions prevents ~25 percent more premature deaths and illnesses compared to the Scoping Plan. Additionally, thirty-seven percent of the total health benefits, nearly $7 billion annually, that can be achieved are within disadvantaged communities, as defined by California' CalEnviroScreen 4.0. These communities constitute about 28% of the state's population. Thus, greater benefits are attained with DAC populations relative to non-DAC populations. Overall, the highest DAC benefits occur within the Southern California Air Basin, particularly the communities surrounding the port areas, and parts of metropolitan Los Angeles.

However, it is important to note that achieving a full zero emission off-road sector represents a major challenge and may not be feasible in the 2045 timeframe used in this study. Barriers include the high energy demand and duty cycles of large equipment, which require batteries that are currently too heavy, costly, or unable to provide sufficient runtime for continuous operation. This is particularly problematic in some vocations including construction and agriculture, where equipment often operates for long shifts in remote or infrastructure-poor areas. Charging and hydrogen refueling infrastructure is another critical limitation, as fast-charging systems are scarce on job sites and farms, and grid access may be inadequate to support high-power charging needs. The durability and ruggedness of ZE technologies under harsh conditions (dust, vibration, temperature extremes) raises concerns for many vocations, while equipment downtime for charging reduces productivity compared to rapid refueling with diesel. Finally, capital costs remain high relative to conventional engines, and uncertainties about battery lifetimes, recycling, and replacement costs add to the risk for fleet operators. These challenges mean that although ZE technologies may be well-suited for smaller equipment and certain controlled environments, scaling to heavy, long-duty off-road applications will require advances in energy density, charging solutions, cost reduction, and supportive infrastructure.

The targeted deployment of ZE equipment and vehicles in high impact areas can maximize benefits in disadvantaged communities. This report further highlights the critical importance of prioritizing ZE deployment in regions with pre-existing poor air quality and high population density, particularly in the South Coast Air Basin. Benefits of ZE off-road technologies are most pronounced in the South Coast Air Basin, which includes the counties of Los Angeles, Orange, Riverside, and San Bernardino with annual reductions up to 2.4 parts per billion (ppb) in nitrogen oxides (NOx), 0.9 micrograms per meter squared ($\mu g/m^3$) in $PM_{2.5}$, and 6 ppb in maximum daily average 8-hour (MDA8) ozone as shown in **Figure ES1**. Major sources of off-road emissions in the basin include construction vehicles and equipment, commercial equipment, and cargo handling equipment at the ports of Los Angeles and Long Beach, and represent important targets for ZE technology deployment, especially within low-income and marginalized communities. This is critical since the region is currently in non-compliance with federal standards for both ozone and $PM_{2.5}$, which could put federal transportation funding dollars in jeopardy. Other populated regions in California, including the Central Valley, the San Francisco Bay area, and greater San Diego would also benefit.

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