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Permalink

<https://escholarship.org/uc/item/8br1k8hw>

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Publication Date

2025-10-01

DOI

10.7922/G2X63K9Z

Switching to Zero Emission Off-Road Vehicles and Equipment Has Significant Air Quality and Environmental Justice Benefits in California

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October 2025

Issue

Off-road vehicles and equipment (e.g., forklifts, tractors, dirt bikes) are a major source of air pollution in California due to their heavy reliance on diesel engines, which emit high levels of nitrogen oxides (NO_x), fine particulate matter (PM_{2.5}), and other emissions. These pollutants cause a range of health impacts, including respiratory diseases like asthma, increased cancer risk, premature death, and other ailments, and disproportionately affect low-income communities located near highways, freight hubs, ports, and industrial areas.

To address this issue, California has a range of policies and programs in place seeking a cleaner off-road sector beginning with Executive Order N-79-20, which sets a goal of 100 percent transition to zero-emission (ZE) off-road vehicles and equipment by 2035 where feasible. Reflecting this, the California Air Resources Board (CARB) 2022 California Scoping Plan outlines ambitious ZE technology adoption, including hydrogen fuel cell and battery electric technologies. To better understand the implications of both current and future policies, our study quantifies 1) the benefits of off-road emission reductions from current policy and 2) potential additional benefits that can be achieved by increasing ZE adoption of off-road vehicles and equipment

over and above the level considered feasible in the Scoping Plan up to and including a full transition to ZE.

Key Research Findings

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, identification of potential gaps in achieving reduction targets, and design of 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.

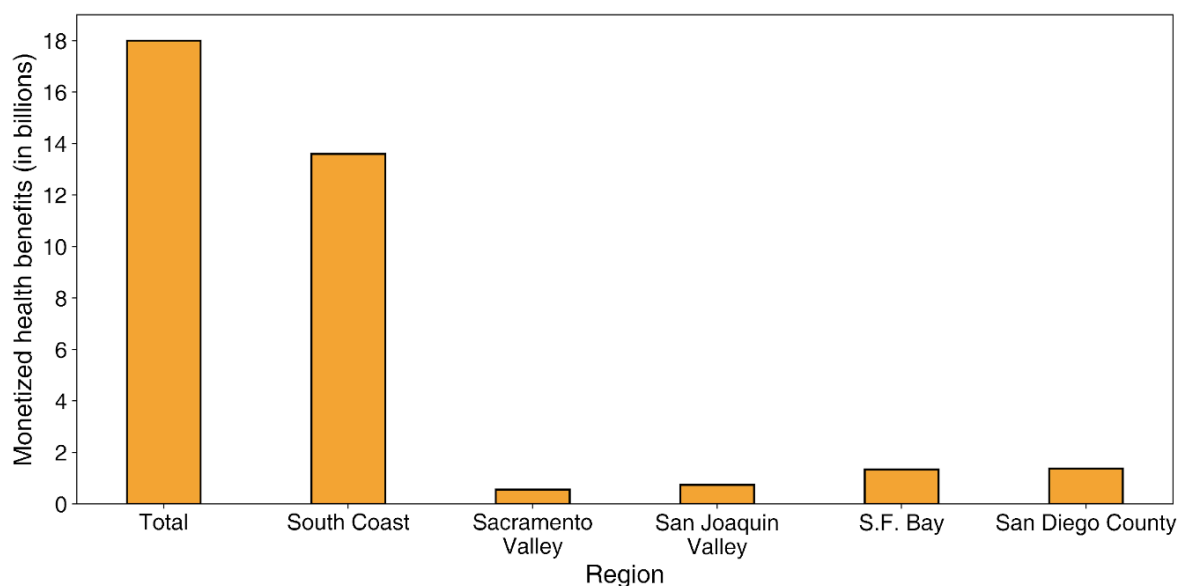


Figure 1. Potential benefits from expanding the use of ZE off-road technologies by region annually in 2045.

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 , $\text{PM}_{2.5}$, 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 (shown in Figure 1).

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's 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 ZE off-road sector represents a major challenge and may

not be feasible in the 2045 time frame used in this study.

Barriers include the high energy demand and duty cycles of large equipment, which require batteries that are currently too heavy, too 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 (NO_x), 0.9 micrograms per meter squared ($\mu\text{g}/\text{m}^3$) in $\text{PM}_{2.5}$, and 6 ppb in maximum daily average 8-hour (MDA8) ozone. 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 $\text{PM}_{2.5}$, 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.

Conclusion and Policy Implications

While Executive Order N-79-20 sets a goal of 100 percent ZE off-road equipment by 2035, the feasibility of reaching the target is less clear. Given the significant air quality and public health benefits of ZE off-road equipment, additional policy support is justified to ensure and accelerate the transition to a ZE off-road sector. The state legislature should consider monitoring and updating policies that 1) set explicit adoption targets for ZE off-road equipment, 2) provide sustained appropriations for incentive programs, and 3) direct CARB to expand its regulatory authority to cover this sector if necessary. Challenges that will need to be addressed include the development of ZE infrastructure to support equipment and vehicles fueling or charging needs, workforce development, and R&D to address technical limitations.

More Information

This policy brief is drawn from the report, “Maximizing the Air Quality and Environmental Justice Benefits of Zero Emission Off-Road Vehicles and Equipment in California” prepared by the authors, which can be found at www.ucits.org/research-project/2024-38/. For more information about the findings presented in this brief, please contact Michael MacKinnon at mam@apep.uci.edu.

Research presented in this policy brief was made possible through funding received by the University of California Institute of Transportation Studies (UC ITS) from the State of California through the Public Transportation Account and the Road Repair and Accountability Act of 2017 (Senate Bill 1). The UC ITS is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, the UC ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

Project ID UC-ITS-2024-38 | DOI: 10.7922/G2X63K9Z