

AIR POLLUTION

Raising standards to lower diesel emissions

California policies protect vulnerable communities the most and should be adopted nationwide

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Air pollution from fine particulate matter (PM_{2.5}) is increasingly driving the global burden of disease (1), and diesel-powered vehicles are substantial contributors. Recognizing the public health impacts of diesel PM_{2.5} (DPM) (2), many countries have reduced emissions of DPM from both on- and off-road mobile sources over the past three decades. The previous US federal administration, however, changed course by eliminating or weakening policies and standards that govern these emissions. In contrast, the State of California has continued to reduce mobile-source DPM emissions using the state's long-standing authority under the Clean Air Act (CAA) to regulate air pollution more stringently than the federal government. Our analysis of mobile-source DPM emissions suggests that many California sector-based policies have been highly effective relative to the rest of the US. To improve health in communities disproportionately affected by these emissions, we point to opportunities to further reduce DPM emissions in California, in the US more broadly, and in parts of the world where countries have less aggressive vehicle emissions policies than the US (3).

The US has targeted emissions of nitrogen oxides (NO_x) and DPM from diesel trucks and buses, railway locomotives, marine vessels, and off-road engines used in construction and agriculture through successively tighter emissions standards phased in since 1994 (table S1). These standards require low- and ultralow-sulfur diesel fuels (LSDF and ULSD), establish

emissions limits, and institute systems for portable emissions measurement and on-board diagnostics (table S1).

The US Environmental Protection Agency (EPA) estimated that full implementation of Obama-era US emissions standards by 2030 would prevent some 12,000 premature deaths annually (4). Despite this, EPA leadership disbanded the PM review panel ahead of the scheduled 2020 update of federal PM standards; it also rolled back, or attempted to roll back, 85 federal air pollution policies (5) and moved to restrict the ability of states to set more stringent emissions standards (6).

CALIFORNIA VERSUS THE REST OF THE UNITED STATES

California, whose economy would rank fifth largest in the world if it were a sovereign nation, hosts the country's two largest ports and moves 60% of its container cargo (see supplementary materials). With the associated truck and rail traffic, California stands out as the largest emitter of DPM in the country. At the same time, California has also led the nation with the largest overall reduction in metric tons of DPM emissions from mobile sources. Over the past three decades, California's policies have systematically targeted high-emitting sectors, reducing mobile-source DPM emissions by, for example, substituting electric for diesel power where feasible, tightening emissions limits for new and existing diesel engines, and requiring ULSD, which emits significantly less PM_{2.5} than higher-sulfur fuels upon combustion and can be combined with particle filters to further reduce emissions.

To understand the impact of California's portfolio of policies, we used DPM emissions data from the EPA National Emissions Inventory (NEI), which assembles a comprehensive estimate of air pollution emissions using data reported by states, combined with modeled and measured inputs. We compared mobile-source DPM emissions in California versus the rest of the

US for the period 1990 to 2014, the earliest and most recent year for which consistent NEI data are available (7). During that time, California reduced overall mobile-source DPM emissions by 78% while the rest of the US saw only a 51% reduction. These reductions came despite a concurrent steady rise in diesel fuel consumption: 20% in California and 28% in the rest of the US (data S1, "Diesel use data" tab).

Emissions reductions from heavy-duty diesel vehicles (HDDVs)—commercial trucks and buses—caused most of this decline, accounting for 67% of DPM emissions reductions in California and 57% in the rest of the US. Although the federal phase-in of ULSD, off-road emissions standards, and the Heavy-Duty Engine and Vehicle Rule has reduced HDDV emissions across the US, California's reductions from HDDVs have been steeper and contribute even more to the overall reductions than would be predicted from the sector's size. Analysis of DPM emissions over time and the relative contributions made by each sector points to the effectiveness of California's policies that require diesel engine retrofits (adding emissions controls to existing HDDVs) and early replacement of older engines with newer, cleaner engines.

DIFFERENT ERAS, DIFFERENT OUTCOMES

Our analysis identifies three distinct phases in mobile-source DPM emissions between 1990 and 2014. Emissions fell overall from 1990 to 2001 in California and from 1990 to 2005 in the rest of the country. Reduced emissions from HDDVs contributed the largest share of the overall drop (see the figure and data S1). These changes are attributable to the introduction of LSDF nationwide, and to California's new requirements for vehicle inspections (table S2).

Then, from 2001 to 2005 in California and from 2005 to 2008 in the rest of the country, emissions rose during an economic boom, driven primarily by increasing emissions from HDDVs and marine sources. Finally, overall DPM emissions once again fell, beginning in California in 2005 and in the rest of the US in 2008. The recession played a role in the early part of this drop (8), but emissions reductions continued through 2014 despite the economic recovery and the corresponding upturn in diesel use. During this final phase, California's 67% drop in DPM emissions outpaced the 40% reduction seen in the rest of the country (see the figure and data S1). Our analysis of individual sectors and each state's HDDV emissions suggests that California policies specifically targeting emissions from HDDVs and marine sources drove this decline.

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SECTOR-BASED POLICY: CALIFORNIA

The later phases of California's emissions reductions correspond to the implementation of two overarching plans by the California Air Resources Board (CARB): the Diesel Risk Reduction Plan and the Emission Reduction Plan for Ports and Goods Movement (Goods Movement Plan), both of which encompassed multiple policies governing emissions from trucks and buses, ports, and off-road engines (table S2). Key policies targeting on-road HDDVs took effect in 2006 and 2007, further lowering the sulfur content of diesel fuel to 15 ppm (table S2) and tightening DPM emissions standards by 90% for new HDDVs (table S2). Beginning in 2010, with a rolling compliance period starting in 2015, all on-road HDDVs that operate in California were required to either retrofit existing engines with particle filters or replace engines older than the 2007 model year (table S2).

By comparison, federal policies do not require retrofit or replacement of old diesel engines to meet emission standards, and HDDV engines typically operate for almost two decades, or about a million miles, before retirement. Our state-level analysis shows that by 2014 California HDDVs were emitting 139 metric tons of DPM for every billion vehicle-miles traveled (VMT), far less than the next-closest state (Oklahoma, 250 metric tons DPM per billion VMT) and the average in the rest of the country (345 metric tons DPM per billion VMT) (data S1). Although HDDVs remain California's largest source of DPM emissions, regulatory actions by CARB (over and above federal standards) have reduced HDDV emissions by 85% since 1990. If California's HDDV sector had followed the trajectory of other US states and D.C., HDDV emissions in the state would have dropped only 58% (95% confidence interval, 52 to 64%) in that period (data S1).

Also notable is the impact of two key CARB policies targeting marine sources. The 2007 At-Berth rule requires that ocean-going vessels switch to electric shore power while in port, or use alternative control technologies to reduce emissions by an equivalent amount (table S2). The Cleaner Ocean Vessel fuel policy, finalized in 2008, requires that ships within 24 nautical miles

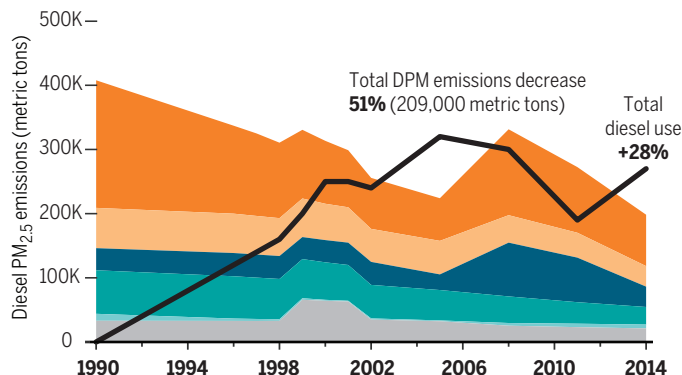
California versus the rest of the United States: Mobile-source DPM emissions declined differently

Mobile-source diesel PM_{2.5} emissions by sector in California versus the rest of the US from 1990 to 2014. HDDV, heavy-duty diesel vehicle; LDDV, light-duty diesel vehicle. All percentage changes reflect values relative to 1990 values.

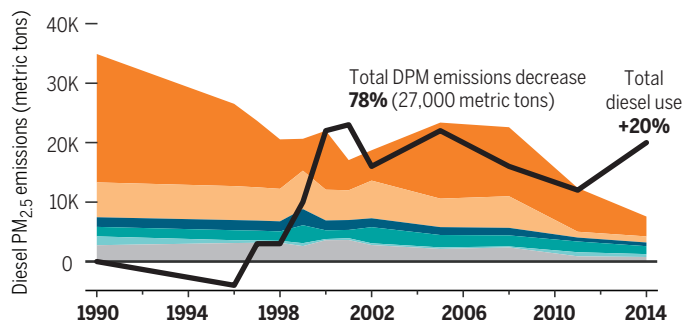
Emissions sectors:

● HDDV ● Construction ● Marine ● Farm ● LDDV ● Other

United States (minus California)



California



of California's shoreline replace heavy fuel oil in their main engines with lower-sulfur fuels (table S2). Between 2008 and 2014, marine DPM emissions in the state dropped 51% overall (see the figure and data S1, "NEI DPM Emissions, CA" tab), and by 2018 emissions measured at the Port of Los Angeles had declined by 37% (fig. S3, A and B, and data S1, "LA Ports data" tab).

On the other hand, California has struggled to target diesel emissions from agriculture (table S2). The sector is responsible for up to 18% of the state's total DPM emissions from mobile sources, but accounted for less than 1% of the total emissions reductions in California between 1990 and 2014. Although these figures do not reflect gains from voluntary tractor engine replacements that are reported differently, opportunities remain to reduce off-road farm emissions in the nation's leading agricultural state.

Voluntary programs have further reduced DPM emissions beyond California's regula-

tory requirements. Incentives to bring engines and equipment to a standard cleaner than required by law are estimated to have reduced DPM emissions by more than 6000 metric tons since 2001 (table S2). A program established in 2006 has provided \$1 billion in grants to update trucks, locomotives, and ships at berth, eliminating an estimated 2200 metric tons of DPM emissions (table S2). Like other policies targeting emissions along goods-movement corridors, this program particularly benefits neighboring communities, which tend to be lower-income communities of color (table S4).

Taken together, CARB's policies reduced emissions to the extent that by 2014 California was emitting less than half the DPM that would be expected had the state followed the same trajectory as the rest of the US (fig. S2 and data S1). Correspondingly, we estimate that more than twice as many Californians would have died from DPM-attributable cardiopulmonary disease in 2014 alone if the state had not so dramatically reduced emissions (fig. S2 and data S1).

SECTOR-BASED POLICY: THE REST OF THE UNITED STATES

The impact of targeted emissions regulation is also evident nationally, but it has come later and never as dramatically as in

California. Farming and construction emissions fell following the 2007 EPA Heavy Duty Engine and Vehicle Rule and the 2008–2015 phase-in of Tier 4 standards targeting off-road emissions from farm and construction equipment (table S1). Federal requirements for LSDF in the 1990s and ULSD beginning in 2006 reduced HDDV emissions from both nonroad and on-road sources (table S1).

In the marine sector, US coastal areas caught up to California's fuel standards in 2012 when ULSD was required for smaller marine engines (table S1), and for the largest vessels in 2015 when requirements for lower-sulfur marine diesel came into effect in the North American Emissions Control Area established by the International Maritime Organization (table S1). By contrast, California has not only taken earlier action on marine emissions, it has also taken aggressive steps to target emissions from the many engines that pollute the air near ports, including marine auxiliary engines, short-

haul trucks, cargo-handling cranes, and yard trucks (table S2).

Individual states that have reduced HDDV emissions more than the national average are more likely to have adopted California's standards, as permitted under the CAA (table S5 and data S1), and the rest of the US could do the same.

GROUND-TRUTHING EMISSIONS REDUCTIONS

Coordination across states and between state and federal agencies means that methodological differences in data collection are unlikely to account for the observed differences in DPM emissions between California and the rest of the US (see supplementary materials). But how do we know that emission inventories are accurate and, furthermore, that CARB policies are responsible for the observed reductions?

Field studies measuring changes in concentrations of DPM serve to ground-truth emissions inventories and substantiate the link between policy interventions and observed outcomes (table S4). For example, following the suite of interventions under the 2006 Goods Movement Plan, California communities in close proximity to goods-movement corridors saw significantly greater air quality improvements relative to non-goods-movement corridors and control areas monitored during the same time period (table S4). These findings show specific, local impacts of regulations targeting high-emitting sectors, distinguishing those changes from secular trends in air pollution and demonstrating their potential to advance environmental justice.

The 2007 CARB regulation requiring retrofit or replacement of older HDDV engines for short-haul "drayage trucks" that operate at ports and railyards corresponded to a 70% reduction in black carbon emissions (a DPM proxy) and a 75% reduction in PM mass specific to drayage trucks measured in and around the ports of Oakland and Los Angeles between 2009 and 2011 (table S4). These changes mirror the emissions reductions measured in laboratory testing of the low-sulfur fuels and retrofit technologies used to meet the drayage truck standards (table S3).

Likewise, the 2009 CARB requirement for low-sulfur fuels in ocean-going vessel engines operating within 24 nautical miles of the California coastline was associated with a measured 64% drop in San Francisco Bay Area concentrations of vanadium, a marker for combustion of heavy fuel oil (table S4). Sampling conducted by aircraft flying in the exhaust plume of a container ship approaching the coast showed that the fuel switch, combined with a required speed re-

duction, dropped DPM emissions by 90% (table S4, Tao *et al.*). That these changes all occurred in the setting of continued growth in California's population, gross state product, and diesel consumption (figs. S4 and S5) further supports the assertion that the observed reductions track to the policies targeting DPM emissions. Observed emissions reductions are further corroborated by epidemiological data that link specific CARB policies to regional reductions in children's exposure to particle pollution and show corresponding improvements in both lung function and development in children with and without asthma (9).

Finally, comparing HDDV sector emissions in California to the rest of the country likely underestimates the actual impact of CARB policies, which apply not only to the nearly half-million trucks and buses registered in California, but also to the same number of out-of-state HDDVs estimated to drive California's highways each year (10). This requirement reduces emissions outside of California as well, although those reductions are attributed to federal policy.

IMPLICATIONS FOR FUTURE STANDARDS

In California, cleaner air has not come at the expense of the state's economy, which in recent years has grown at double the average national rate (11). CARB estimates that every dollar the state has spent controlling air pollution has generated \$38 in benefits attributable to reduced air pollution-related illness, premature death, and lost productivity. California's overall economic gain from health benefits linked to air pollution reduction, including CARB rules and programs, is estimated to have exceeded \$250 billion between 1973 and 2014 (12). The link between PM_{2.5} exposure and increased risk of hospitalization and death from COVID-19 (13) further underscores the public health importance of cleaner air, particularly for communities of color that are disproportionately affected by both.

California could benefit from additional measures to reduce emissions from off-road sectors, such as construction and agriculture, which CARB has not tackled as aggressively (14). Indeed, the nation as a whole could reduce mobile-source DPM emissions by requiring ships at berth to use shore power, and by requiring replacement or retrofit of existing on-road and off-road HDDVs in advance of fleet turnover. Given the long service life of older, dirty diesel engines, the current federal policy of mandating engine upgrades only with vehicle turnover is simply too slow.

As the US initiates new federal rule-making on the proposed Cleaner Trucks Initiative to reduce NO_x emissions from HDDVs, industry and environmental groups are calling

on EPA to address NO_x and DPM emissions in tandem and to create consistent "50-state" standards (15). In doing so, the EPA should align with CARB rules. EPA should also remove federal preemption of state emissions limits for off-road engines used in construction and agriculture. Even absent more aggressive federal policy, states' authority to set and implement their own stricter emissions standards must be protected. ■

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SUPPLEMENTARY MATERIALS

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