$PM_{2.5}$ exposure disparities persist despite strict vehicle emissions controls in California

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Abstract

As policymakers increasingly focus on environmental justice, a key question is whether emissions reductions aimed at addressing air quality or climate change can also ameliorate persistent air pollution exposure disparities. We examine evidence from California's aggressive vehicle emissions control policy from 2000-2019. We find a 65% reduction in statewide average exposure to $PM_{2.5}$ from on-road vehicles, yet for people of color and overburdened community residents, relative exposure disparities increased. Light-duty vehicle emissions are the main driver of the exposure and exposure disparity, although smaller contributions from heavy-duty vehicles especially impact some overburdened groups. Our findings suggest that a continued trend of emissions reductions will likely reduce concentrations but may not reduce relative disparities without greater attention to the systemic factors leading to this disparity.

Main Text

Despite decades of progress improving ambient air pollution in the United States (U.S.), people of color still bear a disparate burden of air pollution (*1–11*). Solutions to this persistent inequality are increasingly a focus for academic research and environmental policy at the federal, state, and local levels (*11–14*). A growing body of research investigates how air quality policies might contribute to a "triple win" that simultaneously achieves meaningful benefits by reducing population-wide exposures; mitigating greenhouse gas emissions; and reducing exposure disparities and extreme exposures (*15*,*16*). Here, we consider how multi-decade emission trends shaped by air quality and climate policies have affected environmental justice (EJ) outcomes, using California's aggressive on-road mobile source strategy as a case study.

Introduction

Recent research on how to reduce air pollution exposure disparities in the U.S. presents two conflicting approaches (*11*,*12*,*15–17*). The first approach starts from the recognition that many major emitting sectors lead to disparate exposures for people of color (*4*). Thus, focusing on emissions reductions for sectors that especially impact people of color could have EJ co-benefits (*16*,*18–21*). This approach mirrors the policy structure in the U.S. and elsewhere, where environmental regulations are targeted to individual economic sectors (e.g., vehicles, industries, power plants) and tailored to relevant technology and infrastructure. The second body of research suggests that sector-oriented policies may not be effective in addressing relative disparities in air pollution. Wang et al. (2022) found that aggressive nationwide emissions reductions targeting economic sectors with higher-than-average disparity impact would not eliminate racial-ethnic fine particulate matter ($PM_{2.5}$) exposure disparities without nearly eliminating emissions (*11*). In contrast, a location-specific approach – i.e., emissions-reductions by location rather than by economic sector – rapidly eliminated disparities. Building upon this finding, Polonik et al. (2023) and Picciano et al. (2023) simulated climate policies with substantial abatement of $PM_{2.5}$ and its precursors across most U.S. economic sectors and found modest potential reductions in disparities. They too reported that "location-specific" policies that target emissions reductions in all sectors within specific overburdened geographies may have high potential to address disparities even with small emissions changes (*11*,*12*).

To complement prospective studies, which model ways to reduce future disparity, we consider the disparity impacts of historical emissions trajectories. We focus on the transportation sector, which is often highlighted as having high potential to reduce disparities. Historically, racist urban planning and infrastructure decisions (e.g., redlining, freeway siting) have concentrated vehicle emissions in communities of color (*4*,*6*,*9*,*18*). Furthermore, people who are exposed to the highest levels of traffic-related air pollution often are not the communities who drive the most (*19*–*21*). As such, a recent study found that emissions controls for the transportation sector have the greatest potential to mitigate racial-ethnic inequality in U.S. air pollution (*16*). Simultaneously, the transportation sector is a priority area for regulatory agencies and EJ-oriented community groups; emissions reductions from these sources could potentially reduce exposure disparities, human health impacts, and greenhouse gas emissions (*22*).

For nearly 60 years, California led the U.S. in reducing on-road vehicle emissions. Because California's motor vehicle emission regulation preceded the Clean Air Act of 1970, California is delegated the authority to set vehicle emissions standards more stringently than the federal equivalent (*23*–*25*). In the present analysis, we consider years 2000 through 2019, during which California's regulatory agencies pursued an aggressive and interlinked suite of multi-pollutant policies to reduce emissions across the entire on-road vehicle fleet (*25*). Examples include requiring cleaner fuels and technological advancements (e.g., hybrid drivetrain, alternative fuel and propulsion technologies, advanced emissions controls) specific to light-duty, medium-duty, and heavy-duty vehicle classes (respectively: LDV, MDV, HDV).

California's mobile source strategy resulted in a large aggregate reduction in on-road vehicle emissions (*26*). Long-term near-road measurements across California confirm declining nitrogen oxides (NO_x) and volatile organic compound (VOC) emission rates (*27–31*). Despite statewide and fleetwide on-road vehicle miles traveled increasing ~24% – from 292 billion (2000) to 364 billion (2019) – emissions of the four species that principally drive population-weighted $PM_{2.5}$ exposures from on-road vehicles have decreased (primary $PM_{2.5}$, NO_x, and VOC: decreased ~70%; ammonia (NH_3): decreased ~15%; Fig. S1) (*31*). Tailpipe primary $PM_{2.5}$ emissions have decreased > 80% from 2000-2019, while non-exhaust (e.g., brake- and tire-wear) emissions of $PM_{2.5}$ have increased ~20% (*33*). Overall, on-road emissions reductions were greater in California than for the national aggregate (excluding California), especially for NO_x and VOC (*34*). On-road mobile emissions are anticipated to continue to decline in California due to two major new regulations: Advanced Clean Cars II (starting in 2035, requires all new passenger cars, trucks, and SUVs sold in California to be zero-emission vehicles) and Advanced Clean Fleets (starting in 2045, all trucks that drive in California must use zero-emissions technology).

Here, we investigate whether the combined impacts of the ensemble of mobile source strategies have contributed to a reduction in $PM_{2.5}$ exposure disparities for overburdened communities on average and at the concentration extremes. We then decompose our results by two aspects (vehicle type; spatial scale) that are central to current regulatory design. We conclude with implications from this California-focused retrospective analysis for future EJ-focused policy for the U.S.

We developed and employed a novel open-source analysis method based on atmospheric simulations from the Intervention Model for Air Pollution (InMAP, see SI) to estimate total $PM_{2.5}$ concentrations resulting from emissions of $PM_{2.5}$, NO_x, VOC, NH_3, and sulfur oxides (SO_x) emitted by California's on-road mobile source sector from 2000 to 2019. Estimates of on-road mobile emissions are from California's regulatory model (EMFAC v2021) and represent the California Air Resources Board's (CARB) best estimate of on-road emissions. Variably sized gridded $PM_{2.5}$ concentrations (1 km – 48 km, higher resolution in greater population density locations) are combined with tract-level 2010 Census population data to estimate exposure disparities among demographic groups (*2*). We disaggregate mobile source impacts into four vehicle types: LDV, MDV, HDV, and all other vehicles (e.g., buses, motorcycles, motorhomes; Table S1).

In the U.S., air pollution disparities tend to be larger by race-ethnicity than by other socioeconomic and demographic indicators (e.g., income, education, urbanicity) (*4*,*5*,*35*,*36*). Accordingly, we focus our analyses on racial-ethnic disparities. In addition, we consider two statutory geographic designations (AB617, SB535) of cumulative impacts that California uses for prioritizing EJ for overburdened communities (Fig. S2) (*37*,*38*). Although these geographies have only recently been established (and thus past policy may or may not have aimed to benefit those communities), we focus on them here because they are an example of location-specific policies that target emissions reductions in overburdened communities. Through the Community Air Protection Program (AB617), California has designated specific communities (2.7M people, year-2010; 8.1% of the state's population) for priority in community-based air pollution monitoring and emissions reduction plans (*37*). A second policy, SB535 (10.2M people, 30.0% of the state's population), focuses on targeting financial investments towards people living in disadvantaged communities, identified using several environmental, socioeconomic, and public health indicators for each US Census tract in California (*38*,*39*). The demographic makeup of residents of these overburdened communities has a higher proportion of people of color than the statewide population (Table S2; people of color: 92.9% in AB617 communities, 82.9% in SB535 disadvantaged communities).

Results and Discussion

Statewide Exposure Disparities Have Sustained Despite Overall Exposure Reductions

California's mobile-source policy has clearly succeeded in its overall goal of reducing population-average mean (PWM) $PM_{2.5}$ exposures (Fig. 1a). We find that the statewide PWM $PM_{2.5}$ exposure concentration attributable to on-road vehicles decreased from approximately 3.2 to 1.1 μg/m^3 from 2000 to 2019, a ~65% (i.e., nearly a factor-of-3) decrease in exposure on average for all Californians. This reduction in $PM_{2.5}$ exposure from on-road vehicles outpaced the overall statewide improvement in ambient air quality. For context, satellite-derived estimates of PWM $PM_{2.5}$ in California decreased 44% from 15.4 to 8.7 μg/m^3 from 2000 to 2019) (*40*).

We evaluate PWM exposure from on-road mobile sources for racial-ethnic groups and residents of overburdened communities (Fig. 1a). PWM declined for all groups, and the ordering of exposures by group is generally consistent over time. Among all racial-ethnic groups, Hispanic Californians experienced the highest PWM exposure for all years, with PWM exposure concentrations of approximately 3.5 and 1.3 μg/m^3 in 2000 and 2019, respectively. Black Californians experienced the next highest exposure concentration, followed by Asian Californians. Of the four racial-ethnic groups in Fig. 1a, White Californians were exposed to the lowest average concentrations: approximately 2.7 and 0.9 μg/m^3 $PM_{2.5}$ from 2000 and 2019, respectively. Residents of SB535 and AB617 communities were exposed to higher average concentrations of $PM_{2.5}$ from on-road mobile sources than the PWM for any racial-ethnic group shown in Fig. 1a.

For each demographic group, we compute disparity as the absolute ($\mu g/m^3$) and relative (percent) difference between the average concentration experienced by a group versus the overall state population (Fig. 1b, see also Methods and Table S3). Reflecting the nearly parallel concentrations evident in Fig. 1a, relative disparities in $PM_{2.5}$ exposure from on-road mobile sources (Fig. 1b) were strikingly persistent and slightly increasing across time. The relative disparity in exposure to on-road mobile sources for Hispanic Californians increased slightly from 12.0% (year-2000) to 13.9% (year-2019) while the relative disparity in exposure for White Californians decreased slightly from -13.5% to -15.5%. Thus, the overall relative difference between the most and least exposed race-ethnicity increased from 30% to 35%. Absolute and relative disparities in AB617 and SB535 communities are even larger. For example, the relative disparity in exposure (i.e., relative to the overall population average) for on-road mobile source $PM_{2.5}$ is more than three times as large for AB617 communities as for the most-exposed racial-ethnic group, and it increased from 40% (year-2000) to 45% (year-2019). Thus, we find the remarkable success in reducing overall PWM exposures and absolute disparities to $PM_{2.5}$ from on-road vehicle emissions is juxtaposed against large and persistent relative disparities.

Disparities in exposure for those living at the extreme ends of the concentration distribution are also relevant for understanding environmental injustice. We estimated population-weighted distributions of exposure by race-ethnicity for each individual vehicle class (Figs. S4-S5). In general, trends at the upper (i.e., 75^{th} and 90^{th}) percentiles are consistent with trends at the PWM and consistent across time. Considering the disparity in exposure at the 75^{th} and 90^{th} percentiles relative to the statewide mean, we find large and increasing relative disparities (e.g., 90th percentile exposure for Hispanic Californians increasing from 104% to 118% higher than statewide PWM from 2000 to 2019).

We also evaluated the degree to which the California populations who experience the *highest* overall exposure to $PM_{2.5}$ from on-road vehicles are disproportionately comprised of people of color, and how this trend evolved over time. To do so, we binned the California population by decile of exposure to $PM_{2.5}$, and then compared the racial-ethnic composition of each decile in 2000 and 2019 (Fig. 2, midpoint result in Fig. S6). From 2000 to 2019, Hispanic Californians are overrepresented at the highest exposure deciles. While the California state population is 37.6% Hispanic, the highest decile of exposure for emissions in 2000 and 2019 consists of 47.9% and 50.8% Hispanic people, respectively. Similarly, White Californians, who comprise 40.1% of the population, are overrepresented among the populations with the lowest exposures (62.0% of the lowest-exposure deciles in 2000 and 2019) and are underrepresented in the highest-exposure decile (29.9% [2000], 27.7% [2019]). The results mentioned here compare only to the 2010 Decennial Census; we do not account for population changes that have occurred between 2000 and 2019. Still, we find that the trend of relative disparities increasing slightly over time is not only true at the PWM, but at the extremes as well.

Light-Duty Vehicles are the Dominant Contributors, but the Highest Relative Disparity is from Heavy-Duty Vehicles

Because California's vehicle emissions control policies generally differentiate by vehicle types, we disaggregate our analyses of emissions, exposures, and disparities by vehicle type based on the official EMFAC2021 documentation (Table S1) (*32*). We evaluate the disparities and additive contributions of each vehicle fleet type at the state-level for the most exposed racial-ethnic group, Hispanic Californians to identify which vehicle types have an especially influential role on their exposures and disparities.

At the statewide average, we find that that LDVs are the vehicle fleet with the largest aggregate impact on overall $PM_{2.5}$ exposures and disparities, but that HDVs also produce the greatest disparate relative impacts. LDVs account for 65-70% of the 0.2-0.4 μg/m^3 $PM_{2.5}$ disparity in exposure for on-road mobile sources for Hispanic Californians (Figs. 3a and 3b). Contributions to disparity from HDVs (16-24%), MDVs (9-14%), and all other vehicles (<5%) are substantially smaller. Owing to the relatively low contributions from MDVs and all other vehicles, the following discussion focuses on comparing LDV and HDVs (full results in Table S6). This LDV-dominated result is consistent across racial-ethnic groups and for residents of AB617 and SB535 communities (Figs. S7-S8), but with different overall magnitudes of exposure for different subpopulations. Over time, the contributions to disparity from individual vehicle fleet types are stable, likely reflecting the relatively constant distribution of vehicle activity patterns by vehicle fleet.

The dominant influence of LDVs on exposures and disparities arises for two reasons. First, LDVs dominate the overall emissions of $PM_{2.5}$ and its precursors. Based on the CARB emissions inventories employed, LDVs contribute most of the NH_3 and VOC emissions (70-95% of NH3, > 80% of VOC) from vehicles, which contribute ~44-56% of total $PM_{2.5}$ exposure from vehicles. LDVs and HDVs contribute more similarly to primary $PM_{2.5}$ (23-45% LDV, 29-56% HDV) and NO_x (35-48% LDV, 36-43% HDV) emissions, and these species contribute the remaining ~44-56% of total $PM_{2.5}$ (Figs. S9-S12). Second, LDV emissions are more concentrated near population centers than other vehicle fleets, so LDVs result in a substantially higher-than-average exposure impact (Fig. S13 metric: μg/m^3 population-weighed exposure per ton of annual emissions; this metric is directly related to intake fraction) (*41-43*). Revisiting the exposure distributions by race-ethnicity and fleet (Fig. S4), we find no remarkable differences between distributions of different fleets (i.e., it is not the case that the most exposed populations are generally exposed to a different mixture of fleet types than the population average).

As a complement to apportioning the overall relative disparity to emissions from individual vehicle types (i.e., largest aggregate impact), in Fig. 3c we also consider which vehicle fleet types have an especially disparate impact on specific racial-ethnic groups (largest relative impact regardless of magnitude of emissions). Here, we find that HDVs are remarkable for the singularly large relative disparities they cause relative to other vehicle types. For example, the relative disparity caused by HDVs for Hispanic Californians (range: 16 – 17%) was larger than the relative disparity caused by LDVs (range: 11 – 14%).

Community-Level Analysis Shows Substantial Spatial Heterogeneity in Fleet-wise Contributions to Exposure Disparity

While trends in contribution at the statewide PWM persist over time, we find that there is substantial spatial heterogeneity in fleet contributions to exposures. We compare contributions by vehicle type at four spatial scales (Fig. 4): (a) statewide, (b) regional, (c) within overburdened communities, and (d) community-scale. Whereas the previous section and Fig. 4c evaluate aggregate exposure and disparity across all AB617 communities, in Fig. 4d we compare contributions to exposure and disparity within individual communities.

The Los Angeles area and its AB617 communities have high PWM exposures and high contributions from LDVs (> 60%). In the Central Valley, while the PWM exposures are lower, the contributions from HDVs are substantially higher (e.g., 60% in Arvin/Lamont). The diversity in fleet contributions to individual communities showcases the importance of community-specific emissions reduction planning. While a community like East Los Angeles may benefit from policy actions that directly reduce emissions from LDVs (e.g., more electric bus routes, street conversion to bicycle paths), communities like Arvin/Lamont would benefit more from policies that reduce emissions from HDVs (e.g., additional diesel fuel emissions limits, truck electrification, low emission zones). These differences likely arise from differences in spatial distributions of sources relative to residences and the magnitude and mixtures of vehicle activity that occur at the community scale. In sum, our results support the approach of enabling communities to identify and mitigate the largest contributors to local exposures and disparities.

Insights from California's Historical Mobile Vehicle Control Policies for More Equitable Future Policy

We have demonstrated that while the PWM $PM_{2.5}$ exposures and absolute exposure-disparities, attributable to on-road mobile sources have decreased over the past two decades across all population groups, relative disparities have remained at both the average and at the extreme ends of the exposure distribution for Californians of color and residents of the AB617 and SB535 communities. At all points of the statewide exposure distribution, emissions from LDVs contribute the most to exposure concentrations and absolute disparity, while emissions from HDVs most disproportionately affect people of color relative to other fleet types. Of the groups considered here, residents of AB617 communities in aggregate experience the highest levels of exposure from on-road vehicles. There is substantial heterogeneity among AB617 communities in terms of the total exposure concentration and the relative contribution from each vehicle type.

These findings are consistent with previous literature. First, we confirm and highlight the successes of California's mobile source strategy in substantially reducing average $PM_{2.5}$ exposures for all groups of Californians (*26*). Second, our finding of highly persistent relative disparities for Californians of color is disappointing but consistent with a growing body of literature on sectoral emissions policy. When policies reduce the overall emissions rate without substantially altering the pattern of *where* emissions occur, relative disparities in exposure can persist (*11*, *16*).

Our results suggest that relative disparities will persist without a paradigm shift in transportation policy. Creating low emissions zones or promoting mode shift away from private automobiles (e.g., dense public transit networks, bike lane infrastructure) could be more likely to reduce exposure disparities from the on-road vehicle fleet than statewide fleet-specific emissions controls (*44*). Without systemic changes to transportation infrastructure, it seems likely that these relative disparities will persist even in an all-electric vehicle future, in which future low levels of exposure from non-exhaust emissions (e.g., brake- and tire-wear) will still disparately affect people of color and residents of overburdened areas (Fig. S14). Conversely: by strategically accelerating emission-reductions, such as vehicle electrification efforts, in overburdened areas, EJ communities could achieve substantial short-term reductions in relative exposure disparity.

While we have focused on one sector within California, our findings contribute to an emerging body of EJ research indicating that to reduce relative disparities in exposure, policy must not merely continue a trend of emissions reduction, but also target the disparate geographical distribution of emissions in overburdened communities. While we focused on California as a case study, it is likely that these general findings apply across the United States, as most state and national approaches broadly have mirrored California's, with a strong focus on emission rate reductions. Our work provides a compelling illustration of how a highly successful emissions reduction strategy does not necessarily reduce relative inequity in exposures (*15*, *16*). More research is needed to identify the specific suite of strategies that can deliver a "triple win" for climate, health, and equity goals. We hypothesize that particularly effective strategies may go beyond aggregate emission rate reductions by ameliorating the inequitable distribution of where emissions take place. For the transportation sector, this means spatially shifting activities and emissions away from the disparate burden on historically disadvantaged communities. Thus, future work could explore the environmental equity impacts of potential policy actions and public investments that fundamentally change transportation infrastructure.

Methods

Emissions Estimates

Estimates of mobile emissions in California were obtained from the CARB's EMission FACtor (EMFAC) model (version EMFAC 2021 with MPOv11) for calendar years 2000 through 2019 (*32*). Estimated emissions were spatially allocated to a 1 km by 1 km grid using surrogates from the Sparse Matrix Operator Kernel Emissions (SMOKE) Modeling System and ARB's Emissions Spatial and Temporal Allocator (ESTA) models. The resulting dataset contained spatially resolved annual total exhaust, evaporative, brake wear, and tire wear emissions for primary $PM_{2.5}$ and four precursor species: NO_x, VOC, NH_3, and SO_x. EMFAC2021 reports results for 54 vehicle categories and four fuel types (gasoline, diesel, natural gas, and electric). Emissions for this analysis were binned into three main vehicle groups: LDVs, MDVs, and HDVs, with all other vehicle types (including motorcycles, motorhomes, and buses) grouped together as "Other" (Table S1).

Estimates of Air Concentrations

Annual average $PM_{2.5}$ concentrations attributable to vehicle emissions in California were estimated using a novel pipeline (see following section) built around the Intervention Model for Air Pollution (InMAP) Source-Receptor Matrix (ISRM) (*2*, *17*, *45*). The ISRM was developed from the United States InMAP, which used WRF-Chem simulations and U.S. Environmental Protection Agency National Emissions Inventory (NEI) emissions estimates for 2014. The national version of InMAP was sampled on a population-weighted irregular grid (n = 21,705; 1 km - 48 km) for the state of California (*2*). Approximately 74% of grid cells are the finest resolution, with a population-weighted grid size of 2.4 km (urban: 1.2 km, rural: 7.4 km). The gridding algorithm ensures that no cell larger than 1 km contains more than 20,000 people or a census block group with population density higher than 2,500 people/km.

The ISRM relates, for the n = 21,705 grid cells in California, marginal changes in ground-level concentration in every grid cell to marginal changes in emissions in every cell. Because this work only evaluates impacts from on-road mobile sources, all concentrations were estimated using the ground-level (i.e., 0 – 57 m above ground) layer.

Novel Open-Source Method: ECHO-AIR

Air pollution modeling, even with reduced complexity modeling tools such as InMAP, can have major accessibility barriers for non-specialists. For the present analysis, we developed an open-source Python-based pipeline that streamlines exposure concentration and health impact analyses. The resulting system, called Estimating Concentrations and Health Outcomes – Automated ISRM Resource (ECHO-AIR), aims to lower barriers of entry for rapid estimation of $PM_{2.5}$ exposure and health assessments.

Running ECHO-AIR for analyses in California requires only estimates of emissions, which can be input as ArcGIS-compatible shapefiles or comma separated value files. ECHO-AIR is modular, enabling users to employ any ISRM, population data, and health input data, so long as they are formatted correctly (see Supplementary Text). ECHO-AIR is managed through a public GitHub repository to ensure transparency, to maximize usability, and to perform routine model upgrades and maintenance. The location of additional details, including instructions on how to download and run ECHO-AIR, are in the Supplementary Text.

Population Estimates

Population data were obtained for 2010 from the United States Census for California from the National Historic Geographic Information System (NHGIS) database version 16.0 (*46*). Static population estimates were queried at the tract level by age, race, and Hispanic origin. Consistent with prior literature (*6*, *10*, *11*), racial-ethnic categories were estimated as follows: the population count for Hispanic Californians was defined as Californians of any race who were of Hispanic origin; Californians who are not of Hispanic origin and are Black or African American alone, Asian alone, or White alone were defined as Black, Asian, and White Californians, respectively; all other Californians were included in the Other category.

Exposure Assessment and Equity Analysis

Statewide group-level exposures to annual average $PM_{2.5}$ concentrations were estimated as population-weighted mean (PWM) concentrations, consistent with other air pollution disparity literature (*5*, *10-12*). For all of the metrics below, only the on-road mobile source exposure was considered. To estimate exposure to $PM_{2.5}$ for each year, we calculate geographic intersections between the 2010 Census tract boundaries and the gridded concentration estimates. Population is down-sampled based on area-apportionment, but concentration estimates are assumed to be constant throughout the grid cell. Exposure concentrations are calculated at the smallest geography possible.

The PWM exposure is estimated by multiplying the annual average $PM_{2.5}$ concentration by the population of the demographic group of interest within that grid cell, summing across all grid cells, and dividing by the total population:

$$PWM_k = \frac{\sum_{i=1}^{n} P_{i,k} \times C_i}{\sum_{i=1}^{n} P_{i,k}}$$

where PWM_k is the population-weighted mean exposure concentration for group k across n grid cells, $P_{i,k}$ is the population of group k in grid cell i, and C_i is the concentration of $PM_{2.5}$ in grid cell i. Equity was assessed using the absolute and relative disparities at the population-weighted mean. The absolute disparity ($D_{A,k}$) is defined as a demographic group's population-weighted mean exposure (PWM_k) subtracted by the statewide population-weighted mean exposure (PWM_T):

$$D_{A,k} = PWM_k - PWM_T$$

Relative disparities ($D_{R,k}$) are estimated as the absolute disparity divided by the statewide PWM exposure to mobile sources.

$$D_{R,k} = \frac{(PWM_k - PWM_T)}{PWM_T} = \frac{D_{A,k}}{PWM_T}$$

Because the ISRM is a linear model and the absolute disparity is an arithmetic equity metric, absolute disparities can be apportioned to individual source categories to find a relative contribution to the absolute disparity. Thus, the fractional contribution of a source's emissions to a group's exposure is estimated as:

$$f_{j,k} = \frac{D_{A,j,k}}{D_{A,t,k}}$$

where $f_{j,k}$ is the fractional contribution from source j on the exposure and disparity for group k, $D_{A,j,k}$ is the absolute disparity from source j for group k, and $D_{A,t,k}$ is the absolute disparity for group k from all on-road mobile sources.

Limitations

Our modeling framework is built around a source-receptor matrix developed from a reduced-complexity model, which has several inherent limitations. First, the temporal resolution of our results is limited to annual average and thus incorporates but lacks temporal precision to investigate exposure disparities that occur on a smaller time scale (e.g., rush hour traffic locations). Additionally, even with the relatively fine scale grid in urban areas (down to 1 km^2), the model misses within-grid near-road exposure gradients; those gradients can occur and be important even at scales smaller than 1 km^2 (*47*). While reduced-complexity modeling cannot replace comprehensive chemical-transport modeling (e.g., CMAQ), our methods have been corroborated against these models and have been shown to adequately represent small changes in emissions on scales similar to the on-road mobile sector.

Additionally, our model employs a static population dataset from the 2010 Decennial Census, which has several limitations in addition to known uncertainty in U.S. Census data. First, we assume that exposure is fully coupled with residential address, which may underestimate overall disparity in exposure by race and ethnicity (*48*). Second, we employ a static population dataset, which neglects changes in population over time. We minimize the impacts of this limitation by using 2010 (the midpoint of the study). In a sensitivity analysis (Fig. S15), we repeated our analysis with 2000 Decennial Census data and confirmed that the core findings are generally unchanged.

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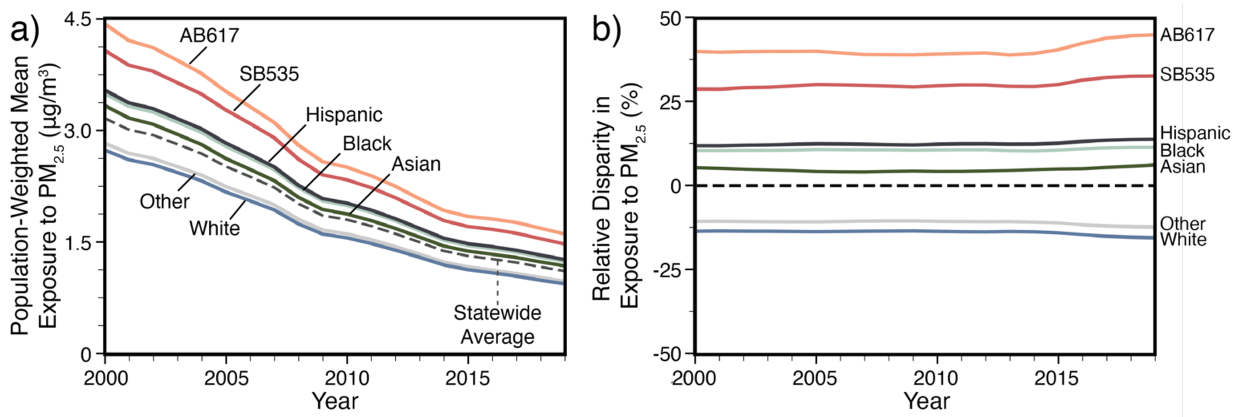


Fig. 1. On-road mobile-source $PM_{2.5}$ exposure and relative disparity in exposure for each demographic group. Statewide population-weighted mean $PM_{2.5}$ exposure concentrations (a) and relative disparity in exposure (b) attributable to on-road mobile sources for the four largest racial-ethnic groups and two policy-relevant environmental justice areas in California. In each year, relative exposure disparities (b) for each racial-ethnic group are computed in reference to statewide average $PM_{2.5}$ concentration attributable to on-road mobile sources. Concentrations in areas designated under California's Community Air Protection Program (AB617, ~10% of state population) and as SB535 Disadvantaged Communities (~25% of state population) substantially exceed those experienced on average for the most-exposed racial-ethnic group, Hispanic Californians. (b) Crucially, despite greater than 50% reductions in mobile-source population-weighted mean $PM_{2.5}$ for all groups (a), relative racial-ethnic disparities increased for Hispanic, Black, and Asian Californians, as well as residents of AB617 and SB535 communities. Here and elsewhere, the "Hispanic" population reflects Californians of any racial group identifying on the US Census as Hispanic, while all other groupings exclude Californians identifying as Hispanic.

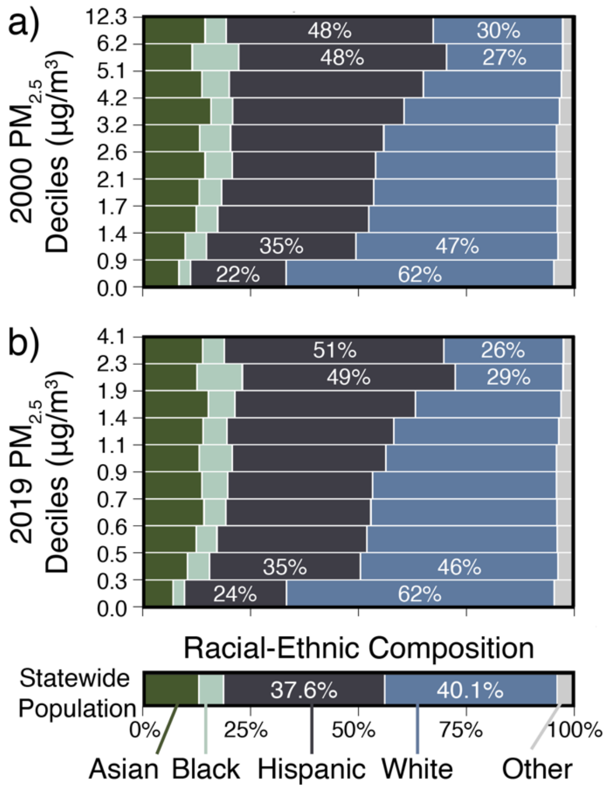


Fig. 2. Racial-ethnic population distribution by exposure decile. Differences in racial-ethnic composition of the California population exposed to each decile of the distribution of $PM_{2.5}$ attributable to on-road mobile sources in (a) 2000 and (b) 2019. The statewide population is binned into ten groups of equal population of $PM_{2.5}$ exposure attributable to the full vehicle fleet. At all years in our assessment, Hispanic Californians are strongly overrepresented among the highest $PM_{2.5}$ exposure deciles (and under-represented in the lowest exposure deciles). The opposite pattern holds for White Californians. Data are plotted for individual vehicle types and the analysis midpoint year (2010) in the SI.

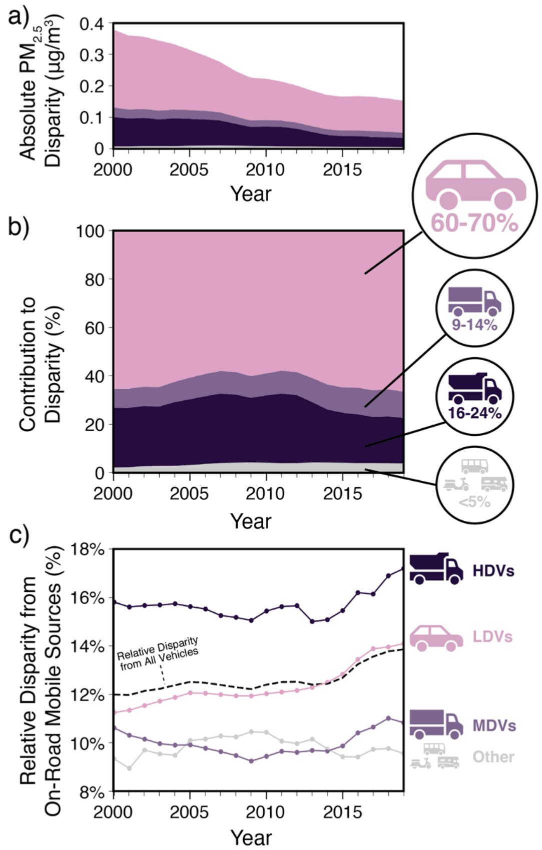
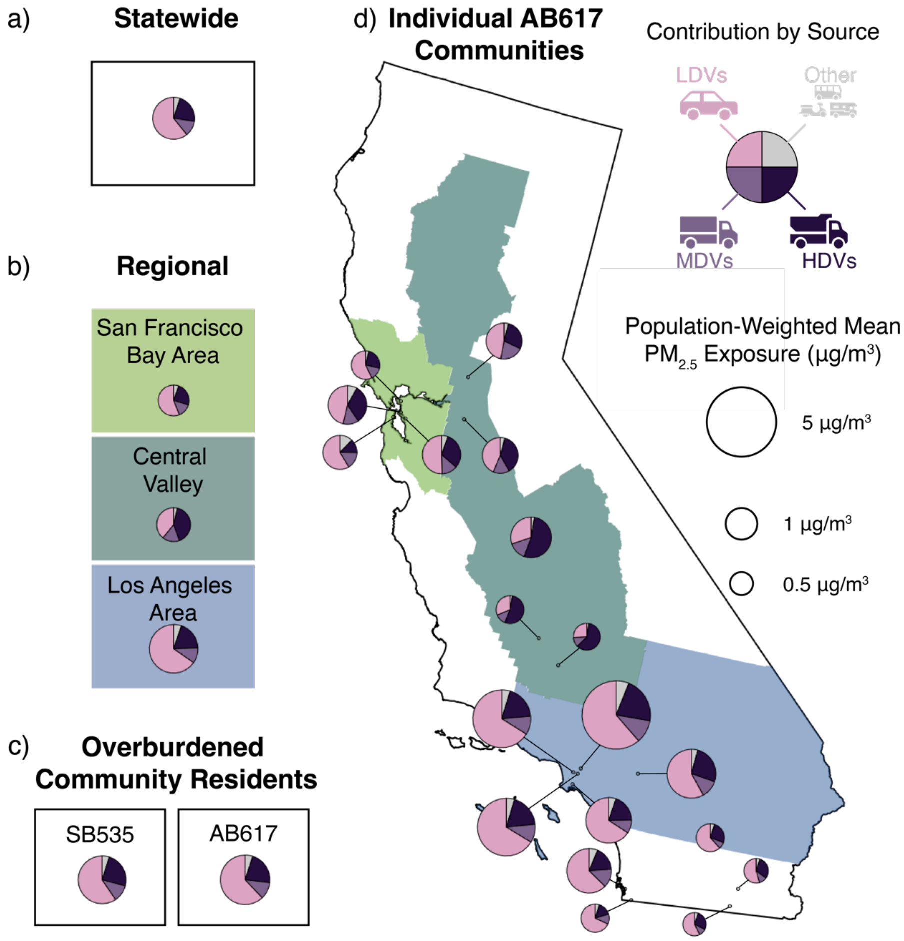


Fig. 3. Contributions to disparity in exposure to mobile-source $PM_{2.5}$ for Hispanic Californians. Two methods of comparing contributions to disparity in $PM_{2.5}$ exposures from on-road vehicle fleet types shown for the most exposed racial-ethnic group, Hispanic Californians. First, we compare the absolute magnitude in contribution from each vehicle group (a, b); then, we compare the relative disparity in exposure to each vehicle group (c). (a) Absolute disparities in $PM_{2.5}$ exposure from vehicles for Hispanic Californians relative to the overall statewide population declined between 2000 and 2019, consistent with the overall reduction in emissions (Fig. S1) and population-weighted mean $PM_{2.5}$ concentrations (Fig. 1). (b) Fractional contributions to the overall disparity that are attributable to each fleet type are estimated by normalizing the absolute contribution to disparity attributable to a single fleet type to the total disparity attributable to all on-road mobile sources. In each year, light-duty vehicle (LDVs) emissions are the dominant contributor to the disparately high exposures experienced by Hispanic Californians. (c) Disparities attributable to emissions of individual vehicle fleet types relative to the statewide average $PM_{2.5}$ exposure attributable to emissions of that individual vehicle fleet. Note that heavy-duty vehicles (HDVs) especially disparately impact Hispanic Californians, even though HDVs are not the dominant contributor to overall emissions (Fig. S1), $PM_{2.5}$ concentrations (Fig. 1), or absolute disparities (c).



612 **Fig. 4. Spatial heterogeneity in contributions by fleet to mobile-source $PM_{2.5}$ exposure.** Contribution to $PM_{2.5}$ exposures from distinct vehicle fleets is shown at four spatial scales: (a) statewide, (b) three major regions, (c) residents of overburdened communities, and (d) for 19 individual communities designated by the state of California through the Community Air Protection Program (AB617; see Fig. S2 for identification of each community). At each spatial scale, pie chart icons indicate the fractional contribution to exposure attributable to each vehicle fleet type, with icons scaled in proportion to the population-weighted mean $PM_{2.5}$ concentration from all vehicle types. Light-duty vehicles contribute especially to mobile-source $PM_{2.5}$ exposures in Southern California, while the relative contribution from MDVs and especially HDVs are comparatively higher in the Central Valley and San Francisco Bay Area. There is considerable heterogeneity among AB617 communities in fleet contributions.