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Journal

Environmental Science & Technology, 58(43)

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Publication Date

2024-10-29

DOI

10.1021/acs.est.4c04126

Peer reviewed

Environmental Science & Technology

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Persistent Environmental Injustice due to Brake and Tire Wear Emissions and Heavy-Duty Trucks in Future California Zero-Emission Fleets

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Cite This: *Environ. Sci. Technol.* 2024, 58, 19372−19384
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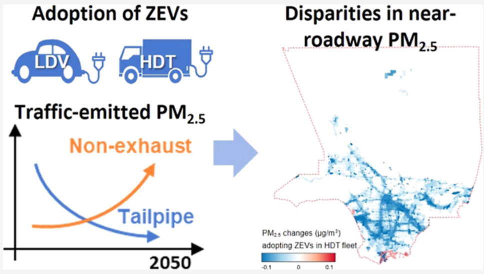
ABSTRACT: The adoption of zero-emission vehicles (ZEVs) offers multiple benefits for the climate, air quality, and public health by reducing tailpipe emissions. However, the environmental justice implications of the nonexhaust emissions from future ZEV fleets for near-roadway communities remain unclear. Here, we model the on-road fine particulate matter ($PM_{2.5}$) emissions across all California counties and assess the near-roadway exposure disparities at the census block group level in the Los Angeles County in 2050, when almost all passenger vehicles are projected to be ZEVs. We found that promoting zero-emission heavy-duty trucks generates more air quality benefits for disadvantaged communities than light-duty passenger vehicles. Persistent disparities in near-roadway $PM_{2.5}$ levels, however, exist due to the remaining brake and tire wear emissions and increased truck traffic in disadvantaged communities. We recommend implementing fleet-specific ZEV policies to address brake and tire wear emissions and optimizing freight structures to address these persistent environmental justice issues in California.



KEYWORDS: *zero-emission vehicles, near-roadway, nonexhaust emissions, exposure disparities, environmental justice*

INTRODUCTION

Zero-emission vehicles (ZEVs) are key climate change mitigation tools that are expected to result in a variety of climate, air quality, and health benefits.[1−3] On-road traffic contributes substantially to air pollution and exposure disparities.[4−7] Exposure to traffic-related air pollution has lasting health impacts in communities that are living in close proximity to high-traffic arterial highways and freeways, resulting in increased risks of childhood asthma, bronchitis, and other cardiovascular diseases.[8,9] Historically, these areas have been characterized by high percentages of low-income, racial, and ethnic minority populations,[10−13] especially those in areas that are located near busy freight corridors that are frequently traversed by heavy-duty trucks (HDTs).[14,15] The U.S. Environmental Protection Agency (EPA) has reported that 72 million Americans live in close proximity to heavy trucking corridors and are more likely to be people of color and in lower-income groups.[15] While HDTs constitute only 6% of the U.S. vehicle fleet, they were the second-largest source of transportation-related CO_2 emissions (∼23%) in 2021[16] and generated 55% of the total particle pollution.[17] Promoting ZEVs, especially zero-emission HDTs,[5] is critical for achieving healthy and equitable energy transitions in the transportation sector.

California has taken a leadership role in promoting ZEVs. The California Air Resources Board (CARB) defines ZEVs as vehicle technologies that include battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). With the goal of achieving carbon neutrality by 2045,[18] the CARB approved the Advanced Clean Cars II rule in 2022,[19] which requires that all new passenger cars, pickup trucks, and sport-utility vehicles sold in California to be ZEVs by 2035. In addition, the CARB adopted the Advanced Clean Fleets regulation in April 2023,[20] which established a world-first mandate to end combustion engine sales for medium- and heavy-duty vehicles in California. This includes a 100% ZEV sales requirement for truck manufacturers starting in 2036.

ZEVs have the potential to substantially reduce tailpipe emissions. However, they still emit nonexhaust particles that are generated from the frictional processes associated with vehicle usage, including brake wear, tire wear, road surface wear, and resuspension of road dust.[21−27] In recent years, nonexhaust particle emissions have surpassed exhaust emissions as contributors to total traffic-attributed fine particulate matter ($PM_{2.5}$) in California.[28,29] This trend is expected to continue, which is driven by the phasing out of older vehicles, larger ZEV fleets, and the absence of legislation

Received: April 25, 2024
Revised: October 8, 2024
Accepted: October 9, 2024
Published: October 18, 2024

https://doi.org/10.1021/acs.est.4c04126

to limit or reduce nonexhaust particles.[21,22,30,31] Recent evidence indicates that the particles generated from brake and tire wear (BTW) emissions are important sources of metals (e.g., Pb, Cr, Zn, Ba, Sb, and Cu)[30,32] and contribute a substantial fraction of the trace elements[33,34] in urban atmospheres, resulting in an increased toxicity per unit mass of $PM_{2.5}$ and adverse health outcomes for traffic-impacted communities.[35] BTW particles also exhibit a greater oxidative potential than other traffic-related sources.[26,36] Unlike secondary $PM_{2.5}$, which is more evenly distributed among communities, BTW particles are primary pollutants with highly localized effects (within 50−100 m from the source) compared to exhaust pollutants. Consequently, BTW particles have been shown to disproportionately impact socially marginalized populations living near roadways.[27,29] Hence, nonexhaust particle emissions, especially those from BTW, are increasingly recognized as major contributors to near-roadway $PM_{2.5}$ exposures.

Prior studies have focused predominantly on the benefits of tailpipe emission reductions on the ambient air quality, with few studies exploring the remaining BTW particles and how they change with the penetration of ZEVs.[1,37−42] One of our recent studies reveals that the near-roadway air quality benefits from ZEVs for $PM_{2.5}$ are less than those for NO_2 because ZEVs only reduce tailpipe emissions, which are not enough to address the historically unjust pollution burden in disadvantaged communities.[42] Moreover, most related studies including our own work[41] have concentrated on LDVs,[37,38,43] with only a few specifically addressing zero-emission HDTs.[1,39] For instance, one study[1] quantified the air quality, health, and equity implications of electrifying 30% of diesel HDTs in Chicago, and another study[39] assessed the air quality benefits of achieving a 69% sales target for zero-emission HDTs by 2050 in California. However, limited studies have addressed California's recent developments in the HDT policy, such as the Advanced Clean Fleets regulation, which requires a 100% ZEV sales target for HDTs since 2036.[20] Moreover, no study has compared the effects of various driving factors, such as changes in vehicle miles traveled (VMT), tailpipe emissions controls, and adoption of ZEVs, between LDV fleets and HDT fleets on air quality benefits and Environmental Justice (EJ) implications. Therefore, it is important to evaluate the potential impacts of increasing zero-emission HDTs and the remaining BTW emissions with regard to the EJ.

In this study, we focus on traffic-emitted primary $PM_{2.5}$ to assess the ZEV-related EJ impacts across California and Los Angeles County in 2050, when almost all passenger vehicles are projected to be ZEVs. We predicted the ZEV adoption trends in California and analyzed the county-level changes in the on-road $PM_{2.5}$ emissions from 2021 to 2050. We quantified the contributions of different fleets (e.g., LDV and HDT) and emission sources (e.g., tailpipes and BTW) separately. We then selected the Los Angeles County to assess the near-roadway $PM_{2.5}$ exposures at the census block group level using a bottom-up assessment framework by integrating ZEV distribution disparities, link-level traffic flows, and a line-source dispersion model. We chose the Los Angeles County due to its highest average $PM_{2.5}$ pollution exposure from on-road traffic,[44] extensive freeway network, and considerable demographic diversity in California. We then compared the efficacy of promoting zero-emission LDVs and HDTs in alleviating environmental injustice across all California counties and Los Angeles census block groups. Finally, we quantified the changes and driving forces of the near-roadway $PM_{2.5}$ disparities in the Los Angeles County from 2021 to 2050. These results provide valuable insights for policy-makers in designing future ZEV adoption strategies to address persistent EJ issues that are associated with the disproportionately greater environmental burdens among disadvantaged populations.

■ MATERIALS AND METHODS

Prediction of ZEV Adoption and Future $PM_{2.5}$ Emissions. To predict the future trends of ZEV adoption in different California communities, we retrieved historical vehicle registration data from 2015 to 2021 from the California Air Resources Board (CARB) Fleet Database.[45] The CARB Fleet Database provides vehicle populations by vehicle type and fuel technology at the census block group level based on registration data obtained from the California Department of Motor Vehicles. As defined by the CARB, LDVs include passenger cars, light-duty trucks, and medium-duty vehicles, while HDTs include light-heavy-duty trucks (LHDTs), medium-heavy-duty trucks (MHDTs), and heavy−HDT (HHDT) (Table S1). The CARB defines ZEV as vehicle technologies that include BEVs (BEVs), plug-in hybrid vehicles (PHEVs), and hydrogen fuel cell vehicles. We utilized the ZEV ownership data for each county in California and each census block group in the Los Angeles County from 2015 to 2021 to establish the ZEV growth trends for LDV and HDT fleets.

For the future scenario in 2050, we applied a logistic growth model to estimate the future ZEV adoption trends of the LDV and HDT fleets. The logistic growth model is a mathematical framework that is commonly used to describe the growth of a population over time and also applicable to predict the adoption rate of new technologies. It describes a *S*-shaped curve that represents a slow initial adoption, followed by rapid growth as the technology becomes more prevalent and eventually leveling off as the market becomes saturated.[42] This model has been widely applied in various fields, including technology diffusion,[46] population growth,[47] and resource consumption,[48] to forecast future trends and inform decision-making processes. After estimating the number of ZEVs in each county or census block group in 2050, we proportionally scaled the ZEV count to achieve the final ZEV population shares in California, as listed in Table S2, which were in accordance with the latest projection of the CARB Mobile Source Strategy report.[49] The CARB report anticipates that approximately 93% of the LDV fleet and 80% of the HDT fleet will reach zero emissions by 2050. The number of ZEVs added to the fleet was subtracted from the number of their internal combustion engine counterparts to ensure that the total vehicle population aligned with the total vehicle ownership projected for 2050 by the EMission FACtors (EMFAC) model, an official emission inventory database developed by the CARB. Figure S1 shows an example of future trends in the percentage of ZEV ownership in the LDV fleet for the state and three counties with varying penetration rates.

To represent this methodology mathematically, we use the following logistic growth equation

$$N(t) = \frac{K}{1 + \frac{K - N_0}{N_0} e^{-rt}} \tag{1}$$

where:

$N(t)$ is the number of ZEVs at time t (in our case, $t = 2050$), K is the carrying capacity, which represents the total number of vehicle populations being zero-emissions, N_0 is the initial number of ZEVs (at $t = 2021$), r is the growth rate estimated from ZEV ownership data from 2015 to 2021, and t is the time (in years) since the initial year.

We then established the county-level emission inventory for California and the link-level vehicle emission inventory for the Los Angeles County (see Note S1 for details). Traffic-emitted $PM_{2.5}$ were categorized into two sources: tailpipe emissions and nonexhaust emissions. EMFAC and VMT of different fleets were obtained from EMFAC version 2021 1.0.2.[28] Tailpipe emissions, include running exhaust emissions, idling emissions, and emissions while starting. In this study, nonexhaust emissions included only brake and tire wear (BTW) emissions. Specifically, BTW EMFAC in EMFAC were measured by using a brake dynamometer simulating real-world driving conditions. Figure S2 illustrates $PM_{2.5}$ EMFAC for LDVs and HDDTs by year, fuel type, and emission process from EMFAC2021. It shows that while tailpipe emissions decrease significantly from 2021 to 2050, BTW emissions remain relatively constant. Brake wear emissions for BEVs are approximately 50% lower than those for ICEVs due to regenerative braking, while tire wear emissions are comparable. Although the BTW emission factor in EMFAC2021 accounts for driving speeds and regenerative braking, it does not consider the potential impact of increased BEV weight due to limited testing,[28] which may lead to underestimations of BTW emissions in our study. As concrete emission factor data for road surface wear and road dust resuspension were absent from the EMFAC data set, we assumed that these factors were not substantially affected by the penetration level of ZEVs; therefore, these factors were not considered in the analysis.

Near-Roadway $PM_{2.5}$ Modeling. We then selected the Los Angeles County to assess the near-roadway $PM_{2.5}$ exposures at the census block group level using a bottom-up assessment framework by integrating the vehicle emission inventory and a line-source dispersion model. We used the R-LINE V1.2 model to simulate the near-roadway $PM_{2.5}$ concentrations that are attributed to on-road vehicle emissions. R-LINE is a line-source dispersion model that was developed by the U.S. EPA using a steady-state Gaussian formulation.[50] It is specifically designed for mobile source emissions, which is in line with the link-level emission data that we simulated from MATSIM (see Note S2 for details). R-LINE is used extensively for near-road air quality analysis and has received thorough verifications and validations.[51] The historical validation and certification from the EPA give us confidence in the accuracy of the outcomes that it provides.

We first generated emission input data from different fleets (e.g., LDV and HDT) and emission sources (e.g., tailpipes and BTW) for each road segment based on the link-level emission inventory established before. These four emission data sets were subsequently input into the R-LINE model one by one to simulate near-roadway $PM_{2.5}$ concentrations induced by different emission sources (i.e., LDV tailpipe, HDT tailpipe, LDV BTW, and HDT BTW). In addition to the emission data, meteorological data are required to simulate the downwind concentrations in R-LINE. We downloaded hourly surface meteorological data for the area near Los Angeles International Airport from the National Centers for Environmental Information in the Integrated Surface Data set format.[52] Data for January, April, July, and October (a total of 123 days) were downloaded to represent the seasonal variations across the four seasons. We also sourced upper air sounding data from the National Oceanic and Atmospheric Administration Radiosonde Database for the area near the Los Angeles International Airport.[53] Surface meteorology and upper air sounding data were then processed using AERMET, a meteorological data preprocessor provided by the EPA, to generate R-LINE compatible meteorology files. For the receptor file, we created a receptor network for the Los Angeles County that included 6423 receptors, each of which represented the centroid of a census block group. We selected receptors within 1500 m for each source (each link segment) for the receptor file, as several studies have shown that 1500 m is the maximum distance at which $PM_{2.5}$ that is directly emitted from traffic can be detected.[54,55] With the input files, R-LINE V1.2 was used to generate the near-roadway $PM_{2.5}$ concentrations from each link segment to all receptors at an hourly resolution. The final concentrations at each census block group receptor were aggregated to annual average concentrations for our final analysis.

Our simulations focus on traffic-emitted $PM_{2.5}$ without considering background pollutant concentrations. Therefore, it is difficult to directly validate our simulation results using ambient monitoring data, which include background levels. To bridge this gap, we found a recent study that evaluated the contributions of nontailpipe emissions to near-road $PM_{2.5}$.[29] This study was conducted in Los Angeles, California, during the winter of 2020 and collected 64 $PM_{2.5}$ samples from 32 pairs of downwind-upwind measurements at two near-road locations (I-5 in Anaheim and I-710 in Long Beach), with I-710 falling within our modeling domain. According to the findings, BTW and tailpipe emissions contributed comparably to near-roadway ambient $PM_{2.5}$ concentrations for I-710 (15−17% vs 15−19% of the total $PM_{2.5}$). To validate our R-LINE simulations, we ran the same scenario using reported on-site traffic counts (approximately 90% LDV and 10% HDV on I-710) and meteorological conditions (winter in 2020). Our results indicate that BTW and tailpipe emissions contribute equally to the traffic-induced near-roadway $PM_{2.5}$ concentrations, which aligns well with the referenced study's findings. The key point of this study lies in the trade-offs between tailpipe and nonexhaust emissions in near-roadway $PM_{2.5}$ levels. Therefore, we consider this a strong validation of the R-LINE simulation used in this study.

EJ Analysis. We adapted Lorenz curves to evaluate the environmental benefits of ZEV adoption at both the California and Los Angeles census block group levels. This method was originally used by the Gini index, which is widely used as a measure of income inequality.[56] The distributions of total environmental benefits among communities are represented as Lorenz curves and are colored by their racial/ethnic shares. The Gini indices, calculated as the ratio of the area that lies between the line of equality and the Lorenz curve, are shown for the adoption of ZEVs in different fleets. A higher Gini index reflects a greater proportion of benefits shared by disadvantaged communities. In this study, the CalEnviroScreen 4.0 environmental justice screening tool, developed by California's Office of Environmental Health Hazard Assessment, was used to rank all California communities.[57] The CalEnviroScreen tool identifies the impacted communities by considering pollution exposure and its effects as well as the health and socioeconomic status, at the census-tract level. The CalEnviroScreen scores were calculated by multiplying the Pollution

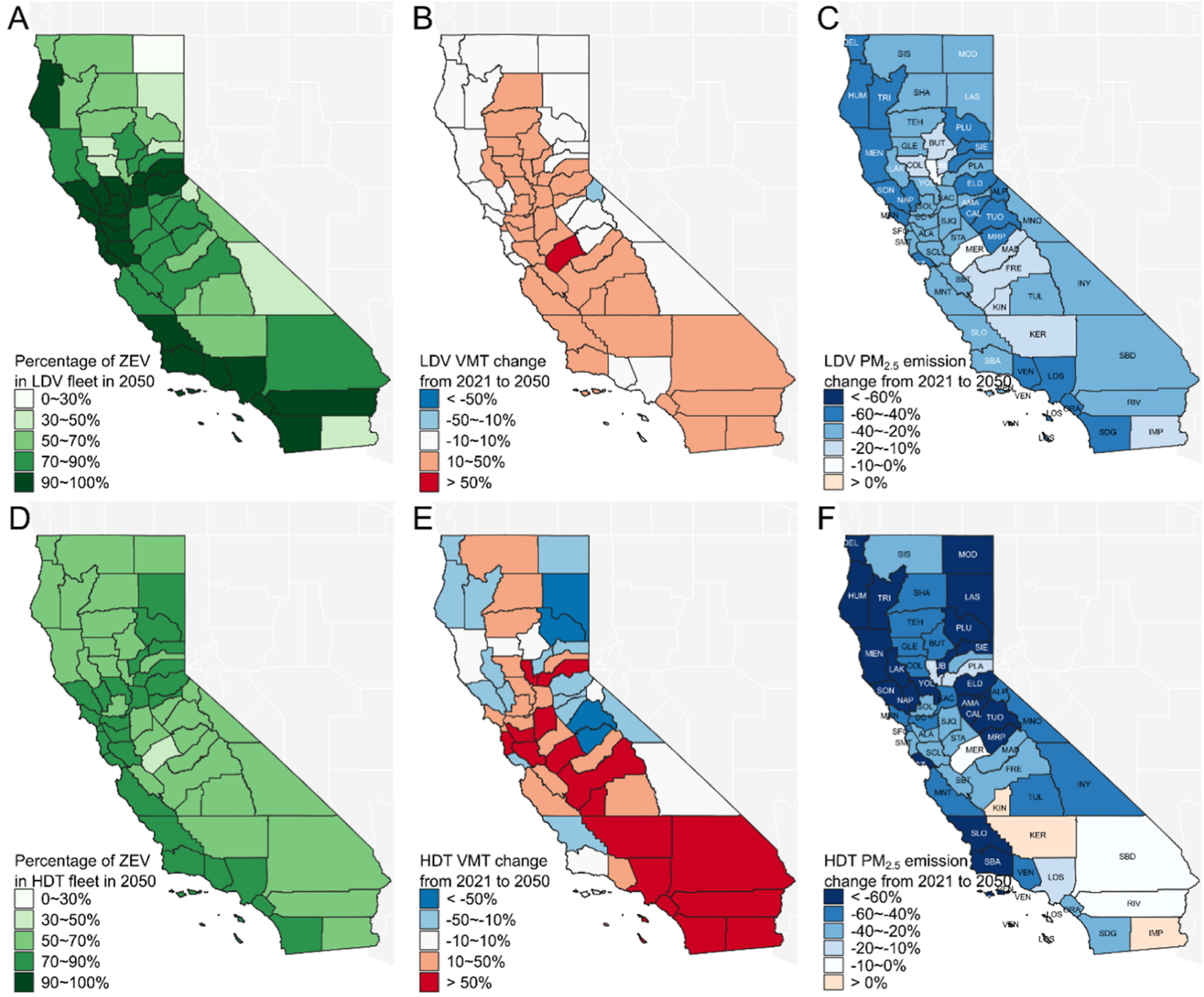


Figure 1. Percentage of ZEV ownership, changes in vehicle mileage traveled (VMT), and changes in $PM_{2.5}$ emissions for both the light-duty vehicle (LDV) fleet and heavy-duty truck (HDT) fleet in California counties in 2050. Percentage of ZEV ownership in (A) LDV and (D) HDT fleets in 2050, percentage changes in VMT for (B) LDV and (E) HDT fleets from 2021 to 2050, and percentage changes in $PM_{2.5}$ emissions from (C) LDV and (F) HDT fleets from 2021 to 2050.

Burden and Population Characteristics scores. The higher the score, the greater the risk the residents face. The CalEnviroScreen scores of each California county were calculated as the population-weighted scores of all census tracts within each county. The CalEnviroScreen score of each census block group in Los Angeles County was assigned the same score as the census tract to which it belongs.

We further quantified the exposures and disparities in the near-roadway $PM_{2.5}$ by race and ethnicity in Los Angeles County in 2021 and 2050. The population-weighted average concentration (PWAC) values, a proxy of exposure, were calculated for both the total population and different racial/ethnic groups by using eqs 4 and 5, respectively. Then, we defined disparity as the percentage difference (%) between a given demographic' s exposure and the average population exposure by using eq 6. A positive disparity indicates that a group is disproportionately impacted, while a negative disparity suggests that a group is less impacted than the average.

$$\mathrm{PWAC} = \sum_j (P_j C_j) / \sum_j (P_j) \tag{4}$$

$$\mathrm{PWAC}_i = \sum_j (P_{i,j} C_j) / \sum_j (P_{i,j}) \tag{5}$$

$$\mathrm{Disparity}_i = (\mathrm{PWAC}_i - \mathrm{PWAC})/\mathrm{PWAC} \tag{6}$$

where i represents racial/ethnic groups, j represents census block groups; PWAC and PWAC_i are the population-weighted average $PM_{2.5}$ concentrations of the total population and racial/ethnic Group i, respectively; P_j and $P_{i,j}$ are the total population and population of racial/ethnic Group i in census block Group j; and C_j is the near-roadway $PM_{2.5}$ concentration in census block Group j. The population data by race-ethnicity are obtained from the U.S. Census 2021 American Community Survey (ACS) 5 Year Estimates at the census block group level of spatial aggregation. In this study, Latino and/or Hispanic individuals were identified as "Hispanic", and non-Hispanic individuals were categorized by race as follows: Asian, Black, White, or other, including Native American, Pacific Islander, multiracial, or other racial identity.

We attributed the changes in $PM_{2.5}$ concentrations from 2021 to 2050 to four major drivers, namely, tailpipe emission controls, VMT increases, adoption of ZEVs in LDVs, and HDT fleets. Tailpipe emission controls include tightening

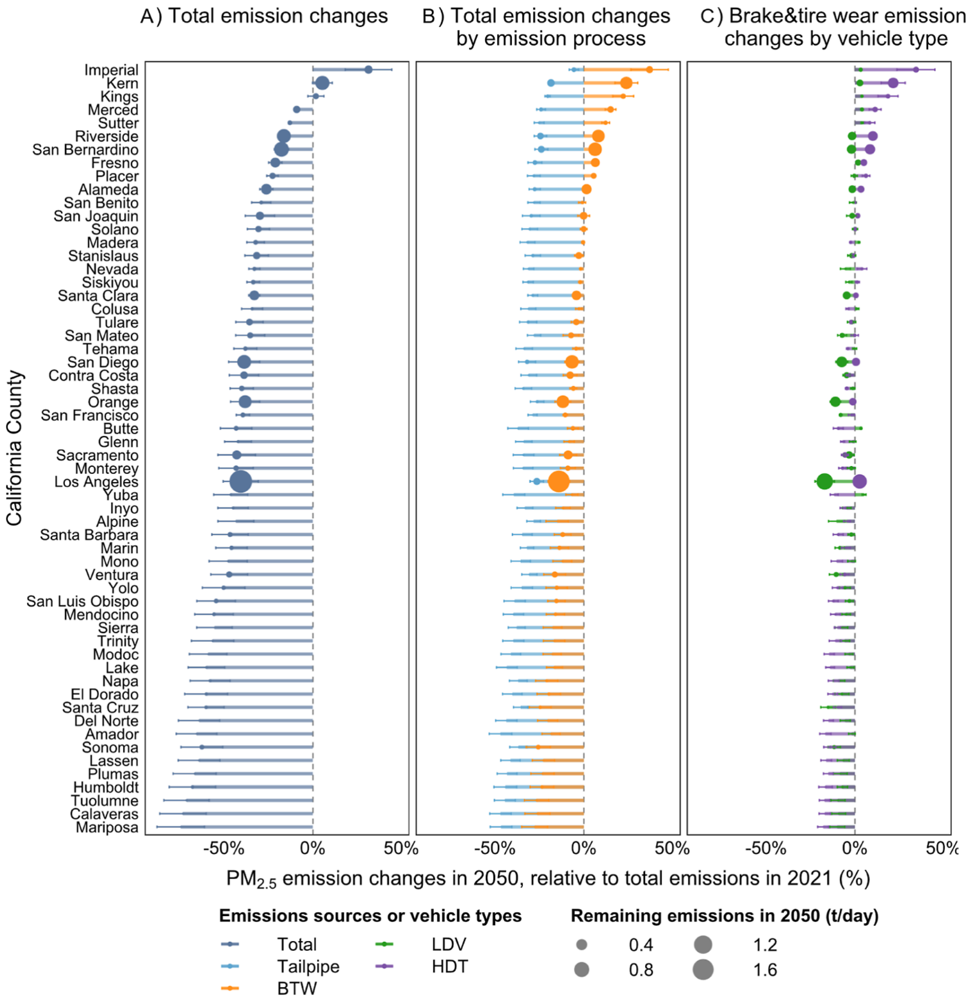


Figure 2. On-road $PM_{2.5}$ emission changes in all California counties in 2050 relative to total emissions in 2021. (A) Percentage changes in total on-road $PM_{2.5}$ emissions; (B) percentage changes in $PM_{2.5}$ emissions, corresponding to tailpipe and brake and tire wear (BTW) emissions; and (C) percentage changes in BTW emissions, corresponding to LDV and HDT fleets. The percentage changes are calculated by dividing the absolute emission changes by the total on-road $PM_{2.5}$ emissions in each county in 2021. The sizes of the circular dots represent the corresponding on-road $PM_{2.5}$ emissions in 2050. Error bars are shown in thinner lines for each county. We conducted a sensitivity analysis to understand the uncertainties in vehicle emissions resulting from changes in the ZEV policy. A Monte Carlo simulation was performed to quantify the uncertainties in emission estimates (represented by error bars), considering ZEV shares ranging from 70% to 100% for LDVs and 60−100% for HDTs in 2050.

tailpipe emission standards, implementing after-treatment systems, and using onboard diagnostics aimed at controlling tailpipe emissions, among other measures. The impacts of these major drivers on the changes in $PM_{2.5}$ levels are quantified by the differences between the PWAC values under various scenarios. For example, the impact of tailpipe emission controls is quantified by assuming no further ZEV adoption and comparing two scenarios: one with and one without tailpipe emission control policies. Similarly, the impact of ZEV adoption is determined by comparing the real-world scenario to that assuming no further ZEV adoption. The scenario settings and a quantification of the impacts of the four driving forces are shown in Note S3, Tables S3 and S4.

RESULTS

County-Level ZEV Adoption and $PM_{2.5}$ Emission Reductions in California. As shown in Figure 1, higher ownership shares were projected in the Bay Area and Southern California for both the LDV and HDT fleets in 2050 (Figure 1A and D), as these regions have higher ZEV growth rates based on ownership data from 2015 to 2021. Figure 1B and E illustrates the percentage changes in vehicle mileage traveled (VMT) for the LDV and HDT fleets in 2050 compared to those in 2021. In EMFAC2021, the future VMT of LDVs is forecasted using a socio-econometric regression model based on historical time-series data from 2003 to 2019, including factors, such as gas prices, human population, and housing starts. The future VMT of heavy-duty vehicles is forecasted using county-level VMT growth rates derived from the California Statewide Travel Demand Model (CSTDM). The CSTDM employs a commodity-based model that forecasts future freight flows by mode on the transportation network under various policy scenarios. It provides county-level VMT forecasts as the primary source for future VMT trends to better reflect regional disparities in freight VMT growth. The VMT for the LDV fleet remain stable or slightly increase in 2050, while larger variations for the HDT fleet are estimated across counties. The total miles traveled by HDT in 2050 are estimated to increase by more than 60% in some Southern California counties, such as Kern (KER), Los Angeles (LOS), San Bernardino (SBD), Riverside (RIV), Orange (ORA), San Diego (SDG), and Imperial (IMP). Yet, the total HDT VMT

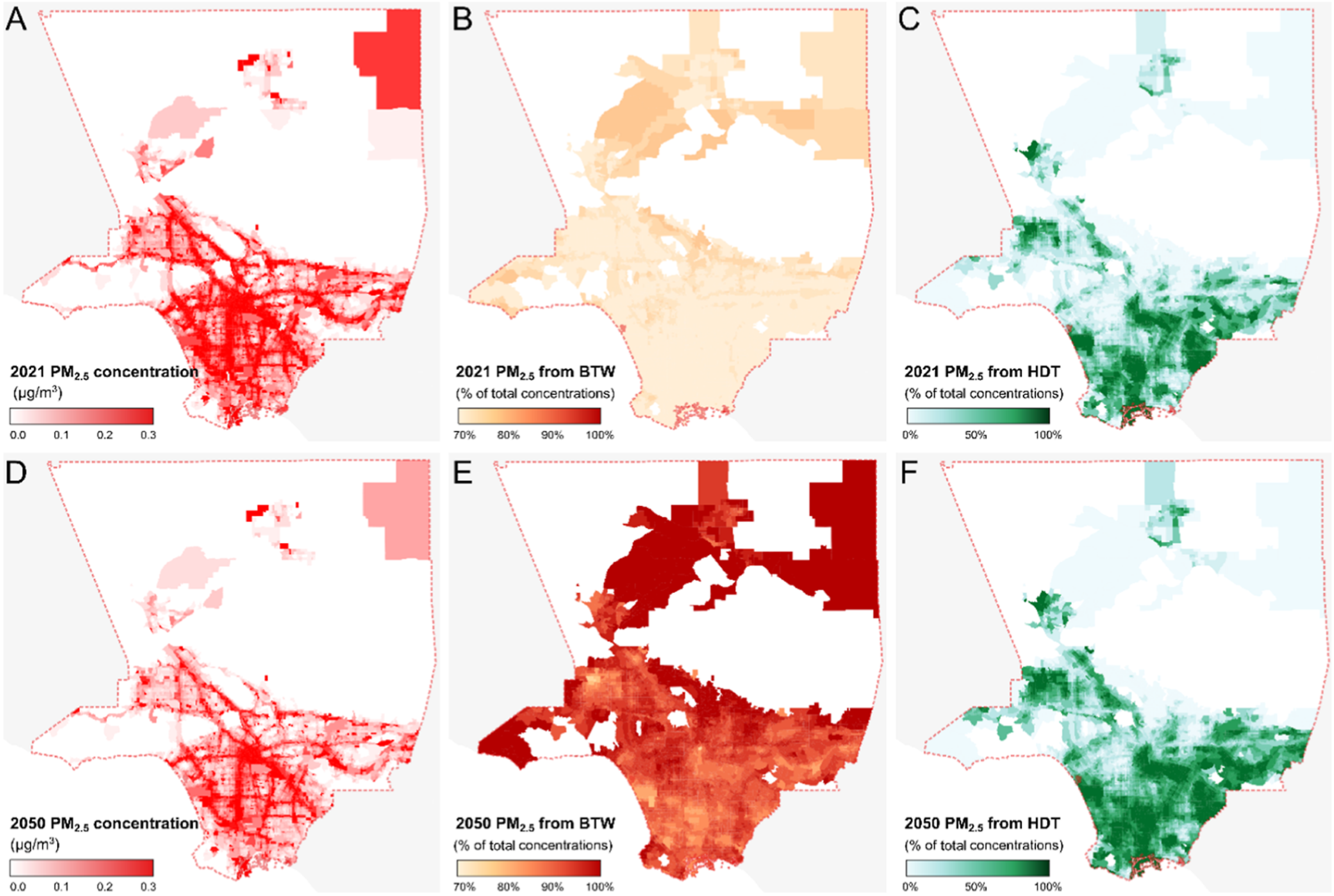


Figure 3. Near-roadway $PM_{2.5}$ concentrations across census block groups in the Los Angeles County in 2021 and 2050. Total near-roadway $PM_{2.5}$ concentrations in (A) 2021 and (D) 2050; percentages of $PM_{2.5}$ concentrations attributable to BTW emissions from the whole fleet in (B) 2021 and (E) 2050; and percentages of $PM_{2.5}$ concentrations attributable to HDT tailpipe and BTW emissions in (C) 2021 and (F) 2050.

remained stable or decreased in most Northern California counties.

The county-level on-road $PM_{2.5}$ emissions by the vehicle type and emission sources in 2021 and 2050 are shown in Figure S3. The on-road $PM_{2.5}$ emissions are affected by both the ZEV adoption levels and VMT changes (Figure S4), with estimated decreases of 34 ± 12% and 47 ± 30% in the LDV and HDT fleets, respectively, across various counties from 2021 to 2050 (Figure 1C and F). The changes in $PM_{2.5}$ emissions from HDT fleets vary greatly among all California counties and are primarily driven by VMT changes (see Figure S4 for impacts of VMT change and ZEV penetration on $PM_{2.5}$ emission changes). As a result, the emission reduction percentages for HDTs in Southern California counties are generally lower than those in Northern California counties.

To identify the causes of the variations in the on-road $PM_{2.5}$ emission changes from 2021 to 2050, we separately quantified the contributions of different fleets and emission sources. As illustrated in Figure 2A, the percentage changes in the total on-road $PM_{2.5}$ emissions in 2050 vary among all California counties, ranging from −74% to +31%. Counties with higher total emissions, as indicated by the sizes of the circles, exhibit relatively lower $PM_{2.5}$ reduction percentages. For instance, Los Angeles County, which has the largest on-road emissions, is estimated to experience a 41 ± 10% reduction in total on-road $PM_{2.5}$ emissions from 2021 to 2050 (Figure 2A). The changes in $PM_{2.5}$ emissions that correspond to tailpipe and BTW emissions are depicted in Figure 2B. Tailpipe emissions decrease with comparable magnitudes across various counties, while the large variations in the total emission changes are dominated by the changes in BTW emissions. Counties with limited total emission reductions generally experience substantial increases in the level of BTW emissions from 2021 to 2050. Notably, the total $PM_{2.5}$ emissions in Imperial, Kern, and Kings Counties in 2050 are projected to increase by 32 ± 13%, 6 ± 5%, and 2 ± 4%, respectively, relative to those in 2021 due to substantial increases in BTW emissions of 38 ± 10%, 24 ± 6%, and 23 ± 6%, respectively, and decreases in tailpipe emissions of 6 ± 3%, 18 ± 1%, and 21 ± 1%, respectively. The changes in BTW emissions that correspond to the LDV and HDT fleets are further depicted in Figure 2C, which shows that the increases in BTW emissions are largely from the HDT fleets. Hence, the variations in on-road $PM_{2.5}$ emissions from 2021 to 2050 across all of the California counties are dominated by BTW emissions, especially those from the HDT fleet.

Near-Roadway $PM_{2.5}$ Concentrations in Los Angeles County. The near-roadway $PM_{2.5}$ concentrations at the census block group level were simulated based on the link-level vehicle emission inventory and a dispersion model. As depicted in Figure 3, the population-weighted near-roadway $PM_{2.5}$ concentrations in the Los Angeles County decrease from 0.27 to 0.17 $\mu g/m^3$ between 2021 and 2050 (Figure 3A and D), with BTW emissions accounting for 0.18 and 0.16 $\mu g/m^3$, respectively. These estimates are comparable with measurement data in other studies. For example, a near-road study

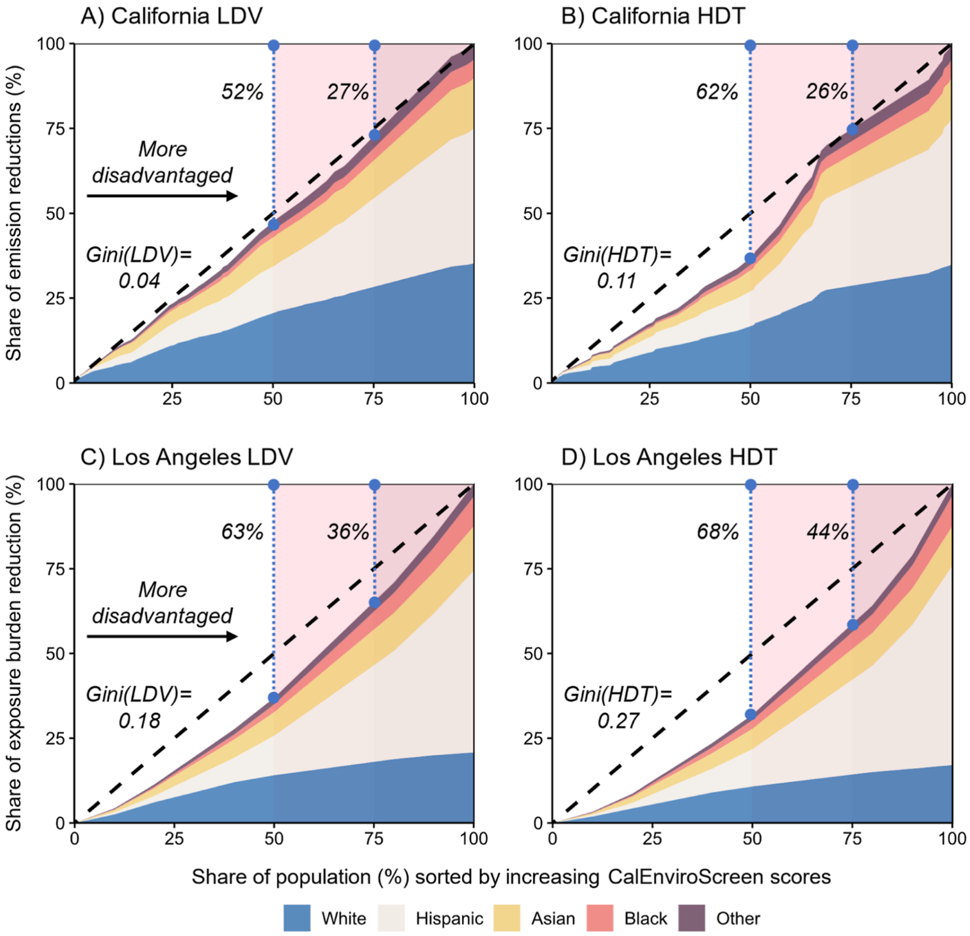


Figure 4. Environmental benefits attributed to the widespread adoption of ZEVs across all California counties and Los Angeles census block groups from 2021 to 2050. Adopting zero-emission (A) LDVs and (B) HDTs across all California counties and adopting zero-emission (C) LDVs and (D) HDTs across Los Angeles census block groups. The *x*-axis represents the cumulative populations across all California counties and Los Angeles census block groups that are sorted by increasing CalEnviroScreen scores, where the higher rankings are considered more disadvantaged. The more disadvantaged half (50−100%) and the most disadvantaged quantile (75−100%) of the population are highlighted in red. The *y*-axis represents the cumulative percentages of total environmental benefits that result from ZEV adoption. The distribution of total environmental benefits among communities is represented as Lorenz curves and is colored by racial/ethnic shares. The Gini index is a measure of inequality, with values ranging from 0 to 1. A Gini index of 0 represents perfect equality (where every community receives the same environmental benefits from ZEV), and a Gini index of 1 indicates maximum inequality (where all benefits are concentrated in one community).

conducted in Toronto reported that brake wear emissions accounted for 0.20 $\mu g/m^3$ of the total $PM_{2.5}$ at downtown sites.[33] As indicated in Figure S5, the total daily on-road $PM_{2.5}$ emissions in the Los Angeles County are estimated to be 2.96 t/day in 2021 and 1.83 t/day in 2050, with tailpipe emissions accounting for 31% and 8% of the total emissions, respectively. The rapid decrease in tailpipe emissions leads to a substantial increase in the share of BTW emissions from 69−92% (Figure 3B and E). The LDV emissions decrease rapidly from 1.92 to 0.98 t/day with ZEV adoption from 2021 to 2050. However, the HDT emissions decrease only slightly from 1.04 to 0.85 t/day. According to EMFAC2021 v1.0.2,[28] the total VMT of the LDV fleet is almost unchanged, while the total VMT of the HDT fleet is projected to increase by 1.7 times the 2021 level, which largely offsets the benefits of ZEV adoption. Consequently, the contribution of HDTs to the total on-road $PM_{2.5}$ emissions increases from 35% to 47% between 2021 and 2050. The HDT fleet will dominate the near-roadway $PM_{2.5}$ concentrations in the central and southeastern areas by 2050 (Figure 3F) owing to the dense freight activities in these areas and an increase in VMT.

To quantify the impacts of multiple driving forces behind the $PM_{2.5}$ changes from 2021 to 2050, we attributed these changes to four major drivers: an increase in VMT (Figure S6A), tailpipe emissions controls (Figure S6B), the adoption of ZEVs in the LDV fleet (Figure S6C), and HDT fleets (Figure S6D). Different spatial distribution patterns of $PM_{2.5}$ concentration reductions are modeled for ZEV adoption in the LDV and HDT fleets. As mentioned earlier, the changes in VMT in the Los Angeles County are primarily driven by the HDT fleet. The spatial distributions of the changes in $PM_{2.5}$ that can be attributed to VMT increases and zero-emission HDT adoption resemble each other. The changing ratios of $PM_{2.5}$ emissions are significantly greater in the major freight corridors than in other areas.

ZEV Adoption Reduces More $PM_{2.5}$ in Disadvantaged Communities. The four Lorenz curves in Figure 4 show that the widespread adoption of zero-emission LDVs and HDTs brings environmental benefits in 2050 across all California counties (Figure 4A, B), as well as in the Los Angeles census block groups (Figure 4C, D). The Lorenz curve was initially developed to represent income inequality, where the horizontal

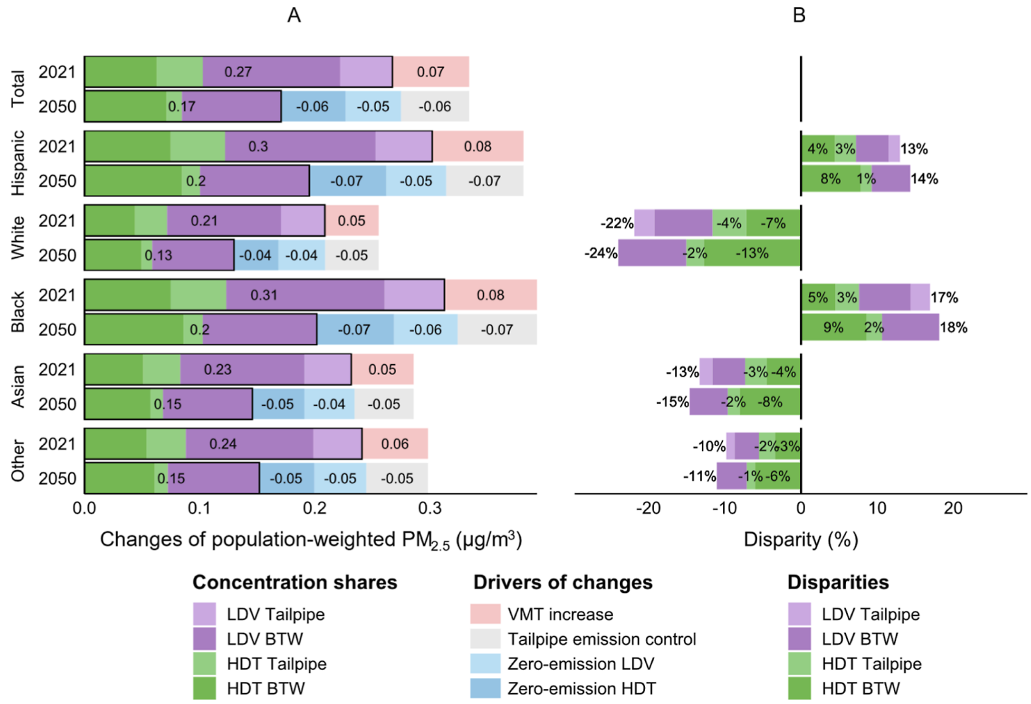


Figure 5. Near-roadway $PM_{2.5}$ exposure disparities by race-ethnicity in the Los Angeles County in 2021 and 2050. (A) Near-roadway $PM_{2.5}$ concentrations in 2021 and 2050 along with the driving forces of $PM_{2.5}$ changes from 2021 to 2050 among various racial/ethnic groups. The $PM_{2.5}$ concentrations are represented by light/dark purple and green colors, which indicate the tailpipe and BTW emissions from the LDV and HDT fleets, respectively. The bars colored pink, gray, light blue, and dark blue depict the impacts of the four major drivers on $PM_{2.5}$ changes: VMT increase, tailpipe emission control, adoption of zero-emission LDVs, and HDTs. (B) Racial/ethnic disparities in $PM_{2.5}$ concentrations and the contributions of different fleets and emission sources in 2021 and 2050. The racial/ethnic disparities were calculated as the percentage differences between the PWAC of each racial/ethnic group and the total population.

axis represents the cumulative population and the vertical axis represents the cumulative population income.[56] Here, we adapt the Lorenz curve concept and plot the environmental benefits on the vertical axis to evaluate the EJ impacts of ZEV adoption. The environmental benefits are defined as the $PM_{2.5}$ emission reductions across all California counties (Figure 4A, B) and exposure burden reductions across the Los Angeles census block groups (Figure 4C, D) that are due to the adoption of ZEVs. The reductions in exposure burdens were calculated as $\Sigma(P \times \Delta C)$, where P represents the population by race-ethnicity in each census block group, and ΔC represents the concentration change that is attributed to ZEV adoption in each census block group (Figure S6C, D). We acknowledge that the county-level analyses are not as refined as the block-group-level analysis in LA, as the county-level analyses used $PM_{2.5}$ emission reductions rather than exposure changes to represent environmental benefits. However, both analyses are necessary, as they address the disproportionate environmental benefits among different regions and subregions.

Taking Figure 4D as an example, the Lorenz curve illustrates the cumulative exposure reductions across the Los Angeles census block groups that are attributed to the adoption of zero-emission HDTs, which are color-coded by racial/ethnic shares. The populations are sorted on the x-axis by increasing CalEnviroScreen scores, with the left side representing the less disadvantaged and the right side representing the more disadvantaged populations. The more disadvantaged half (50–100%) and the most disadvantaged quantile (75–100%) of the population are highlighted in red shades. The blue dotted lines represent the cumulative benefits that are shared by these two groups, indicating that the more disadvantaged 50% and the most disadvantaged 25% of the population experience 68% and 44%, respectively, of the total environmental benefits that result from promoting zero-emission HDTs in Los Angeles. The relationship between the level of disadvantage and racial/ethnic attribution is apparent with the deceleration of white attribution and the rapid growth of nonwhite attributions toward the right end (more disadvantaged census block groups), especially for the Hispanic population.

As shown in Figure 4, for both the state and Los Angeles County, more disadvantaged communities experience a greater share of environmental benefits from ZEV adoption. The more disadvantaged half (50–100%) of the population experiences 57% and 66% of the total environmental benefits that arise from promoting ZEVs across all California counties and Los Angeles census block groups, respectively. Given that the Los Angeles County has a greater demographic diversity than the state average, the benefits of ZEV adoption are more notable for the more disadvantaged half (50–100%) of the population.

In addition, under our projected future ZEV scenarios, promoting zero-emission HDTs generates more benefits for disadvantaged communities than promoting LDVs, as indicated by the greater Gini indices and larger shares of environmental benefits. In the Los Angeles County, the most disadvantaged quantile of the population (75–100%) experiences 36% and 44% of the total environmental benefits from promoting zero-emission LDVs and HDTs, respectively, which are 2.4 and 3.7 times greater than the benefits shared by the least disadvantaged quantile (0–25%) (Figure S7B). In comparison, the environmental benefits that result from adopting zero-emission LDVs are evenly distributed among the four population quantiles across all California counties

(Figure S7A). The third quantile of the population (50−75%) received the most benefit (36%) from adopting zero-emission HDTs, with Riverside, San Bernardino, and Kern Counties accounting for 8%, 10%, and 8%, respectively, of the total benefits. This is because those counties have a higher share of HDT emissions in both 2021 and 2050. Transferring HDTs into zero emissions brings more benefits. Despite the considerable emission reduction benefits of HDT ZEV adoption, these counties are expected to experience substantial increases in HDT VMT in 2050 (e.g., 1.65, 1.63, and 1.86 times greater than those in 2021 for Riverside, San Bernardino, and Kern Counties, respectively), which substantially offsets the benefits of ZEV adoption. To maximize the benefits of ZEV adoption, it is crucial to address the increase in the level of HDT activities.

Disparities in $PM_{2.5}$ Exposures Among Racial/Ethnic Groups. We quantified the disparities in near-roadway $PM_{2.5}$ exposures by race-ethnicity in the Los Angeles County at the census block group level for 2021 and 2050 (Figure 5). As shown in Figure 5A, $PM_{2.5}$ concentrations are represented by light/dark purple and green colors with a black border indicating the tailpipe and BTW emissions from the LDV and HDT fleets, respectively. The impacts of four major drivers on $PM_{2.5}$ concentrations—(1) VMT increases, (2) tailpipe emission controls, (3) adoption of zero-emission LDVs, and (4) adoption of zero-emission HDTs—are depicted by translucent bars colored in pink, gray, light blue, and dark blue, respectively. Increases in VMT contributed to a rise in the $PM_{2.5}$ concentration, while tailpipe emission controls and the adoption of ZEVs led to decreases in $PM_{2.5}$. The racial/ethnic disparities shown in Figure 5B are defined as the percentage differences (%) between the PWAC of a given racial/ethnic group and the total population. A positive number indicates that a group is disproportionately impacted by near-roadway $PM_{2.5}$, while a negative number suggests that a group is less impacted than the average.

As shown in Figure 5A, from 2021 to 2050, tailpipe emission controls and the adoption of ZEVs in LDV and HDT fleets contributed to a decrease of 0.05−0.06 $\mu g/m^3$ in $PM_{2.5}$ concentrations in the Los Angeles County, while the increased VMT offset 0.07 $\mu g/m^3$ of the total benefits. Consequently, the population-weighted near-roadway $PM_{2.5}$ concentrations in the Los Angeles County decrease from 0.27 to 0.17 $\mu g/m^3$ between 2021 and 2050. In comparison, Skipper et al.[58] reported reductions in annual average $PM_{2.5}$ concentrations of 0.24 ± 0.18 $\mu g/m^3$ and 0.17 ± 0.14 $\mu g/m^3$ for 2016 and 2028, respectively, under the 100% EV scenario. The reduction in 2050 is expected to be lower due to reduced tailpipe emissions. According to our results, reductions in annual average near-roadway $PM_{2.5}$ concentrations were 0.10 (0.008 and 0.32) $\mu g/m^3$ (population-weighted average, fifth and 95th percentiles) among census block groups in Los Angeles in 2050. It is important to note that our study considered only primary $PM_{2.5}$, while Skipper et al. included both primary and secondary $PM_{2.5}$ using CMAQ. These differences explain why the $PM_{2.5}$ concentration reductions in our study are lower than those reported by Skipper et al.

As indicated in Figure 5B, the White and Asian populations experienced 22% and 13% lower near-roadway $PM_{2.5}$ concentrations, respectively, than the average in 2021, while the Hispanic and Black populations experienced 13% and 17% higher concentrations than the average, respectively. These results compare well with those of other studies. For example, Reichmuth[44] stated that White Californians are exposed to 17% lower traffic-derived $PM_{2.5}$ concentrations than the state average, while African American and Latino Californians experience 19% and 15% higher concentrations, respectively. The LDV and HDT fleets contributed comparably to these disparities in 2021. However, the disparities in 2050 persist or worsen despite substantial tailpipe emission reductions resulting from ZEV adoption, with increased disparities largely attributed to HDT BTW emissions. The increase in HDT fleet VMT is the main reason, which offsets a large portion of the net benefits derived from promoting ZEVs. In fact, the contributions of HDT BTW emissions to the total disparities nearly doubled from 2021 to 2050 among the different population groups. In 2050, the White and Asian populations experience 24% and 15% lower near-roadway $PM_{2.5}$ concentrations, respectively, than average, with the HDT fleet accounting for 63% and 67%, respectively, of the total disparities. In contrast, the Hispanic and Black populations in the Los Angeles County experienced 14% and 18% higher near-roadway $PM_{2.5}$ concentrations than the average, respectively, with the HDT fleet accounting for 64% and 58%, respectively, of the total disparities. Therefore, solely adopting zero-emission HDTs without addressing the increased HDT activities is not enough to reduce environmental injustice in the future, especially for racial and ethnic minority populations, who are more likely to reside near busy freight corridors. To address this persistent disparity, future policies would need to address BTW emissions, which are expected to dominate more than 90% of the near-roadway $PM_{2.5}$ exposure disparities in 2050.

DISCUSSION

On-road traffic emissions contribute substantially to exposure disparities and environmental injustice.[4−7] Thus, a clean transportation transition is critical to addressing persistent EJ issues related to traffic emissions. While the cobenefits of ZEV adoption for ambient air quality and EJ have been well documented in previous studies, few studies have focused on the remaining BTW particles in near-roadway communities and how they evolve with the increased penetration of ZEVs. Unlike secondary $PM_{2.5}$, which is more evenly distributed among communities, BTW particles are particularly important in near-roadway environments and disproportionately affect the low-income, racial, and ethnic minority populations living near roadways. Thus, analyzing near-roadway $PM_{2.5}$ at equity-relevant scales is important from an EJ perspective.

Our study contributes to a more comprehensive analysis framework for addressing EJ issues related to ZEV penetrations. We developed a bottom-up assessment framework that involves three key components: an integrated link-level traffic model, a line-source dispersion model, and an environmental benefit analysis based on Lorenz curves. This framework allows us to evaluate the impacts of future ZEV adoptions on near-roadway air quality and EJ implication. Unlike previous studies assuming that a uniform portion of the future fleet across the road network is composed of ZEVs, our bottom-up traffic modeling method enables us to model the spatial distribution of ZEVs from individual trips at the link level. Another contribution of our EJ analyses is the utilization of the Lorenz curve and Gini index to evaluate the normalized distributions of environmental benefits among different populations. This approach establishes a comparable standard for policy evaluations regardless of the distinct absolute total benefits. This method enables comparisons of policy efficacy in reducing environmental injustice across different regions or subregions (e.g., California counties and Los Angeles census block groups) and between different policies (e.g., promoting zero-emission LDVs and HDTs).

Under the assumption of future scenarios in this study, adopting zero-emission HDT fleets provides greater benefits for disadvantaged communities compared to LDV fleets in both California and Los Angeles County. Additionally, the HDT fleet is becoming increasingly important because of its contributions to both total on-road $PM_{2.5}$ emissions and exposure disparities. Thus, ZEV policies targeting HDTs for disadvantaged communities are more promising for reducing historical environmental injustice. This can be achieved by directing more rebates and incentives for the adoption of zero-emission HDTs, prioritizing the development of charging or refueling infrastructure for zero-emission HDTs, and implementing regulations or mandates to use zero-emission HDTs in disadvantaged communities.[3,59,60] Moreover, historical unjust urban planning and demographic distributions have resulted in disadvantaged communities hosting heavier freight activities. These areas are also expected to experience greater increases in the freight travel demand (i.e., VMT of HDTs) in the future,[61] which could offset the environmental benefits of ZEV adoption. Based on our results, changes in $PM_{2.5}$ emissions from HDT fleets vary greatly among California counties and are primarily driven by VMT changes. The HDT fleets dominate near-roadway $PM_{2.5}$ concentrations in the central and southeastern areas of Los Angeles County due to dense freight activities in these regions. To maximize the benefits of ZEVs, it is crucial to simultaneously reduce the heavier freight burdens (i.e., reduce the VMT of HDT fleets) in disadvantaged communities. For example, optimizing land-use plans for industrial and freight-related activities, implementing smart logistics and route optimization technologies to minimize the impact of freight traffic in disadvantaged areas, and promoting alternative transportation modes such as rail and waterways.

Another important implication of our study is that future policies aimed at addressing environmental inequality from transportation emissions in California need to address BTW emissions, which are expected to dominate near-roadway $PM_{2.5}$ exposure disparities and pose a greater risk of toxicity and adverse health outcomes for traffic-impacted communities in the future.[30,32] Many factors may affect BTW emissions from ZEVs, including increased vehicle weights due to the battery packs, regenerative braking, and driving conditions.[21−23,62−64] For example, brake wear emissions for BEVs and PHEVs are expected to be approximately 50% lower than those for combustion engine cars due to the possibility of installing regenerative braking systems in addition to conventional frictional brakes.[31,62] However, the tire wear emissions are expected to increase for BEVs due to their increased weight.[23,31] BEVs are reported to be 14.6−28.7% heavier than their ICEV counterparts, leading to a 10−28% increase in tire wear emissions.[31,65] Uncertainties also persist regarding the future adoption of alternative fuels and their impacts on vehicle weights, such as battery electric versus hydrogen fuel cells. Currently, there is limited regulation of BTW emissions or product standards that govern the compositions of brake pads and tires that are explicitly designed to limit emissions.[22,63] To reduce the adverse health impacts of BTW emissions, a range of legislative, traffic management, and scientific engineering measures are needed.[21,23] Efficient traffic management strategies may include reducing the volume, speed, and braking intensity of traffic. Scientific engineering measures could involve lighter vehicle weights, especially for ZEVs (e.g., by size, design, and lighter materials) and exploring alternative materials for rubber and brake pads. Setting limits on the contents of certain heavy metals and compositions might also reduce the toxicity of the BTW emissions.

Our study has several limitations. First, we considered only primary $PM_{2.5}$ in the assessment of near-roadway $PM_{2.5}$ concentrations, without exploring secondary $PM_{2.5}$ and other non-$PM_{2.5}$ pollutants associated with reductions in tailpipe emissions. In one of our previous studies, we discussed the impacts of ZEVs on near-roadway NO_2 and $PM_{2.5}$ in Los Angeles County.[42] Here, we aim to address the remaining issues by focusing on nontailpipe particle emissions. Second, we projected ZEV adoption levels in different areas based on historical trends and recent policy penetration targets without considering other potential interventions or incentives that could influence ZEV penetration patterns. Also, we assumed that demographic patterns in our research domain would remain the same and used 2021 data for our 2050 future scenario, including the distribution of racial/ethnic groups. Third, we utilized EMFAC obtained directly from EMFAC. While EMFAC2021 accounts for driving speeds and regenerative braking, it does not consider the potential impact of increased BEV weight due to limited tests[28] which may lead to underestimations of total BTW emissions by 6−16% and 4−10% for LDVs and HHDTs, respectively, in our study. Finally, we acknowledge the impact of upstream emissions from electricity generating units resulting from increased electricity demand due to ZEVs. However, we anticipate that these emissions would have a minimal impact on near-roadway $PM_{2.5}$ levels in Los Angeles County. Studies have suggested that a clean energy portfolio is key to reducing upstream emissions and ensuring environmental justice.[66,67] Shifting from fossil fuels to clean energy sources has the potential to substantially reduce upstream emissions from electricity generating units in Los Angeles and California.

Despite these limitations, our conclusion remains robust: disparities in near-roadway $PM_{2.5}$ levels persist in 2050 due to the remaining BTW emissions and increased HDT traffic in disadvantaged communities. Addressing these EJ issues requires more targeted ZEV policies and BTW emission abates in California.

■ ASSOCIATED CONTENT

Data Availability Statement

The data sets analyzed in this study are sourced from publicly available databases as cited within the manuscript. These resources are open-access and can be freely accessed for further research and validation. Specifically, the Environmental Justice Index can be accessed from California government Web sites (https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40). California ZEV registration data and emission rate data can be found in the EMFAC Database (https://arb.ca.gov/emfac/fleet-db and https://arb.ca.gov/emfac/). Meteorological data are available from the National Oceanic and Atmospheric Administration (https://www.ncei.noaa.gov/data/global-hourly/archive/isd/and https://rucsoundings.noaa.gov/). The R-LINE modeled hourly traffic-attributable $PM_{2.5}$ concentrations for all scenarios are open access at DOI: 10.6084/m9.figshare.25560897.

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.4c04126.

> Detailed descriptions of vehicle emission inventory calculations, simulation of link-level vehicle volumes in Los Angeles County, driver analysis of changes in $PM_{2.5}$ levels, future trends in the percentage of ZEV ownership, $PM_{2.5}$ emission factors, on-road $PM_{2.5}$ emissions, impacts of VMT change and ZEV penetration, changes in the near-roadway $PM_{2.5}$ concentrations, share of environmental benefits, spatial distribution of simulated daily traffic flows, link-level daily $PM_{2.5}$ emissions, division of vehicle types, ZEV shares, scenario settings, and driving force analysis (PDF)

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Author Contributions

Y.W., Q.Y., and Y.Z. designed the research. B.H. performed the transportation analysis. Y.W. calculated the on-road emission inventories. Q.Y. performed the near-roadway PM2.5 simulations. Y.W. performed the equity and air quality analysis. Y.Z. supervised the research. Y.W. and Q.Y. wrote the manuscript and S.Z., Y.W., and Y.Z. reviewed the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by University of California Office of the President Climate Action under grant number R02CP6948 to Y.Z., the National Natural Science Foundation of China (Grant no. 42305189), and the China National Postdoctoral Program for Innovative Talents (no. BX20220179) to Y.W. The views, opinions, findings, and conclusions or recommendations expressed in this paper are strictly those of the authors. They do not necessarily reflect the views of funding agencies and/or authors' affiliated institutes.

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