Pavement resurfacing and supply chains are significant contributors to PM$_{2.5}$ exposure from road transportation: evidence from the San Francisco Bay Area

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Abstract
There are hundreds of millions of kilometers of paved roads and many people live in proximity. Pollution from road transportation is a well-documented problem potentially leading to chronic health impacts. However, research on the raw material production, construction, operation, maintenance, and end-of-life phases of paved roads, and corresponding supply chains, is generally limited to energy consumption and greenhouse gas emissions. No previous research efforts on the life-cycle stages of pavements and road operation connect pollutant emission inventories to intake of inhaled pollutants and resulting damages to exposed populations. We have developed a first-of-its-kind model quantifying human exposure to fine particulate matter (PM$_{2.5}$) due to emissions from routine pavement resurfacing and vehicle operation. We utilize the Intervention Model Pollution Source-Receptor Matrix to calculate marginal changes in ground-level PM$_{2.5}$ concentrations and resulting exposure intake from a spatially resolved primary and secondary PM$_{2.5}$ emission precursors inventory. Under a scenario of annual road-resurfacing practices within the San Francisco Bay Area in California (population: 7.5 million), resurfacing activities, material production and delivery (i.e. cement, concrete, aggregate, asphalt, bitumen), and fuel (i.e. gasoline, diesel) supply chains contribute almost 65% to the annual PM$_{2.5}$ intake from all the sources included in the study domain (the remaining 35% being due to on-road tailpipe emissions). Exposure damages range from $170 to $190 million (2019 USD). Complete electrification of on-road mobile sources would reduce annual intake by 64%, but a sizable portion would remain from material supply chains, construction activities, and brake and tire wear. Future mitigation policies should be enacted equitably. Results show that people of color experience higher-than-average PM$_{2.5}$ exposure disparities from the emission sources included in the study, particularly from material production.

1. Introduction
There are over 2.8 million miles of paved roads in the United States alone [1]. Vehicle operation and necessary maintenance of roads emit air pollutants of which fine particulate matter (PM$_{2.5}$) and its precursors are of particular concern for health damages. More than 19% of the U.S. population lives near high traffic volume roads [2]. People of color and lower-income populations disproportionately live near high-traffic roads [3].
precursor emissions ranging from $52 to $120 billion (2018 USD) or as much as $182 billion (2018 USD) [14, 15].

Health impacts and exposure damages from PM$_{2.5}$ due to roadway construction are less known than from on-road mobile sources. Studies often assess worker exposure to carcinogens from asphalt paving [16–18]. One study identified which activities (material processing and delivery) contribute the most to pollution from roadway construction [19], while another identified paving operations leading to peak PM$_{2.5}$ for a hot mix asphalt pavement [20]. Documented PM$_{2.5}$ air pollution from production of materials used in roadways is relatively minimal. Concentrations of PM$_{2.5}$ were calculated for two cement plants in varying seasons [21] and for aggregate quarries, finding that concentrations vary seasonally [22, 23]. Kiln type is a contributing factor to air pollution intensity from the cement industry, at least in China [24].

Multiple studies incorporate life-cycle assessment (LCA) to evaluate pollutant emissions from the raw material production, construction, operation, maintenance, and end-of-life phases of paved roads. Pavement LCAs typically focus on inventorying greenhouse gas and criteria air pollutant emissions for a variety of asphalt and concrete pavement designs in various countries [25–35], but very few include inventories of PM$_{2.5}$ [29, 30, 36]. No pavement LCAs connect pollutant emission inventories to intake of inhaled pollutants and estimate resulting damages for exposed populations.

There is extensive evidence that Black, Hispanic/Latino, and Asian populations in the United States experience a disparate exposure burden of PM$_{2.5}$ and other criteria air pollutants [37–39]. Addressing these disparities is increasingly a focus of state and federal policies [40–43]. Because air pollution is often most effectively addressed at its source, efforts to advance environmental justice can be informed by assessment of the degree to which specific pollution source types lead to exposure disparities. In aggregate, people of color are estimated to experience higher-than-average burdens of air pollution from most economic sectors, with highest absolute disparities from industry, vehicle, and construction emission sources [44]. Efforts to estimate PM$_{2.5}$ exposure burden at finer spatial scales and by source for different demographic groups are ongoing [45]. Recent work models PM$_{2.5}$ intake from on-road vehicle emissions for a major U.S. metropolitan transportation network [46]. Given that differences in air pollution burden can change at the city block level [47], it is important to make determinations about which emission sources and mitigation options are most significant at a local scale.

We have developed a human exposure assessment model capturing pavement resurfacing and vehicle traffic on roadways in metropolitan regions. We estimate population-weighted concentration and intake values of primary and secondary PM$_{2.5}$ at the census tract level for the raw material and fuel production, material delivery and resurfacing activities, and vehicle operation phases of a paved road. We fill a gap in exposure studies by cataloging a portfolio of sources related to all phases of a roadway’s life cycle. Our research answers questions critical for future transportation and human health policy planning, including:

(a) What is the full scope, accounting for material and fuel supply chains, of PM$_{2.5}$ exposure impacts from the operation and full-width resurfacing of roadways within a metropolitan region such as the San Francisco Bay Area?

(b) How significant are impacts from material and fuel supply chains and expected resurfacing of roadways compared to exposure from on-road mobile sources?

(c) Do specific demographic groups experience undue exposure burdens from on-road mobile sources, roadway resurfacing, and supply chain operations?

(d) How do policies such as electrification of on-road/off-road vehicles, increased fuel efficiencies, and implementation of pollution control technologies change exposure burdens?

(e) Which mitigation strategies should be selected given their reduction to external damage costs?

Our research objectives are centered on:

(a) understanding the full range of exposure impacts from road transportation for a region’s population to build upon previous exposure studies which only examine the impacts from on-road mobile sources and do not explicitly link impacts from construction activities, material production facilities, and oil refineries to a specific roadway network; (b) identifying mitigation strategies that are effective in minimizing human health impacts; (c) determining the extent to which transportation policies such as electrification can mitigate the full scope of exposure burdens from a roadway network; (d) exploring limitations of completely eliminating exposure burdens from road transportation and its supply chains; and (e) assigning economic value to the harm caused by the full range of exposure impacts from road transportation so that decision-makers can prioritize areas of pollution mitigation strategies.

The remainder of the article is structured as follows: section 2. Methods outline the inputs, models, and expected results associated with the exposure assessment, section 3. Results provide the results from the baseline PM$_{2.5}$ exposure assessment and from application of mitigation strategies, section 4. Discussion details the significance of the results from
both an academic and broader policy context, and section 5. Conclusions finish with suggestions for viewing the significance of the study’s results and for guiding future research efforts.

2. Methods

We estimate PM$_{2.5}$ intake and exposure damages using a spatially resolved inventory including tailpipe and supply-chain emissions from annual pavement resurfacing and vehicle use on road segments within the San Francisco Bay Area using 2019 data. Figure 1 highlights the key modeling steps. By knowing the location of emissions, both from on-road and off-road mobile sources along road segments and from stationary sources at material and fuel production facilities, we can identify which receptors (i.e. population groups inhaling pollutants) are most susceptible.

2.1. Study domain: San Francisco Bay Area

The San Francisco Bay Area, a nine-county metropolitan region in Northern California, is home to more than 7.5 million people [48]. It is racially diverse, but remains racially, ethnically, and economically segregated among communities and neighborhoods. All but three counties (Marin, Napa, Sonoma) have majority people-of-color populations [49]. Four of the nine counties (Marin, San Francisco, San Mateo, Santa Clara) rank in the top four statewide in per-capita income [49]. California, and the Bay Area in general, is an appropriate study domain for examining disparate exposure impacts from roadway infrastructure. Roughly 40% of Californians live within 500 meters of a high-traffic road [2]. California, the most populous U.S. state, emits the most PM$_{2.5}$ from road transportation in the country and has the highest premature mortality attributable to road transportation-related PM$_{2.5}$ [50].

The Bay Area’s ‘racialized geography’ [51], partially influenced by historical practices that have contributed to disparities in air pollution exposure [58], suggests that multiple racial-ethnic groups may be asymmetrically burdened in their exposure resulting from polluting roadway infrastructure. We select roadway segments from all nine counties to analyze. The segments are a mixture of low-, medium-, and high-volume highways and expressways (interstate and state routes), routinely rehabilitated/main- tained by the state’s Department of Transportation (Caltrans) and local municipalities. The selected segments capture differences in population densities and demographic characteristics. Spatial variety is important to account for differences in how physical transport and chemical transformations influence the formation of secondary PM$_{2.5}$.

2.2. Selection & design, operation, resurfacing characteristics of roadway segments

The number of roadway segments included in the analysis is based on a set of realistic scenarios that parameterize how many separate miles of pavement would be maintained on an annual basis. Two sce- narios of pavement resurfacing activities are analyzed: (a) Scenario 1 roadway segments are in all nine counties in the Bay Area with various levels of low, medium, and high average annual daily traffic (AADT); (b) Scenario 2 roadway segments are located solely in census tracts designated as disadvantaged communities (DAC) according to California State Bill 535 [52, 53]. The DAC census tracts fall into the 25% highest pollution-burdened areas as per CalEnviroScreen, the state’s pollution mapping tool [54].

We estimate roadway length in the Bay Area to be about 10 000 miles, but that includes every road, even the smallest street, that is infrequently overlaid with new pavement material. No annual data are available; thus, we cautiously estimate that at the minimum 30–45 one-mile segments would be full-width repaved in any given year. All road segments and associated characteristics are provided in detail in tables 8 through 11 in the Supplemental Information (SI).

2.2.1. Roadway design

Paved roadways consist of multiple layers of materials, typically subbase, base, and surface layers. Surface layers are either rigid (concrete), flexible (asphalt), or a composite of the two (typically old concrete pavements overlaid with asphalt). As per the Caltrans Highway Design Manual (HDM), there are different design and maintenance requirements for each pavement type. The material composition and thickness of each layer within the pavement structure is determined by the roadway’s location and the expected volume of truck traffic on the roadway [55]. Each pavement type needs a fleet of distinct equipment during the material delivery and repaving phases of the roadway.

The surface layer type for each roadway, which dictates the material composition and thickness of each layer within the pavement structure, was determined using satellite view on Google Maps (in absence of specific data from the agency maintaining the road). Measured AADT counts from Caltrans were used to calculate the traffic intensity for each roadway segment in the dataset [56]. The traffic intensity metric indicates the traffic volume of multiple-axle trucks on a roadway over a given period of time; expected maximum weight on a roadway dictates the depths of each pavement layer [57]. California’s pavement climate region map was utilized in determining the depth of layers for rigid pavements [58].
2.2.2. Roadway resurfacing
Pavement structure type determines necessary resurfacing activities and construction equipment. Activities (e.g. milling, grading, paving, compacting) and equipment (e.g. millers, graders, pavers, etc) were determined using the Caltrans HDM and the RSMeans Heavy Construction Cost Database [57, 59]. The assumed resurfacing process for rigid pavements is mill (of the old pavement), recompaction of base, and full-width overlay with new material; for flexible pavements, the assumed resurfacing process is hot-mix recycling of the entire length and width of the road in addition to base recompaction. RSMeans lists equipment needed for a wide range of activities, including those related to constructing and maintaining flexible and rigid pavement layers, base layers, and subbase layers [59]. Equipment productivity (i.e. how much work equipment can complete in a given time period) is determined using operation specifications from prototypical manufacturers (table 12 in the SI). As explained in section 2.3, productivity affects the equipment’s tailpipe emissions and fuel consumption.

2.2.3. Roadway operations
Average annual traffic volumes for each road segment are estimated from measured AADT count data from Caltrans [56]. The 2019 Bay Area fleet composition (i.e. the amount and type of each vehicle) for each road segment comes from California Air Resources Board (ARB) projections [60] (see table 12 in the S.I.)

2.3. PM$_{2.5}$ exposure modeling
2.3.1. Emissions inventory
As indicated in figure 1, a spatially resolved emissions inventory of primary PM$_{2.5}$ and secondary formation of PM$_{2.5}$ from nitrogen oxides (NO$_x$), volatile organic compounds (VOCs), sulfur dioxides (SO$_2$), and ammonia (NH$_3$) precursors is the key input for assessing population exposure concentrations and pollution intake. Figure 2 depicts the scope of emission sources accounted for in the exposure assessment. Pacific Gas and Electric Company (PG&E) supplies Bay Area’s electricity. As the study domain is limited to the Bay Area, any exposure impacts from natural-gas-fired electricity generation sources that PG&E might purchase or import from out of state to meet demand are excluded. (There is no coal in the electricity mix.)

In general, mobile-source emissions are calculated using equation (1):

$$E_M = \sum_{i=1}^{n} EF_{M,i} \times T_{M,i}$$

where $E_M$ is the sum of emissions from the total number of mobile sources $n$ (Vehicle Operation, Construction Maintenance, Material Delivery), $EF_{M,i}$ is the emission rate (in mass per unit time) for mobile source $i$, and $T_{M,i}$ is the amount of time the mobile source $i$ emits pollutants. Stationary source emissions are calculated with equation (2):

$$E_S = \sum_{i=1}^{p} EF_{S,i} \times V_{S,i}$$

where $E_S$ is the sum of emissions from the total number of stationary sources $p$ (Material Production, Crude Oil Production), $EF_{S,i}$ is the emission factor (in mass per unit volume) for stationary source $i$, and $V_{M,i}$ is the volume of material $i$.

Emission rates for primary PM$_{2.5}$, NO$_x$, SO$_2$, NH$_3$, and VOCs for on-road and off-road mobile sources come from ARB’s emission factor (EMFAC) modeling tool [61]. All emission rates are modeled for the 2019 calendar year within the boundary of the Bay Area Air Quality Management District (BAAQMD), the agency that regulates ambient air pollution within the Bay Area’s nine counties [62]. Stationary source emission factors depend upon the respective volumes of materials needed for the roadway segment. Detailed emission equations for each main source are provided in section 7 of the SI.
2.3.2. Material production facilities
Realistic volumetric production rates are assumed, based on prior experience, of material per year for prototypical cement, ready-mixed concrete, asphalt, and aggregate production facilities. Relevant facilities within the boundaries of BAAQMD are identified in ARB’s Facility Search Engine using Facility SIC (Standard Industrial Classification) Codes [63]. Codes related to the manufacturing of cement, construction sand and gravel, ready-mixed concrete, and asphalt pavement mixes are used to identify relevant facilities. ARB tracks each facility’s annual emissions of criteria air pollutants and toxic substances.

Based on each facility type’s assumed production rate and the annual emissions rate for each facility in the dataset, an emission factor for each facility is calculated. Total material emissions for each pavement segment are estimated by multiplying the unique volumes of materials in each segment (i.e. the volume of asphalt, volume of aggregate, etc) by the emission factor for that road segment’s closest respective material production facility.

2.3.3. Oil refineries
There are seven crude-oil refineries within the Bay Area. Two refineries (Chevron in Richmond and Shell in Martinez) are used as proxy locations of where the gasoline, diesel, and bitumen products would be manufactured. The assumption that 50% of products is sourced from either refinery does not affect the final exposure results as the refineries are located close enough that dispersion of pollutants will not significantly differ.

Well-to-pump emission factors, in grams of pollutant per gallon of consumed gasoline or diesel, are derived from the California Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (CA-GREET) from ARB [64]. Volumes of gasoline and diesel from on-road and off-road sources are estimated. On-road volumes of fuel for each one-mile road segment are derived by multiplying average fuel economies for different vehicle types (e.g. passenger, light duty trucks, etc) by CA-GREET emission factors. Off-road fuel economies are provided in EMFAC in units of grams of pollutant per hour of equipment use.

Bitumen emission factors are estimated in a manner similar to the method employed in estimating material production facility emission factors. Measured production rates, in terms of number of barrels produced at each facility per day, are tabulated for each refinery [65]. It is assumed that 4%, by volume, of each crude oil barrel is transformed to bitumen (see SI section 5). Using annual emissions data from each refinery from ARB, an emission factor is calculated in tons of emission per cubic yard of bitumen.

2.3.4. Construction/Resurfacing
Pollutant-specific off-road mobile source emission factors from ARB’s EMFAC emission inventory webtool are used. The 2019 BAAQMD fleet for ‘Construction and Mining’ equipment is utilized, assuming an aggregate range of model years. Tailpipe emissions from construction are estimated by multiplying the equipment’s specific emission factor by the equipment’s total activity hours. Total activity hours depend upon the physical dimensions of the road pavement structure to be constructed and the productivity of the specific piece of equipment performing the work.

2.3.5. Material delivery
It is assumed that materials will be delivered from the closest respective facility to each road segment.
Only last-mile deliveries (i.e., deliveries from final material facilities to the road segment) are accounted for; deliveries between facilities (e.g., deliveries from the aggregate plant to the ready-mixed concrete plant) are excluded. For each road segment, the distance of the nearest respective production facility (figure 6 in the SI) is multiplied by the on-road emission factor from EMFAC for the relevant delivery truck (concrete transit mixer or asphalt dump truck).

2.3.6. Vehicle operation
The 2019 BAAQMD fleet from EMFAC is assumed to provide an average annual representation of the percentage of passenger vehicles, light-duty trucks, medium-duty trucks, and heavy-duty trucks on any given road segment within the dataset. Aggregate speeds are used to account for the varying levels of congestion that could be encountered on the road segments throughout a year. On-road emissions from vehicle operation for each road segment are estimated by multiplying the emission factor, in grams per mile, by the length of the segment (one mile) and the average number of vehicles on the specific roadway segment. Vehicle counts for each roadway segment are included in figures 1, 2 and tables 8, 10 in the SI.

2.4. Exposure intake and damages
Intake is defined as the mass of air pollutant inhalation for a given population over a period of time [66]. An emissions inventory is used to determine how polluted the air is in a discrete area. Air is characterized as polluted depending on the amount of pollutant in volume of air (i.e., the concentration, $\mu g m^{-3}$). Changes in ambient ground-level PM$_{2.5}$ concentrations, as a result of the emission inventory, are estimated using a mechanistic air quality model.

Following the methods outlined in Bin Thaneya et al [46], we utilize the Intervention Model for Air Pollution (InMAP) Source-Receptor Matrix (ISRM) to calculate marginal changes in ground-level PM$_{2.5}$ concentrations and resulting inhalation intake from the spatially resolved emissions inventory. The ISRM models changes in concentrations at receptor locations from changes in emissions at source locations (i.e., where the pollutants are emitted) [67]. ISRM is a linearized extension of InMAP, a reduced-complexity air quality model. InMAP simplifies computational time by varying grid cell sizes [68]. Smaller grid sizes in more populated areas yield higher resolved exposure results, which is critical in accurately assessing exposure disparities among population groups [69]. InMAP and ISRM account for secondary PM$_{2.5}$, which forms from long-range transport and atmospheric chemical reactions among emission precursors including NOx, VOCs, SO$_2$, and NH$_3$. Accounting for secondary PM$_{2.5}$ formation allows for a more realistic representation of all receptor locations. Most PM$_{2.5}$ is secondary, not primary, and most emission sources produce at least as much exposure from secondary PM as from primary PM [70]. Secondary PM exposures happen at greater average distances than primary PM exposures [70]. Exposure concentrations from IRSM are overlaid with population census tracts and annual average breathing rates [71, 72]. The exposure concentrations and breathing rates produce a spatial representation of the mass of PM$_{2.5}$ everyone in each census tract inhales from the yearly resurfacing and operation of each roadway segment. Following methodologies outlined in Goodkind et al [67], the exposure concentrations are transformed into premature mortality rates using concentration-response functions. Premature mortality rates (number of deaths per year) and the value of statistical life (VSL) are used to calculate health damages. VSL measures the economic costs society would be willing to pay to avoid premature death from a mortality risk such as exposure to PM$_{2.5}$ emissions [73].

2.5. Mitigation strategies
Emissions inventories, population-weighted exposure concentrations, PM$_{2.5}$ intakes, and exposure damages are calculated for the mitigation strategies listed in table 1. Of course, other strategies are also possible, such as the use of alternative fuels [74] instead of electrification, but the strategies in table 1 are most likely to bring the largest exposure reductions. Details are provided in section 8 of the SI.

2.6. Uncertainty assessment
Uncertainty associated with the accuracy and relevance of system inputs (i.e., data and assumptions), models, and outputs are qualitatively explored. The material emissions data utilized in the study are in keeping with recent studies that analyzed concrete [75] and roadway pavements [76]. The on-road and

| Strategy Number | Description |
|-----------------|-------------|
| 1               | 100% on-road electrification |
| 2               | 100% off-road electrification |
| 3               | Reduce vehicle flow by 10% |
| 4               | 2045 on-road electrification |
| 5               | 2045 off-road electrification |
| 6               | Reduce refinery emissions by 20% |
| 7               | Reduce cement emissions by 20% |
| 8               | Reduce aggregate emissions by 20% |
| 9               | Reduce ready-mixed concrete (RMC) emissions by 20% |
| 10              | Reduce asphalt emissions by 20% |
| 11              | Move refineries and cement plant to low-intake-fraction census tracts |
| 12              | Combine all strategies (2045 electrification) |

Table 1. Mitigation strategies tested in ISRM.
off-road data, which come from EMFAC, are reliable. While not as accurate as real-time monitoring, EMFAC emission factors have previously been validated in many studies as reasonable for calculating emissions inventories [77, 78]. We use standard pavement design guidelines maintained by the State of California, in addition to informed discussions with pavement designers at Caltrans.

Goodkind et al [67] assessed the uncertainty of the ISRM, concentration-response functions, and the exposure damages in their study on impacts from PM$_{2.5}$ pollution in the United States, finding that the ISRM VSL estimate was within 8% of estimates from the U.S. EPA [67]. Uncertainty is highest for the exposure damages. The uncertainties with a reduced-complexity air quality model, such as InMAP, are reasonable enough that decision-makers can feel confident in using their results [79]. Uncertainties for concentration-response functions (i.e. how many premature deaths can be attributed to some amount of pollution) can be higher when considering low changes in annual PM$_{2.5}$ concentrations [80], which could be relevant if only a limited number of emission sources are being considered. Uncertainty assessment with respect to outputs, by validating model results with prior studies, is presented in the Discussion section.

3. Results

People living in each of the 1566 census tracts included in the Bay Area inhale PM$_{2.5}$ from the resurfacing and vehicle operation of the distributed one-mile roadway segments and from the material and fuel supply chains supporting roadway resurfacing and vehicle operation activities. Average exposure concentrations from the emission sources included in the study domain are presented in figure 3. Exposure concentration hotspots occur around census tracts near emissions-intensive facilities (e.g. oil refineries in northern part of the East Bay, cement facility in the South Bay) and in proximity of dense population centers co-located with high-traffic roads (e.g. interstate highways in San Francisco, Oakland, Palo Alto, San Jose). While previous work has shown that the majority of exposure damages occur within a certain distance of the emissions source [67], census tracts not located within proximity of these sources still experience some exposure, partially as a result of secondary formation of PM$_{2.5}$.

The PM$_{2.5}$ intake for all the people within the study domain for the baseline conditions (i.e. as-is, no applied mitigation) and a selected number of mitigation strategies for Scenario 1 is shown in figure 4. While only five mitigation strategies are discussed within the main text to show a range of possible intake reductions, the SI contains all mitigation strategy results (figure 8). Similar intake trends by emission source are observed for Scenario 2 (figure 9). Overall intake is lower in Scenario 2 as fewer road segments are analyzed. Under baseline conditions for the 45 miles of roads, on-road tailpipe emissions (978 g yr$^{-1}$) represent 35% of total intake. Road resurfacing activities (1.5 g yr$^{-1}$), material deliveries (104 g yr$^{-1}$) and material/fuel supply chain sources (1673 g yr$^{-1}$) account for 65% of total annual intake. Mitigation strategies reduce PM$_{2.5}$ intake by a range of 64% (future electrification of all on-road vehicles and construction material delivery) to 0.10% (interim electrification of off-road equipment). Note that even in the 100% electrification scenario of on-road mobile sources (Strategy #1), PM$_{2.5}$ intake from vehicle operation is not eliminated. Brake and tire wear from vehicle operation still contributes 22% (218 g yr$^{-1}$) of that scenario’s total intake. Aside from combining all strategies under an interim (in the year 2045) electrification scenario, the third most-effective strategy in terms of reducing total intake is to relocate the cement production facility and oil refineries away from their current locations to census tracts with low intake fraction values (such relocations have been discussed in public for several reasons, including environmental, for years). Intake fraction is a unitless metric which characterizes how much pollutant mass a population inhales relative to the total emissions of that pollutant [81, 82] (the methodology for moving facilities is provided in SI section 8).

Exposure burden trends by each emission source (i.e. the roadway segments, material and fuel production facilities, material delivery) are specific to the parameters (e.g. historical zoning practices, geographic and dispersion characteristics) of the exposure assessment and study domain. The annual average population-weighted exposure concentration from all road segment sources accounted for in the study domain is 0.07 μg m$^{-3}$. Figures 5(a), (b) and 6(a), (b) depict two key representations of exposure. The total heights of figures 5(a) and 6(a) (i.e. the y-axis) show the absolute annual population-weighted exposure concentration from all emission sources for each specified demographic group. Each bar width on the x-axis represents how much higher or lower the exposure from a distinct emission source is for a demographic group compared to the population-weighted average exposure of that source. Figures 5(b) and 6(b) depict the ranked order, from highest to lowest, of sources causing exposure burdens, with the y-axis showing each source’s percentage contribution to absolute exposure. As an example, the Asian population experiences PM$_{2.5}$ exposure burden from the cement facility, the source they are most differentially exposed to, 65 times higher than the general population.

Of the 7.5 million people living in the Bay Area, the White population accounts for around 60%, the
Figure 3. Average PM$_{2.5}$ exposure concentrations from all emission sources for Scenario 1. Red-colored census tracts experience higher exposure concentrations compared to green-colored tracts. The population-weighted average PM$_{2.5}$ concentration from the sources included in this case study is around 0.07 $\mu$g m$^{-3}$. The population-weighted average PM$_{2.5}$ concentration experienced in the Bay Area from all sources is 4 $\mu$g m$^{-3}$[44].

Pacific Islander population for 0.3%, the Asian population for 6%, the Hispanic or Latino population for 19%, and the Black population for 14% [48]. Across all racial demographic groups for Scenario 1, the Black population in the Bay Area experiences the highest relative level of PM$_{2.5}$ exposure burden from the operation, resurfacing activities, material delivery, and material and fuel production associated with the roadway segments at 15% ($9.9 \times 10^{-3}$ $\mu$g m$^{-3}$). The Hispanic population experiences 0.50% ($4.1 \times 10^{-4}$ $\mu$g m$^{-3}$) higher-than-average exposure disparities, while the White, Asian, Pacific Islander, and Native American populations experience lower-than-average exposure disparities at −1% ($−7.9 \times 10^{-4}$ $\mu$g m$^{-3}$), −6% ($−3.6 \times 10^{-3}$ $\mu$g m$^{-3}$), −13% ($−8.2 \times 10^{-3}$ $\mu$g m$^{-3}$), and −5% ($−3.2 \times 10^{-3}$ $\mu$g m$^{-3}$).

In Scenario 1, the Black population experiences higher-than-average PM$_{2.5}$ exposure from 66% of sources in the study domain (figure 5(a)). While not depicted in figure 5(a), people of color bear higher-than-average PM$_{2.5}$ exposure from 65% of emission sources. Among the five income quintiles, people in the lowest income quintile (i.e. the annual median
household income for the 20% lowest-earning households) suffer from the highest exposure burden (figure 6(a)). People in Q1 (annual median household income < $73,000) experience higher-than-average exposure from 96% of source types. The exposure burden for the highest income quintile, Q5 (annual median household income > $151,000), is the second most significant, with 63% of sources, and is partially attributed to the cement facility which is located near an affluent community in Santa Clara County. Similar trends are observed for Scenario 2 (figures 10 and 11 in the SI).

Figures 5(b) and 6(b) list the ranking of sources in terms of highest-to-lowest absolute exposure disparity for each demographic group for Scenario 1. Some clear trends are present. Aggregate (stone and gravel mining and processing) production is the emission source that causes the highest absolute disparity for the Black, Pacific Islander, Native American, and income Q1 populations. People of color, in general, also experience highest absolute disparity from aggregate production. The White, Black, Q1, and Q2 population groups experience higher absolute disparities from oil refinery operations. Of note, the cement facility is one of the higher contributors for the Asian and Q5 demographics. When analyzing the percentage of total exposure (table 3 in the SI), except for the White, Black, and Q1 populations (of which the reverse is true), the highest contributing source comes from on-road mobile sources on the roadway segments and the second highest contributing source is from oil refinery production of on-road fuel. Aggregate production is the third highest contributing source to exposure for people of color. Pavement resurfacing and associated fuel usage are the two lowest contributors to absolute exposure for all demographic groups.

Table 2 lists the range of annual exposure damages, expressed as exposure damages for baseline and mitigated conditions for Scenario 1. A range is provided as two damage models are used. The values for the mitigation strategies represent percent
reductions in exposure damages relative to baseline conditions. Complete electrification of all on-road mobile sources yields the largest reduction in exposure damages. Combining all mitigation strategies from table 1 with interim electrification conditions that occur in 2045, leads to the second largest damage reduction. Under a revised assumption that pavement resurfacing occurs more regularly in one year (i.e. 100 construction days), the baseline exposure damages increase by a range of $10,000,000 to $12,000,000 (2019 USD). Off-road electrification yields increased, albeit still modest, reductions in exposure damages relative to the other mitigation strategies. Complete Scenario 1 and 2 results are included in tables 4 through 7 in the SI. Mitigation reductions are marginally larger for each strategy, suggesting that DAC census tracts might benefit even more from strategy implementation.

4. Discussion

The results demonstrate that under the realistic if not cautious assumption of how much road resurfacing occurs annually within the Bay Area, routine resurfacing of roadways, accounting for construction activities, production and delivery of materials, and fuel and materials produced at oil refineries, significantly contribute to the full scale of exposure impacts from roadways. The top contributors to exposure in the study domain (i.e. on-road vehicle operation, crude-oil production) are in keeping with principal source contributors for intake and incidences of premature mortality [45, 83].

The exposure results provide additional and necessary context to the scope of impacts from the road transportation sector. Rather than siloing exposure impacts into potentially overly broad sectors, our results suggest that more context can be gained from thinking about our exposure burdens from the perspective of a portfolio of sources from distinct projects. Resurfacing activities and material/fuel supply chains, under the realistic assumption of how much road resurfacing occurs annually, contribute to almost 65% of annual PM$_{2.5}$ intake for the Bay Area population. For added context and a fair comparison between supply chain impacts, roadway construction,
Figure 6. (a) Absolute and relative PM$_{2.5}$ exposure for Scenario 1 by income quintile. The dashed horizontal line indicates the percentage of emission sources causing higher-than-average exposure for each group. (b) Ranked order of exposure disparity for Scenario 1 by source type for each income quintile. The $y$-axis shows the percentage that each source contributes to total absolute exposure.

Table 2. Exposure damages for baseline and select mitigation strategies. Three significant digits are shown to make distinctions in the ranges.

| Strategy                        | Scenario 1 Exposure Damages ($M/year) | Scenario 1 Exposure Damages—100 d ($M/year) |
|---------------------------------|--------------------------------------|---------------------------------------------|
| Baseline                        | 170–190                              | 180–200                                      |
| 100% On-road Electrification    | $-65.7\%$ to $-66.1\%$              | $-61.7\%$ to $-62.2\%$                     |
| 2045 On-road Electrification    | $-18.3\%$ to $-18.6\%$              | $-17.2\%$ to $-17.5\%$                    |
| 2045 Off-road Electrification   | $-0.049\%$ to $-0.050\%$            | $-4.60\%$ to $-4.70\%$                    |
| Move Cement/Refinery Facilities | $-9.90\%$ to $-10.3\%$              | $-9.60\%$ to $-9.90\%$                    |
| Combination                     | $-38.1\%$ to $-37.5\%$              | $-40.0\%$ to $-40.6\%$                    |

and vehicle operations on roads, it is important to acknowledge the repaving schedule for a roadway: any single one-mile segment of a high-traffic road is only going to be reconstructed once every 10 to 15 years, or when budgets are available [84]. It should be emphasized that the individual roadways in the case study serve as proxies for a certain number of roadways with the same design characteristics and traffic loads that would be reconstructed in any given year.

Electrification ranks as one of the more effective PM$_{2.5}$ intake and damage mitigation strategies, but benefits are constrained by implementation timeframe and vehicle attributes [85, 86]. Electrification of on-road mobile sources mitigates the
baseline PM$_{2.5}$ intake by a range of 18% (interim electrification based on the projected ARB vehicle fleet composition for the year 2045) to 64% (complete electrification in some future unknown year). Even with complete electrification, primary PM$_{2.5}$ emissions from brake and tire wear still contribute 22% of that mitigation strategy’s (Strategy #2) annual intake. Most significantly, complete electrification still leaves 78% of that strategy’s (Strategy #2) remaining annual intake. Given the restricted effectiveness of other mitigation strategies (figures 8 and 9 in the SI), we are essentially locked into the remaining intake amount from construction, materials, and supply chains.

For the remaining PM$_{2.5}$ emissions that cannot be eliminated through electrification alone, what policies should then be explored and prioritized to try and reduce exposure as much and as quickly as possible? Of the 12 mitigation strategies investigated, no individual strategy, or a combination of strategies, is going to be a magic solution for mitigating human-health impacts. The six individual mitigation strategies (Strategy #3, #6–#10) probably represent a realistic expectation of how much PM$_{2.5}$ can be mitigated in the interim. Beyond these current, limited options, future hypothetical strategies might revolve around relocating (Strategy #11) the highly polluting facilities (e.g. oil refineries, cement facility) to low-intake-fraction areas or implementing a suite of mitigation options (Strategy #12). Exposure is a hyper-local issue that a broad and necessary climate-change policy such as electrification cannot solve alone. The results point to a need to be pragmatic about the scale of benefits that complete electrification can yield and the need to push for additional public/environmental/health policies to further tackle the remaining exposure sources.

Although the exposure disparity results are specific to the San Francisco Bay Area, some trends consistent with previous equity studies can be observed. In general, the Black population and the population in the lowest income bracket suffer the highest relative exposure disparities from the emission sources in the study domain. People of color experience exposure burdens from 60% of the emissions sources in the study domain, with aggregate and other material production causing the highest exposure disparity for the Black, Hispanic, Asian, and Native American populations. On-road vehicle operation and fuel production at oil refineries are the two leading contributors to each demographic group’s total exposure profile. Of note, the cement facility in the South Bay disproportionately exposes the Asian population to PM$_{2.5}$.

There are limitations associated with the methods and assumptions employed in the study. The VSL metric is predicated on how much one would be willing to pay to reduce premature fatalities from some cause of harm (e.g. traffic accidents, air pollution). The exposure results come from ambient exposure concentrations in census tracts that InMAP produces, which might not reflect realistic conditions. People spend most of their time indoors. Average annual traffic might not capture real-time conditions. Damages are assessed on an annual timescale, reflecting chronic exposure. The methods might be failing to accurately capture acute events (e.g. a two-day roadway paving job) or assess health impacts for those working on paving jobs who endure exposure throughout their careers.

There are no equivalent studies with which to exactly compare our exposure results. The average population-weighted exposure concentration for Scenario 1 (0.07 µg m$^{-3}$) from the ten emission sources included the scope is around 1% of the reported PM$_{2.5}$ exposure concentration from all sources within the United States (7 µg m$^{-3}$) [44]. Scenario 1’s on-road mobile weighted concentration from the 45 one-mile segments (0.02 µg m$^{-3}$) represents 1.5% of exposure concentration from all on-road mobile sources within California [45]. As an additional point of reference, the annual average PM$_{2.5}$ exposure concentration for the San Francisco Bay Area is around 4 micrograms per cubic meter [44]. The discrepancies are reasonable and expected as only operation, resurfacing activities, and associated supply chains for the 45 one-mile segments are accounted for.

The results highlight the need to equitably mitigate exposure disparity among demographic groups by targeting the specific emission sources that affect each group the most. When stakeholders are making decisions on transportation infrastructure, it is imperative that they consider and incorporate into final projects how distinct groups will be affected [87] as each group does not experience harms or benefits at the same rate.

5. Conclusions

Construction activities and material and fuel supply chains are a critical yet underappreciated contributor to exposure from the road transportation sector. The best-case scenarios of both on-road and off-road electrification roughly reduce the study’s annual PM$_{2.5}$ intake by two-thirds. Roadway resurfacing activities and ensuing supply chains become much more consequential emission sources. The importance of construction/materials/supply chains is even more pronounced when accounting for the fact that roadway resurfacing, as defined in the study, is a discrete event which occurs over a couple of days in a typically 10–15 year period while on-road vehicle operation is year-round. Clear results from the study support the need to recognize the burden that certain groups bear from the production of roadway and other infrastructure materials [88].

As noted in this study, electrification will not entirely eliminate on-road sources of PM$_{2.5}$ due to persistent brake and tire wear. National, state, and local governments should work in tandem with
environmental justice groups to equitably mitigate human health impacts from PM$_{2.5}$ sources. As exposure is hyper-localized, it makes sense that the process for attaining sensible, effective mitigation policies likely lies at the community level [89].

If a region, even with electrification and other feasible mitigation strategies, is still going to be locked into construction- and supply-chain-sourced PM$_{2.5}$ exposure from the road transportation sector, it is justifiable to rethink our transportation future. There are a myriad of health- and climate-change co-benefits associated with transforming the transportation sector [90, 91]. A future transportation sector should prioritize improving access while minimizing material and fuel consumption.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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Conflict of interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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