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Mitigating Exposure and Climate Change Impacts from Transportation Projects: Environmental Justice-Centered Decision-Support Framework and Tool

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Authors

Horvath, Arpad, PhD
Greer, Fiona, PhD
Apte, Joshua, PhD
et al.

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UNIVERSITY
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CALIFORNIA

Mitigating Exposure and Climate Change Impacts from Transportation Projects: Environmental Justice-Centered Decision-Support Framework and Tool

Arpad Horvath, Ph.D., Professor, Department of Civil and Environmental Engineering, University of California, Berkeley
Fiona Greer, Ph.D., Postdoctoral Researcher, Department of Civil and Environmental Engineering, University of California, Berkeley
Joshua Apte, Ph.D., Associate Professor, Department of Civil and Environmental Engineering and School of Public Health, University of California, Berkeley
Jasenka Rakas, Ph.D., Deputy Director, Federal Aviation Administration Consortium in Aviation Operations Research (NEXTOR III), University of California, Berkeley

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7. Author(s)
Arpad Horvath, Ph.D. https://orcid.org/0000-0003-1340-7099; Fiona Greer, Ph.D. https://orcid.org/0000-0001-9453-0640; Joshua Apte, Ph.D. https://orcid.org/0000-0002-2796-3478; Jasenka Rakas, Ph.D. https://orcid.org/0000-0001-9694-3588

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16. Abstract
California must operate and maintain an effective and efficient transportation infrastructure while ensuring that the health of communities and the planet are not compromised. By assessing transportation projects using a life-cycle perspective, all relevant emission sources and activities from the construction, operation, maintenance, and end-of-life phases can be analyzed and mitigated. This report presents a framework to assess the life-cycle human health and climate change impacts from six types of transportation projects: (1) Roadways; (2) Marine ports; (3) Logistical distribution centers; (4) Railyards; (5) Bridges and overpasses; and (6) Airports. The framework was applied using an integrated model to assess fine particulate matter ($PM_{2.5}$) and greenhouse gas (GHG) emissions, noise impacts, and monetized damages (Value of Statistical Life, Social Cost of Carbon) from two case studies: routine resurfacing and vehicle operations on road segments within the San Francisco Bay Area using 2019 data, and annual marine, cargo, rail, trucking, and infrastructure maintenance operations at the Port of Oakland in 2020. The results suggest that emission sources in a project's supply chain and construction (material production and deliveries, construction activities, fuel refining) can significantly contribute to the full scope of impacts from transportation systems. Equitable mitigation policies (e.g., electrification, pollution control technologies) need to be tailored to address the sources that impact communities the most.

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Table of Contents

Table of Contents

List of Tables

List of Figures

Executive Summary

Executive Summary

The transportation infrastructure in California, from paved roads and highways to airports, railways, marine ports, and logistical distribution facilities move people and goods across communities, the state, and beyond. There are, however, significant environmental and human health impacts from these transportation systems. The full scope of those impacts is not just limited to their operational activities. All life-cycle stages of transportation systems, including their raw material production, supply chain logistics, construction, operation and maintenance, and end-of-life activities, contribute to the overall effects on climate change and the health of local communities. Using a life-cycle framework to map the environmental impacts from the existing transportation infrastructure and new projects accounts for all relevant sources.

Researchers at UC Berkeley recently created a framework to assess the life-cycle human health and climate change impacts from six types of transportation projects: (1) Roadways; (2) Marine ports; (3) Logistical distribution centers; (4) Railyards; (5) Bridges and overpasses; and (6) Airports. The framework was applied with an integrated model to assess fine particulate matter ($PM_{2.5}$) and greenhouse (GHG) emissions, noise impacts, and monetized damages from two case studies: routine resurfacing and vehicle operations on road segments within the San Francisco Bay Area using 2019 data and annual marine, cargo, rail, and trucking operations at the Port of Oakland in 2020. Both case studies demonstrate how decision-makers can better incorporate supply chain activities and equity into mitigation solutions.

Supply chain sources can significantly contribute to the full scope of impacts from transportation systems. In a comprehensive SF Bay Area roadway case study, direct emissions from on-road vehicles accounted for only 35 percent of inhaled $PM_{2.5}$ relative to the supply chain sources (i.e., road resurfacing activities, material deliveries, materials, fuels) included in the study (Figure 1). The breakdown between on-road and supply chain emissions was almost the reverse for GHG emissions, with 65 percent of climate change-inducing emissions coming from vehicle operation on road segments. With the Port of Oakland case study, supply-chain sources were found to be less prominent contributors to overall impacts, partly because maintenance of Port surfaces is limited, and the amounts of relevant fuels consumed are not documented. Operational emissions from ocean-going vessels dominate impacts attributable to the Port of Oakland.

Electrification strategies yielded greater relative decreases in GHG emissions than reduced $PM_{2.5}$ exposure in the SF Bay Area roadway case study. Electrifying all on-road vehicles results in an almost 97 percent reduction in annual GHG emissions, but only reduces fine $PM_{2.5}$ intake by two thirds in the SF roadway case. Electrification is a necessary policy for mitigating climate change, but our study indicates that it will not eliminate all human health burdens. Even under a hypothetical scenario where all vehicles are electrified, communities will still be exposed to emissions from vehicle brake and tire wear. The results suggest that a suite of mitigation strategies is needed to tackle both climate change and health impacts from transportation systems.

Environmental mitigation policies need to be equitable and tailored to address the sources that impact human communities the most. Our results show that emission and noise sources differentially affect communities by race and income level. Regarding air pollution, people of color are disproportionally exposed to $PM_{2.5}$ from 65 percent of sources in the roadway study, compared to the White population's disparate exposure to 47 percent of sources. People of color and lower income populations are disproportionally exposed to air pollution from material (cement, concrete, asphalt) production facilities. The Black population in the Bay Area is disparately exposed to 97 percent of the sources attributable to the Port of Oakland, highlighting the necessity of policies such as Assembly Bill 617 which allows communities that have been designated as hotspots for air pollution to develop and implement their own air pollution and emission reduction plans.

Better accounting of produced and consumed resources can inform hazard analysis. Production volumes for refining crude oil are publicly available at the facility level. Commercial airports publish fuel sales for aircraft. Just as the State of California mandates tracking of such data, the same type of information should be tracked and made publicly available for concrete, cement, asphalt, and aggregate production facilities. Ports, such as the Port of Oakland, should track and publish fuel sales for ocean-going vessels and commercial harbor craft. Publishing these commodity production and consumption data, incorporated with an integrated equity assessment, will aid policy makers in analyzing California's transportation projects.

This study offers a blueprint for stakeholders to use as they embark on tackling climate change and human health impacts from designing, constructing, operating, maintaining, and decommissioning the state's transportation systems and infrastructure. Near-term next steps should be to expand the analysis presented in Section 1 by assessing other critical transportation projects in California (e.g., logistical distribution facilities, future vertiport terminals). Finally, connecting with both community groups and policymakers offers an opportunity to target the most significant emission sources and to pinpoint the most equitable mitigation strategies. Rigorous, systematic analysis coupled with community engagement points to a winning combination to fight climate change and support environmental justice outcomes.

Contents

1. Introduction

Background

Transportation systems support the mobility and economic growth of urban and rural communities throughout California. The transportation infrastructure in California, from paved roads and highways to airports, railways, marine ports, and logistical distribution facilities move people and goods across communities, the state, and beyond. There are, however, significant environmental and human health impacts from these transportation systems. Transportation accounts for almost 40 percent of the state's annual greenhouse gas (GHG) emissions.[1] Direct on-road mobile emissions of fine particulate matter ($PM_{2.5}$) and relevant precursors, an important source of transportation pollution, are significant contributors to the state's population-weighted average exposure concentration.[2] Exposure to $PM_{2.5}$ is connected with an increased risk of asthma, cardiovascular diseases, and other negative human health impacts.[3] Unhealthy levels of noise pollution are concentrated in major metropolitan areas (San Francisco Bay Area, Los Angeles) in the state[4] where high-traffic and noise-intensive road networks and international airports are located. The full scope of impacts from transportation systems are not just limited to their operational activities. All life-cycle stages of transportation systems, including their raw material production, supply chain logistics, construction, operation and maintenance, and end-of-life activities, contribute to the overall effects on climate change and the health of local communities.

The manner in which impacts from transportation systems can be cataloged and mitigated is generally affected by the type of pollutant emitted. With climate change, GHG emissions are globally mixed. Climate change-induced events, such as increased frequency and intensity of extreme weather, sea level rise, and spread of vector-borne diseases, can affect locations differentially depending upon several spatial and temporal factors. The consensus around addressing climate change is that emitters (whether that be individual companies, cities, states, or entire nations) must reduce their GHG emissions to meet certain thresholds so as not to exceed future global average temperature increases. For example, Assembly Bill (AB) 1279 mandates that California reduce its GHG emissions by 85 percent below 1990 levels by the year 2045.[5] While the state must comply with air pollution limits set by the federal government under the Clean Air Act, air pollution (and noise pollution, for that matter) tends to be addressed at a more local level.[6,7] Each region's air district is responsible for monitoring air pollution sources and making sure the sources comply with regulations.

There are strong intersections between climate change, local impacts on communities, and environmental justice. Air pollutants, such as $PM_{2.5}$ and its precursors, are often co-pollutants with GHG emissions, especially during the direct combustion of fossil fuels. Climate change mitigation policies can potentially lead to reductions in co-pollutants as well. Communities of color and lower-income groups have experienced greater-than-average $PM_{2.5}$ exposure burdens from transportation systems and their supporting industries (e.g., oil refineries, material production facilities) due to practices such as redlining and siting of facilities near communities of color.[8–11] On average, people of color and lower-income groups have also experienced greater level of noise pollution.[4] Accounting for past practices that have led to increased burdens on specific communities is imperative when designing, constructing, and operating the state's transportation infrastructure. Recent policy interventions are beginning to account for this need. Senate Bill (SB) 535 mandates that a portion of the proceeds from the state's Cap-and-Trade program must be prioritized for GHG mitigation projects located in disadvantaged communities (DAC).[12] Under AB 617, communities that have been designated as hotspots for air pollution (often located in areas with high GHG-producing sources) can develop and implement their own air pollution and emission reduction plans. SB 535 and AB 617 emphasis that, when thinking about how to mitigate the harm from the pollution caused by transportation projects, it is vitally important to map the pollution burdens that specific communities experience and to identify and mitigate the most harmful pollution sources.

Using a life-cycle framework to map the environmental impacts from the existing transportation infrastructure and new projects accounts for all relevant sources. In addition to cataloging use-phase impacts (e.g., combustion of fuels in vehicles), impacts from material production and delivery, construction, and necessary maintenance are identified. Life-cycle assessment (LCA) is a standardized framework[13] used to systematically inventory the outputs to air, water, and land associated with the inputs (energy, water) for a system throughout the system's entire life cycle from cradle to grave. This study does not perform a complete LCA but does rely on life-cycle principles to estimate impacts from various stages within the life cycle of a transportation project. A life-cycle approach allows us to identify the whole range of sources and activities that contribute to one transportation project. This more holistic framework is useful because it can help identify sources connected with a project that would not necessarily otherwise be addressed.

In addition to applying a life-cycle framework to mapping and mitigation of pollution, it is important to consider pollutants and their sources when identifying mitigation strategies to implement. At the beginning of the COVID-19 pandemic, much transportation activity was curtailed, resulting in reduced pollution near their sources. As in one case where air traffic was curtailed at a busy international airport, reductions in ultrafine particle concentrations were dependent upon aircraft flight activity and specific seasonal location factors.[14] An important mitigation strategy, and one that is promoted by recent legislation,[15] is electrification of fossil fuel-combusting sources. As explored further in this report, vehicle electrification is a necessary climate change mitigation strategy, but on its own, it will not completely eliminate air pollutants such as $PM_{2.5}$. There will still remain $PM_{2.5}$ emissions from brake and tire wear, as well as from upstream sources related to maintaining paved roadways.

Research Questions

In order to equitably minimize emissions-related negative externalities from the planning, design, construction, operation, and decommissioning of transportation infrastructures several overarching research questions should be addressed, including:

1. What are the health exposure and climate change impacts throughout the life cycle of a specific transportation project?
2. How does relative exposure change by race/ethnicity groups, and are there specific populations shouldering an undue burden from projects?
3. What are the external costs, and how do they compare between projects?
4. What strategies and actions can reduce external costs?

Research Objectives

This report creates a framework, comprehensive model, and accessible decision-support tool that can be used to identify and minimize:

1. Primary and secondary $PM_{2.5}$ formed from emission precursors, including nitrogen oxides (NO_x), volatile organic compounds (VOCs), sulfur dioxides (SO_x), and ammonia (NH_3);
2. GHG emissions associated with life-cycle stages of transportation projects in California; and
3. Noise impacts.

Where appropriate, the direct and indirect costs from GHG emissions, exposure to $PM_{2.5}$, and noise burdens of transportation projects are also presented.

Methodological Overview

This report presents a framework to assess the life-cycle human health and climate change impacts of six types of transportation projects: (1) Roadways – both rigid and flexible; (2) Marine ports; (3) Logistical distribution centers; (4) Railyards; (5) Bridges and overpasses; and (6) Airports. The process flow diagrams for each project type are presented in Figure 1 through Figure 7. The framework is applied with an integrated model to assess $PM_{2.5}$ and GHG emissions, noise impacts, and monetized damages from two case studies: routine resurfacing and vehicle operations on road segments within the San Francisco Bay Area using 2019 data, and annual marine, cargo, rail, and trucking operations at the Port of Oakland in 2020. Detailed methods are explored within each of the two main case studies. We also developed a decision-support tool to support benchmarking baseline and mitigated impacts for the paved roadway case study.

Figure 8 depicts the general methodological overview of both case studies. In general, an emission inventory is cataloged for each relevant source within the study area boundary. The level of GHG emissions is then monetized to estimate climate change damages. Primary and secondary $PM_{2.5}$ emissions are inventoried and fed into a reduced-complexity air quality model. From the air quality model, exposure intake and monetized health damages are estimated. Noise impacts are explored in a similar manner with noise emissions being connected to health and economic outcomes.

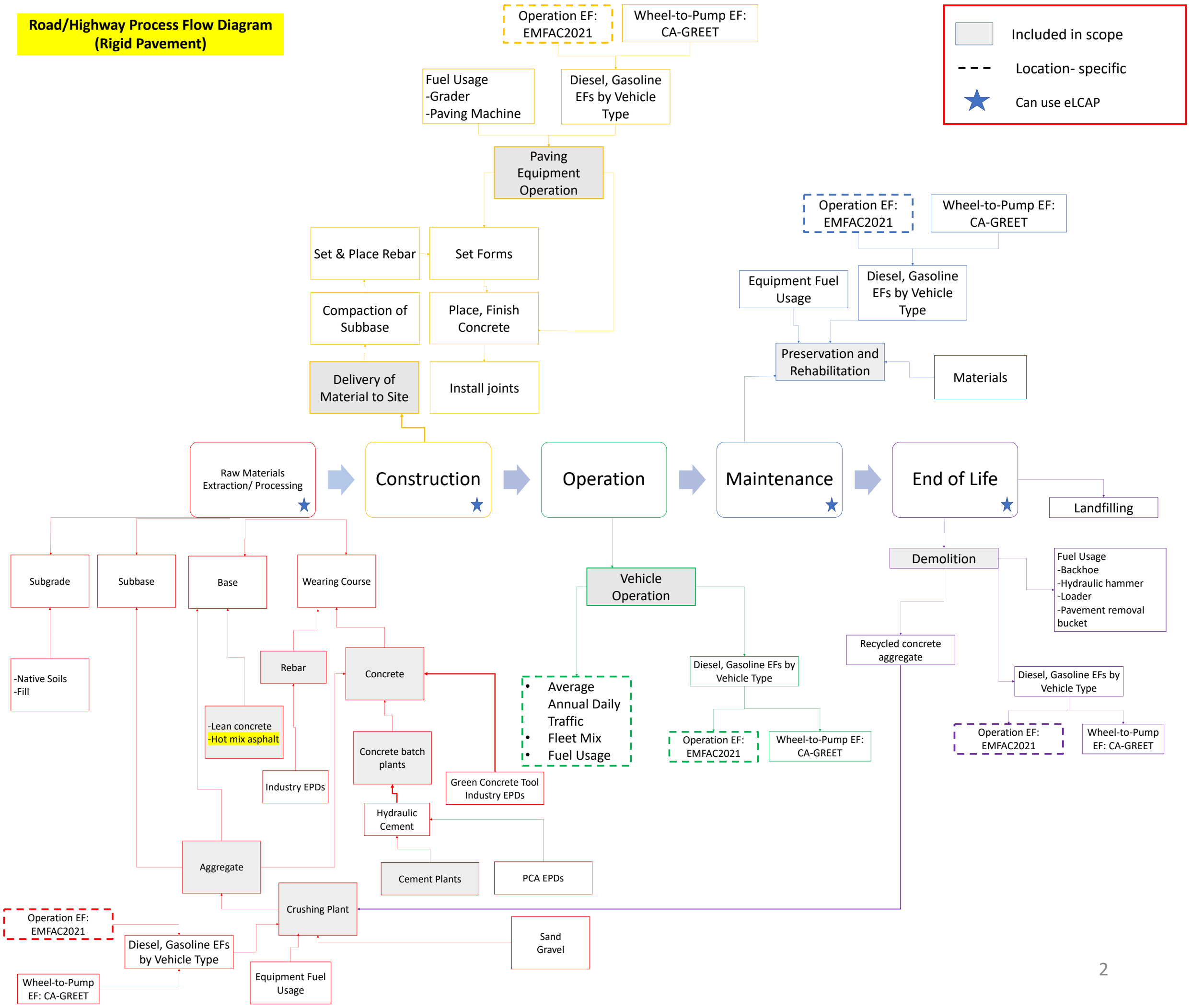


Figure 1. Rigid (concrete) pavement process flow diagram for all five life-cycle stages.

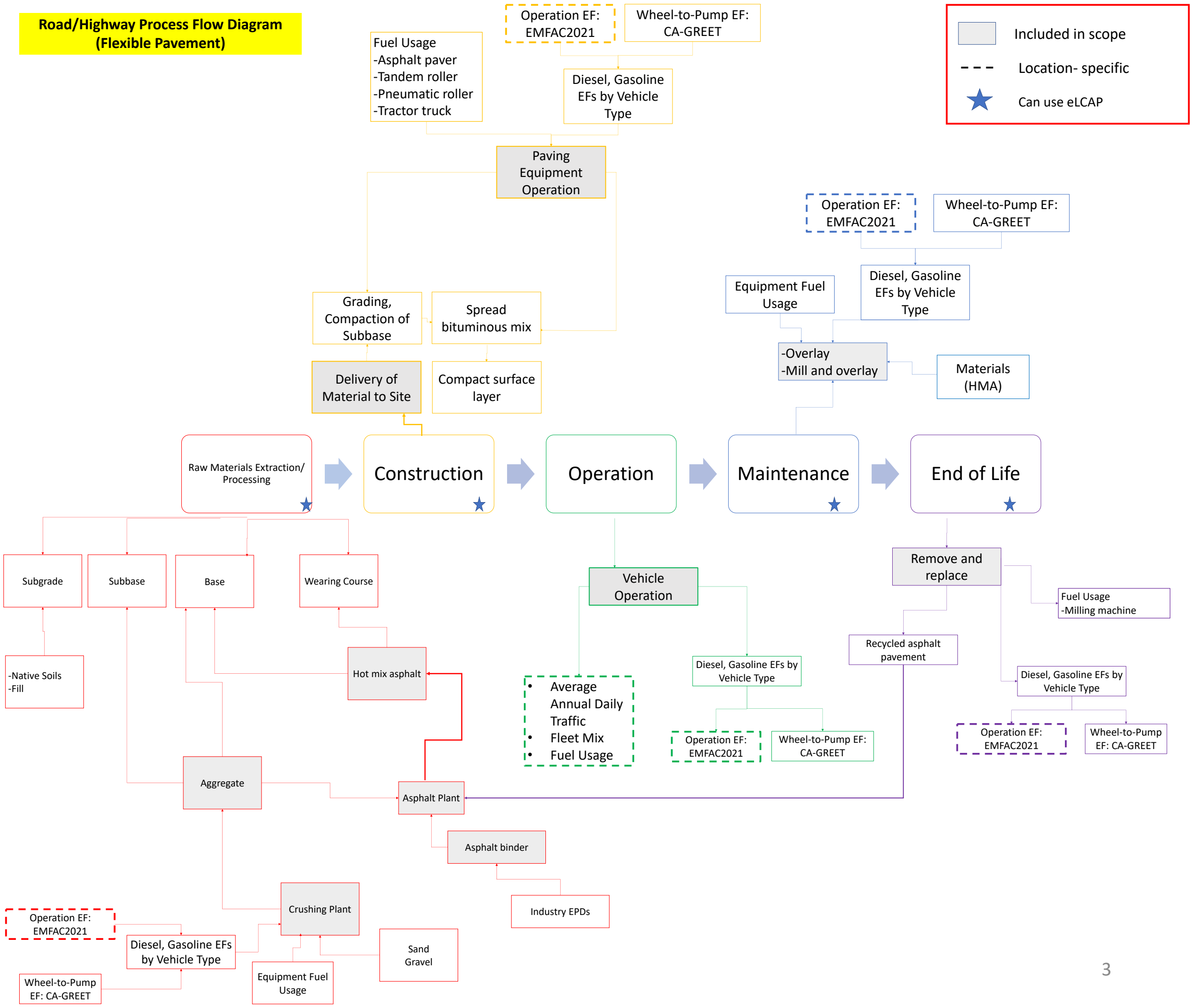


Figure 2. Flexible (asphalt) pavement process flow diagram.

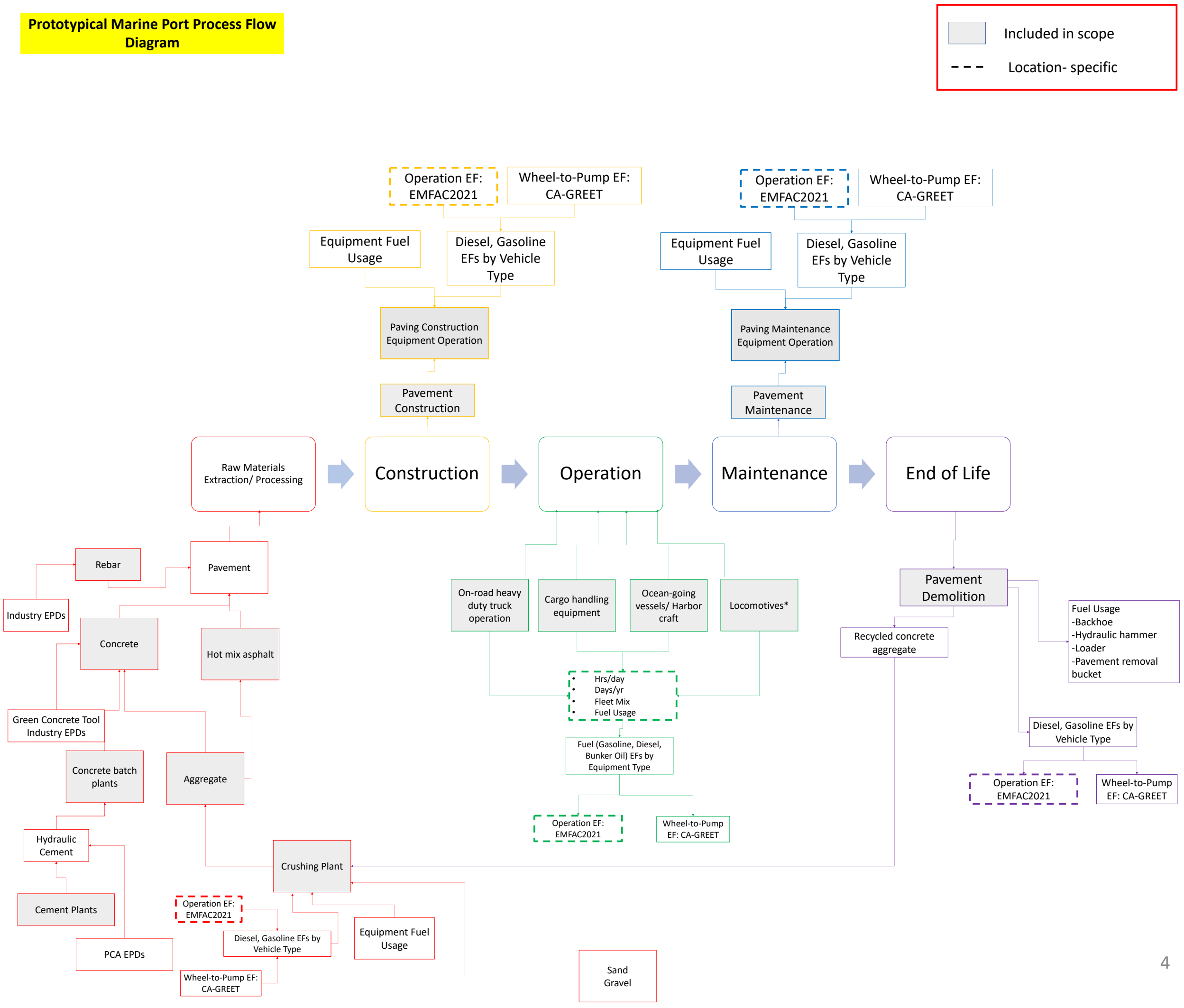


Figure 3. Marine port process flow diagram.

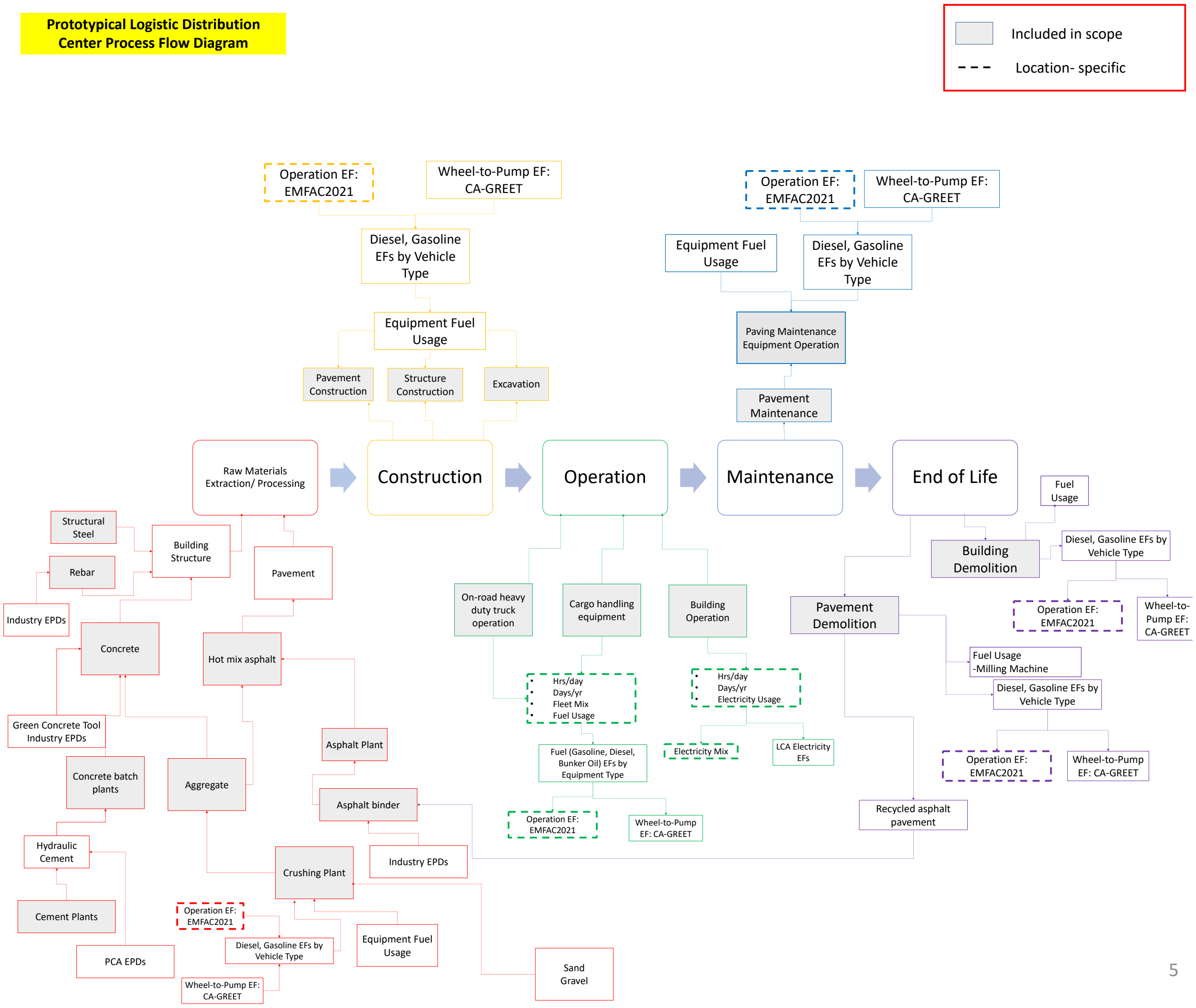


Figure 4. Logistical distribution center process flow diagram.

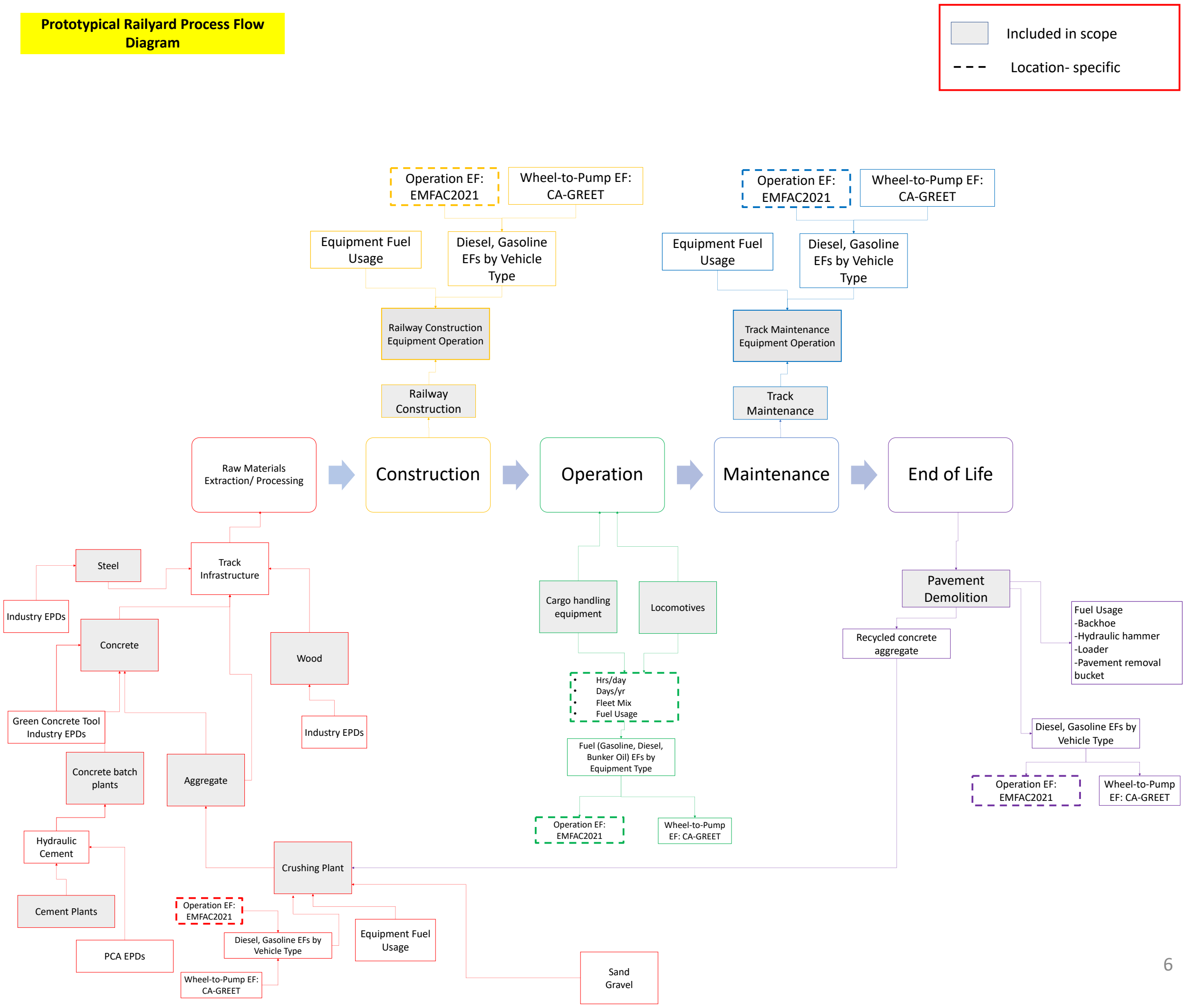


Figure 5. Railyard process flow diagram.

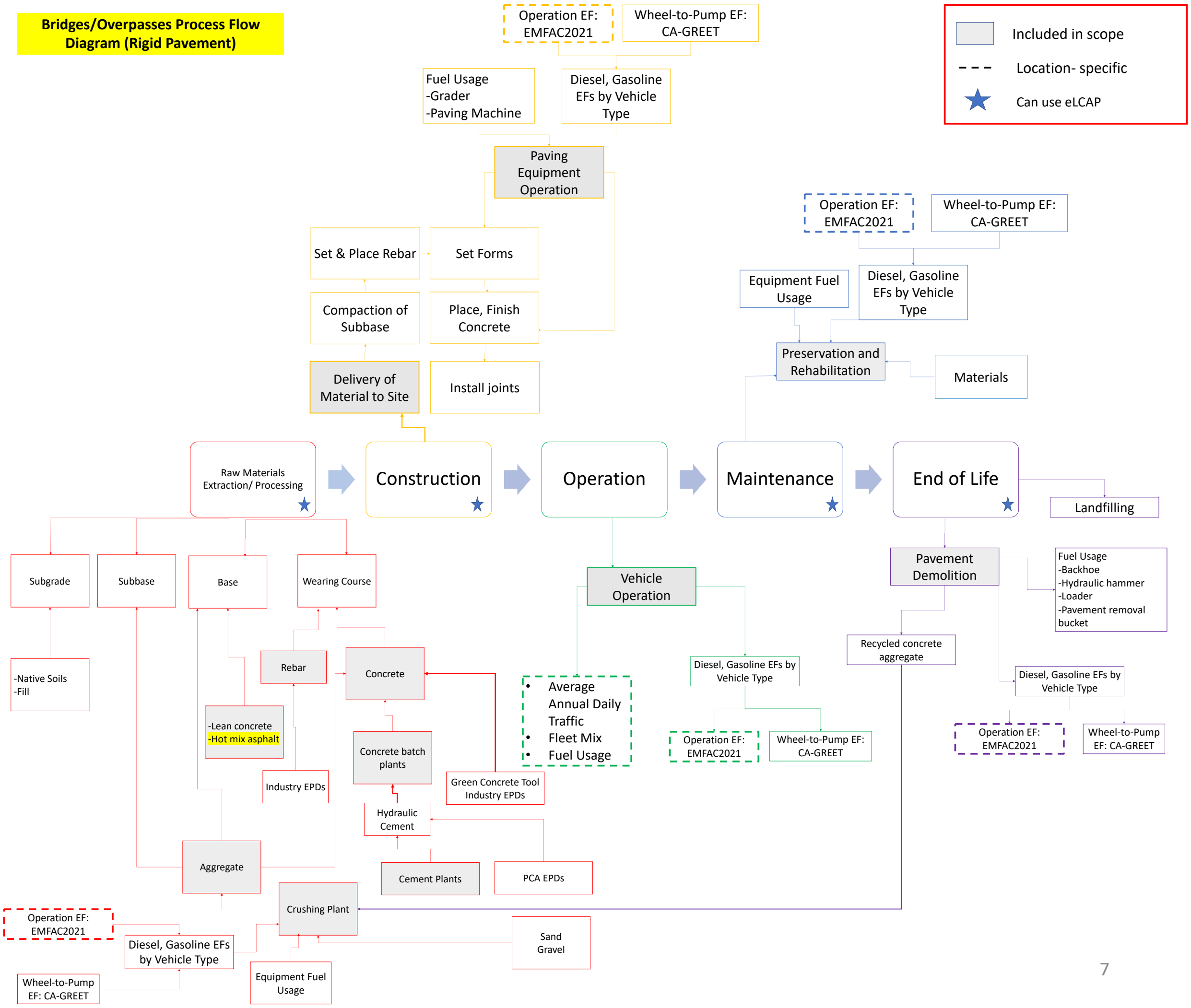


Figure 6. Bridges/overpasses process flow diagram.

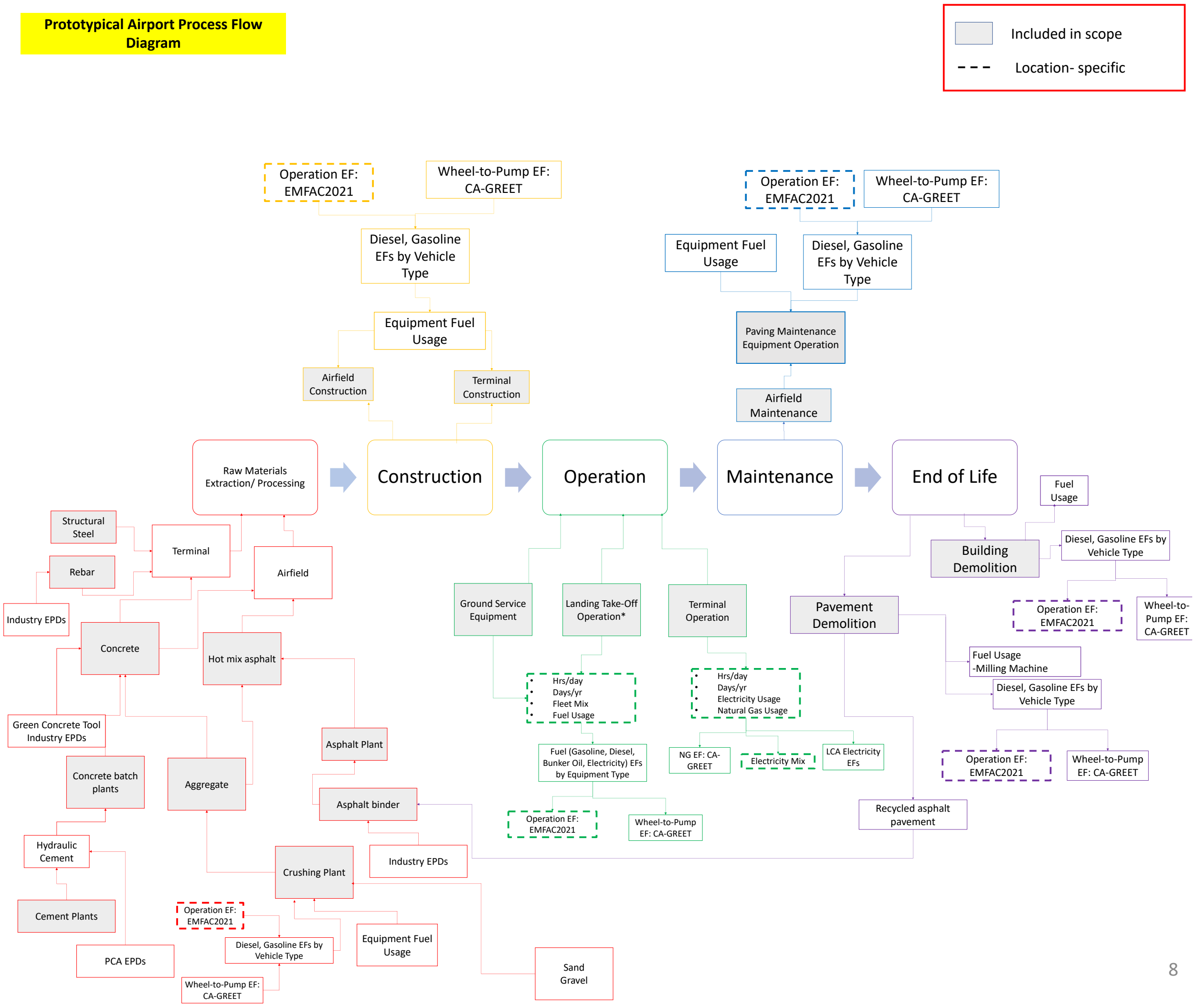


Figure 7. Airport process flow diagram.

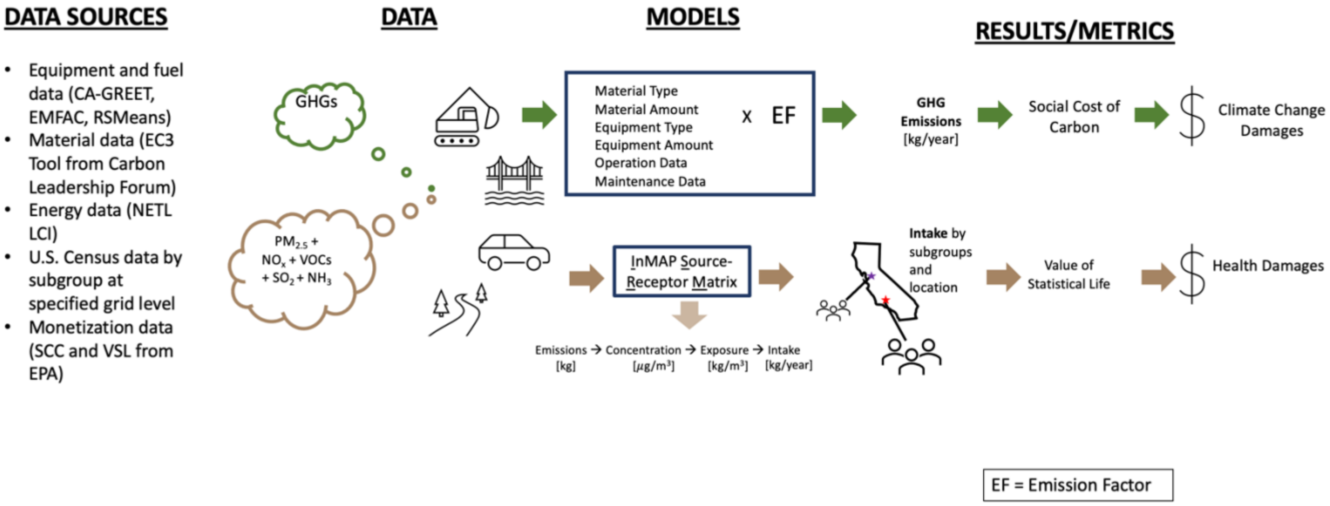


Figure 8. Overview of data sources, data, models, and results/metrics used in calculating GHG emissions and $PM_{2.5}$ exposure intake for transportation projects included in study.

Report Outline

The remainder of the report presents the two case studies and is structured as follows:

- Section 2: San Francisco Bay Area Roadway PM2.5 Exposure
- Section 3: San Francisco Bay Area Roadway GHG Emissions
- Section 4: San Francisco Bay Area Roadway Noise Exposure
- Section 5: Port of Oakland PM2.5 Exposure and GHG Emissions
- Section 6: Decision-Support Tool
- Section 7: Conclusions

Sections 2 through 5 of this report each typically contain the following subsections: A. Introduction; B. Methods—outlines the inputs, models, and expected results associated with the exposure assessment; C. Results—provides the results from the baseline $PM_{2.5}$ exposure assessment or GHG emissions analysis and from applying mitigation strategies; D. Discussion—details the significance of the results from both an academic and broader policy context, and E. Conclusions—finishes with suggestions for viewing the significance of the study's results and for guiding future research efforts. Section 6 describes our Decision-Support Tool, and Section 7 presents our conclusions and recommendations.

2. Roadway Segments: $PM_{2.5}$ Exposure

Section 2 is a reproduction of the peer-reviewed article "Pavement resurfacing and supply chains are significant contributors to PM2.5 exposure from road transportation: evidence from the San Francisco Bay Area" available at https://iopscience.iop.org/article/10.1088/1748-9326/aca2bc/meta. The Supplemental Information mentioned in Section 2 is available with the published article[167].

A. Introduction

There are over 2.8 million miles of paved roads in the United States alone.[16] Vehicle operation and necessary road maintenance emit air pollutants of which fine particulate matter ($PM_{2.5}$) and its precursors are of particular concern for health damages. More than 19 percent of the U.S. population lives near high traffic volume roads.[17] People of color and lower-income populations disproportionately live near high-traffic roads.[18]

Pollution from road transportation is a well-documented problem. Adverse health effects for exposed populations include cardiovascular and lung diseases.[19–21] Studies have documented other health impacts for those exposed to traffic-related pollution, including higher incidences of cancers,[22–24] complications during pregnancies,[25,26] and dementia.[27] On-road mobile sources of $PM_{2.5}$ are the largest contributor to premature mortality in the United States.[28] The economic harm is significant, with annual costs from transportation-related $PM_{2.5}$ and precursor emissions ranging from $52 to $120 billion (2018 USD) to $182 billion (2018 USD).[29,30]

Health impacts and exposure damages from $PM_{2.5}$ due to roadway construction are less well known than from on-road mobile sources. Studies often assess worker exposure to carcinogens from asphalt paving.[31–33] One study identified which activities (material processing and delivery) contribute the most to pollution from roadway construction,[34] while another identified paving operations leading to peak $PM_{2.5}$ for a hot mix asphalt pavement.[35] Documented $PM_{2.5}$ air pollution from production of materials used in roadways is relatively minimal. Concentration of $PM_{2.5}$ were calculated for two cement plants in varying seasons[36] and for aggregate quarries, finding that concentrations vary seasonally.[37,38] Kiln type is a contributing factor to air pollution intensity from the cement industry, at least in China.[39]

Multiple studies have incorporated life-cycle assessments to evaluate 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,[40–50] but very few include inventories of $PM_{2.5}$.[44,45,51] Heretofore no pavement LCAs have connected emission inventories to intake of inhaled pollutants and estimated resulting damages for exposed populations.

There is 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.[8–10] Addressing these disparities is increasingly a focus of state and federal policies.[52–55] Because air pollution is often most effectively addressed at its source, efforts to advance environmental justice can be informed by assessing the degree to which specific types of pollution sources lead to exposure disparities. In aggregate, estimates are that people of color experience higher-than-average burdens from air pollution from most economic sectors, with the highest absolute disparities from industry, vehicle, and construction sources.[11] Efforts to estimate $PM_{2.5}$ exposure at finer spatial scales and by source for different demographic groups are ongoing.[2] Recent research has modeled $PM_{2.5}$ intake from on-road vehicle emissions for a major U.S. metropolitan transportation network.[56] Given that differences in air pollution burden can change at the city block level,[57] 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:

1. 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?
2. How significant are impacts from material and fuel supply chains and expected resurfacing of roadways compared to exposure from on-road mobile sources?
3. Do specific demographic groups experience undue exposure burdens from on-road mobile sources, roadway resurfacing, and supply chain operations?
4. How do policies such as electrification of on-road/off-road vehicles, increased fuel efficiencies, and implementation of pollution control technologies change exposure burdens?
5. Which mitigation strategies should be selected given their external damage costs?

Our research objectives are centered on: (1) understanding the full range of exposure impacts from road transportation for a region's population to build upon previous exposure studies which only examined the impacts from on-road mobile sources and did not explicitly link impacts from construction activities, material production facilities, and oil refineries to a specific roadway network; (2) identifying mitigation strategies that are effective in minimizing human health impacts; (3) determining the extent to which transportation policies such as electrification can mitigate the full scope of exposure burdens from a roadway network; (4) exploring limitations of completely eliminating exposure burdens from road transportation and its supply chains; and (5) assigning economic value to the harm caused by the full range of exposure impacts from road transportation so that decision-makers can prioritize pollution mitigation strategies.

B. Methods

We estimated $PM_{2.5}$ intake and exposure damages using an inventory of specific pollution sources and their location 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 9 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 population groups are most susceptible to exposure.

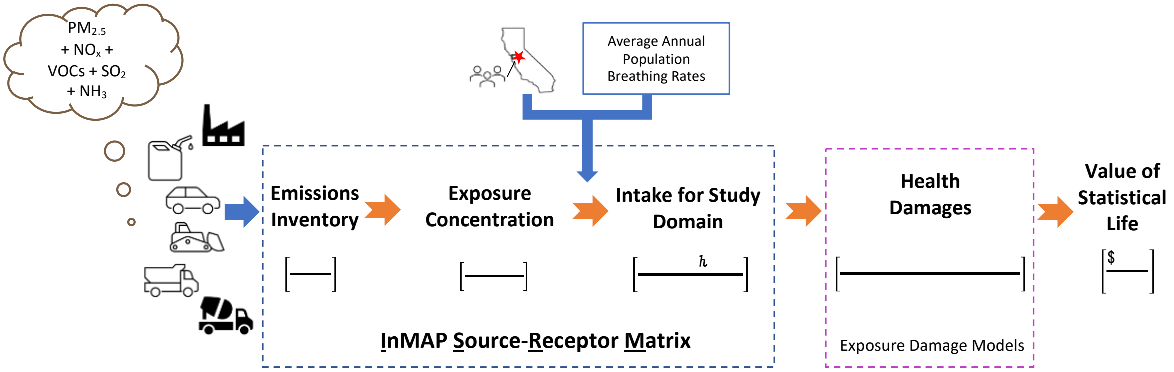


Figure 9. Overview of key modeling steps for exposure assessment.

Notes: Annual emissions from sources, shown in Figure 2, are fed into the InMAP Source-Receptor Matrix (ISRM). Exposure concentrations from ISRM are used to monetize health damages using the value of a statistical life metric.

Study Area: 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.[58] 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.[59] Four of the nine counties (Marin, San Francisco, San Mateo, and Santa Clara) rank as the top four statewide in per-capita income.[59] California, and the Bay Area in general, is an appropriate place to examine disparate exposure impacts from roadway infrastructure. Roughly 40 percent of Californians live within 500 meters of a high-traffic road.[17] 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 $PM_{2.5}$.[60]

The Bay Area's "racialized geography,"[61] partially influenced by historical practices that have contributed to disparities in air pollution exposure,[9] suggests that multiple racial-ethnic groups may be asymmetrically burdened in their exposure to polluting roadway infrastructure. We selected 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/maintained 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 $PM_{2.5}$.

Selection and Design, Operation, Resurfacing Characteristics of Roadway Segments

The number of roadway segments included in our analysis is based on a set of realistic scenarios that specify how many separate miles of pavement would be maintained on an annual basis. Two scenarios for pavement resurfacing activities were analyzed: (1) 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; (2) Scenario 2 roadway segments are located solely in census tracts designated as Disadvantaged Communities (DAC) according to California State Bill 535.[12,62] The DAC census tracts fall into the 25 percent highest pollution-burdened areas as per CalEnviroScreen, the state's pollution mapping tool.[63]

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 a minimum 30 to 45 one-mile segments would have their full-width repaved in any given year. All road segments and associated characteristics are provided in detail in Table 8 through Table 11 in the Supplemental Information in the published paper on this topic.

Roadway Design

Paved roadways consist of multiple layers of material, typically with 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 explained in 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.[64] 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 the absence of specific data from the agency maintaining the road). Measured average annual daily traffic counts, which is the total annual volume of traffic divided by 365 days, from Caltrans were used to calculate the traffic intensity for each roadway segment in the dataset.[65] 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.[66] California's pavement climate region map was utilized in determining the depth of layers for rigid pavements.[67]

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.[66,68] The assumed resurfacing process for rigid pavements is milling (of the old pavement), recompaction of the 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.[68] 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 below, productivity affects the equipment's tailpipe emissions and fuel consumption.

Roadway Operations

Average annual traffic volumes for each road segment were estimated from measured average annual traffic count data from Caltrans.[65] 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[69] (see Table 12 in the Supplemental Information).

$PM_{2.5}$ Exposure Modeling

Emissions Inventory

As indicated in Figure 9, a mapped 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 10 depicts the scope of emission sources accounted for in the exposure assessment. Pacific Gas and Electric Company (PG&E) supplies the Bay Area's electricity. As the study area is limited to the Bay Area, any impacts from exposure to 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.)

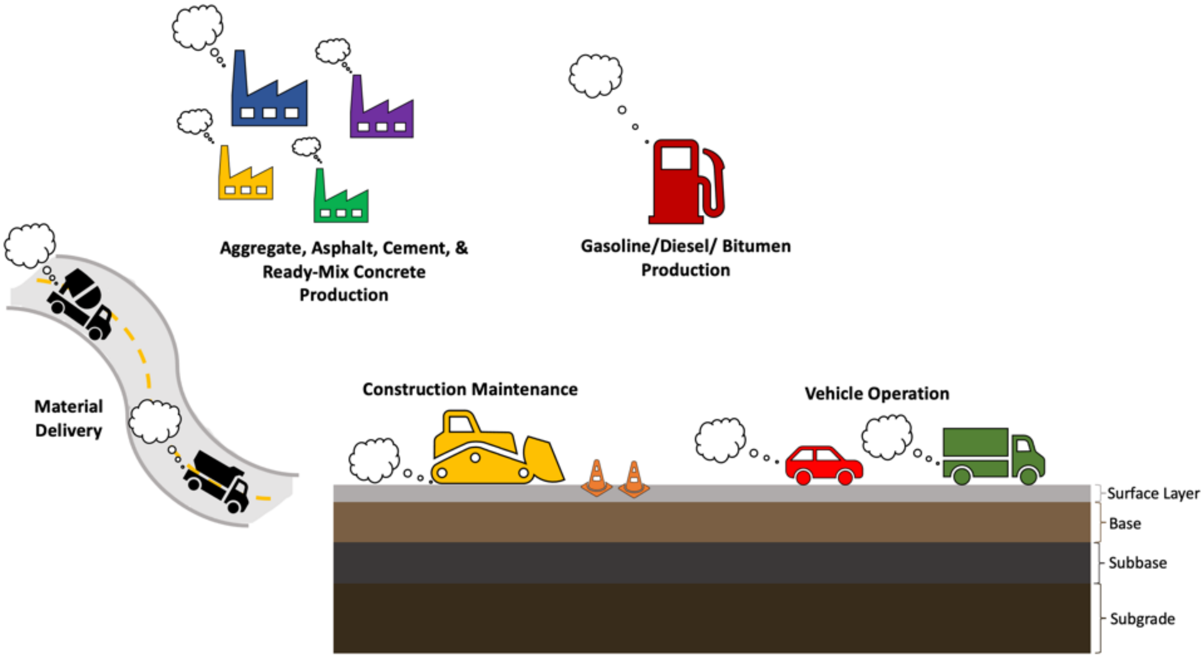


Figure 10. Scope of emission sources included in exposure assessment.

In general, mobile-source emissions are calculated using Equation 1:

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

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:

$$E_S = \sum_{i=1}^{p} EF_{S,i} \times V_{S,i} \quad (2)$$

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.[70] 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.[71] 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.

Material Production Facilities

Realistic volumetric production rates are assumed, based on prior experience, of material per year for prototypical cement, ready-mix 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.[72] 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.

Oil Refineries

There are seven crude-oil refineries within the Bay Area. Two oil refineries (Chevron in Richmond and Shell in Martinez) are used as proxy locations of where gasoline, diesel, and bitumen products would be manufactured. The assumption that 50 percent 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.[73] 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.[74] It is assumed that four percent, by volume, of each crude oil barrel is transformed into bitumen (see the Supplemental Information, Section 5). Using annual emission data from each refinery from ARB, an emission factor is calculated in tons of emissions per cubic yard of bitumen.

Construction/Resurfacing

Pollutant-specific off-road mobile source emission factors from ARB's EMFAC emission inventory webtool were used. The 2019 BAAQMD fleet for "Construction and Mining" equipment was utilized, assuming an aggregate range of model years. Tailpipe emissions from construction were 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.

We assumed that materials would 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 Supplemental Information) is multiplied by the on-road emission factor from EMFAC for the relevant delivery truck (concrete transit mixer or asphalt dump truck).

Vehicle Operation

We assumed that the 2019 BAAQMD fleet from EMFAC provides 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 were 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 were 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 Figure 1 and Figure 2 and Table 8 and Table 10 in the Supplemental Information.

Exposure Intake and Damages

Intake is defined as the mass of air pollutant inhalation for a given population over a period of time.[75] An emissions inventory was used to determine how polluted the air is in a discrete area. Air is considered polluted depending on the amount of pollutant in a 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, were estimated using a mechanistic air quality model.

Following the methods outlined in Thaneya et al.,[56] 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 mapped emissions inventory. The IRSM models changes in concentrations at receptor locations from changes in emissions at source locations (i.e., where the pollutants are emitted).[76] ISRM is a linearized extension of InMAP, a reduced-complexity air quality model. InMAP simplifies computational time by varying grid cell sizes.[77] Smaller grid sizes in more populated areas yield exposure results with higher resolution, which is critical in accurately assessing exposure disparities among population groups.[78] InMAP and ISRM account for secondary $PM_{2.5}$, which forms from long-range transport and atmospheric chemical reactions among emission precursors including NO_x, 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 emissions sources produce at least as much exposure from secondary PM as from primary PM.[79] Secondary PM exposures occur at greater average distances than primary PM exposures.[79]

Exposure concentrations from IRSM were overlaid with population census tracts and annual average breathing rates.[80,81] 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.,[76] the exposure concentrations are transformed into premature mortality rates using linearized concentration-response functions. Premature mortality rates (number of deaths per year) and the Value of Statistical Life (VSL) were 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 $PM_{2.5}$ air pollution.[82]

Mitigation Strategies

Emissions inventories, population-weighted exposure concentrations, $PM_{2.5}$ intakes, and exposure damages were calculated for the mitigation strategies listed in Table 1. Of course, other strategies are also possible, such as the use of alternative fuels [83] instead of electrification, but the strategies in Table 1 are most likely to bring the biggest PM benefits. Details are provided in Section 8 of the Supplemental Information.

Table 1. Mitigation strategies tested in ISRM.

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 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)

Uncertainty Assessment

We also explored the uncertainty associated with the accuracy and relevance of system inputs (i.e., data and assumptions), models, and outputs. The material emissions data utilized in the study were in keeping with recent studies that analyzed concrete[84] and roadway pavements.[85] The on-road and off-road data, which comes 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.[86,87] We used standard pavement design guidelines maintained by the State of California, in addition to informed discussions with pavement designers at Caltrans.

Goodkind et al.[76] assessed the uncertainty of the ISRM, concentration-response functions, and the exposure damages in their study of impacts from $PM_{2.5}$ pollution in the United States, finding that the ISRM Value of

Statistical Life estimate was within eight percent of estimates from the U.S. Environmental Protection Agency.[76] 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.[88] 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,[89] which could be relevant if only a limited number of emission sources are being considered. Uncertainty with outputs, by validating model results with prior studies, are presented in the Discussion section.

C. Results

Persons living in each of the 1,566 census tracts 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 area are presented in Figure 11. 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 to 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,[76] census tracts not located within proximity to these sources still experience some exposure, partially as a result of the secondary formation of $PM_{2.5}$.

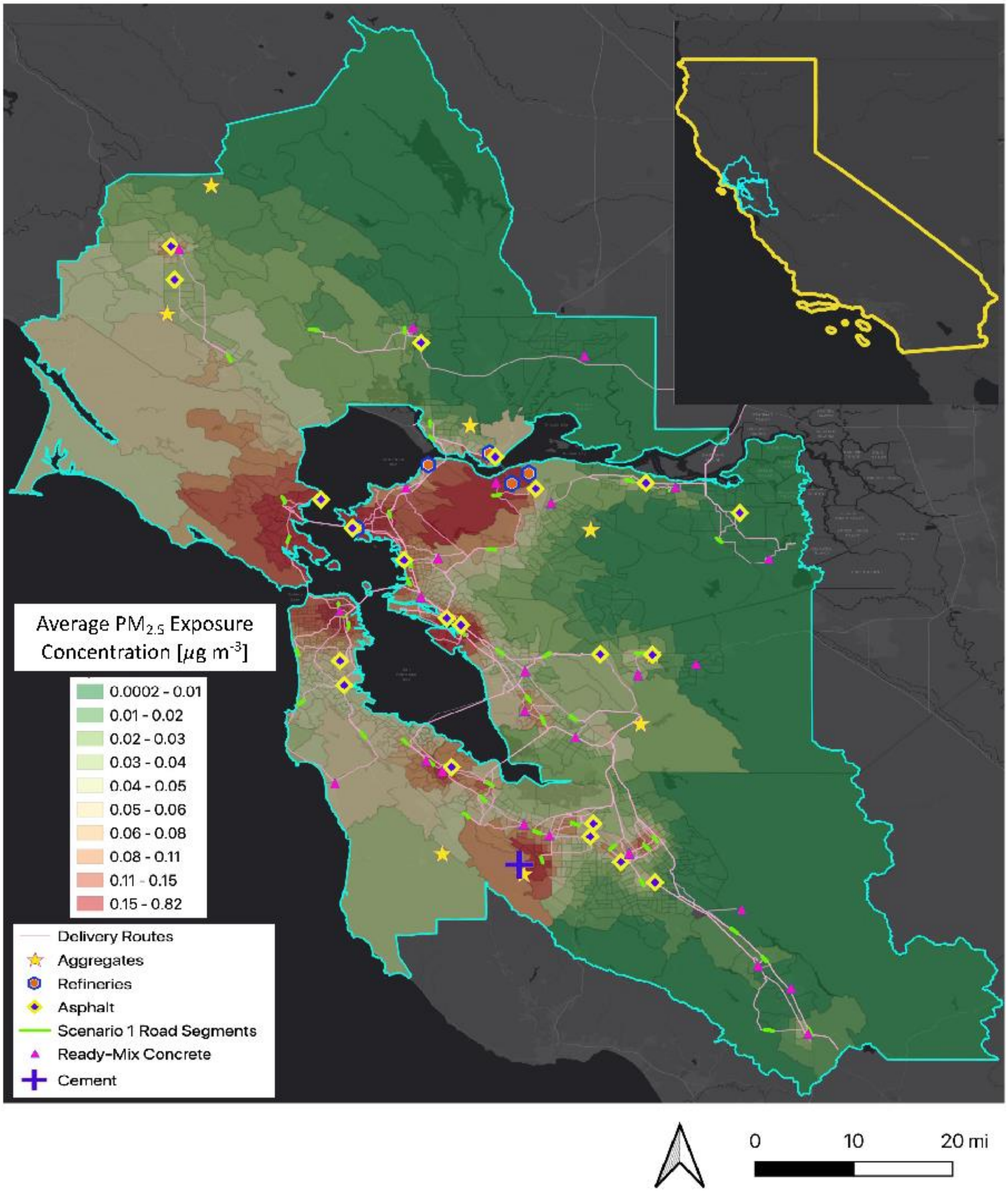


Figure 11. Average PM2.5 exposure concentrations from all emission sources for Scenario 1.

Notes: Red colored census tracts experience higher exposure concentrations compared to green colored tracts. The population weighted average PM$_{2.5}$ concentration experienced in the Bay Area from all sources is on the order of 7-8 µg/m3.

The $PM_{2.5}$ intake for all persons within the study area 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 12. While only five mitigation strategies are discussed within the main text to show a range of possible intake reductions, the Supplemental Information 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/year) represent 35 percent of total intake. Road resurfacing activities (1.5 g/year), material deliveries (104 g/year) and material/fuel supply chain sources (1673 g/year) account for 65 percent of total annual intake. Mitigation strategies reduce $PM_{2.5}$ intake by a range of 64 percent (future electrification of all on-road vehicles and construction material delivery) to 0.10 percent (interim electrification of off-road equipment). Note that even in the 100 percent electrification scenario for 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 percent (218 g/year) 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.[90,91] (The methodology for moving facilities is provided in the Supplemental Information, Section 8.)

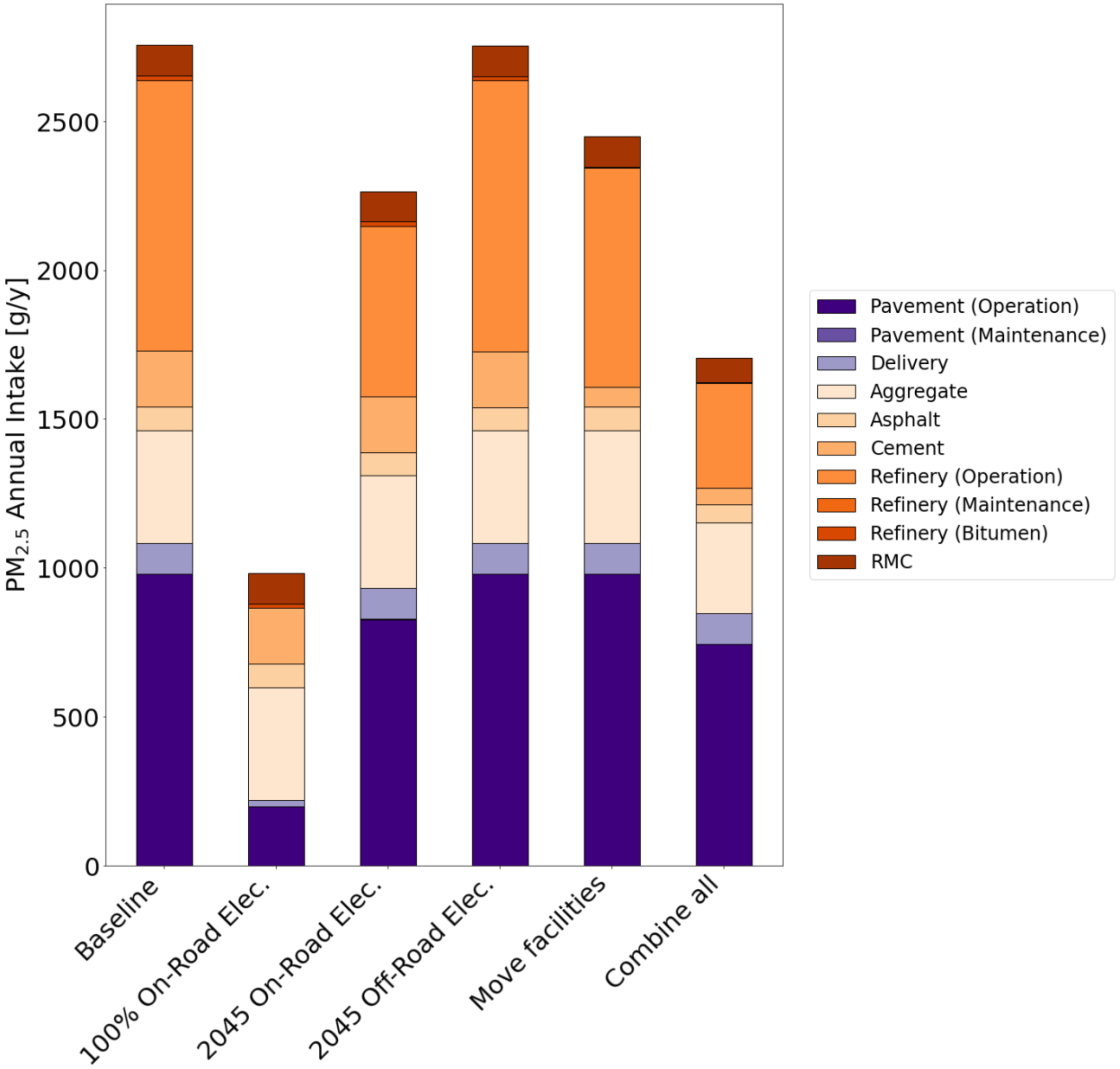


Figure 12. Annual PM$_{2.5}$ intake within study area (San Francisco Bay Area) for baseline and mitigated conditions for Scenario 1.

Notes: Mitigation strategy descriptions are listed in Table 1. RMC: ready-mixed concrete.

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 area. The annual average population-weighted exposure concentration from all road segment sources accounted for in the study area is 0.07 μg/m^3. Figure 13(a), Figure 13(b) and Figure 14(a), Figure 14(b) depict two key representations of exposure. The total heights of Figure 13(a) and Figure 14(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 for that source. Figure 13(b) and Figure 14(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 65 times the $PM_{2.5}$ exposure burden from the cement facility, the source they are most differentially exposed to, then the general population.

Of the 7.5 million people living in the Bay Area, the White population accounts for around 60 percent of the total population, the Pacific Islander population for 0.3 percent, the Asian population for 6 percent, the Hispanic or Latino population for 19 percent, and the Black population for 14 percent.[58] 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, 15 percent (9.9 e-3 $\mu g/m^3$), from the operation, resurfacing activities, material delivery, and material and fuel production associated with the roadway segments. The Hispanic population experiences 0.50 percent (4.1 e-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 minus one percent (-7.9 e-4 $\mu g/m^3$), minus 6 percent (-3.6 e-3 $\mu g/m^3$), minus 13 percent (-8.2 e-3 $\mu g/m^3$), and minus 5 percent (-3.2 e-3 $\mu g/m^3$).

In Scenario 1, the Black population experiences higher-than-average $PM_{2.5}$ exposure from 66 percent of sources in the study area (Figure 13(a)). While not depicted in Figure 13(a), people of color bear higher-than-average $PM_{2.5}$ exposure from 65 percent of emission sources. People in the lowest income quintile (i.e., the annual median household income for the 20 percent lowest-earning households) suffer from the highest exposure burden (Figure 14(a)). People in Q1 (annual median household income < \$73,000) experience higher-than-average exposure from 96 percent 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 percent 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 (Figure 10 and Figure 11 in the Supplemental Information).

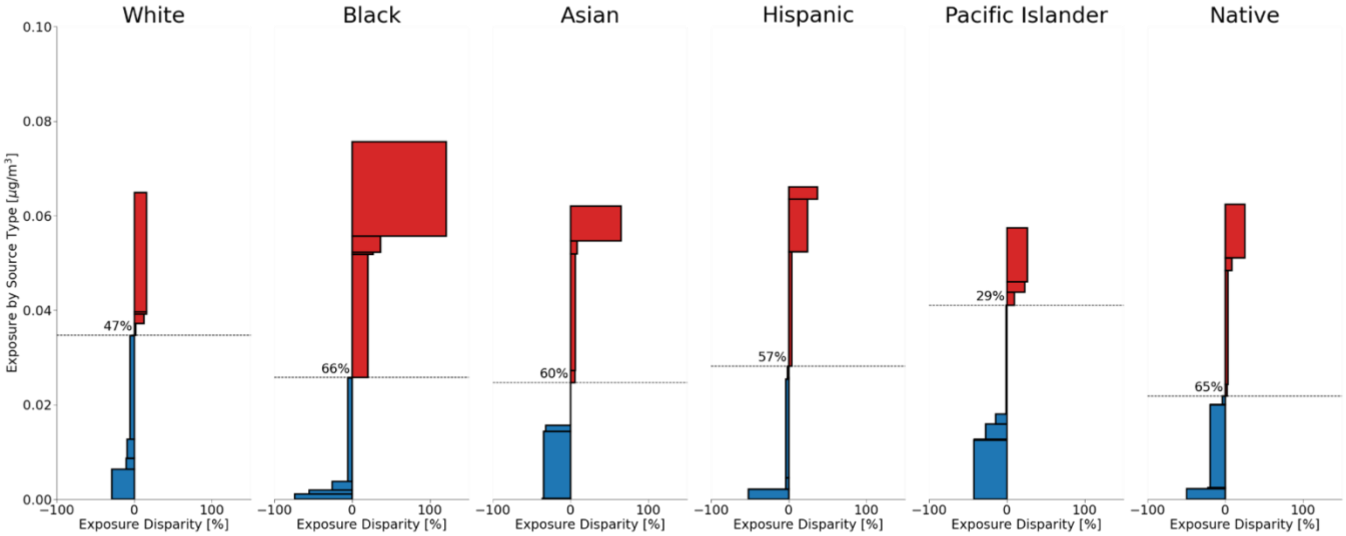


Figure 13. Absolute and relative PM2.5 exposure for Scenario 1 by racial demographic.

Notes: The dashed horizontal line indicates the percentage of emission sources causing higher-than-average exposure for each group.

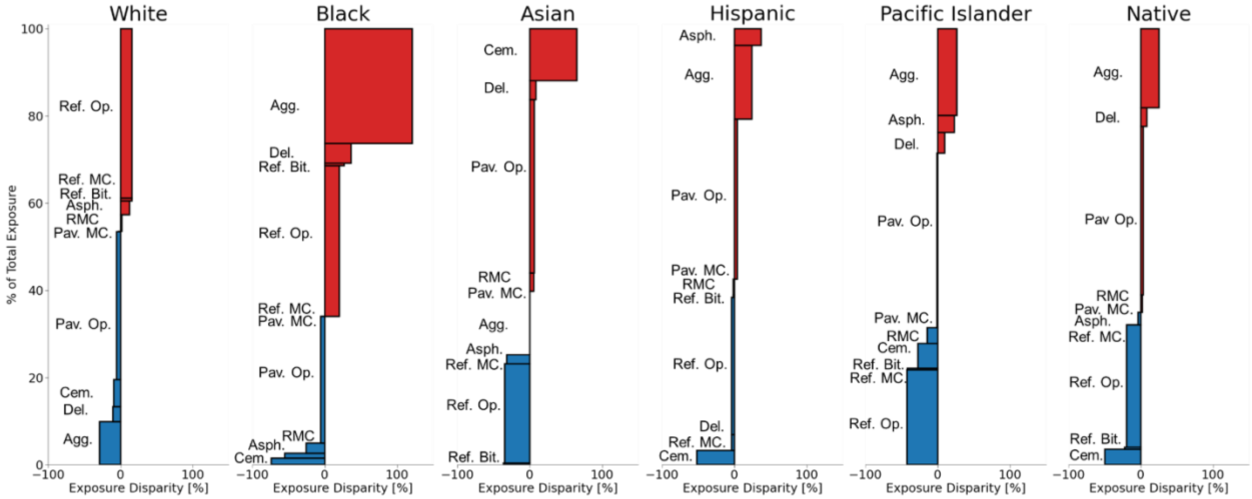


Figure 14. Ranked order of exposure disparity for Scenario 1 by source type for each racial demographic.

Notes: The y-axis shows the percentage that each source contributes to total absolute exposure.

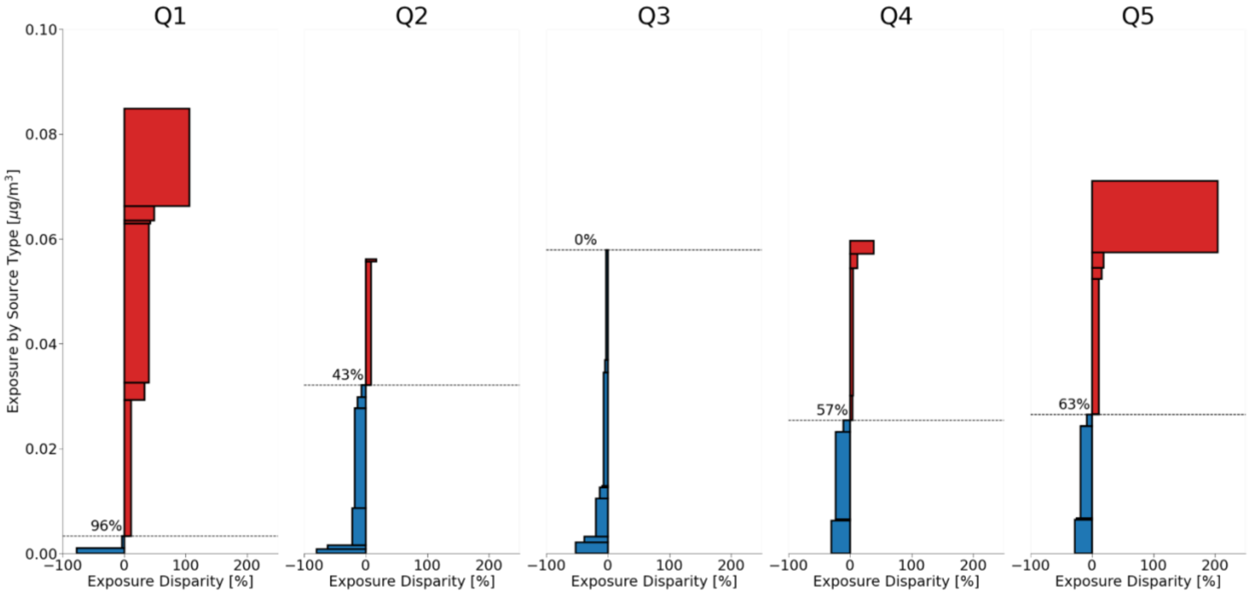


Figure 15. Absolute and relative PM2.5 exposure for Scenario 1 by income quintile.

Notes: The dashed horizontal line indicates the percentage of emission sources causing higher-than-average exposure for each group.

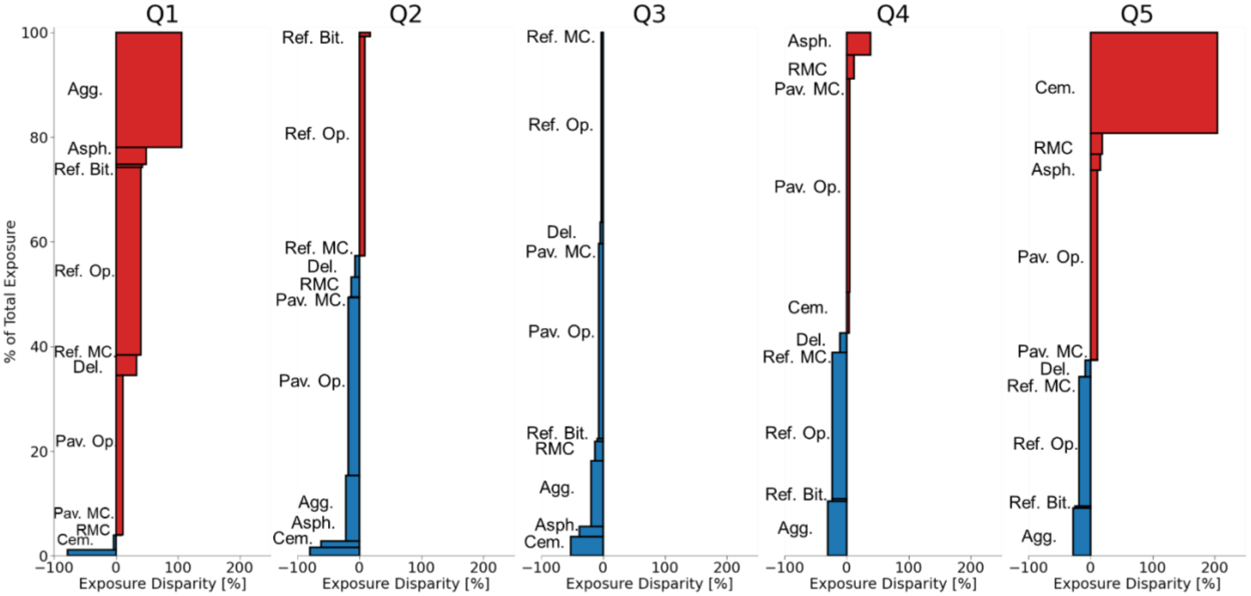


Figure 16. Ranked order of exposure disparity for Scenario 1 by source type for each income quintile.

Notes: The y-axis shows the percentage that each source contributes to total absolute exposure.

Figure 13(b) and Figure 14(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 percentage of total exposure (Table 3 in the Supplemental Information) except for the White, Black, and Q1 populations (for 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 of 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 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). 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 Table 4 through Table 7 in the Supplemental Information. Mitigation reductions are marginally larger for each strategy, suggesting that DAC census tracts might benefit even more from strategy implementation.

Table 2. Exposure damages for baseline and select mitigation strategies.

Strategy	Scenario 1 Exposure Damages ($M/year) / Percent Change	Scenario 1 Exposure Damages – 100 days ($M/year) / Percent Change
Baseline	$170 – 190	$180 – 200
100% On-road Electrification	-65.7% – -66.1%	-61.7% – -62.2%
2045 On-road Electrification	-18.3% – -18.6%	-17.2% – -17.5%
2045 Off-road Electrification	-0.0490% – -0.0500%	-4.60% – -4.70%
Move Cem/Ref Facilities	-9.90% – -10.3%	-9.60% – -9.90%
Combination	-38.1% – -37.5%	-40.0% – -40.6%

Note: Three significant digits are shown to make distinctions in the ranges.

D. 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 area (i.e., on-road vehicle operation, crude-oil production) are in keeping with principal source contributors for intake and incidences of premature mortality.[2,92]

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 percent of annual $PM_{2.5}$ intake for the Bay Area population. For added context and a fair comparison between supply chain impacts, roadway construction, 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 ten to fifteen years, or when budgets are available.[93] 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.[94,95] Electrification of on-road mobile sources mitigates the baseline $PM_{2.5}$ intake by a range of 18 percent (interim electrification based on the projected ARB vehicle fleet composition for the year 2045) to 64 percent (complete electrification in some future unknown year). Even with complete electrification, primary $PM_{2.5}$ emissions from brake and tire wear still contribute 22 percent of that mitigation strategy's (Strategy #2) annual intake. Most significantly, complete electrification still leaves 78 percent of that strategy's (Strategy #2) remaining annual intake. Given the restricted effectiveness of other mitigation strategies (Figure 8 and Figure 9 in the Supplemental Information), 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 from electrification alone, what policies should then be explored and prioritized to try and reduce exposure as much and as quickly as possible? Of the twelve 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 high 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 area. People of color experience exposure burdens from 60% of the emissions sources in the study area, with aggregate and other material production causing the highest exposure disparity for the Black, Hispanic, Asian, and Native Americans. 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 Value of Statistical Life 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 $\mu g/m^3$) from the ten emission sources included the scope is around one percent of the reported $PM_{2.5}$ exposure concentration from all sources within the United States (7 $\mu g/m^3$).[11] Scenario 1's on-road mobile weighted concentration from the 45 one-mile segments (0.02 $\mu g/m^3$) represents 1.5 percent of exposure concentration from all on-road mobile sources within California.[2] As an additional point of reference, the annual average $PM_{2.5}$ exposure concentration for the San Francisco Bay Area is around four micrograms per cubic meter.[11] 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[96] as each group does not experience harms or benefits at the same rate.

E. 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 for 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 this study, is a discrete, one-time event which occurs over a couple days in a typically 10-15-year period and 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.[97]

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.[98]

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 myriad health and climate change co-benefits associated with transforming the transportation sector.[99,100] A future transportation sector should prioritize improving access while minimizing material and fuel consumption.

3. Roadway Segments: GHG Emissions

A. Introduction

Greenhouse gas (GHG) emissions from the transportation sector are a significant contributing source to global climate change. The transportation sector accounts for 27 percent of the United States' annual anthropogenic GHG emissions, the single largest source.[101] Light-duty passenger vehicles and medium-and-heavy-duty trucks comprise 83 percent of annual transportation sector emissions.[102] In California, transportation comprises the majority of the state's approximately 420 million annual metric tons of GHG emissions; on-road transportation alone accounts for 31 percent of total emissions.[1] Transitioning the transportation sector, and especially on-road transportation, to low or zero-carbon is paramount for achieving GHG emission reduction targets and limiting rises in global average temperatures.[103]

Without any intervention, increasing anthropogenic GHG emissions will lead to catastrophic effects from climate change, namely sea level rise and extreme weather events. Observable impacts from climate change for both natural ecosystems (e.g., species range, phenology timing) and human-made infrastructures (e.g., flooding, damages) are already apparent across the globe and in North America.[104] In California, climate change is highly likely contributing to increased drought and wildfire activities.[105–107]

Examining the full range of GHG sources related to on-road transportation, including emissions from materials used in paved roads, construction of paved roads, and associated fuel supply chains, allows for determining potential regulation and mitigation opportunities. Life-cycle assessment (LCA), a standardized methodology that tracks the cradle-to-grave impacts of a process, product, or entire infrastructure system, is well-suited for holistically assessing the on-road transportation sector. There are numerous LCA studies that inventory GHG emissions from paved roads, on-road vehicle operations, and off-road equipment operations.[45,108–111] As discussed in the section on $PM_{2.5}$ exposure, these studies often limit their scope to creating an inventory of emissions for a defined system boundary and functional unit (e.g., constructing one mile of paved road, traveling one passenger-kilometer in the United States, etc.).

The Federal Highway Administration (FHWA) and California's Department of Transportation (Caltrans) routinely conduct life-cycle cost analyses on pavement projects to estimate the direct and indirect costs that the agencies and road users will experience throughout the pavement's life cycle.[112,113] Life-cycle cost analyses performed by the FHWA and by Caltrans do not include external costs from emissions that society bears as a result of paved road construction, operation, and maintenance. Few LCA studies of pavements and on-road transportation evaluate economic damages or the harm to society that resulting emissions cause. The Social Cost of Carbon metric measures the economic harm (i.e., costs incurred from damaged property, harmed populations, etc.) from climate change impacts. Specifically, the Social Cost of Carbon metric is defined as the economic harm caused by emitting one additional ton of carbon dioxide equivalents (CO_2(eq)) to the atmosphere.[114] Under various U.S. administrations, the Social Cost of Carbon has been used in benefit-cost analyses on federal projects and in relevant legislation.[115]

Social Cost of Carbon is an appropriate metric to use in environmental assessment methods such as LCA to connect GHG emissions to an understandable outcome.[116] The use of Social Cost of Carbon in LCAs of pavements and on-road transportation in the academic literature is a growing field of research. One study evaluated the socioeconomic costs of CO_2, from just the production of materials used in various asphalt pavement rehabilitation techniques using a value of $171 per ton of emitted CO_2.[117] Researchers analyzed the Social Cost of Carbon from constructing alternative preservation, maintenance, and rehabilitation techniques of pavements in a case study in Chile.[118] Another study calculated Social Costs of Carbon from the use phase of a pavement's life cycle, analyzing how pavement roughness influences vehicle emissions.[119] No existing research estimates the cost of all phases of a pavement's life cycle, from the production of materials and construction of roads to vehicle operation on road segments and routine maintenance activities. To fill this research gap, we investigated the following questions:

1. What is the full scope of GHG emissions, accounting for material and fuel supply chains, from the operation and maintenance of roadways within a metropolitan region such as the San Francisco Bay Area?
2. How do policies such as electrification of on-road/off-road mobile sources, increased fuel efficiencies, and implementation of pollution control technologies change GHG emissions?
3. What are the external damage costs from total GHG emissions? Which mitigation strategies should be selected given their external damage costs?

Similarly to the objectives outlined in the section above on $PM_{2.5}$ exposure, our objectives point towards: (1) identifying mitigation strategies that are effective in minimizing GHG emissions; (2) determining how effective transportation policies such as electrification are in mitigating GHG emissions from a roadway network and how that effectiveness compares for mitigating fine $PM_{2.5}$ emissions; and (3) calculating the economic value of the harm caused by GHG emissions so decision-makers can understand the true costs that society bears from road transportation.

B. Methods

We calculated a GHG emissions inventory and resulting climate change economic damages for the same case study described in the $PM_{2.5}$ exposure section. Emission sources included are the same as depicted in Figure 10. The methods employed in calculating the GHG emissions inventory from roadway segments are almost identical to the methods described in the $PM_{2.5}$ exposure section, with CO_2 (eq) emissions factors used instead of $PM_{2.5}$ emission factors. One notable exception is that emissions from the manufacturing and production of raw materials used in the roadway segments come from environmental product declarations which are industry-reported; certified inventories of the life-cycle emissions of distinct products, rarely contain data on $PM_{2.5}$ emissions. The values used in this study come from the Embodied Carbon in Construction Calculator database,[120] which is one of the most prominent repositories for building and construction material information.

Since the Social Cost of Carbon metric is highly sensitive to multiple factors (e.g., choice of discount rate, integrative assessment model, spatial boundary of climate change impacts),[121–124] we utilize a range of values. Table 3 indicates the values, in 2019 USD per metric ton of CO_2(eq), utilized to estimate economic harm from the inventoried GHG emissions. The values in Table 3 provide a realistic, near-term range that federal and state agencies could incorporate into decision-making and are in keeping with estimates for the United States.[125] It should be noted that a recent study valued the Social Cost of Carbon at a mean of $185 per ton, which is over 3.5 times higher than the current U.S. government estimate.[126] It is not unreasonable to think that the newly revised estimate will be adopted by the federal government in the near future.

Table 3. Social Cost of Carbon (SCC) values (in 2019 USD) used in analysis.

SCC Range	SCC Value (2019 USD/ton)	Source (see References)
Low Estimate	$43	#114
Latest U.S. Gov't Estimate	$51	#115
High Estimate	$309	#114

The economic harm from GHG emissions is calculated using Equation 1:

$$D_{GHG} = E_{GHG} \times SCC_i \qquad (1)$$

where D_{GHG} are the total damages from the GHG emissions inventory, E_{GHG} are the GHG emissions from the inventory, and SCC_i is the Social Cost of Carbon for the respective range i (i.e., Low, U.S. Gov't, High).

C. Results

Figure 17 highlights the total annual GHG emissions for baseline and mitigated strategies for the Scenario 1 road pavement case study. Direct GHG emissions from on-road vehicles account for 65 percent of total baseline emissions; supply chain and embodied sources account for the remaining 35 percent. Complete electrification of on-road sources results in an almost 97 percent reduction in annual GHG emissions (Table 4). Off-road mitigation strategies are less effective, yielding very modest annual reductions on the order of 0.01 to 0.03 percent. Off-road strategies yield modest reductions due to the scale of operation; our study is assessing continuous year-round on-road vehicle operation compared to discrete 1–2-day off-road construction equipment operation. As with the $PM_{2.5}$ exposure case, supply chain and embodied GHG sources are important within the larger context of operating and maintaining roadways.

Table 4 shows the economic costs, in terms of monetized climate change damages, for the baseline and mitigated strategies for the road pavement case study. Reduction percentages for climate change economic damages by strategy are the same as for annual GHG emissions because damages are calculated using a linear expression (Equation 1). While there is a wide range of climate change damages ($84 to 601 million USD), they are on the same order of magnitude as the damages for $PM_{2.5}$ exposure in the previous section ($170-190 million USD).

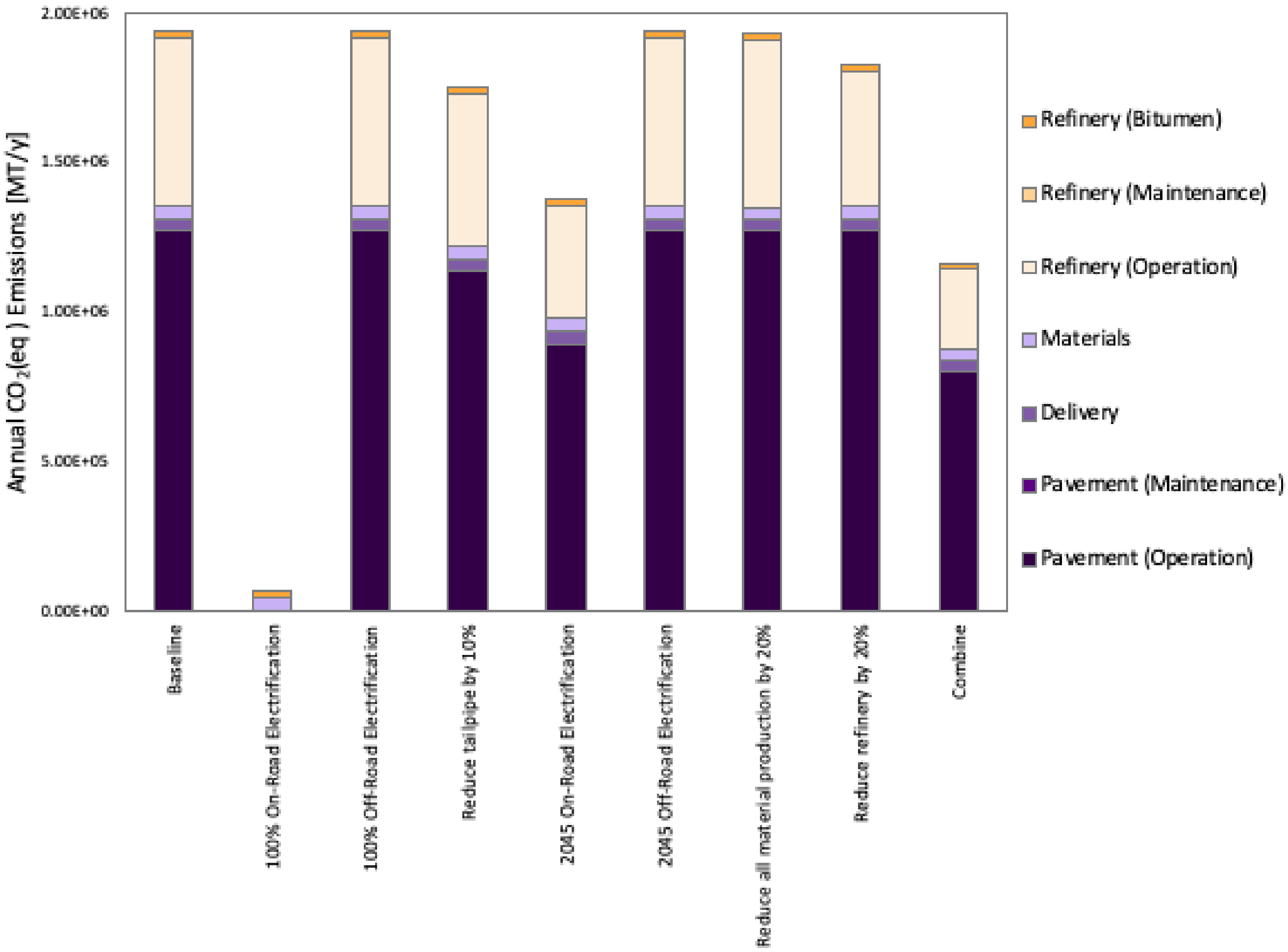


Figure 17. Annual GHG emissions for Scenario 1.

Table 4. Social Cost of Carbon results for Scenario 1 baseline and mitigation strategies.

Strategy	SCC ($M/year) / Percent Reductions
Baseline	84 – 601
100% On-Road Electrification	97%
100% Off-Road Electrification	0.029%
Reduce tailpipe emissions by 10%	9.7%
2045 On-Road Electrification	29%
2045 Off-Road Electrification	0.010%
Reduce all material production by 20%	0.45%
Reduce refinery by 20%	6.0%
Combine	40.%

D. Discussion

Compared with the results of mitigation strategies on $PM_{2.5}$ exposure as presented in Section 2 above, the effectiveness of mitigation strategies on reducing GHG emissions is even more pronounced. Electrification of on-road vehicles is a comparatively more effective GHG mitigation strategy than a $PM_{2.5}$ exposure intake mitigation strategy. With 100 percent electrification of all on-road sources, GHG emissions (and the linearly dependent monetized damages) are reduced by 97 percent compared to baseline conditions. The same mitigation strategy for $PM_{2.5}$ exposure yields a 64 percent reduction by comparison, because unlike with GHG emissions, complete electrification does not entirely eliminate all $PM_{2.5}$ vehicle sources (e.g., brake and tire ware). Clearly, vehicle electrification is a commonsense strategy to combat climate change because it eliminates direct emissions from fuel combustion as well as the emissions from refining vehicle fuels.

However, policy makers should have realistic expectations for the roll out timeline for complete on-road electrification. The interim electrification scenario is set to occur in 2045 (more than 26 years from the baseline year of 2019) yielding a 29 percent reduction in annual GHG emissions. The 2045 vehicle fleet composition comes from ARB's EMFAC model. The timeline for when California's vehicle fleet will be entirely electrified is far into the future.

There are further similarities and differences between the effectiveness of mitigation strategies for GHG emissions and $PM_{2.5}$ exposure. For example, off-road mitigation strategies yield modest GHG emission reductions, similar to the apparent "lack" of effectiveness exhibited for reducing $PM_{2.5}$ intake. When adjusting for more frequent construction activity throughout the year, the reductions are on the order of 0.5 to 1.5 percent in annual GHG emissions for off-road mitigation strategies. Road materials (aggregate, cement, concrete, asphalt), unlike in the exposure study, appear to be a comparatively less significant source of GHGs within the study area. The results for the off-road and material sources should not cause policy makers to completely neglect any respective mitigation opportunities. Rather, the results underscore the importance of a systematic and nuanced approach to addressing pollution from our transportation systems.

Monetized climate change damages are on the same order of magnitude as the $PM_{2.5}$ exposure health damages presented in Section 2. This result highlights that the economic burdens caused by both sets of emissions are significant (on the order of millions of USD), especially considering that the number of roads that are resurfaced in this case study are likely an underestimate of the actual amount of repaving that occurs annually. Given that recent estimates for the Social Cost of Carbon are greater than 3.5 times the current federal estimate of $51 USD per metric ton of carbon dioxide emissions, the results from the paved road case study indicate that stakeholders can save money by implementing climate reducing policies.

E. Conclusion

Across both $PM_{2.5}$ exposure and GHG emissions, the results from the San Francisco Bay Area roadway case study indicate that mitigation strategies have differing levels of effectiveness based upon the pollutant that is mitigated. Policymakers and other stakeholders should strive to ensure that transportation policymaking is tailored to meet specific end goals (e.g., climate change mitigation, racial equity). End goals are not necessarily mutually exclusive, but their solutions likely need to be more nuanced than what is represented in current practice and in policy rule making. It is important to apply systems-level thinking to solve problems caused from designing, constructing, and operating transportation projects. Road transportation is not just on-road vehicles but a whole portfolio of sources (materials, delivery, fuels) that need to be taken into consideration when developing mitigation policies.

4. Roadways: Noise Exposure

A. Introduction

Transportation and related construction are some of the most prominent sources of environmental noise in the United States.[127] A likely cautious estimate is that over 18 million people in the United States are negatively impacted by surface (vehicle) transportation noise.[128] Noise pollution can lead to negative health and social impacts for exposed populations. Negative impacts can be acute (e.g., annoyance, hearing loss, sleep disturbances), chronic (e.g., hypertension), or eventually long-term (e.g., permanent hearing loss, ischemic heart disease).[127,129]

Background on Noise

A noise immission is the sound heard by an observer, as opposed to noise emission which is the amount of sound emitted from a source.[128] Both noise immissions and emissions are measured in decibels, or most commonly, in A-weighted decibels (dBA), which are a measurement of how loud the human hear perceives a particular sound. Decibels are a unit of sound pressure level.[128] As a point of reference, a sound source of 160 dBA would instantly perforate a human's ear drum.[130] Conversation at a whisper level correlates to a sound pressure level of around 20 dBA.[130] The U.S. Environmental Protection Agency states that "an average 24-hr exposure limit of 55 dBA" should not be exceeded in order "to protect the public from all adverse effects on health and welfare in residential areas."[127]

As has been done with other environmental pollutants that cause harm to society, it is common practice to evaluate the economic impacts, both in direct and indirect costs, of noise pollution. The impacts from noise on health were developed with exposure-response curves in a seminal work.[131] Various studies then calculated the costs associated with noise-caused health impacts. Researchers estimated changes in total direct and indirect costs of hypertension and heart disease for the United States as a result of implementing a hypothetical mitigation action, finding that mitigation could yield close to $4 billion in savings annually.[132]

Some studies have specifically examined the compensatory damages associated with construction noise with a predicative construction noise model applying methods developed by the Ministry of Environment of South Korea.[133] One study calculated health damage costs, based upon the value of a statistical life of their citizens, from construction noise exposure in South Korea.[134] Implementing an optimal noise barrier reduced health damages costs by 10 percent. Another study estimated marginal costs associated with road noise for a case study in Sweden, accounting for damages resulting from direct noise disturbances (e.g., sleep disruptions) and health impacts resulting from chronic noise exposure (e.g., health care costs, loss in productivity, premature deaths).[135] A case study for Berlin used dynamic spatial and temporal data (tracking where people are throughout the day) to estimate real-time road traffic noise so as to provide a realistic representation of exposure damages.[136] Few studies incorporate life-cycle assessment (LCA) into noise exposure analyses, but one research effort did explore how noise should be included in LCA efforts and offered a structural framework and model measuring human health impacts from a life-cycle perspective.[137]

This work offers an opportunity to fill a knowledge gap in transportation studies by exploring the economic damages from noise exposure emanating from both vehicle operation and road construction.

Research Questions

Research questions that will fill the knowledge gap are:

1. What is the noise exposure from road traffic and construction of select road segments within the San Francisco Bay Area?
2. How do hypothetical mitigation efforts to reduce noise exposure from road traffic affect health damage costs?
3. How is noise exposure from the case study sources stratified by race and income level in the San Francisco Bay Area?

The primary objective of this research is to offer a methodological framework for evaluating the health and economic impacts from noise exposure for a metropolitan population. The remainder of this section includes a description of methods, an overview of results, and a discussion of broader implications.

B. Methods

The overall methods for measuring noise impacts are broadly similar to the steps outlined in the $PM_{2.5}$ exposure case study of road segments in the San Francisco Bay Area presented above. Methodological steps include:

1. Identify the amount of noise, in dBA, coming from vehicle traffic and construction activities.
2. Determine how that source is experienced by people using source-receptor relationships. Road traffic source-receptor results come from a Bureau of Transportation Statistics dataset. Road construction source-receptor results are modeled using geographic information system software.
3. Compare how noise exposure affects people by calculating the average road traffic noise levels experienced by racial and socio-economic groups within each exposure study area, in this case the entire San Francisco Bay Area. We evaluated road construction noise for census tracts that fall within a 100-meter buffer of each evaluated road.
4. Evaluate economic costs (from road traffic noise only) based on the method described in Swinburn et al.[132] where changes in direct and indirect health costs associated with two key components of noise-related health impacts (hypertension and heart disease) are evaluated. This entails:
    a. Determining how many people in the San Francisco Bay Area have hypertension and ischemic heart disease (IHD) using population statistics and county-specific prevalence rates for each health condition (presented in the accompanying decision-support tool in Section 7).

b. Determining how much of the population within each county is exposed to traffic noise levels above 55 dBA, which is the level at which the U.S. Environmental Protection Agency has determined leads to health damages such as hypertension and IHD. The population not exposed to traffic noise levels above 55 dBA is also calculated.

c. Calculating the risk of a health condition (i.e., hypertension, IHD) for a population not exposed to noise levels above 55 dBA using Equation 1 as modeled from Swinburn et al:

$$R_{UE,i} = \frac{P_{Disease,i}}{P_{E<55\ dBA} + \left(P_{E\geq 55\ dBA} * RR_{Disease,i}\right)} \quad (1)$$

Where:

R_{UE} = Risk for the population unexposed to traffic levels above 55 dBA for each health condition "*i*"

$P_{Disease,i}$ = Total population with health condition "*i*" in the exposure area

$P_{E<55\ dBA}$ = Total population exposed to traffic noise levels less than 55 dBA in the exposure area

$P_{E>=55\ dBA}$ = Total population exposed to traffic noise levels greater than or equal to 55 dBA in the exposure area

$RR_{Disease,i}$ = Relative risk of the health condition "*i*" among the population exposed to noise levels above 55 dBA

d. The prevalence rate from Equation 1 is then used to calculate the reduction in the population with health condition, *i*, as the result of implementing a hypothetical traffic noise mitigation measure using Equation 2:

$$P_{R,i} = P_{E<55\ dBA} * R_{UE,i} + P_{E\geq 55\ dBA} * R_{UE,i} \quad (2)$$

Where:

$P_{R,i}$ = Total reduction in population with health condition “*i*” in the exposure area

$R_{UE,i}$ = Risk of a health condition “*i*” for the population unexposed to traffic noise levels above 55 dBA

$P_{E<55\ dBA}$ = Total population exposed to traffic noise levels less than 55 dBA in the exposure area

$P_{E>=55\ dBA}$ = Total population exposed to traffic noise levels greater than or equal to 55 dBA in the exposure area

e. The direct health care costs and indirect costs (e.g., from loss in productivity) for each county are calculated by multiplying the per-capita direct and indirect costs[138] for a health condition “i” by the population within the county with health condition “*i*”. Reductions in direct and indirect costs are calculated with Equation 3:

$$\Delta_{C,i} = C_{C,i} * \left(\frac{P_{Disease,i} - P_{R,i}}{P_{Disease,i}}\right) \quad (3)$$

Where:

$\Delta_{C,i}$ = Change in direct and indirect costs for health condition “*i*”

$C_{C,i}$ = County-specific per capita direct and indirect costs for health condition “*i*”

$P_{Disease,i}$ = Total population with health condition “*i*” in the exposure area

$P_{R,i}$ = Total reduction in population with health condition “*i*” in the exposure area

Road Traffic Noise Data

The source of noise data used to estimate exposure impacts from vehicle operation comes from the FHWA Traffic Noise Model version 2.5.[139] The model uses annual average daily traffic data to determine the vehicle fleet mix for all road segments within the United States. Average speeds are assumed for each roadway type (e.g., interstate, arterial, collector). From vehicle fleet mix and speeds, the noise emissions are determined at each location in the United States. To prepare the data for use in the San Francisco Bay Area study, we spatially “clip” the rasterized noise data to the Bay Area boundaries. We then take the average of the noise level (in dBA) in every cell within each census tract for the exposure area. Finally, we vectorize the raster data and use the average of all cells' noise levels within a census tract as the respective noise level for that census tract.

Construction Noise Data

Noise emissions from constructing a road segment are determined by inputting values for the specific construction equipment used into the Roadway Construction Noise Model Version 1.0 developed by the FWHA. On average, the noise exposure associated with constructing a road segment is 83.5 dBA. The construction noise emission level is used as an input into the open-source plug-in in QGIS, a Geographic Information System software, called OpeNoise.[140] OpeNoise models the noise levels at receiver points. We have selected receiver points as buildings within a 100-meter buffer (a conservative estimate of how far sound from a construction point source would travel) of a road segment. We calculate the weighted average of noise experienced by people living within the census tracts that immediately intersect within the 100-meter buffer zone around a road segment. We do not calculate economic health care direct and indirect costs from construction noises as the Swinburn et al.[132] method is relevant for sustained noise events such as continuous road operation.

Limitations

With road traffic noise, we have clipped the Traffic Noise Model data to our roadway segments of interest. The noise sources are not just from the segments of interest, but all road noise around those segments (i.e., noise not just from interstates but from arterial and collector roadways). This leads to an overestimation of the total noise that people are experiencing due to traffic on a roadway segment within a given area as well as an overestimation of health damage costs which are predicated on the basis of total number of people exposed to road noise levels above 55 dBA.

With the construction noise analysis, a cautious estimate of how far construction noise might travel is assumed in order to create a buffer around each analyzed road segment. A more realistic analysis would model all three-dimensional barriers (e.g., existing highway noise barriers, non-residential structures, trees/shrubbery) that might impede construction noise travel.

The method potentially does not capture the true exposure experienced by populations. People do not spend their entire days within their residences so the methodology presented is potentially not capturing the most realistic set of conditions that would more accurately represent the health burden from noise exposure. How we are evaluating health damage costs is also likely not capturing all conceivable health impacts as a result of chronic noise exposure since we are only accounting for IHD and hypertension.

C. Results

Road Traffic

The noise levels from all road traffic within the San Francisco Bay Area are presented in Figure 18. Figure 19 shows an enhanced view of Figure 18 for noise exposure levels in the vicinity of San Francisco, the Bay Bridge, and Oakland/San Leandro. In general, interstate routes have the highest levels of noise (64.4 to 83.9 dBA); arterials and collectors have lower levels of noise (45 to 54 dBA). Figure 20 shows the vectorized results from the road traffic noise dataset, which means the noise levels from individual roads have been averaged over the respective, overlapping census tracts. Higher noise levels (red) are concentrated along interstate routes.

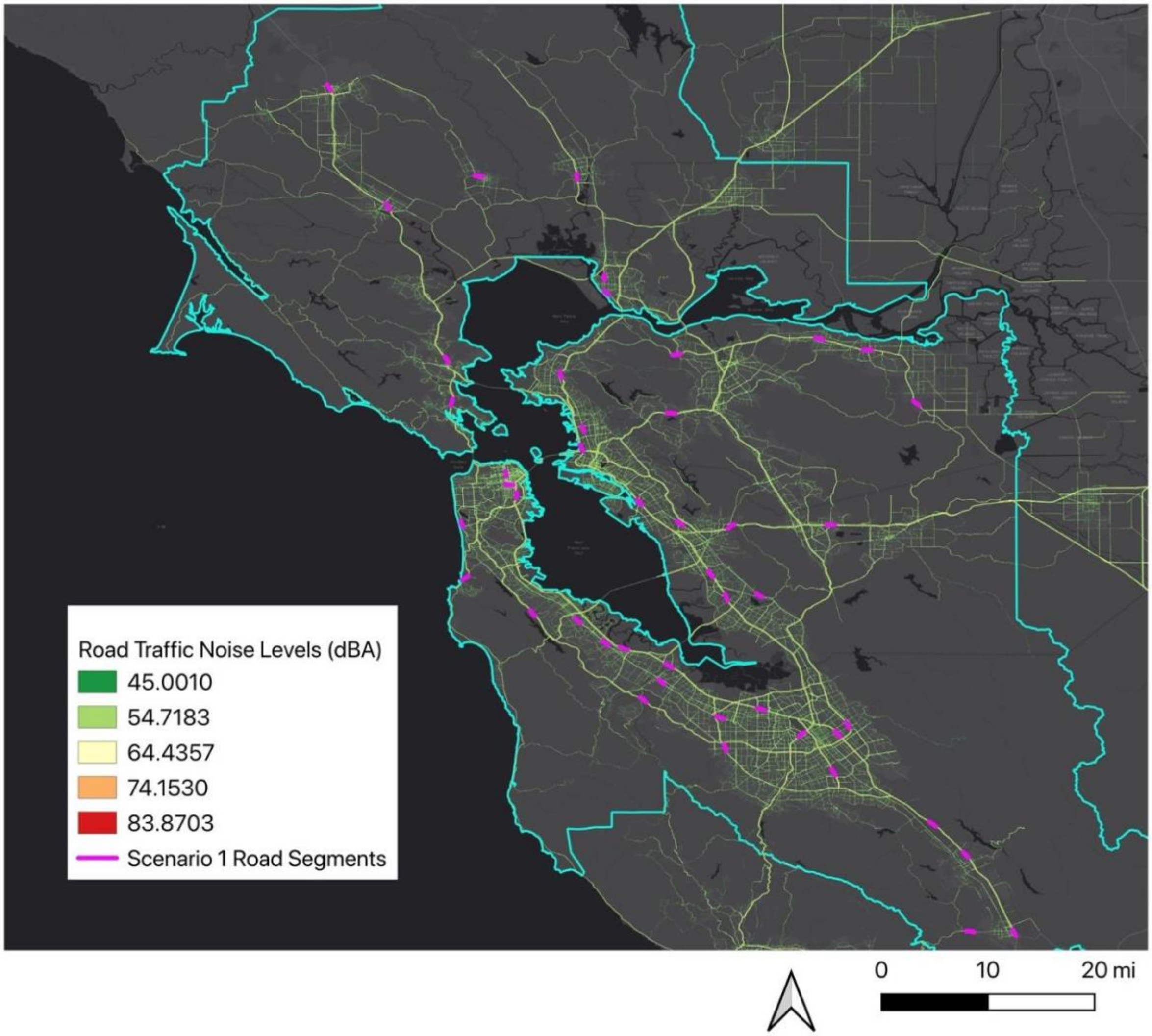


Figure 18. Road traffic noise levels (dBA) within San Francisco Bay Area system boundary.

Notes: NHWA road surface dataset has been clipped to nine-county Bay Area boundary.

Figure 19. Enhanced view of road traffic noise levels (dBA) for portions of San Francisco, Emeryville, Berkeley, Oakland, and San Leandro.

Notes: Road traffic noise levels (dBA) within San Francisco Bay Area system boundary. NHWA road surface dataset has been clipped to the nine-county Bay Area boundary.

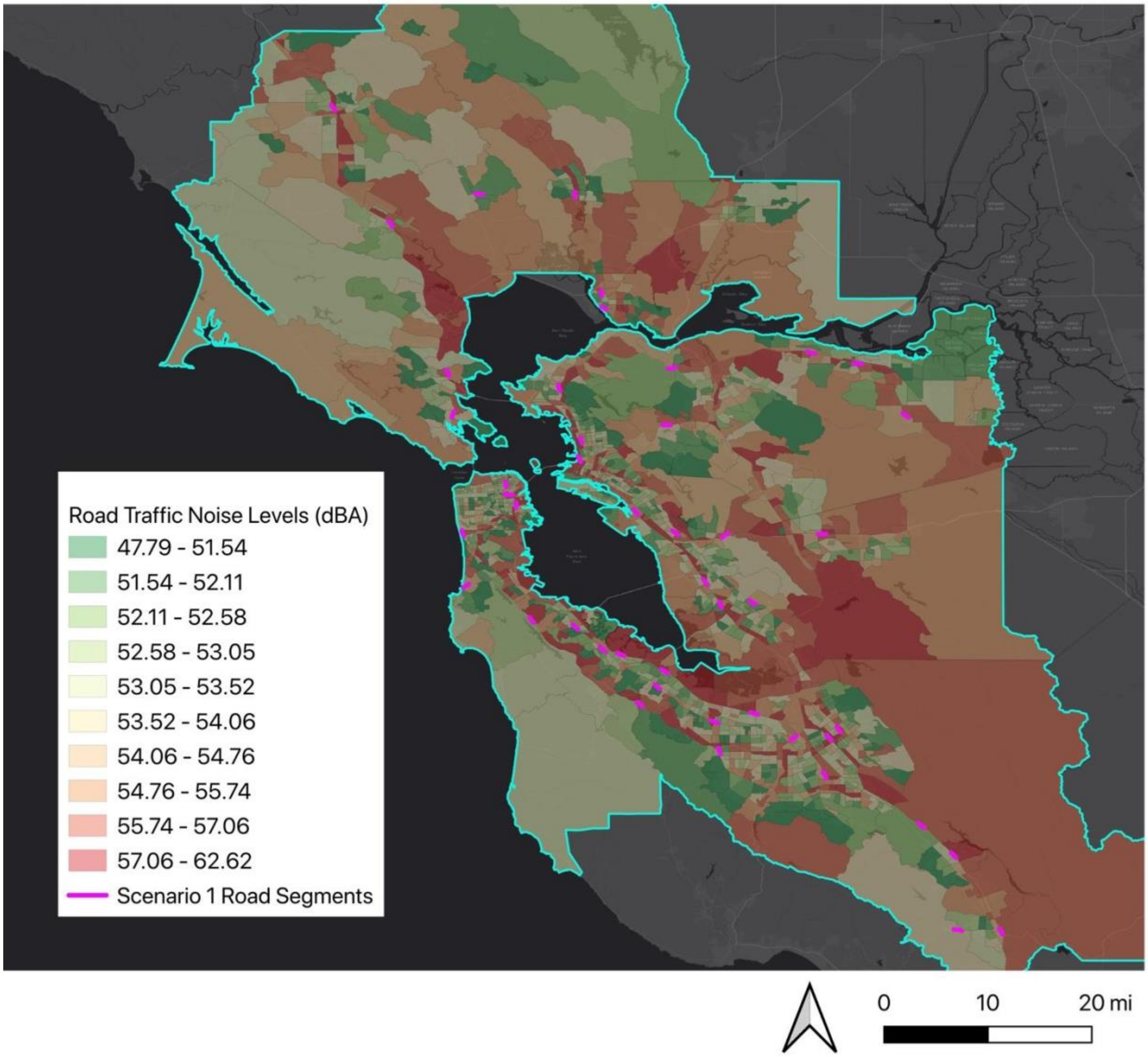


Figure 20. Vectorized road traffic noise (dBA) for the San Francisco Bay Area.

Table 5, Table 6, and Table 7 depict reductions in direct and indirect costs and population counts afflicted with road-noise-induced IHD and hypertension as a result of implementing a hypothetical road-noise mitigation strategy. Results vary within each county. Across all nine counties within the San Francisco Bay Area, implementing a road noise mitigation measure could yield a $45-million reduction in both direct and indirect costs associated with health conditions. Hypothetical road noise mitigation could yield 2.5 million fewer people living with vehicle traffic-induced hypertension and over 300,000 fewer people diagnosed with ischemic heart disease caused by road traffic noise.

Table 5. County-level savings in direct and indirect health costs (in 2019 USD) associated with road noise induced ischemic heart disease and hypertension after implementation of a hypothetical noise mitigation strategy.

Bay Area County	Direct Cost Savings - Traffic-related IHD	Direct Cost Savings – Traffic-related Hypertension	Indirect Cost Savings – Traffic-related IHD	Indirect Costs – Traffic-related Hypertension
Alameda	$3,700,000	$1,600,000	$4,200,000	$180,000
Contra Costa	$2,900,000	$1,200,000	$3,300,000	$130,000
San Francisco	$1,500,000	$640,000	$1,700,000	$72,000
San Mateo	$1,900,000	$800,000	$2,100,000	$90,000
Santa Clara	$4,000,000	$1,700,000	$4,600,000	$190,000
Napa	$560,000	$220,000	$640,000	$25,000
Solano	$1,200,000	$4,900,000	$1,400,000	$55,000
Sonoma	$1,200,000	$430,000	$1,300,000	$48,000
Marin	$480,000	$200,000	$540,000	$23,000
Bay Area	$17,000,000	$7,200,000	$20,000,000	$810,000

Table 6. County-level reductions in population with road noise induced ischemic heart disease (IHD) and hypertension after implementation of hypothetical noise mitigation strategy.

Bay Area County	Reductions in Cases of IHD	Reduction in Cases of Hypertension
Alameda	68,000	580,000
Contra Costa	51,000	400,000
San Francisco	32.000	280,000
San Mateo	28,000	240,000
Santa Clara	73,000	610,000
Napa	6,000	46,000
Solano	6,200	49,000
Sonoma	22,000	160,000
Marin	11,000	88,000
Bay Area	300,000	2,500,000

Table 7. Reduction in direct/indirect costs (2019 USD) for all road noise-induced diseases (IHD and hypertension) and in population with road noise induced IHD and hypertension after implementation of hypothetical noise mitigation strategy for the San Francisco Bay Area.

	Direct Cost Savings) - Traffic	Indirect Cost Savings - Traffic	Reduction in Cases of IHD	Reduction in Cases of Hypertension
SF Bay Area	$25,000,000	$20,000,000	300,000	2.500,000

Figure 21 and Figure 22 show how racial and economic demographic groups experience differences in road noise exposure across the entire Bay Area. The average road noise exposure for the study area is 53.9 dBA, which is below the 55 dBA noise level that the U.S. Environmental Protection Agency recognizes as a threshold for causing adverse health impacts. On average, people of color in the Bay Area experience higher-than-average levels of road traffic noise. The White population experiences lower-than-average road-induced noise levels. The two lowest income quintiles, Q1 (median household income less than $72,000) and Q2 (median household income $72,000 and $95,000), are exposed to greater-than-average road noise levels. Figure 23 and Figure 24 depict the spread of road traffic noise exposure levels for all demographic groups. The average noise level experienced by each demographic group is denoted with the symbol “μ”; the median noise level is denoted with the symbol “η”.

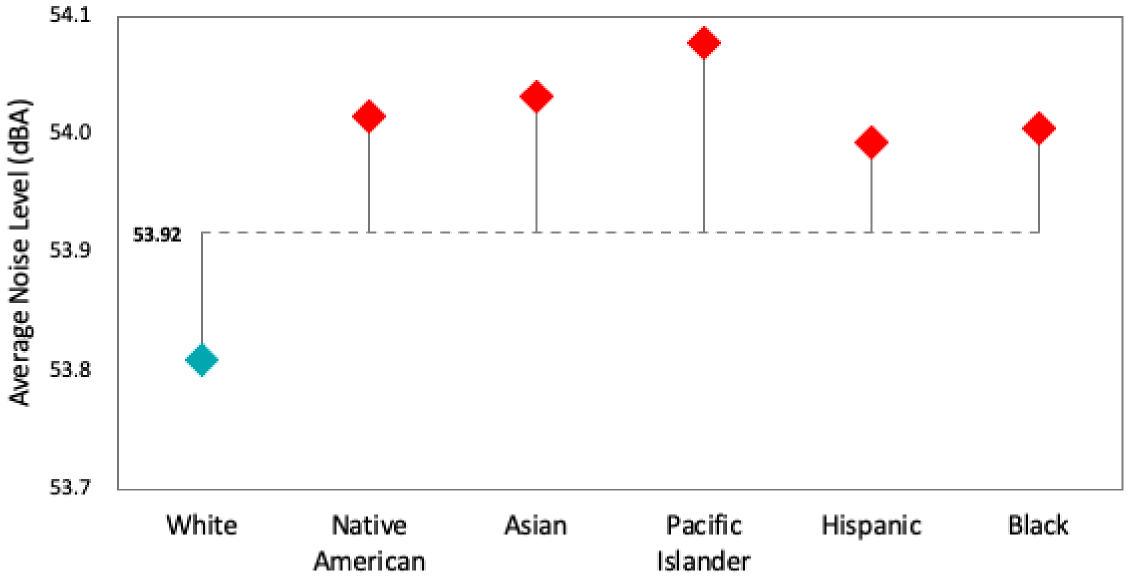


Figure 21. Average road traffic noise levels (dBA) across racial demographics within the San Francisco Bay Area.

Notes: Horizontally dotted line represents the average road noise level for the entire Bay Area.

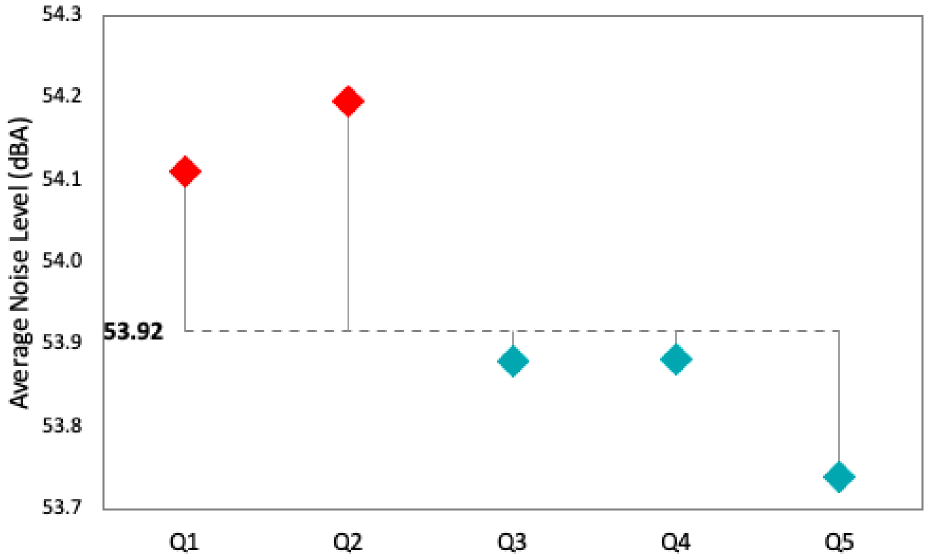


Figure 22. Average road traffic noise levels (dBA) across income quintiles within the San Francisco Bay Area.

Notes: Horizontally dotted line represents the average road noise level for the entire Bay Area.

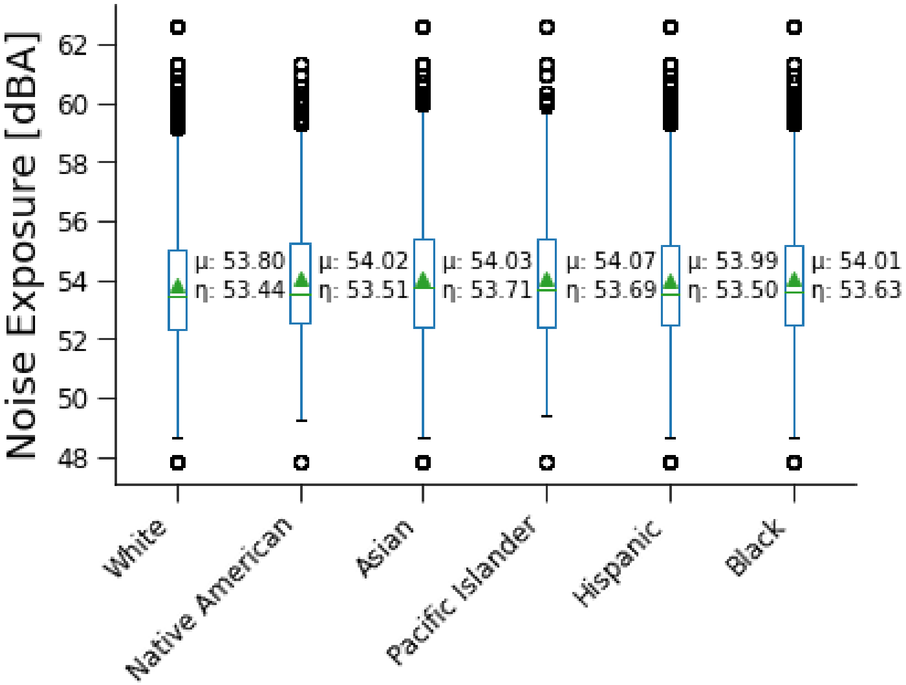


Figure 23. Spread of noise levels for each racial demographic group within the San Francisco Bay Area.

Notes: Averages are denoted with the character μ, and medians are denoted with η.

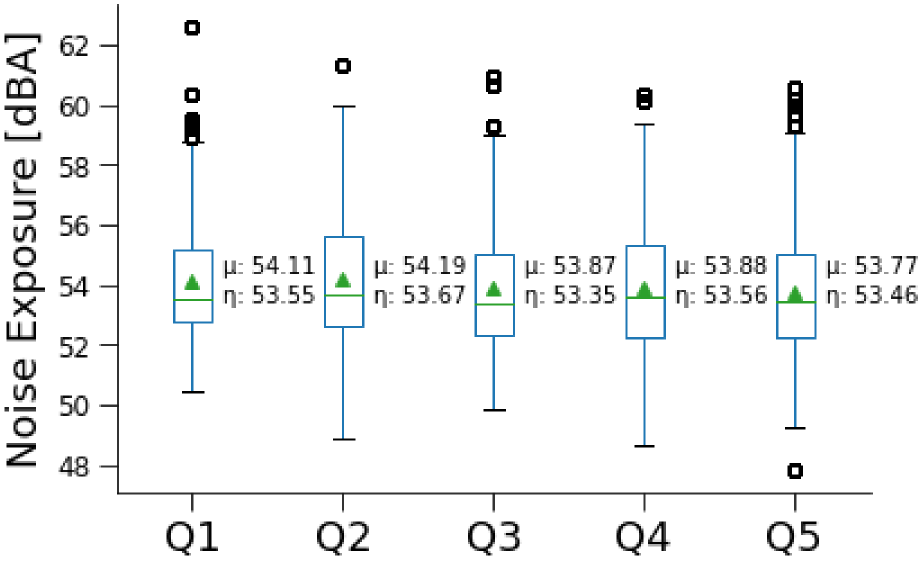


Figure 24. Spread of noise levels for each economic quintile group within the San Francisco Bay Area.

Notes: Averages are denoted with the character μ, and medians are denoted with η.

Table 8 and Table 9 offer a finer-grained examination of how demographic groups experience road noise exposure at the county level. A county-level analysis might be more appropriate for examining noise level impacts because noise is a relatively more localized impact than air pollution, for example. Some trends are readily apparent at the county level. The White populations in each county experience lower-than-average exposures from road noise. The Native American and Pacific Islander populations are exposed to greater-than-average road noise levels in four counties, while the Black and Hispanic populations are exposed to greater-than-average road noise levels in five counties. The Asian population suffers higher-than-average road noise exposure in seven of the Bay Area's nine counties. Trends for quintiles are more varied. Although data availability precludes this analysis, future efforts might focus on examining noise exposure differences at a finer spatial scale.

Table 8. Percentage differences relative to county-average road noise exposure by racial demographic.

County	White	Native American	Asian	Pacific Islander	Hispanic	Black	County Average (dBA)
Alameda	-0.05%	-0.11%	0.29%	0.06%	-0.28%	-0.03%	54.02
Contra Costa	-0.08%	-0.51%	0.30%	0.19%	-0.24%	0.28%	53.99
Marin	-0.19%	0.59%	0.79%	0.47%	0.78%	0.97%	53.73
Napa	-0.27%	-0.12%	1.26%	-1.54%	0.14%	1.43%	53.44
Santa Clara	-0.32%	0.70%	0.15%	-0.59%	0.41%	0.15%	53.98
San Mateo	-0.23%	0.46%	-0.21%	2.19%	0.61%	1.26%	53.75
Solano	-0.01%	-0.60%	0.31%	-0.97%	-0.08%	-0.32%	54.09
Sonoma	-0.42%	-0.27%	-0.52%	-0.58%	-0.23%	-0.64%	53.89
San Francisco	-0.30%	0.77%	0.36%	-1.02%	0.27%	-0.22%	53.72

Notes: A positive value indicates that the demographic group experiences a higher-than-average noise exposure level in that county.

Table 9. Percentage differences relative to county-average road noise exposure by median household income quintile.

County	Q1	Q2	Q3	Q4	Q5	County Average (dBA)
Alameda	0.12%	0.19%	-1.22%	0.22%	0.33%	54.02
Contra Costa	-0.59%	1.41%	-0.48%	-0.13%	0.02%	53.99
Marin	1.75%	-0.19%	-0.42%	-0.29%	0.03%	53.73
Napa	-3.09%	0.59%	-0.19%	-0.13%	0.31%	53.44
Santa Clara	2.20%	0.12%	0.53%	-0.08%	-0.62%	53.98
San Mateo	1.63%	-0.63%	1.74%	-0.23%	-0.70%	53.75
Solano	-0.87%	0.83%	-1.57%	1.72%	-0.19%	54.09
Sonoma	0.77%	0.07%	-0.20%	-0.47%	-0.15%	53.89
San Francisco	-0.37%	1.62%	0.81%	-1.03%	-0.42%	53.72

Notes: A positive value indicates that the demographic group experiences a higher-than-average noise exposure level in that county.

Construction Noise

Results for the construction of two of the Scenario 1 road segments are presented here. The results offer a starting point for future, detailed analysis of all road segments. Figure 25 shows the construction noise exposure results for one of the road segments located in San Francisco. Higher levels of construction noise are received on the sides of buildings facing the road segment.

Figure 25. Construction noise exposure results for road segment in San Francisco.

Table 10 and Table 11 show the demographic results for two road segments. It is impractical to extrapolate any trends from the results because the demographic parameters for each road segment vary. For example, the road segment located in San Mateo only includes people in the Q3 and Q4 median household income quintiles.

Table 10. Percentage differences relative to 100-meter buffer-average construction noise exposure by racial demographic.

Road Segment Location	White	Native American	Asian	Pacific Islander	Hispanic	Black	Road Segment Average (dBA)
San Francisco	-0.23%	3.21%	0.38%	-5.06%	-0.19%	0.61%	83.55
San Mateo	0.05%	-3.48%	0.11%	-0.56%	-0.26%	0.73%	83.45

Notes: A positive value indicates that the demographic group experiences a higher-than-average noise exposure level within the census tracts in the buffer area.

Table 11. Percentage differences relative to 100-meter buffer-average construction noise exposure by median household income quintile.

Road Segment Location	Q1	Q2	Q3	Q4	Q5	Road Segment Average (dBA)
San Francisco	5.2%	4.3%	-5.3%	-	-2.4%	83.55
San Mateo	-	-	-3.4%	1.5%	-	83.45

Notes: A positive value indicates that the demographic group experiences a higher-than-average noise exposure level within the census tracts in the buffer area.

D. Discussion and Conclusions

Exposure to noise from vehicle traffic and construction on road segments can have an impact on peoples' well-being and their short-term and long-term health outcomes. Road traffic noise exposure is essentially continuous and occurs year-round. Construction noise on the road segments is a discrete event over a few hours or days. While construction noise levels are much higher than the 55 dBA limit, road construction occurs relatively infrequently so it is more difficult to analyze trends across demographic groups and to monetize health impacts. Reductions in direct and indirect health costs associated with traffic noise (which can be viewed as damages that would be accrued without the hypothetical noise mitigation strategy) are on the same order of magnitude (i.e., in the millions of USD) as the damages estimated for $PM_{2.5}$ exposure and for the release of GHG emissions, suggesting that noise exposure is as important an economic impact to consider as air pollution and climate change.

The differences in how various demographics experience noise exposure are not necessarily as stark as for the $PM_{2.5}$ exposure case study. However, similar trends appear. In general, people of color experience greater-than-average road traffic noise exposure than the White population. Additionally, the two lowest income quintiles (median family incomes less than $72,000 and between $72,000 and $95,000) are exposed to higher-than-average road traffic noise pollution. While on average demographic groups within the Bay Area all experience average noise levels less than the threshold at which the U.S. Environmental Protection Agency indicates long-term health damages, there are still census tracts (as evident in Figure 20) that experience unhealthy levels of noise pollution. As noise travels less farther than air pollution, refining the analysis to the county level offers an opportunity for better understanding of how noise pollution impacts specific demographic groups within the entire study area. Although beyond the scope of this report, further analysis of noise impacts at the county/neighborhood/block level (demonstrated with the construction noise analysis) can improve understanding of how noise impacts populations. Future research efforts should also explore, in detail, efficacious and practical mitigation policies.

5. Port of Oakland: PM$_{2.5}$ Exposure and GHG Emissions

A. Introduction

Freight movement is an essential cornerstone of the United States economy. Marine ports, which typically include intermodal freight facilities such as trucking and railyards, facilitate the movement of on average $2.7 trillion in imports and exports.[141] The goods supply chain is sensitive to shipping container port operation; disruptions caused by the COVID-19 pandemic led to backlogs at multiple U.S. ports leading to increases in pollution in port-adjacent communities.[142,143]

The Port of Oakland is the ninth busiest container port in the U.S. and one of the four busiest in ports on the West Coast.[144] The Port is a documented source of pollution within the San Francisco Bay Area and of special concern as a significant contributing source of pollution within the West Oakland community.[145] West Oakland (pink shading in Figure 26) is a community of historical and social political significance within the city of Oakland and the Bay Area.[146] West Oakland, previously identified as a disadvantaged community according to CalEnviroScreen metrics, was selected in 2018 to participate in ARB's Community Air Protection Program.[147] Participation in the program entails community-led development of an emission reduction program to mitigate exposure from freight, trucking, industrial manufacturing, and Port sources.

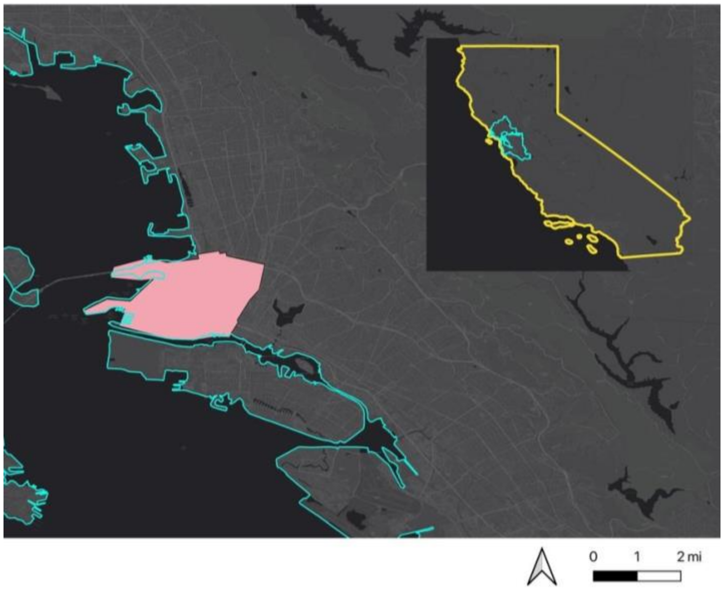


Figure 26. Map of West Oakland community.

Source: https://ww2.arb.ca.gov/resources/documents/west-oakland-ab-617-boundaries

The Port of Oakland has been an area of interest, not only as a pollution source that the residents and community members are working to mitigate, but as a research area for testing mitigation and pollution monitoring strategies. Previous work has focused on sources directly adjacent to the community such as drayage trucks, which are the heavy-duty diesel-powered trucks that carry shipping containers out of the Port to their destination (e.g., wholesale distribution centers). An early mobile monitoring study showed that that diesel particulate matter concentrations along high-trafficked roadways near the Port of Oakland were five times higher than the community's average[148] One study examined the effectiveness of regulations (e.g., mandatory diesel particle filters on trucks, cleaner fleets) on drayage trucks in the port, estimating that mitigation efforts reduced black carbon and nitrogen oxide (NO_x) emission factors by 50 percent and 40 percent, respectively.[149] Analysis of previous regulations on drayage trucks operating at the Port indicated that regulations resulted in a 75 percent decrease in primary particulate matter emissions from trucks.[150] Further efforts estimated that drayage trucks equipped with diesel particle filters and selective catalytic reduction systems can greatly reduce NOx by 69 ± 15 percent, black carbon by 92 ± 32 percent, and particle number emission factors, by 66 ± 35 percent.[151] A source-oriented Weather Research and Forecasting-Chem model simulated elemental carbon concentrations from ships, trains, and on-road diesel trucks for the West Oakland community.[152] Other port mitigation strategies, such as shifting freight operations to night hours, can lead to increases in ambient concentrations of $PM_{2.5}$ and specifically for the Port of Oakland lead to no change in reducing $PM_{2.5}$ intake.[153]

Outside of the efforts organized by West Oakland community groups and through AB 617[154] there are fewer research efforts that investigate other emissions sources from the Port of Oakland or attempt to connect pollution from the Port to a measurable impact (e.g., increased risk of mortality). A study investigating the effects of regulating the heavy fuel oil for port container ships in the Bay Area concluded that regulations implemented on reducing the high sulfur content of the fuel led to reducing ambient $PM_{2.5}$ concentrations by 3.19 ± 0.6 percent.[155] One study focusing on the West Oakland neighborhoods around the Port demonstrated that mortality from pollution-attributed risks can vary at fine spatial scales within an individual city.[156] Examining emissions such as primary and secondary $PM_{2.5}$, GHG sources (e.g., trucks, rail, ships, cargo handling equipment), and attributable impacts (e.g., economic damages from human health impacts, climate change) is necessary to guide future policy decisions aimed at making marine ports as sustainable as possible. It is also vital that policy decisions rely on analysis centered on life-cycle, systems-level thinking incorporating life-cycle phases (e.g., material manufacturing, supply chains) which has been shown to significantly increase GHG and criteria air pollutant emissions from goods movements.[95] Critical research questions include:

1. Using the 2020 emissions inventory for the Port of Oakland, excluding emissions from cruise ships confined to the Port because of COVID-19 restrictions, what is the baseline $PM_{2.5}$ exposure, in terms of intake, from a typical marine port's operations and routine maintenance? How does exposure impact demographic groups by race/ethnicity and median income?
2. What is the baseline GHG emission inventory for the Port by source?
3. How do port operating emissions compare to embodied emissions from some of the fuel supply chains and materials used in maintaining the port?

4. How effective are mitigation strategies in reducing exposure from specific sources? Which mitigation strategies are most important to consider?
5. What are the $PM_{2.5}$ exposure damages, based on Value of a Statistical Life metric for the Port of Oakland?
6. What is the economic damage from climate change impacts for the Port of Oakland?

The objective of this case study is to map the $PM_{2.5}$ exposure burden for the entire San Francisco Bay Area from the Port of Oakland's annual operations and routine maintenance, explore effective $PM_{2.5}$ and GHG emission mitigation strategies, and offer a reasonable estimation of the economic harm caused by the Port.

B. Methods

We follow the same general methodologies described in full in the pavement case study on $PM_{2.5}$ exposure and GHG emissions (Sections 2 and 3, respectively). The $PM_{2.5}$ emissions inventory, which comes from both a 2020 report commissioned by the Port of Oakland as well as a report from the West Oakland Environmental Indicators Project,[154,157] was fed into the Intervention Model Air Pollution (InMAP) Source-Receptor Matrix (ISRM). The ISRM calculates marginal changes in ground-level $PM_{2.5}$ concentrations and resulting exposure intake from the spatially resolved emissions inventory. Census tract data for the exposure area (SF Bay Area) was applied to investigate $PM_{2.5}$ exposure concentration and intake values by mitigation strategy and demographic group.[81] We then took the average exposure concentration and calculated human health damages using the Value of Statistical Life metric. The 2020 GHG emissions inventory from the Port of Oakland is related to economic damages using the Social Cost of Carbon metric, again relying upon a range of values to account for the sensitivity of the measurement to multiple factors (see Table 3 in Section 2). We do not include noise pollution in this case study due to a lack of available, reliable data.

Emission sources, depicted in Figure 27 and Figure 28, primarily consist of three main categories: (1) direct emissions from ocean-going vessels or large container ships, entering the Bay Area and anchoring at the Port of Oakland; (2) direct emissions from both smaller ships that assist those vessels within the Port's harbor and from intermodal operations at the Port itself; (3) embodied emissions from materials used in maintaining the structural integrity of the Port's surface and from fuel used by the drayage trucks. We excluded emissions from material delivery, construction activities, and ocean vessel fuel supply chains primarily due to a lack of reliable data. Table 12 describes the specific sources included within the study area:

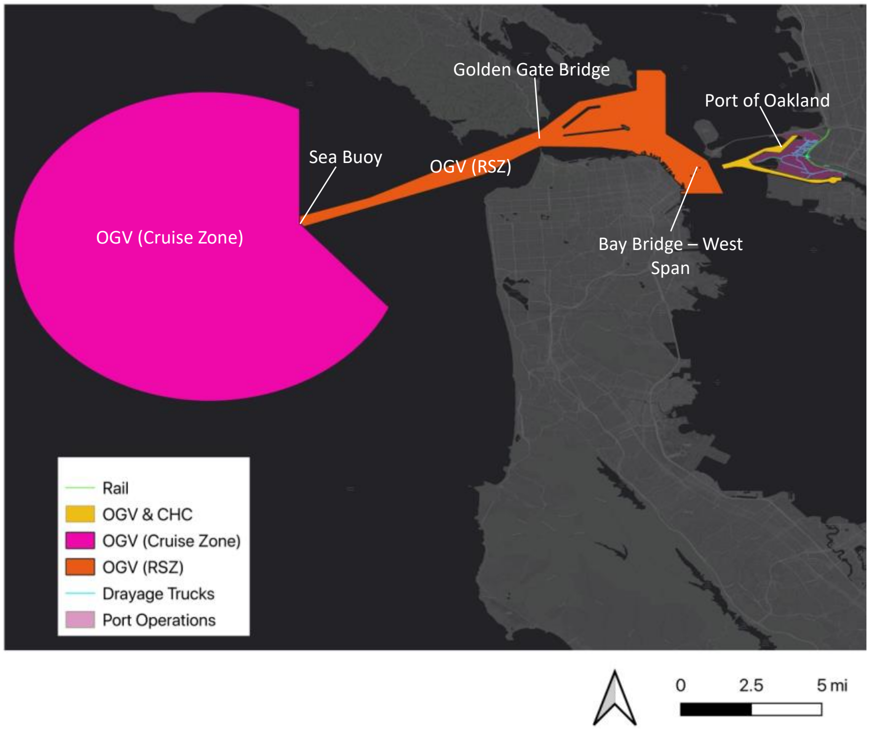


Figure 27. Scope of operational sources from Port of Oakland accounted for in study.

Notes: OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone.

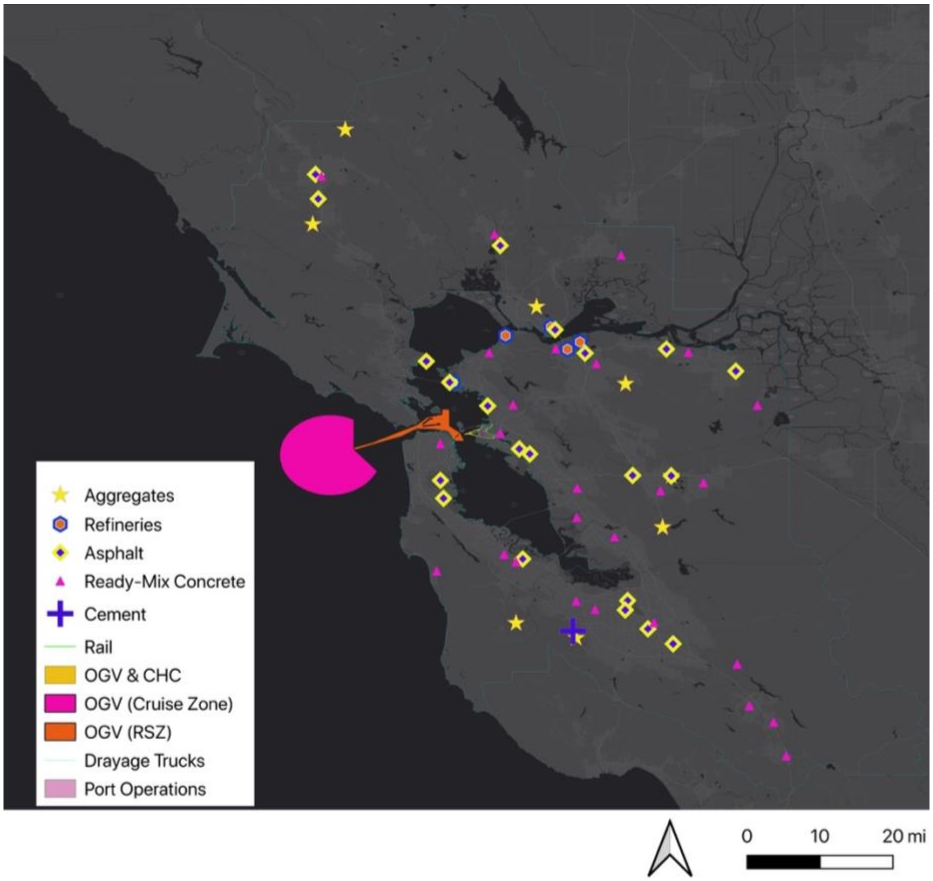


Figure 28. Location of material facilities within the Bay Area relative to the Port of Oakland.

Notes: The closest ready-mix concrete production facility is used as the representative supplier of concrete used in the annual maintenance of the Port. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone.

Table 12. Description of sources included in Port of Oakland system boundary.

Source	Description
Ocean-going Vessels	Ships enter the cruise zone from three shipping channels in the Pacific Ocean. Once the ship reaches the sea buoy, they reduce speeds and enter the Reduced Speed Zone. Once they pass the west span of the Bay Bridge, commercial harbor craft assist in tugging the vessels into berth at the Port of Oakland. Within the harbor area of the Port of Oakland, ocean vessel activities include maneuvering, shifting, berth operations, and anchorage.
Commercial Harbor Craft	Includes any tug operations and dredging activities associated with maintaining the channel and berth integrity.
Port of Oakland Operations	Includes cargo handling equipment such as cranes and forklifts used in transferring cargo containers within the Port of Oakland and any off-road equipment used in the construction and maintenance of the Port as well as railyard activities that happen within the Port.
Drayage Trucks	Emissions from within terminal idling and driving as well as driving from terminal to freeway entrances. We do not account for emissions beyond the freeway entrance.
Rail	Emissions associated with rail operations in the Union Pacific Railyard.
Materials from Port Maintenance	Concrete Cement Asphalt Aggregate Bitumen
Fuel	Fuel from operating drayage trucks, delivery of maintenance materials, commercial harbor craft.

Port operation emissions inventory data, as previously discussed, come from the Port of Oakland and a West Oakland community report. The latest available inventory report is for the year 2020. As such, we excluded any emissions associated with cruise ships that were docked at the Port of Oakland in the year 2020 because of the COVID-19 pandemic. The 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 were joined to geospatial shapefiles in QGIS for the Port of Oakland sources.[158–160]

The area of the Port is just over two square miles (5.3 square kilometers).[161] Information about the design of the Port's surface is limited to a report on the construction of two of the berths from the early 2000s.[162] We assumed that the berth design was an approximate representation of the entire surface area for the Port of Oakland. The design encompasses an approximately four-inch surface layer of concrete (assumed to be normal strength), one-inch layer of aggregate, three-inch layer of asphalt, and an almost 19-inch layer of compacted aggregate base. We assumed that for maintenance purposes, around two to five percent of the total Port area would be reconstructed each year, but that new material would not be brought in for the compacted aggregate base layer. Total embodied emissions were calculated, as with the pavement case study, by multiplying the volumes of each material type by their respective emission factors. GHG emission factors come from the Embodied Carbon in Construction Calculator database. $PM_{2.5}$ emission factors are based upon emission rates from plants within the Bay Area that have ARB annual emissions data (see Section 2). We assumed that all concrete comes from the closest available ready-mix concrete plant. All other material needs are sourced from respective plants within the Bay Area.

A variety of realistic and future mitigation options to reduce the emissions footprint from Port of Oakland operation and maintenance were explored. Mitigation strategies are listed in Table 13. Note that Strategy #3 is excluded for GHG analysis because there is no available GHG emissions data for the Union Pacific railyard. Methods similar to the pavement case study described above were employed for investigating the emissions changes from Strategy #1 and Strategy #2. We used emission factors from EMFAC for POAK Class 8 Drayage (i.e., trucks that transport goods from a marine port to their destination) vehicle types for an interim electrification scenario (2045) and a future scenario where all drayage trucks are electric. Fuel supply chains for future diesel and electric-operated drayage trucks were calculated using CA-GREET for its latest year (2018) for which it forecasts emission factors for diesel (i.e., 2045). We assumed that electricity used in the 100 percent electrification scenario for drayage trucks is produced entirely by solar sources and we applied LCA emission factors to estimate emissions (referenced in Section 2).

Table 13. Port of Oakland mitigation strategies.

Strategy Number	Description
1	Truck 2045 Scenario
2	Truck Electrification
3	Rail Reduction (20%)
4	Trucking Reduction (20%)
5	OGV Cruise Reduction (20%)
6	OGV In-Harbor Reduction (20%)
7	CHC Reduction (20%)
8	OGV RSZ Reduction (20%)
9	OGV + CHC All Reduction (20%)
10	Port CHE Reduction (20%)
11	Port Other Reduction (20%)

Strategy Number	Description
12	Port Rail Reduction (20%)
13	Port + CHC All Reduction (20%)
14	Cement (20%)
15	RMC (20%)
16	Asphalt Reduction (20%)
17	Aggregate Reduction (20%)
18	Refineries Reduction (20%)
19	All Facility Reduction (20%)
20	OGV Harbor + CHC Emission Elimination
21	Combine All

Notes: OGV In-Harbor Reduction refers to the following ocean-going vessel operations: Shifts, Berths, Anchorage, Maneuvers. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone; CHE = Cargo Handling Equipment.

C. Results

$PM_{2.5}$ Exposure

The average exposure concentration under the two percent Port resurfacing scenario is 0.035 μg m^{-3} and 0.037 μg m^{-3} under the five percent scenario. Figure 29 depicts the annual baseline $PM_{2.5}$ intake for the Port of Oakland, in addition to the five most effective mitigation scenarios. All scenarios' intakes are shown in Figure 30. The annual intake from Port of Oakland sources is 1598 grams of $PM_{2.5}$ per year in the two percent resurfacing scenario. Ocean going vessel sources dominate PM2.5 intake in the baseline condition. Assuming two percent of Port surface volume gets refurbished each year, all such sources account for 73 percent of annual intake. Ocean vessel operations within the harbor (i.e., maneuvering, berthing, shifts, and anchorage), account for over 51 percent of the annual $PM_{2.5}$ intake. In-harbor ocean vessel operations along with commercial harbor craft operations (tugging) represent almost 62 percent of annual intake amounts. In-port trucking is relatively small (3.3% of annual intake). Intake from supply chain sources (material production, fuel production, material delivery) represents 3.2 percent of annual intake. When five percent of the surface volume is resurfaced annually, supply chain sources represent 6.9 percent of annual intake.

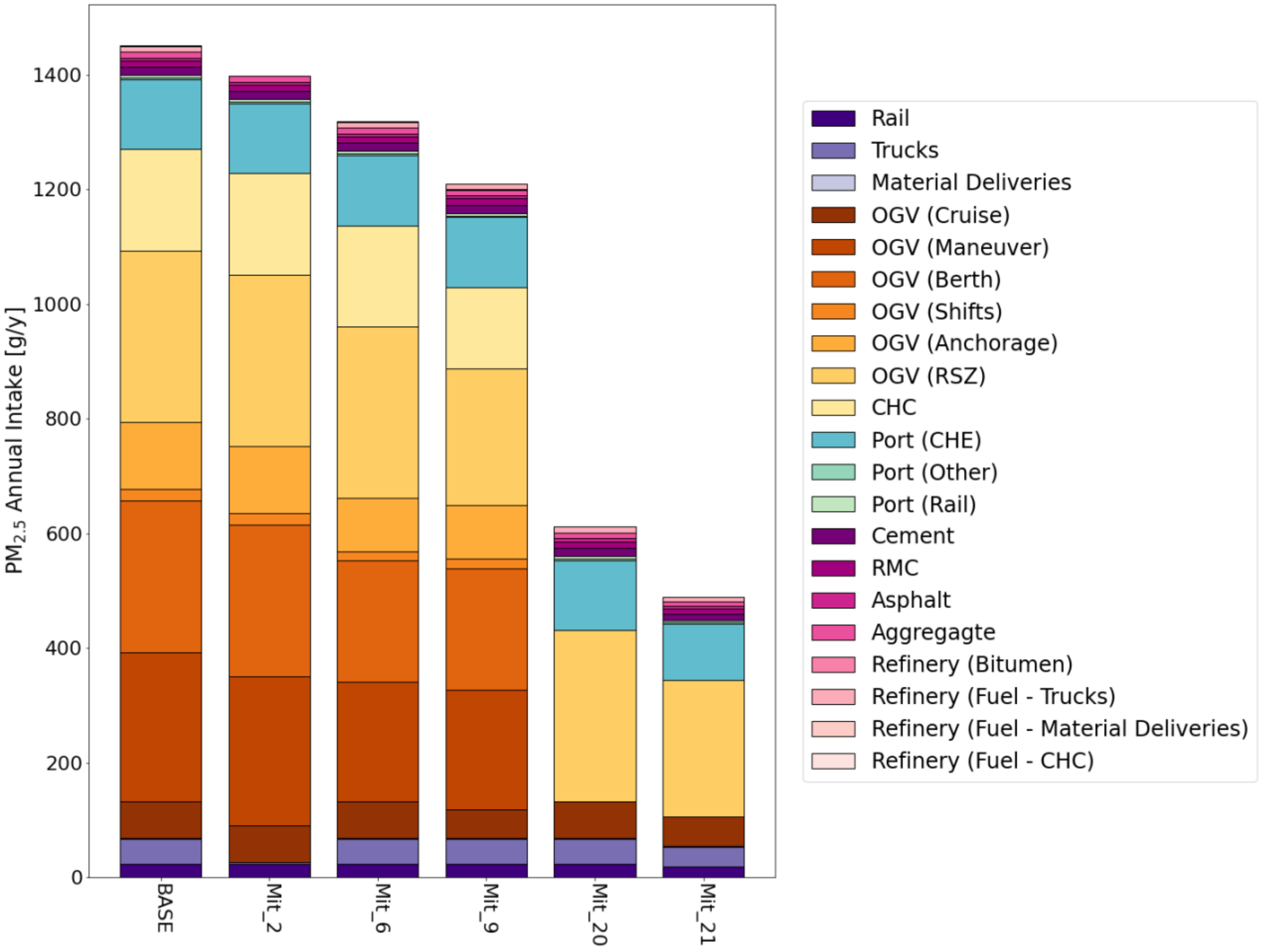


Figure 29. Annual $PM_{2.5}$ intake for the Port of Oakland for baseline and four top-reducing mitigation strategies.

Notes: See Table 2 for descriptions of mitigation strategies. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone; CHE = Cargo Handling Equipment.

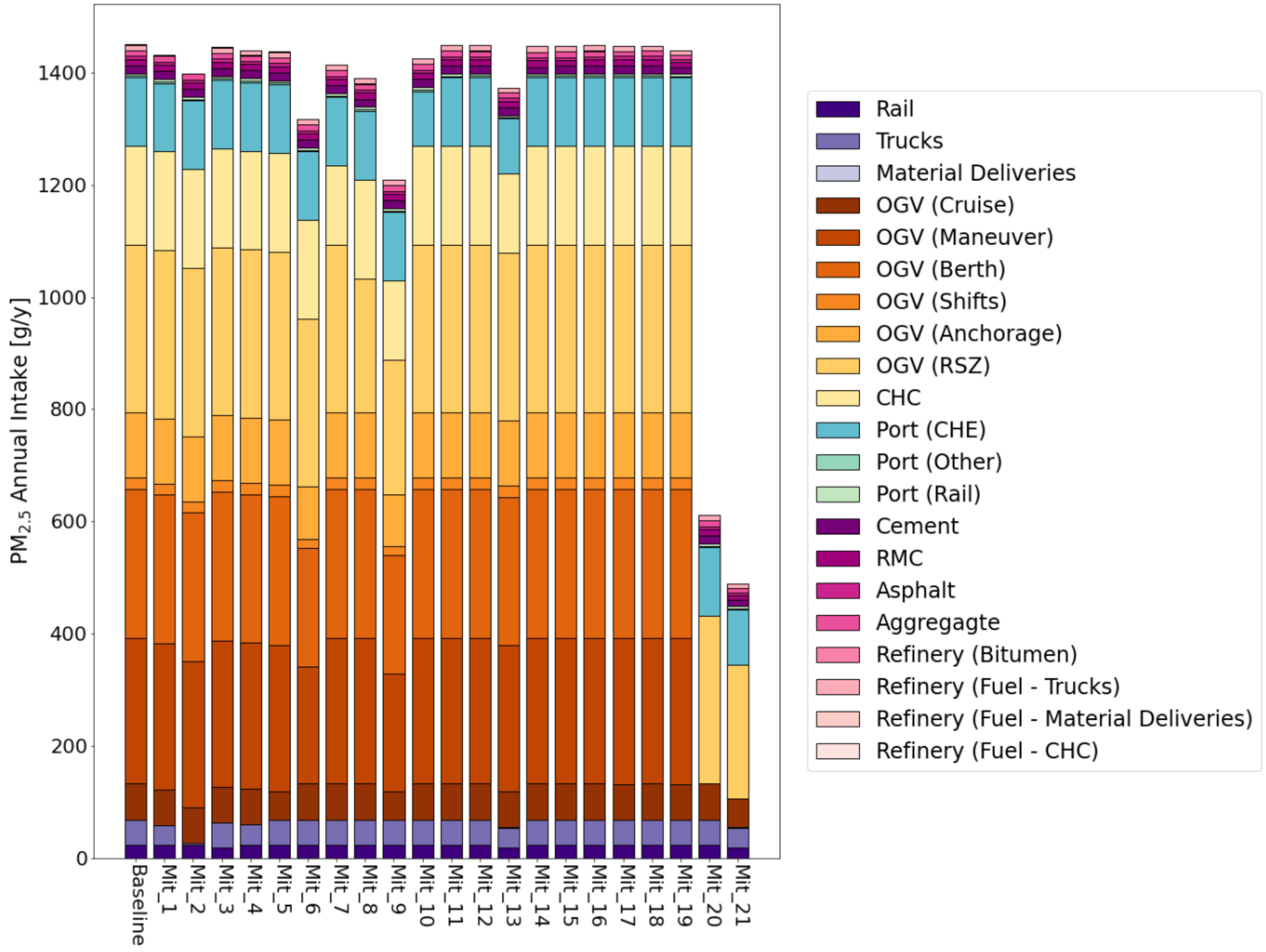


Figure 30. Annual $PM_{2.5}$ intake for the Port of Oakland.

Notes: See Table 2 for descriptions of mitigation strategies. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone; CHE = Cargo Handling Equipment.

Mitigation strategies aimed at reducing ocean vessel and harbor craft sources yield larger reductions in annual intake values than any other mitigation strategy directed at mitigating individual sources. When all these emissions are eliminated, annual intake is reduced by 62 percent from 1598 grams of $PM_{2.5}$ intake to 612 grams of $PM_{2.5}$ intake. Most other related mitigation strategies yield modest reductions. The only strategy that results in moderate reductions is a scenario where all in-port trucking operations are completely electrified (3.2% reduction). The largest reduction in annual intake occurs if all mitigation strategies are combined. This reduces annual intake by 69 percent.

The equity results are stark. The Black population overwhelmingly experiences greater-than-average $PM_{2.5}$ exposure burden from Port of Oakland sources (Figure 31). Under the two percent annual maintenance scenario, the Black populations' relative exposure disparity is 121 percent greater than the average exposure concentration of 0.035 μg m^{-3}. The Native American population also experiences a greater-than-average exposure disparity (16.5% greater than the average). The White, Asian, Hispanic/Latino, and Pacific Islander groups all experience lower-than-average exposure concentrations from the Port of Oakland at minus 7.4 percent, minus 13.3 percent, minus 15.2 percent, and minus 10.4 percent, respectively. The only income quintile with greater-than-average relative exposure disparity is Q1 with 89 percent (Figure 32). Table 14 and Table 15 list, in order from greatest to smallest, the percentage by which an emission source causes a greater than or less than average PM$_{2.5}$ exposure disparity for each demographic group. People of color within the Bay Area experience higher exposure disparities from the materials used in annual Port resurfacing than the White population does. Outside of cruising operations outside of the Golden Gate Bridge, all ocean vessel operations disparately impact the Black population.

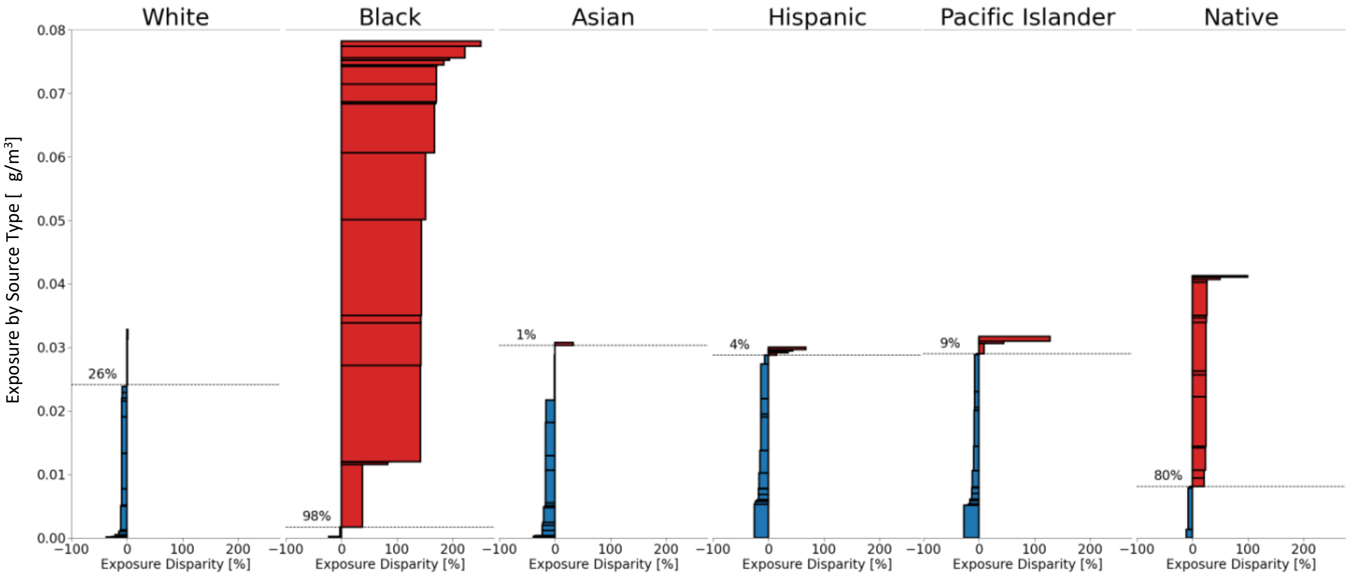


Figure 31. Absolute and relative PM2.5 exposure from Port of Oakland sources by racial demographic.

Notes: The dashed horizontal line indicates the percentage of emission sources causing higher-than-average exposure for each group. Scenario assumes two percent of the Port's surface is reconstructed annually.

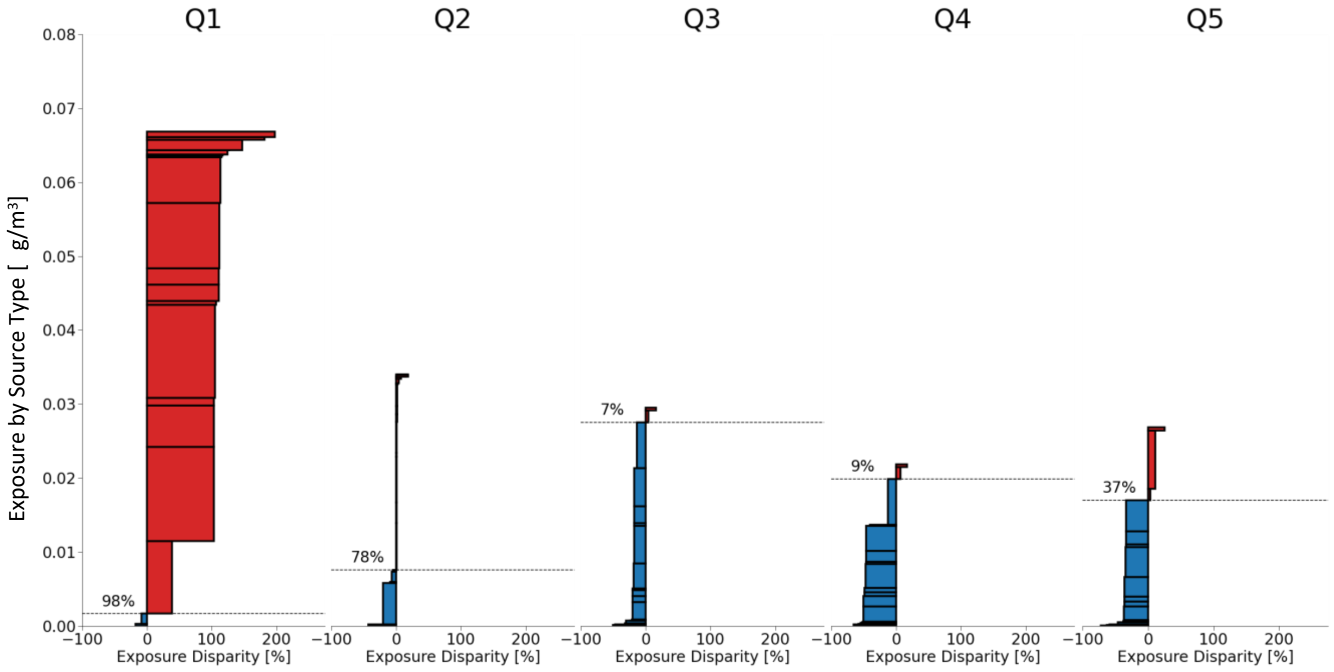


Figure 32. Absolute and relative $PM_{2.5}$ exposure from Port of Oakland sources by income quintile.

Notes: The dashed horizontal line indicates the percentage of emission sources causing higher-than-average exposure for each group. Assumes two percent of the Port's surface is reconstructed annually.

Table 14. Ranking of sources by exposure disparity for each racial demographic.

	White		**Black**		**Asian**		**Hispanic**		**Pacific Islander**		**Native American**	
Ranking of Sources by Exposure Disparity Percentage	OGV – Cruise	1.46%	Aggregate	250%	Cement	32.40%	Aggregate	67.00%	Cement	128%	Asphalt	99.00%
	OGV – RSZ	0.54%	Rail (UP)	222%	OGV – Cruise	-0.20%	Bitumen	43.80%	Aggregate	44.60%	Aggregate	49.90%
	Drayage Trucks – Fuel	-0.16%	Asphalt	194%	OGV – RSZ	-0.60%	Asphalt	43.80%	OGV – Cruise	9.34%	Cement	26.00%
	CHC – Fuel	-0.16%	RMC	184%	CHC	-15.80%	Deliveries – Fuel	35.60%	Asphalt	-3.99%	CHC	25.70%
	Material Deliveries – Fuel	-0.16%	Port – Other	171%	OGV – Berths	-16.50%	Drayage Trucks – Fuel	35.60%	OGV - Berths	-7.55%	RMC	25.40%
	Bitumen	-2.45%	Drayage Trucks	170%	OGV – Anchorage	-16.60%	CHC – Fuel	35.60%	OGV – Anchorage	-7.80%	Rail (UP)	24.80%
	Material Deliveries	-8.52%	Material Deliveries	170%	OGV – Maneuvers	-16.70%	Cem.	14.00%	OGV – Shifts	-7.91%	OGV – Maneuvers	24.50%
	Drayage Trucks	-8.52%	Port – Rail	170%	OGV – Shifts	-16.70%	OGV – Cruise	-6.71%	OGV – Maneuvers	-8.34%	OGV – Shifts	24.40%
	OGV – Shifts	-9.30%	Port – CHE	167%	RMC	-18.00%	OGV – Berths	-13.30%	CHC	-8.93%	OGV – Anchorage	24.40%
	OGV – Anchorage	-9.34%	CHC	151%	Port – Other	-19.70%	OGV – Anchorage	-13.40%	CHE	-11.80%	OGV – Berths	24.30%
	OGV – Berths	-9.38%	OGV – Maneuvers	144%	Port – Rail	-20.00%	OGV – Shifts	-13.40%	Port – Rail	-11.90%	Port – Rail	23.50%

	White		Black		Asian		Hispanic		Pacific Islander		Native American	
Ranking of Sources by Exposure Disparity Percentage	OGV – Maneuvers	-9.40%	OGV – Shifts	143%	CHE	-20.20%	OGV – Maneuvers	-13.80%	Port – Other	-12.00%	Port – Other	23.50%
	CHE	-9.57%	OGV – Anchorage	142%	Rail (UP)	-21.60%	CHC	-15.00%	Material Deliveries	-12.80%	CHE	23.10%
	Port – Rail	-10.00%	OGV – Berths	142%	Drayage Trucks	-22.50%	CHE	-17.00%	Drayage Trucks	-12.80%	Drayage Trucks	21.30%
	Port – Other	-10.30%	Bitumen	91.00%	Material Deliveries	-22.50%	Port – Rail	-17.30%	RMC	-16.00%	Material Deliveries	21.30%
	CHC	-10.70%	Deliveries – Fuel	82.80%	Asphalt	-34.80%	Trucks	-17.40%	Rail (UP)	-16.40%	CHC – Fuel	-4.92%
	RMC	-11.40%	CHC – Fuel	82.80%	CHC – Fuel	-37.40%	Material Deliveries	-17.40%	CHC – Fuel	-18.40%	Drayage Trucks – Fuel	-4.92%
	Rail (UP)	-14.30%	Drayage Trucks – Fuel	82.80%	Drayage Trucks - Fuel	-37.40%	Port – Other	-17.80%	Drayage Trucks – Fuel	-18.40%	Deliveries – Fuel	-4.92%
	Cem.	-20.80%	OGV – RSV	38.00%	Deliveries – Fuel	-37.50%	RMC	-20.90%	Deliveies – Fuel	-18.40%	Bitumen	-6.74%
	Asphalt	-27.10%	OGV – Cruise	-2.79%	Aggregate	-38.40%	Rail (UP)	-23.80%	Bitumen	-23.10%	OGV – RSZ	-7.83%
	Aggregate	-37.30%	Cement	-22.70%	Bitumen	-38.80%	OGV – RSZ	-25.30%	OGV - RSZ	-27.10%	OGV – Cruise	-10.90%

Notes: Positive values indicate a greater-than-average exposure from that source; negative values indicate a lower-than-average exposure. For example, the Black population experiences 2.5 times greater-than-average $PM_{2.5}$ exposure from aggregate facilities compared to all people within the San Francisco Bay Area. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone; CHE = Cargo Handling Equipment.

Table 15. Ranking of sources by exposure disparity for each income quintile.

	Q1		Q2		Q3		Q4		Q5	
Ranking of Sources by Exposure Disparity Percentage	Aggregate	197%	Deliveries – Fuel	18.50%	Cement	15.90%	Cement	17.10%	Cement	25.50%
	Asphalt	182%	Drayage Trucks – Fuel	18.50%	OGV – Cruise	3.98%	OGV – Cruise	6.96%	OGV – RSZ	10.70%
	Rail (UP)	147%	CHC – Fuel	18.50%	OGV – RSZ	-13.10%	OGV – RSZ	-12.90%	OGV – Cruise	3.45%
	Bitumen	128%	Bitumen	16.50%	OGV – Berths	-17.70%	Drayage Trucks – Fuel	-40.10%	OGV – Berths	-33.60%
	RMC	124%	RMC	7.68%	OGV – Anchorage	-17.70%	CHC – Fuel	-40.10%	OGV – Anchorage	-33.70%
	Port – Other	116%	Rail (UP)	4.52%	OGV – Shifts	-17.70%	Deliveries – Fuel	-40.10%	OGV – Shifts	-33.80%
	Port – Rail	115%	Port – Rail	2.17%	OGV – Maneuvers	-17.80%	OGV – Berths	-46.00%	OGV – Maneuvers	-34.20%
	CHE	113%	Port – Other	2.10%	CHC	-18.60%	OGV –Anchorage	-46.10%	CHC	-36.10%
	CHC	111%	CHE	1.97%	Drayage Trucks - Fuel	-20.00%	OGV – Shifts	-46.20%	Drayage Trucks	-36.20%
	Drayage Trucks	110%	Drayage Trucks	1.96%	CHC – Fuel	-20.00%	OGV – Maneuvers	-46.80%	Material Deliveries	-36.20%
	Material Deliveries	110%	Material Deliveries	1.96%	Deliveries – Fuel	-20.00%	Bitumen	-47.70%	CHE	-37.10%
	Deliveries – Fuel	107%	CHC	0.80%	Material Deliveries	-20.50%	Drayage Trucks	-49.10%	RMC	-37.20%
	CHC – Fuel	107%	OGV – Shifts	0.49%	Drayage Trucks	-20.50%	Material Deliveries	-49.10%	Port – Rail	-37.80%
	Drayage Trucks – Fuel	107%	OGV – Maneuvers	0.49%	CHE	-20.60%	CHE	-50.50%	Port – Other	-38.00%
	OGV – Maneuvers	105%	OGV – Anchorage	0.49%	Port – Rail	-20.90%	CHC	-50.70%	Rail (UP)	-46.00%
	OGV –Shifts	103%	OGV –Berths	0.47%	Port –Other	-21.10%	Asphalt	-51.50%	CHC – Fuel	-59.00%
	OGV – Anchorage	103%	Agg.	-5.05%	Bitumen	-26.00%	Port – Rail	-51.80%	Drayage Trucks – Fuel	-59.00%
	OGV – Berths	103%	OGV – Cruise	-6.46%	Rail (UP)	-30.60%	Port –Other	-52.50%	Deliveries – Fuel	-59.00%
	OGV – RSZ	38.30%	Asphalt	-8.94%	RMC	-32.30%	RMC	-54.80%	Asphalt	-63.30%
	OGV – Cruise	-8.57%	OGV – RSZ	-20.50%	Asphalt	-47.30%	Aggregate	-58.10%	Bitumen	-63.30%
	Cement	-17.40%	Cement	-42.70%	Aggregate	-50.10%	Rail (UP)	-65.60%	Aggregate	-72.40%

Notes: Positive values indicate a greater-than-average exposure from that source; negative values indicate a lower-than-average exposure. For example, the Q1 income quintile experiences 1.97 times greater-than-average $PM_{2.5}$ exposure from aggregate facilities compared to all people within the San Francisco Bay Area. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone; CHE = Cargo Handling Equipment.

Exposure damages are listed in Table 16. Depending upon how much Port area is resurfaced each year, baseline exposure damages range from $103 to 119 million (in 2020 USD). The most effective mitigation strategies for reducing annual intake are the same for reducing exposure damages.

Table 16. Exposure damages for baseline and mitigation strategies.

Description	Exposure Damages ($M/year) 2% Scenario	Exposure Damages (M$) - 5% Scenario
Baseline	102.9 – 114.9	106.5 – 118.9
Truck 2045 Scenario	1.08% – 1.10%	1.05% – 1.06%
Truck Electrification	2.95% – 3.02%	2.89% – 2.97%
Rail Reduction (20%)	0.26% – 0.28%	0.25% – 0.27%
Trucking Reduction (20%)	0.61% – 0.63%	0.59% – 0.61%
OGV Cruise Reduction (20%)	0.78% – 0.76%	0.75% – 0.73%
OGV In-Harbor Reduction (20%)	10.39% – 10.70%	10.00% – 10.30%
CHC Reduction (20%)	1.98% – 2.05%	1.91% – 1.98%
OGV RSZ Reduction (20%)	3.63% – 3.64%	3.50% – 3.51%
OGV + CHC All Reduction (20%)	16.79% – 17.14%	16.20% – 16.60%
Port CHE Reduction (20%)	1.36% – 1.41%	1.31% – 1.37%
Port Other Reduction (20%)	0.03% – 0.03%	0.03% – 0.03%
Port Rail Reduction (20%)	0.05% – 0.05%	0.05% – 0.05%
Port + CHC All Reduction (20%)	4.29% – 4.45%	4.14% – 4.29%
Cement Reduction (20%)	0.16% – 0.15%	0.37% – 0.36%
RMC Reduction (20%)	0.13% – 0.13%	0.30% – 0.32%
Asphalt Reduction (20%)	0.06% – 0.06%	0.14% – 0.15%
Aggregate Reduction (20%)	0.12% – 0.12%	0.29% – 0.29%
Refineries Reduction (20%)	0.13% – 0.13%	0.13% – 0.13%
All Facility Reduction (20%)	0.59% – 0.59%	1.24% – 1.25%
OGV Harbor + CHC Emission Elimination	62.81% – 63.70%	60.60% – 61.50%
Combine All	70.19% – 70.96%	68.40% – 69.20%

Notes: A negative percentage change indicates a reduction in monetized exposure damages. Three significant digits are shown to make distinctions in the ranges. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone; CHE = Cargo Handling Equipment.

GHG Emissions

Figure 33 shows the annual GHG emissions for the Port of Oakland for baseline and mitigated conditions, apportioned by emission source. As with $PM_{2.5}$ exposure sources, emissions from ocean vessel sources dominate the total GHG footprint for the Port of Oakland. Cargo handling equipment and drayage trucks are the next largest source of emissions. The share that ocean vessels contribute to the overall GHG footprint changes depending upon how much Port surface resurfacing is assumed to occur each year. Under the two percent area resurfacing assumption, ocean vessels account for 50 percent of GHG emissions. If five percent of the area is resurfaced each year, they account for 46 percent of total emissions. Port resurfacing materials and supply chain sources (material deliveries, fuel) range from 8.7 to 15 percent of total GHG emissions depending upon the maintenance scenario. Ocean vessel activities within the harbor (after the Bay Bridge) dominate, accounting for 33 percent of all GHG emissions. The GHG emission results present an interesting contrast with the pavement case study (Sections 2 and 3), where materials and supply chain sources are a more significant contributor to impacts. Note that the Port of Oakland sources included in this analysis are not fully capturing all relevant sources (e.g., fuel used for ocean vessel operations).

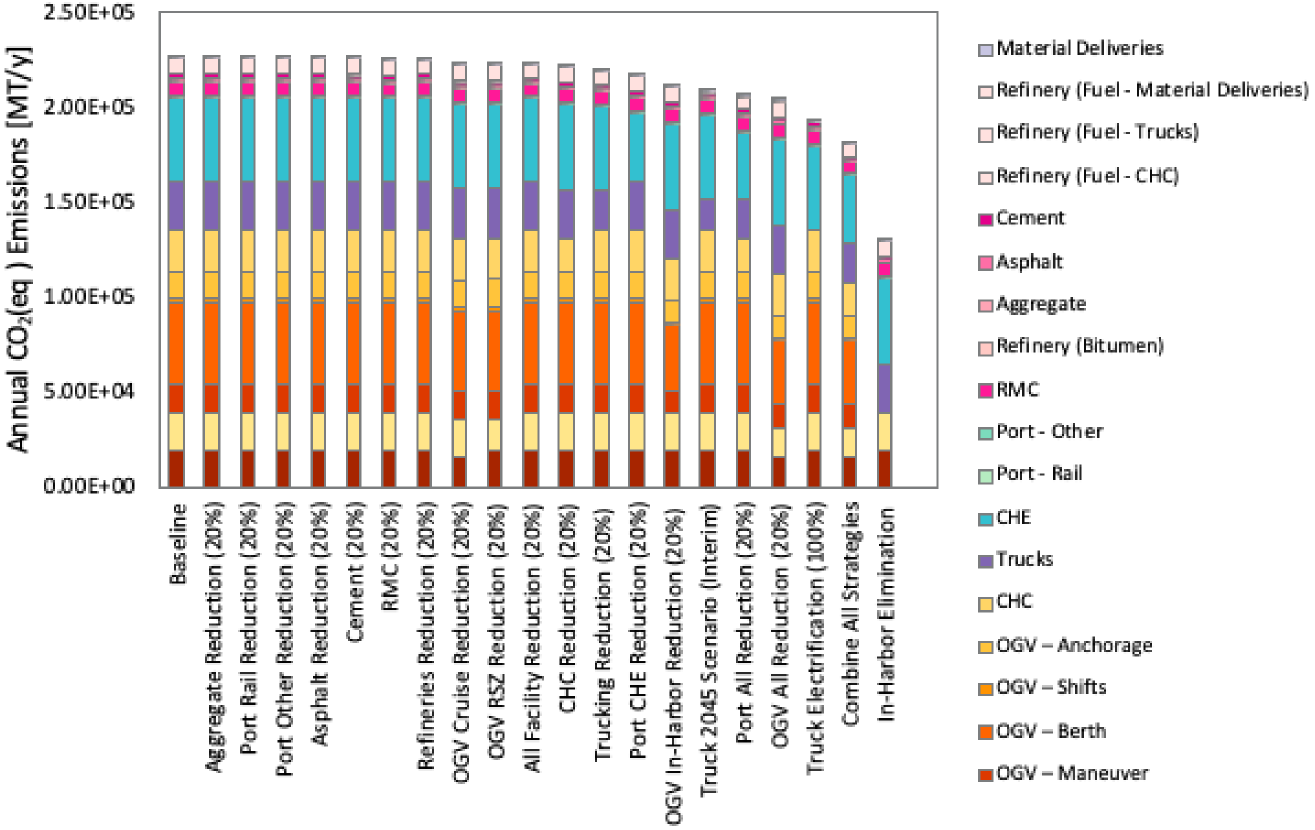


Figure 33. Annual GHG emissions for Port of Oakland by source.

Notes: Material emissions assume that 2% of annual Port surface volume is maintained and replaced. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone; CHE = Cargo Handling Equipment.

Table 17 lists the monetized climate change damages for baseline and mitigated strategies for the Port of Oakland. The most effective strategies for reducing GHG emissions, and monetized climate change damages, are to: 1) completely eliminate ocean vessel and commercial harbor craft emissions from activities within the harbor (through electrification for example), 2) reduce all ocean vessel activities by 20 percent through some hypothetical pollution control technology, 3) complete electrification of drayage truck operations within the Port system boundary, 4) reduce commercial harbor craft and on-ground Port operations (e.g., trucks, cargo handling equipment, rail, other), or 5) combine all mitigation strategies under a more conservative scenario where trucking emissions are reduced by 20 percent. Savings in incurred damages for mitigation strategies range from a low of $2,200 to $15,500 per year (reducing aggregate production emissions by 20%) to a high of $4.2 million to $29.7 million (eliminating in-harbor watercraft emissions).

Table 17. Monetized climate change damages for baseline and mitigated conditions at the Port of Oakland. Low, Medium, and High ranges are provided for the Social Cost of Carbon metric.

	2% Resurfacing Scenario – Climate Change Damages ($M/year)	5% Resurfacing Scenario – Climate Change Damages ($M/year)
Baseline	$9.8 – $69.8	$10.5 –$75.0
Truck 2045 Scenario (Interim)	7.88%	7.33%
Truck Electrification (100%)	15.06%	14.02%
Trucking Reduction (20%) [Reduce fuel for trucking by 20% as well]	3.01%	2.80%
OGV Cruise Reduction (20%)	1.73%	1.61%
OGV RSZ Reduction (20%)	1.73%	1.61%
OGV In-Harbor Reduction (20%) [Shift, Man., Berth, Anchor]	6.54%	6.09%
OGV All Reduction (20%)	10.01%	9.32%
CHC Reduction (20%) [Reduce fuel for CHC by 20% as well]	1.96%	1.82%
Port CHE Reduction (20%)	3.94%	3.67%
Port Other Reduction (20%)	0.06%	0.05%
Port Rail Reduction (20%)	0.04%	0.04%
Port All [trucks, CHC, CHE, other, both rail] Reduction (20%)	9.01%	8.39%
Cement (20%)	0.17%	0.38%
RMC (20%)	0.64%	1.48%
Asphalt Reduction (20%)	0.11%	0.25%
Aggregate Reduction (20%)	0.02%	0.05%
Refineries Reduction (20%)	0.79%	0.80%
All Facility Reduction (20%)	1.72%	2.96%
OGV In-Harbor and CHC Emission Elimination	42.51%	39.59%
Combine All [Reduce every source by 20%]	20.00%	20.00%

Notes: The Social Cost of Carbon (SCC) is calculated for the two percent and five percent maintenance scenario. Note that the “Medium” scenario reflects the most recent SCC estimation from the federal U.S. government. See the Supplemental Information for SCC unit costs. OGV = Ocean Going Vessel; CHC = Commercial Harbor Craft; RSZ = Reduced Speed Zone; CHE = Cargo Handling Equipment.

D. Discussion

It makes sense to prioritize which sources to mitigate based upon those that have the most impact on $PM_{2.5}$ exposure and on GHG emissions. Based upon the results of this study, ocean-going vessels appear to be one of the most important sources. Their operations within the vicinity of the Port (the area between the San Francisco-Oakland Bay Bridge to the Port harbor) seem to be the most impactful. Regulation of specific activities (e.g., at berth phase) is important. ARB appears to be negotiating with Port authorities to specifically address exposure impacts by implementing regulations to reduce diesel PM and NOx emissions.[163] ABR’s efforts began in 2007 with regulations for ocean vessel ports within California, including the Port of Oakland. Compliance needed to start in 2014, with the goal of reducing PM and NOx from ocean vessels at berth operations by 80 percent by 2020. ARB is currently exploring how to expand these regulations to include other vessel types (e.g., commercial harbor craft).

ARB has other regulatory efforts and there is a port-specific program for drayage trucks at the Port of Oakland called the Comprehensive Truck Management Program.[164] The drayage trucks are regulated by limiting the model years for truck engines to those that meet a certain emission threshold. If truck engines do not meet the threshold, the truck must either be phased out or meet separate emission requirements from both ARB and the Port of Oakland.

It is especially important to consider how to efficiently mitigate $PM_{2.5}$ exposure and GHG emission as demand for maritime shipping fluctuates. As demonstrated with the backlog at the end of 2021/beginning of 2022, where drastic increase in port throughput from cargo handling equipment and more instances of idling from both ocean vessels and drayage trucks, pollutant emissions from these phases can be significant.

The extreme exposure disparities faced by the Black population (and to a lesser extent by the Native American population) from emission sources from the Port of Oakland highlights how important it is that mitigation efforts be developed for specific communities and by specific groups (as is occurring with the West Oakland Community Action Plan under AB 617).

6. Decision-Support Tool

A. Introduction

Use of a decision-support tool is a key component in assessing air pollution, climate change, and noise pollution impacts from the design, construction, operation, and maintenance of transportation projects. In this study we designed an Excel-based decision-support tool for use in for the San Francisco roadway case study. The tool was used to calculate the primary and secondary $PM_{2.5}$ and GHG emissions inventories discussed in Sections 2 and 3, respectively.

The tool can be used to calculate GHG, primary $PM_{2.5}$, and $PM_{2.5}$ precursor emissions from the design, construction, operation, and maintenance of paved roads. Specifically, the tool can be used throughout any stage of a project including construction and operation of new roads, renovations of existing roads, and lane widenings/shortenings. Note that the results of the case study presented in Sections 2 and 3 only represent the design, operation, and maintenance of the roadways. In addition to assessing emissions from baseline conditions, users can assess conditions after various mitigation strategies have been applied. The tool incorporates California-based emission factors for construction equipment, vehicles, fuel, and electricity, but users can customize it with their own emission factors. The tool does not calculate emissions from material or fuel production facilities. The only supply chain activity calculated within the tool is material delivery. Note that final results for material delivery (annual emissions and monetized climate change damages) are provided in units of emissions or dollars per mile. This allows for users to connect material delivery results to the exact number of miles driven between the material production site and the roadway segment. The tool can also be used to assess changes in direct and indirect health care costs associated with two of the primary health conditions attributable to unhealthy exposure of roadway noise, but currently only with data from the San Francisco Bay Area.

It is important to understand how the tool's outputs fit into the larger goals of addressing environmental justice and climate change concerns. In terms of climate change, the tool's GHG emissions inventory is converted to monetized damages using a range of estimates for the Social Cost of Carbon metric. The air pollution output from the tool (i.e., the primary and secondary $PM_{2.5}$ emissions inventory) can be used as an input for external analysis outside of the tool itself (as shown in Figure 34). The InMAP Source-Receptor Matrix is used to calculate exposure intake, but users are not bound to this specific air quality model. The emissions inventory calculated by the decision-support tool has units of mass of pollutant per year and can be fed as an input into other air quality models.

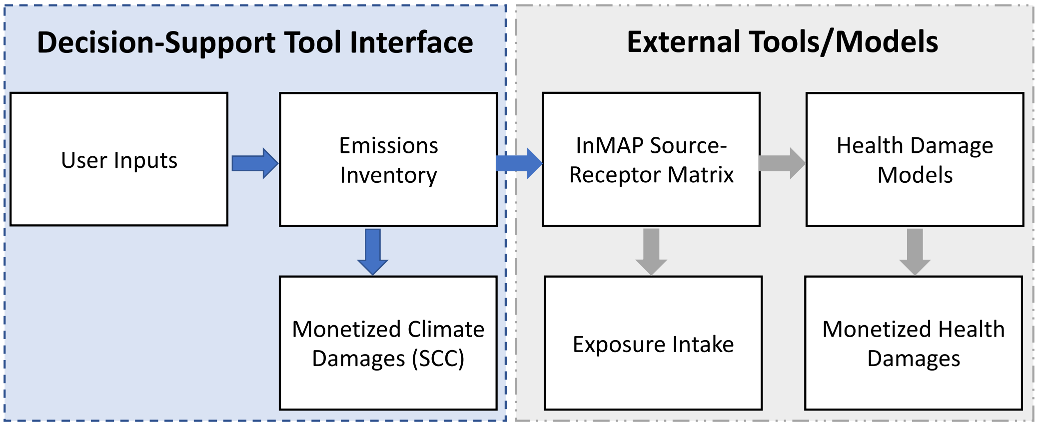


Figure 34. Process flow diagram detailing how the emissions inventory output from the decision-support tool is used for final results (second row).

Ultimately, the decision-support tool can be used to help in answering the following types of questions, either directly within the tool's interface or by providing input to external tools:

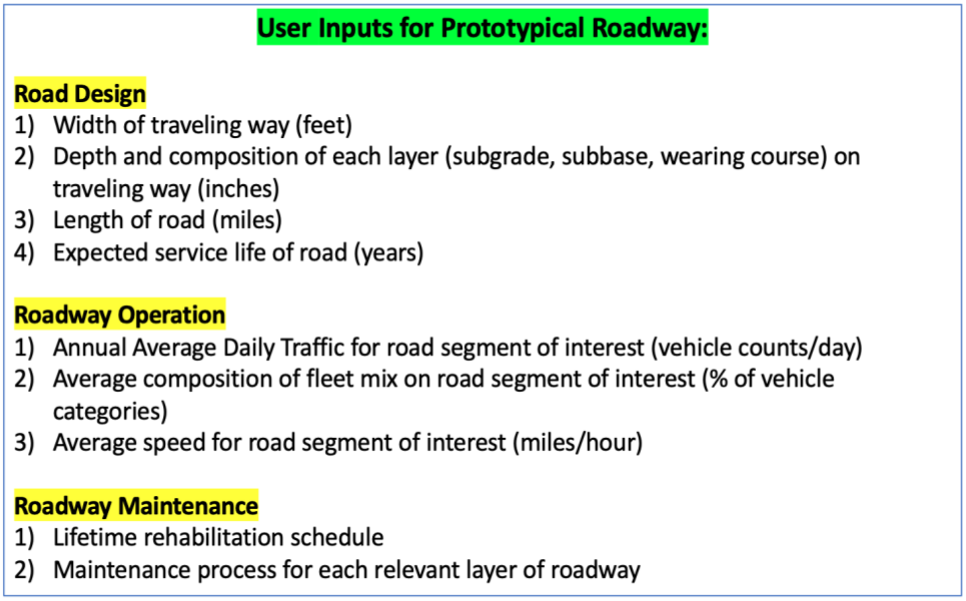
1. What are the GHG emissions and monetized damages from climate change impacts associated with designing, constructing, operating, and maintaining paved roads in California?
2. What is the $PM_{2.5}$ exposure intake for the cradle-to-grave impacts from a paved road (including vehicle operation)? How does that exposure change by demographic group?
3. What are the monetized health damages from the $PM_{2.5}$ intake?
4. How do direct and indirect health care costs change from implementing hypothetical vehicle noise mitigation strategies, given changes in risk instances of health conditions associated with roadway noise exposure?

B. Decision-Support Tool Overview

The decision-support tool consists of three main modules, each displayed in several sheets. The three main modules are: (1) user inputs; (2) calculations and background data; and (3) results. A brief description of the key attributes of each module is provided.

Module 1: User Inputs

Users can assess the emissions implications from a wide variety of paved roadway designs, vehicle fleet mixes, and roadway maintenance procedures. Figure 35 lists the general information that users must enter to assess the emissions impact from road networks.



User Inputs for Prototypical Roadway:

Road Design

1) Width of traveling way (feet)
2) Depth and composition of each layer (subgrade, subbase, wearing course) on traveling way (inches)
3) Length of road (miles)
4) Expected service life of road (years)

Roadway Operation

1) Annual Average Daily Traffic for road segment of interest (vehicle counts/day)
2) Average composition of fleet mix on road segment of interest (% of vehicle categories)
3) Average speed for road segment of interest (miles/hour)

Roadway Maintenance

1) Lifetime rehabilitation schedule
2) Maintenance process for each relevant layer of roadway

Figure 35. User inputs for road design, roadway operation, and roadway maintenance in decision-support tool.

Users can define and select among more specific roadway design, operation, and maintenance options. Roadway design and maintenance options are presented in Table 18. The tool can calculate emissions for a roadway with up to two wearing courses, two bases, two subbases, and one subgrade layer. The shoulder and embankment are also definable. Depending upon the composition choice of each pavement layer, users are presented with selecting one maintenance process per layer. The only maintenance process to choose from for the subbase, subgrade, and shoulder/embankment are replacement and compaction.

Table 18. User selection options for roadway design and maintenance processes.

Pavement Layer	Composition Choice (Select one per layer)	Road Maintenance Process (Select one per layer)
Wearing Course 1	Jointed Plain Concrete Pavement (JPCP) Continuously Reinforced Concrete Pavement (CRCP) Hot Mix Asphalt (HMA)	IF JPCP/CRCP: Patching Mill and Overlay Overlay
Wearing Course 2		IF HMA: Cold In-Place Recycling Hot In-Place Recycling Warm Mix Asphalt Full-Depth Reclamation
Base 1	Aggregate HMA Lean Concrete Base Asphalt Treated Permeable Base	IF Aggregate: Replacement and Compaction
		IF HMA: Cold In-Place Recycling Hot In-Place Recycling Warm Mix Asphalt Full-Depth Reclamation
Base 2		IF Lean Concrete Base: Patching Mill and Overlay Overlay
		If Asphalt Treated Permeable Base Replacement and Compaction
Subbase 1	Aggregate Cement Stabilized Soil Lime Stabilized Soil	Replacement and Compaction
Subbase 2		
Subgrade	Fill Native Soils	Replacement and Compaction
Shoulder and Embankment	Ready-Mixed Concrete (RMC) HMA	Replacement and Compaction

Users also define the fleet mix composition for their road segment of interest by inputting the percentage of each vehicle type on the roadway. The vehicle counts and average vehicle speed for the roadway segment is also defined by the user. Vehicle speeds are connected to look-up tables for the respective vehicle operation emission factor from EMFAC. Table 19 lists the vehicle categories and descriptions that users can allocate to the roadway segment of interest.

Table 19. Vehicle categories and descriptions which users can allocate to their roadway segment of interest (by % of vehicle type).

Vehicle Category	Vehicle Description
LDA	Passenger Cars - Gasoline
	Passenger Cars - Diesel
	Passenger Cars - Electric
	Passenger Cars - Plug-in Hybrid
LDT1	Light-Duty Trucks (GVWR*<6000 lbs and ETW** <=3750 lbs) - Gasoline
	Light-Duty Trucks (GVWR*<6000 lbs and ETW** <=3750 lbs) - Diesel
	Light-Duty Trucks (GVWR*<6000 lbs and ETW** <=3750 lbs) - Electric
	Light-Duty Trucks (GVWR*<6000 lbs and ETW** <=3750 lbs) - Plug-in Hybrid
LDT2	Light-Duty Trucks (GVWR*<6000 lbs and ETW** 3751-5750 lbs) - Gasoline
	Light-Duty Trucks (GVWR*<6000 lbs and ETW** 3751-5750 lbs) - Diesel
	Light-Duty Trucks (GVWR*<6000 lbs and ETW** 3751-5750 lbs) - Electric
	Light-Duty Trucks (GVWR*<6000 lbs and ETW** 3751-5750 lbs) - Plug-in Hybrid
MDV	Medium-Duty Trucks (GVWR 5751-8500 lbs) - Gasoline
	Medium-Duty Trucks (GVWR 5751-8500 lbs) - Diesel
	Medium-Duty Trucks (GVWR 5751-8500 lbs) - Electric
	Medium-Duty Trucks (GVWR 5751-8500 lbs) - Plug-in Hybrid
LHD1	Light-Heavy-Duty Trucks (GVWR 8501-10000 lbs) - Gasoline
	Light-Heavy-Duty Trucks (GVWR 8501-10000 lbs) - Diesel
LHD2	Light-Heavy-Duty Trucks (GVWR 10001-14000 lbs) - Gasoline
	Light-Heavy-Duty Trucks (GVWR 10001-14000 lbs) - Diesel
T6 Public Class 4	Medium-Heavy Duty Public Fleet Truck (GVWR 14001-16000 lbs) - Diesel
	Medium-Heavy Duty Public Fleet Truck (GVWR 14001-16000 lbs) - NG
T6 Public Class 5	Medium-Heavy Duty Public Fleet Truck (GVWR 16001-19500 lbs) - Diesel
	Medium-Heavy Duty Public Fleet Truck (GVWR 16001-19500 lbs) - NG
T6 Public Class 6	Medium-Heavy Duty Public Fleet Truck (GVWR 19501-26000 lbs) - Diesel
	Medium-Heavy Duty Public Fleet Truck (GVWR 19501-26000 lbs) - NG
T6 Public Class 7	Medium-Heavy Duty Public Fleet Truck (GVWR 26001-33000 lbs) - Diesel
	Medium-Heavy Duty Public Fleet Truck (GVWR 26001-33000 lbs) - NG
T7 Public Class 8	Heavy-Heavy Duty Public Fleet Truck (GVWR >33001 lbs) - Diesel
	Heavy-Heavy Duty Public Fleet Truck (GVWR >33001 lbs) - NG

Notes: GVWR = Gross Vehicle Weight Rating. ETW = Equivalent Test Weight. NG = Natural Gas.

Users can estimate the direct and indirect health care costs for two diseases that are linked to exposure of unhealthy levels of roadway noise: (1) ischemic heart disease (IHD) and (2) hypertension. Costs are presented for both baseline and mitigated roadway noise levels. Additionally, users can see how many fewer people in each exposure area are diagnosed with IHD and hypertension after implementing roadway noise mitigation strategies. Users can currently select an exposure area at the county-level for each of the nine counties within the San Francisco Bay Area. The other input users can change is the relative risk for an individual to be diagnosed with either IHD or hypertension because of their exposure to roadway noise. Default values for these each respective risk level are provided within the tool.

Module 2: Calculations and Background Data

Emissions are calculated based upon the amount and type of materials, fuel, and energy used in the design, construction, operation, and maintenance of the roadway segment(s) of interest. All calculation methodology is detailed within Sections 2, 3, and the accompanying Supplemental Information. Roadway noise impacts are calculated according to the methods outlined in Section 4. In the current iteration of the spreadsheet tool, background data that is used to calculate emissions from raw materials, construction, vehicle operation and fuel supply chains, and roadway maintenance mainly come from California-based sources (e.g., CA-GREET, EMFAC). A description of each data sheet is listed in Table 20. Mitigation versions of the ONROAD/OFFROAD/CA-GREET emission factor sheets are also included in the tool but they are kept hidden. The mitigation versions include emission factors from future years (i.e., 2045).

Table 20. Descriptions of background data in decision-support tool.

Sheet Name	Description
Paved Roads - Emissions	Includes: User input interface for calculating emissions. Calculation/result displays for: (1) Raw Materials; (2) Construction from Material Delivery, Roadway Construction Activities; (3) Roadway Vehicle Operation and Fuel Consumption; (4) Maintenance from Material Delivery, Roadway Maintenance Activities.
Paved Roads - Noise	Includes: User input interface for calculating emissions. Result displays for: (1) direct and indirect health care costs from roadway noise-induced IHD and hypertension; (2) changes in population numbers by county who are diagnosed with IHD/hypertension after noise mitigation.
EPDs	Includes: Environmental Product Declaration values (GHG emissions per unit of material) and descriptions for all relevant roadway materials.
Vehicle Categories	Includes: Detailed descriptions of vehicle classes from EMFAC; Average fuel economies for each vehicle type.

Sheet Name	Description
ONROAD Vehicle Emission Factors	Includes: Direct emission factors for vehicles, in grams per mile, for GHGs, NOx, PM2.5, PM10, VOCs, NH3, CO, SOx. Emission factors are from 2019 values from EMFAC, assuming aggregate vehicle speed.
OFFROAD Emission Factors	Includes: Direct emission factors for construction equipment, in tons per hour of use, for GHGs, NOx, PM2.5, PM10, VOCs, NH3, CO, SOx. Emission factors are from 2019 values from EMFAC.
CA-GREET	Includes: Well-to-pump emission factors for various fuels (gasoline, diesel, electricity) Emission factors are from the latest version of CA-GREET v3.0 (2018)
Equipment	Includes: Descriptions and operational parameters (e.g., construction equipment production rates) for all construction equipment used in the construction/maintenance of respective pavement layers
Populations	Includes: Population counts for each county within the San Francisco Bay Area (relevant for noise impacts)
County Noise	Includes: Calculations and results for noise impacts for each county
Bay Area – IHD/Hypertension	Includes: Existing incidence levels (in percentage) for IHD and hypertension each county within the San Francisco Bay Area

Module 3: Results

The results for the GHG and primary and secondary $PM_{2.5}$ emissions inventories are displayed for users in the "Results Summary" sheet. Results are aggregated by pollutant, overarching life-cycle stage (e.g., construction), and activity (e.g., material delivery). Monetized climate damage results are presented in the same manner. If users choose to investigate mitigation strategies (e.g., various degrees of vehicle electrification), results will also be displayed on the "Results Summary" sheet. Noise exposure results are displayed in the "Paved Roads – Noise" sheet.

C. Discussion and Conclusions

The decision-support tool presented here is intended to be used to estimate life-cycle emission impacts from paved roads and vehicle operation efficiently and accurately. It can be used to provide a demonstration of how mitigation strategies can yield reductions in noise-induced health conditions. The results from the GHG emissions inventory can be used to assess the monetized damages from climate change impacts using the SCC metric. The results from the primary and secondary $PM_{2.5}$ emissions inventory can be used as input for external tools (i.e., reduced-complexity air quality model such as InMAP or ISRM) to estimate the exposure intake for communities. Concentration data from ISRM can then be related to external health damage models to estimate the economic costs from $PM_{2.5}$ exposure leading to premature mortality. Changes in how populations respond to different levels of hypothetical road noise mitigation efforts are also possible within the decision-support tool framework.

The tool can analyze a wide range of design iterations and maintenance procedures, beyond what is explored in Sections 2 and 3. The tool supports further understanding of what procedures an agency such as Caltrans might consider adopting to mitigate their GHG and air pollution impacts. Perhaps most significantly, the decision-support tool and the larger analysis framework can be thought of as an opportunity/blueprint for agencies (such as Caltrans) to identify how they can quantitatively incorporate climate change and environmental justice into their decision making and short- and long-term planning for transportation infrastructure projects. While the tool is currently set up with California-based background data and preselected Environmental Product Declarations, users can change and incorporate data that best reflects their project conditions as long as the data units are compatible with the tool’s existing framework. Additionally, users can conduct their own sensitivity analysis on key input and data parameters by running multiple iterations within the tool. The tool is not without limitations. As identified in Table 18 and Table 19, there is only a certain level of customizability regarding road design and maintenance procedures. If what is offered for users to select does not match the conditions for their road(s)/region, then the users would need to greatly modify the tool.

7. Conclusions

There is a strong and urgent need to address big societal issues like climate change, and health, social, and economic disparities. In order to tackle the negative impacts caused by climate change and human health-harming emissions, it is imperative that there is a clear understanding of how much emissions are attributable to transportation systems and infrastructures. Climate change impacts can be estimated by cataloguing GHG emissions. Health disparities can be determined by estimating the amount of primary and secondary $PM_{2.5}$ emissions that people inhale within a given exposure area. In the case of noise, health and cost implications can be estimated by evaluating rates of disease occurrences from resulting noise emissions.

It is imperative that policymakers and stakeholders understand how all life-cycle stages of California's transportation infrastructure projects can impact the environment and both local and global communities. Taking a holistic, comprehensive approach allows for identification of emission sources and activities that might not otherwise be considered (e.g., supply chain and embodied emissions, as opposed to just considering operational emissions).

Transportation projects need to be evaluated in a way that accounts for the entire relevant scope of emission sources and activities. The evaluation of projects should be quantitative. Measurable results are necessary for incorporating environmental justice into transportation project planning and to address racial and socioeconomic disparities in pollution exposure from transportation projects. Incorporating environmental justice into infrastructure decision-making, which has been missing, is now beginning to be one of the driving criteria in project assessment. When evaluating the state's transportation systems, it is necessary to consider a range of evaluation criteria (e.g., impacts on climate change, human health). Evaluation criteria need to be able to address intersections among climate change, environmental justice, and human health as all are interconnected. Having multiple evaluation criteria helps identify the suite of mitigation strategies that can help the most people possible. For example, a mitigations strategy such as electrification might yield different rates of effectiveness in terms of a climate change mitigation strategy as compared to a $PM_{2.5}$ exposure mitigation strategy.

The results from the two case studies presented in this report demonstrate important conclusions:

- When accounting for a wider scope of emission sources for a specific type of transportation project, supply chain activities and raw materials can be significant contributing sources to overall impacts, especially exposure and human health impacts. The purported significance of supply chain sources on exposure impacts could drive future regulatory policy. In Section 2, typical exposure mitigation strategies were assessed, where 20 percent reductions in annual $PM_{2.5}$ emissions from material production facilities were applied. A 20 percent reduction corresponds to a hypothetical application of a best available pollution control technology. An example of a hypothetical mitigation policy that the results support, but that was not investigated in this study, could be a regulation similar to AB 262 (Buy

Clean California Act). AB 262 requires contractors on state-funded projects (e.g., Caltrans building highway bridges) to use construction materials (specifically structural steel, concrete, reinforcing steel, mineral wool insulation board, flat glass) whose emission impacts do not exceed a specified threshold.[165] The hypothetical mitigation policy could mandate that contractors only use materials supplied from facilities that do not adversely contribute to people's $PM_{2.5}$ exposure intake. Another hypothetical mitigation strategy, again not modeled in this report, could be to define certain routes that material delivery drivers must follow to ensure that human exposure and intake are reduced. Such a policy is somewhat in line with existing California regulations that ban trucks over 9,000 pounds from portions of Interstate 580 in the Bay Area.[166]

- Electrification is a key mitigation strategy for minimizing GHG emissions, $PM_{2.5}$ exposure, and noise exposure (although noise mitigation through electrification is not explicitly modeled in this report). Electrification is especially effective as a tool for addressing climate change, and while it can also have a significant impact on reducing $PM_{2.5}$, it will not solve exposure impacts alone. This is particularly clear in the San Francisco Bay Area paved roadway case study (Sections 2-4) where even under a scenario where all on-road mobile sources are 100 percent electrified, there are still $PM_{2.5}$ emissions from vehicle brake and tire wear. The results point towards the likely necessity of implementing a suite of more feasible mitigation strategies, including electrification, best available pollution control technologies, and efficiency measures. Longer-term mitigation strategies such as moving sources (e.g., material production facilities) away from populations or moving populations away from sources could potentially be included in the suite of strategies.

- Applying rigorous analytical frameworks that account for racial and demographic disparities is key to incorporating environmental justice into the state's transportation project planning, construction, and utilization. Different racial and socioeconomic groups experience differential burdens from both noise and $PM_{2.5}$ intake. For both the San Francisco Bay Area paved roadway network and the Port of Oakland, people of color, and especially the Black population, experience higher-than-average $PM_{2.5}$ exposure burdens. Documenting which emission sources affect which groups by how much provides policymakers with a clear roadmap for designing equitable regulations. The results of the roadway and marine port case studies support continued adoption of legislation such as AB 617, where individual communities can develop their own customized mitigation plans.

- The economic implications of the damages and costs incurred by pollution from the state's transportation systems are not insignificant. For the two case studies included in this report, which amount to a minimum of all transportation systems/projects within the state, damages and direct/indirect costs from climate change and human health impacts run into the eight figures. Assigning a dollar amount to the negative impacts from constructing, operating, and maintaining the state's transportation infrastructure provides stakeholders with needed context.

Moving forward, this study offers a blueprint for stakeholders to use as they embark on tackling climate change and human health impacts from designing, constructing, operating, maintaining, and decommissioning the state’s transportation systems and infrastructure. Near-term next steps should be to expand the analysis presented in Section 1 by assessing other critical transportation projects in the state (e.g., logistical distribution facilities, future vertiport terminals). Finally, connecting with both community groups and policymakers offers an opportunity to target the most significant emission sources and to pinpoint the most equitable mitigation strategies. Rigorous and systematic analysis coupled with community engagement points to a winning combination to fight climate change and support environmental justice outcomes.

References

1. CARB. Greenhouse Gas Emission Inventory | California Air Resources Board. https://ww2.arb.ca.gov/applications/greenhouse-gas-emission-inventory-0 (2022).

2. Apte, J. S. A Tool to Prioritize Sources for Reducing High PM2.5 Exposures in Environmental Justice Communities in California. *California Air Resources Board* https://ww3.arb.ca.gov/research/single-project_ajax.php?row_id=67021 (2019).

3. Feng, S., Gao, D., Liao, F., Zhou, F. & Wang, X. The health effects of ambient PM2.5 and potential mechanisms. *Ecotoxicol. Environ. Saf.* 128, 67–74 (2016).

4. Casey, J. A., Morello-Frosch, R., Mennitt, D.J., Fristrup, K., Ogburn, E.L., & James, P. Race/ethnicity, socioeconomic status, residential segregation, and spatial variation in noise exposure in the contiguous United States. *Environ. Health Perspect.* 125, 077017 (2017).

5. Muratsuchi, A. Bill Text - AB-1279 The California Climate Crisis Act. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1279 (2022).

6. CARB. California Air Districts | California Air Resources Board. https://ww2.arb.ca.gov/california-air-districts (2022).

7. OPR. General Plan Information - Office of Planning and Research. https://opr.ca.gov/planning/general-plan/ (2022).

8. Jbaily, A., Zhou, X., Liu, J., Lee, T.H., Kamareddine, L., Verguet, S., & Dominici, F. Air pollution exposure disparities across US population and income groups. *Nature* 601, 228–233 (2022).

9. Lane, H. M., Morello-Frosch, R., Marshall, J. D. & Apte, J. S. Historical Redlining Is Associated with Present-Day Air Pollution Disparities in U.S. Cities. *Environ. Sci. Technol. Lett.* 9, 345–350 (2022).

10. Liu, J., Clark, L.P., Bechle, M.J., Hajat, A., Kim, S.Y., Robinson, A.L., Sheppard, L., Szpiro, A.A., & Marshall, J.D. Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environ. Health Perspect.* 129, 127005 (2021).

11. Tessum, C. W., Paolella, D.A., Chambliss, S.E., Apte, J.S., Hill, J.D., & Marshall, J.D. $PM_{2.5}$ polluters disproportionately and systemically affect people of color in the United States. *Sci. Adv.* 7, eabf4491 (2021).

12. Monserrat, L. SB 535 Disadvantaged Communities. *OEHHA* https://oehha.ca.gov/calenviroscreen/sb535 (2022).

13. Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K. & Klüppel, H.-J. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. *Int. J. Life Cycle Assess.* 11, 80–85 (2006).

14. Mueller, S. C., Hudda, N., Levy, J.I., Durant, J.L., Patil, P., Lee, N.F., Weiss, I., Tatro, T., Duhl, T., & Lane, K. Changes in Ultrafine Particle Concentrations near a Major Airport Following Reduced Transportation Activity during the COVID-19 Pandemic. *Environ. Sci. Technol. Lett.* 9, 706–711 (2022).

15. California, S. of. Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California's Fight Against Climate Change. *California Governor* https://www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce-demand-for-fossil-fuel-in-californias-fight-against-climate-change/ (2020).

16. United States. Department of Transportation. Bureau of Transportation Statistics. National Transportation Statistics (NTS). doi:10.21949/1503663. (2019)

17. Rowangould, G. M. A census of the US near-roadway population: Public health and environmental justice considerations. *Transp. Res. Part Transp. Environ.* 25, 59–67 (2013).

18. Tian, N., Xue, J. & Barzyk, T. M. Evaluating socioeconomic and racial differences in traffic-related metrics in the United States using a GIS approach. *J. Expo. Sci. Environ. Epidemiol.* 23, 215–222 (2013).

19. Alotaibi, R., Bechle, M., Marshall, J.D., Ramani, T., Zietsman, J., Nieuwenhuijsen, M.J., & Khreis, H. Traffic related air pollution and the burden of childhood asthma in the contiguous United States in 2000 and 2010. *Environ. Int.* 127, 858–867 (2019).

20. Kurt, O. K., Zhang, J. & Pinkerton, K. E. Pulmonary health effects of air pollution. *Curr. Opin. Pulm. Med.* 22, 138 (2016).

21. Pope III, C. A., Lefler, J.S., Ezzati, M., Higbee, J.D., Marshall, J.D., Kim, S.Y., Bechle, M., Gilliat, K.S., Verson, S.E., Robinson, A.L., & Burnett, R.T. Mortality risk and fine particulate air pollution in a large, representative cohort of US adults. *Environ. Health Perspect.* 127, 077007 (2019).

22. Beelen, R., Hoek, G., van der Brandt, P.A., Goldbohm, R.A., Fischer, P., Schouten, L.J., Armstrong, B., & Brunekreef, B. Long-term exposure to traffic-related air pollution and lung cancer risk. *Epidemiology* 702–710 (2008).

23. Cheng, I., Tseng, C., Wu, J., Yang, J., Conroy, S.M., Shariff-Marco, S., Li, L., Hertz, A., Gomez, S.L., Le Marchand, L., & Whittemore, A.S. Association between ambient air pollution and breast cancer risk: the multiethnic cohort study. *Int. J. Cancer* 146, 699–711 (2020).

24. Danysh, H. E., Zhang, K., Mitchell, L. E., Scheurer, M. E. & Lupo, P. J. Maternal residential proximity to major roadways at delivery and childhood central nervous system tumors. *Environ. Res.* 146, 315–322 (2016).

25. Green, R. S., Malig, B., Windham, G.C., Fenster, L., Ostro, B., & Swan.S. Residential exposure to traffic and spontaneous abortion. *Environ. Health Perspect.* 117, 1939–1944 (2009).

26. Rich, D. Q., Demissie, K., Lu, S.E., Kamat, L., Wartenberg, D., & Rhoads, G.G. Ambient air pollutant concentrations during pregnancy and the risk of fetal growth restriction. *J. Epidemiol. Community Health* 63, 488–496 (2009).

27. Chen, H. Kwong, J.C., Copes, R., Tu, K., Villeneuve, P.J., Van Donkelaar, A., Hystad, P., Martin, R.V., Murray, B.J., Jessiman, B., & Wilton, A.S. Living near major roads and the incidence of dementia, Parkinson's disease, and multiple sclerosis: a population-based cohort study. *The Lancet* 389, 718–726 (2017).

28. Davidson, K., Fann, N., Zawacki, M., Fulcher, C. & Baker, K. R. The recent and future health burden of the US mobile sector apportioned by source. *Environ. Res. Lett.* 15, 075009 (2020).

29. Heo, J., Adams, P. J. & Gao, H. O. Public health costs of primary PM2. 5 and inorganic PM2. 5 precursor emissions in the United States. *Environ. Sci. Technol.* 50, 6061–6070 (2016).

30. Tschofen, P., Azevedo, I. L. & Muller, N. Z. Fine particulate matter damages and value added in the US economy. *Proc. Natl. Acad. Sci.* 116, 19857–19862 (2019).

31. Burstyn, I., Kromhout, H. & Boffetta, P. Literature review of levels and determinants of exposure to potential carcinogens and other agents in the road construction industry. *AIHAJ-Am. Ind. Hyg. Assoc.* 61, 715–726 (2000).

32. Burstyn, I., Boffetta, P., Heederik, D., Partanen, T., Kromhout, H., Svane, O., Langard, S., Frentzel-Beymen, R., & Kauppinen, T., Stucker, I., & Shaham, J. Mortality from obstructive lung diseases and exposure to polycyclic aromatic hydrocarbons among asphalt workers. *Am. J. Epidemiol.* 158, 468–478 (2003).

33. Xu, Y., Karedal, M., Nielsen, J., Adlercreutz, M., Bergendorf, U., Strandberg, B., Antonsson, A.B., Tinnerberg, H., & Albin, M. Exposure, respiratory symptoms, lung function and inflammation response of road-paving asphalt workers. *Occup. Environ. Med.* 75, 494–500 (2018).

34. Giunta, M. Assessment of the environmental impact of road construction: Modelling and prediction of fine particulate matter emissions. *Build. Environ.* 176, 106865 (2020).

35. Lin, S., Hung, W. & Leng, Z. Air pollutant emissions and acoustic performance of hot mix asphalts. *Constr. Build. Mater.* 129, 1–10 (2016).

36. Sánchez-Soberón, F., Rovira, J., Mari, M., Sierra, J., Nadal, M., Domingo, J.L., & Schuhmacher, M. Main components and human health risks assessment of PM10, PM2. 5, and PM1 in two areas influenced by cement plants. *Atmos. Environ.* 120, 109–116 (2015).

37. Peng, X., Shi, G.L., Zheng, J., Liu, J.Y., Shi, X.R., Xu, J., & Feng, Y.C. Influence of quarry mining dust on PM2. 5 in a city adjacent to a limestone quarry: Seasonal characteristics and source contributions. *Sci. Total Environ.* 550, 940–949 (2016).

38. Sairanen, M. & Rinne, M. Dust emission from crushing of hard rock aggregates. *Atmospheric Pollut. Res.* 10, 656–664 (2019).

39. Lei, Y., Zhang, Q., Nielsen, C. & He, K. An inventory of primary air pollutants and CO2 emissions from cement production in China, 1990–2020. *Atmos. Environ.* 45, 147–154 (2011).

40. Horvath, A. & Hendrickson, C. Comparison of environmental implications of asphalt and steel-reinforced concrete pavements. *Transp. Res. Rec.* 1626, 105–113 (1998).

41. Häkkinen, T. & Mäkelä, K. *Environmental adaption of concrete: Environmental impact of concrete and asphalt pavements*. (VTT Technical Research Centre of Finland, 1996).

42. Hassan, M. Evaluation of the environmental and economic impacts of warm-mix asphalt using life-cycle assessment. *Int. J. Constr. Educ. Res.* 6, 238–250 (2010).

43. Park, K., Hwang, Y., Seo, S. & Seo, H. Quantitative assessment of environmental impacts on life cycle of highways. *J. Constr. Eng. Manag.* 129, 25–31 (2003).

44. Weiland, C. & Muench, S. T. Life-cycle assessment of reconstruction options for interstate highway pavement in Seattle, Washington. *Transp. Res. Rec.* 2170, 18–27 (2010).

45. Zhang, H., Keoleian, G. A., Lepech, M. D. & Kendall, A. Life-cycle optimization of pavement overlay systems. *J. Infrastruct. Syst.* 16, 310–322 (2010).

46. Yu, B. & Lu, Q. Life cycle assessment of pavement: Methodology and case study. *Transp. Res. Part Transp. Environ.* 17, 380–388 (2012).

47. Harvey, J. Meijer, J., Ozer, H., Al-Qadi, I.L., Saboori, A., & Kendall, A. *Pavement life cycle assessment framework*. https://www.fhwa.dot.gov/pavement/sustainability/hif16014.pdf (2016).

48. Santero, N. J., Masanet, E. & Horvath, A. Life-cycle assessment of pavements. Part I: Critical review. *Resour. Conserv. Recycl.* 55, 801–809 (2011).

49. Santero, N. J., Harvey, J. & Horvath, A. Environmental policy for long-life pavements. *Transp. Res. Part Transp. Environ.* 16, 129–136 (2011).

50. Jiang, R. & Wu, P. Estimation of environmental impacts of roads through life cycle assessment: a critical review and future directions. *Transp. Res. Part Transp. Environ.* 77, 148–163 (2019).

51. Yeon, J., Rew, Y., Choi, K. & Kang, J. Environmental effects of accelerated pavement repair using 3D printing: life cycle assessment approach. *J. Manag. Eng.* 36, 04020003 (2020).

52. U.S. Environmental Protection Agency. Summary of Executive Order 12898 - Federal Actions to Address Environmental Justice in Minority Populations and Low-Income Populations. https://www.epa.gov/laws-regulations/summary-executive-order-12898-federal-actions-address-environmental-justice (2022).

53. Senate Bill 535 (de León). California Global Warming Solutions Act of 2006: Greenhouse Gas Reduction Fund. *Calif. State Senate* (2012).

54. Garcia, C. *AB-617: Nonvehicular air pollution: Criteria air pollutants and toxic contaminants*. *California Legislative Information, Sacramento, CA*. (2017).

55. Washington State Legislature. SB 5141 - 2021-22: Implementing the recommendations of the environmental justice task force. https://app.leg.wa.gov/billsummary?BillNumber=5141&Year=2021&Initiative=False (2022).

56. Thaneya, A. B., Apte, J. S. & Horvath, A. A human exposure-based traffic assignment model for minimizing fine particulate matter (PM2. 5) intake from on-road vehicle emissions. *Environ. Res. Lett.* 17, 074034 (2022).

57. Chambliss, S. E. Pinon, C.P., Messier, K.P., LaFranchi, B., Upperman, C.R., Lunden, M.M., Robinson, A.L., Marshall, J.D., & Apte, J.S. Local-and regional-scale racial and ethnic disparities in air pollution determined by long-term mobile monitoring. *Proc. Natl. Acad. Sci.* 118, (2021).

58. U.S. Census Bureau. County Population Totals: 2020-2021. https://www.census.gov/data/tables/time-series/demo/popest/2020s-counties-total.html. (2022)

59. U.S. Census Bureau. QuickFacts: San Francisco County, California. https://www.census.gov/quickfacts/geo/chart/sanfranciscocountycalifornia/RHI825220. (2022)

60. Dedoussi, I. C. & Barrett, S. R. Air pollution and early deaths in the United States. Part II: Attribution of PM2.5 exposure to emissions species, time, location and sector. *Atmos. Environ.* 99, 610–617 (2014).

61. Golub, A., Marcantonio, R. A. & Sanchez, T. W. Race, Space, and Struggles for Mobility: Transportation Impacts on African Americans in Oakland and the East Bay. *Urban Geogr.* 34, 699–728 (2013).

62. California Office of Environmental Health Hazard Assessment. CalEnviroScreen. https://oehha.ca.gov/calenviroscreen (2022).

63. Witteborg, J. About CalEnviroScreen. https://oehha.ca.gov/calenviroscreen/about-calenviroscreen (2019).

64. Sathaye, N., Horvath, A. & Madanat, S. Unintended impacts of increased truck loads on pavement supply-chain emissions. *Transp. Res. Part Policy Pract.* 44, 1–15 (2010).

65. California Department of Transportation. Traffic Census Program https://dot.ca.gov/programs/traffic-operations/census. (2023)

66. California Department of Transportation. Highway Design Manual. https://dot.ca.gov/programs/design/manual-highway-design-manual-hdm (2022).

67. California Department of Transportation. Climate https://dot.ca.gov/programs/maintenance/pavement/concrete-pavement-and-pavement-foundations/climate. (2023)

68. Gordian. Means heavy construction costs with RSMeans data. (2016).

69. California Air Resources Board. EMFAC. https://arb.ca.gov/emfac/emissions-inventory/0736f434eef49afe1042ae7089aed89058368c06 (2022).

70. California Air Resources BoardCARB. MSEI - Modeling Tools | California Air Resources Board. https://ww2.arb.ca.gov/our-work/programs/mobile-source-emissions-inventory/msei-modeling-tools (2022).

71. Bay Area Air Quality Management District. Bay Area Air Quality Management District website. https://www.baaqmd.gov/ (2022).

72. California Air Resources Board. Air Resources Board: Facility Search Form. https://www.arb.ca.gov/app/emsinv/facinfo/facinfo.php?dd= (2022).

73. California Air Resources Board. California Greenhouse Gas Emission Inventory Program https://ww2.arb.ca.gov/our-work/programs/ghg-inventory-program (2021).

74. California Energy Commission. California's Oil Refineries. https://www.energy.ca.gov/data-reports/energy-almanac/californias-petroleum-market/californias-oil-refineries (2022).

75. Lobscheid, A. B., Nazaroff, W. W., Spears, M., Horvath, A. & McKone, T. E. Intake fractions of primary conserved air pollutants emitted from on-road vehicles in the United States. *Atmos. Environ.* 63, 298–305 (2012).

76. Goodkind, A. L., Tessum, C. W., Coggins, J. S., Hill, J. D. & Marshall, J. D. Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions. *Proc. Natl. Acad. Sci.* 116, 8775–8780 (2019).

77. Tessum, C. W., Hill, J. D. & Marshall, J. D. InMAP: A model for air pollution interventions. *PloS One* 12, e0176131 (2017).

78. Paolella, D. A., Tessum, C.W., Adams, P.J., Apte, J.S., Chambliss, S., Hill, J., Muller, N.Z., & Marshall, J.D. Effect of model spatial resolution on estimates of fine particulate matter exposure and exposure disparities in the United States. *Environ. Sci. Technol. Lett.* 5, 436–441 (2018).

79. Robinson, A. L., Grieshop, A. P., Donahue, N. M. & Hunt, S. W. Updating the conceptual model for fine particle mass emissions from combustion systems Allen L. Robinson. *J. Air Waste Manag. Assoc.* 60, 1204–1222 (2010).

80. Marty, M. A. Blaisdell, R.J., Broadwin, R., Hill, M., Shimer, D., & Jenkins, M. Distribution of daily breathing rates for use in California's air toxics hot spots program risk assessments. *Hum. Ecol. Risk Assess.* 8, 1723–1737 (2002).

81. United States Census Bureau. 2019 American Community Survey 5-Year Estimates. https://www.census.gov/programs-surveys/acs/ (2022).

82. United States Environmental Protection Agency, O. Mortality Risk Valuation. https://www.epa.gov/environmental-economics/mortality-risk-valuation (2014).

83. Amato, F. Cassee, F.R., van der Gon, H.A.D., Gehrig, R., Gustafsson, M., Hafner, W., Harrison, R.M., Jozwicka, M., Kelly, F.J., Moreno, T., & Prevot, A.S. Urban air quality: the challenge of traffic non-exhaust emissions. *J. Hazard. Mater.* 275, 31–36 (2014).

84. Gursel, A. P. *Life-cycle assessment of concrete: decision-support tool and case study application*. (University of California, Berkeley, 2014).

85. Lea, J., Harvey, J., Saboori, A. & Butt, A. A. eLCAP: A Web Application for Environmental Life Cycle Assessment for Pavements. (2022).

86. Yu, K. A., McDonald, B. C. & Harley, R. A. Evaluation of Nitrogen Oxide Emission Inventories and Trends for On-Road Gasoline and Diesel Vehicles. *Environ. Sci. Technol.* 55, 6655–6664 (2021).

87. Fujita, E. M. Campbell, D.E., Zielinska, B., Chow, J.C., Lindhjem, C.E., DenBleyker, A., Bishop, G.A., Schuchmann, B.G., Stedman, D.H., & Lawson, D.R. Comparison of the MOVES2010a, MOBILE6. 2, and EMFAC2007 mobile source emission models with on-road traffic tunnel and remote sensing measurements. *J. Air Waste Manag. Assoc.* 62, 1134–1149 (2012).

88. Thakrar, S. Tessum, C.W., Apte, J.S., Balasubramanian, S., Millet, D.B., Pandis, S.N., Marshall, J.D., & Hill, J.D. Global, High-Resolution, Reduced-Complexity Air Quality Modeling for PM2. 5 Using InMAP (Intervention Model for Air Pollution). (2022).

89. Coffman, E., Burnett, R. T. & Sacks, J. D. Quantitative Characterization of Uncertainty in the Concentration–Response Relationship between Long-Term PM2.5 Exposure and Mortality at Low Concentrations. *Environ. Sci. Technol.* 54, 10191–10200 (2020).

90. Bennett, D. H. *et al.* Defining intake fraction. *Environ. Sci. Technol.* 36, (2002).

91. Humbert, S. Manneh, R., Shaked, S., Wannaz, C., Horvath, A., Deschenes, L., Jolliet, O., & Margni, M. Assessing regional intake fractions in North America. *Sci. Total Environ.* 407, 4812–4820 (2009).

92. Thakrar, S. K. *et al.* Reducing mortality from air pollution in the United States by targeting specific emission sources. *Environ. Sci. Technol. Lett.* 7, 639–645 (2020).

93. Lidicker, J., Sathaye, N., Madanat, S. & Horvath, A. Pavement resurfacing policy for minimization of life-cycle costs and greenhouse gas emissions. *J. Infrastruct. Syst.* 19, 129–137 (2013).

94. Taptich, M. N., Horvath, A. & Chester, M. V. Worldwide greenhouse gas reduction potentials in transportation by 2050. *J. Ind. Ecol.* 20, 329–340 (2016).

95. Nahlik, M. J., Kaehr, A. T., Chester, M. V., Horvath, A. & Taptich, M. N. Goods movement life cycle assessment for greenhouse gas reduction goals. *J. Ind. Ecol.* 20, 317–328 (2016).

96. Patterson, R. F. & Harley, R. A. Effects of freeway rerouting and boulevard replacement on air pollution exposure and neighborhood attributes. *Int. J. Environ. Res. Public. Health* 16, 4072 (2019).

97. Brinkman, L. & Miller, S. A. Environmental impacts and environmental justice implications of supplementary cementitious materials for use in concrete. *Environ. Res. Infrastruct. Sustain.* 1, 025003 (2021).

98. Wier, M., Sciammas, C., Seto, E., Bhatia, R. & Rivard, T. Health, traffic, and environmental justice: Collaborative research and community action in San Francisco, California. *Am. J. Public Health* 99, S499–S504 (2009).

99. Castillo, M. D. Anenberg, S.C., Chafe, Z.A., Huxley, R., Johnson, L.S., Kheirbek, I., Malik, M., Marshall, J.D., Naidoo, S., Nelson, M.L., & Pendleton, N.V. Quantifying the health benefits of urban climate mitigation actions: Current state of the epidemiological evidence and application in health impact assessments. *Front. Sustain. Cities* 123 (2021).

100. Sharma, A. & Strezov, V. Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies. *Energy* 133, 1132–1141 (2017).

101. United States Environmental Protection Agency. Inventory of U.S. Greenhouse Gas Emissions and Sinks. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (2022).

102. United States Environmental Protection Agency. Fast Facts on Transportation Greenhouse Gas Emissions. https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions (2022).

103. California Energy Commission. Transforming Transportation. https://www.energy.ca.gov/about/core-responsibility-fact-sheets/transforming-transportation (2022).

104. Pörtner, H. O., Roberts, D.C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R.A., Betts, R., Kerr, R.B., Biesbroek, R., & Birkmann, J. Climate change 2022: impacts, adaptation and vulnerability. (2022).

105. Williams, A. P. Abatzoglou, J.T., Gershunov, A., Guzman-Morales, J., Bishop, D.A., Balch, J.K., & Lettenmaiser, D.P. Observed impacts of anthropogenic climate change on wildfire in California. *Earths Future* 7, 892–910 (2019).

106. Williams, A. P. Cook, E.R., Smerdon, J.E., Cook, B.I., Abatzoglou, J.T., Bolles, K., Baek, S.H., Badger, A.M., & Livneh, B. Large contribution from anthropogenic warming to an emerging North American megadrought. *Science* 368, 314–318 (2020).

107. Goss, M. Swain, D.L., Abatzoglou, J.T., Sarhadi, A., Kolden, C.A., Williams, A.P., & Diffenbaugh, N.S. Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environ. Res. Lett.* 15, 094016 (2020).

108. Loijos, A., Santero, N. & Ochsendorf, J. Life cycle climate impacts of the US concrete pavement network. *Resour. Conserv. Recycl.* 72, 76–83 (2013).

109. Batouli, M., Bienvenu, M. & Mostafavi, A. Putting sustainability theory into roadway design practice: Implementation of LCA and LCCA analysis for pavement type selection in real world decision making. *Transp. Res. Part Transp. Environ.* 52, 289–302 (2017).

110. Chester, M. V. & Horvath, A. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environ. Res. Lett.* 4, 024008 (2009).

111. Li, X., Zhu, Y. & Zhang, Z. An LCA-based environmental impact assessment model for construction processes. *Build. Environ.* 45, 766–775 (2010).

112. California Department of Transportation. Life Cycle Cost Analysis. https://dot.ca.gov/programs/maintenance/pavement/concrete-pavement-and-pavement-foundations/life-cycle-cost-analysis (2022).

113. Federal Highway Administration. Life-Cycle Cost Analysis - Life Cycle Cost Analysis - Design & Analysis – Pavements.. https://www.fhwa.dot.gov/infrastructure/asstmgmt/lcca.cfm (2020).

114. Nordhaus, W. D. Revisiting the social cost of carbon. *Proc. Natl. Acad. Sci.* 114, 1518–1523 (2017).

115. Interagency Working Group. *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide Interim Estimates under Executive Order 13990*. https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf (2021).

116. Isacs, L., Finnveden, G., Dahllof, L., Hakansson, C., Petersson, L., Steen, B., Swanstrom, L., & Wikstrom, A. Choosing a monetary value of greenhouse gases in assessment tools: A comprehensive review. *J. Clean. Prod.* 127, 37–48 (2016).

117. Offenbacker, D. Saidi, A., Ali, A., Mehta, Y., Decarlo, C.J., & Lein, W. Economic and environmental cost analysis of cold in-place recycling. *J. Mater. Civ. Eng.* 33, 04020496 (2021).

118. Torres-Machí, C., Chamorro, A., Pellicer, E., Yepes, V. & Videla, C. Sustainable pavement management: Integrating economic, technical, and environmental aspects in decision making. *Transp. Res. Rec.* 2523, 56–63 (2015).

119. Pellecuer, L., Assaf, G. J. & St-Jacques, M. Influence of pavement condition on environmental costs. *J. Transp. Eng.* 140, 04014050 (2014).

120. Building Transparency. EC3 - Product EPDs. https://buildingtransparency.org/ec3/epds (2022).

121. Anthoff, D. & Tol, R. S. The uncertainty about the social cost of carbon: A decomposition analysis using fund. *Clim. Change* 117, 515–530 (2013).

122. Anthoff, D., Tol, R. S. & Yohe, G. W. Risk aversion, time preference, and the social cost of carbon. *Environ. Res. Lett.* 4, 024002 (2009).

123. Guo, J., Hepburn, C. J., Tol, R. S. & Anthoff, D. Discounting and the social cost of carbon: a closer look at uncertainty. *Environ. Sci. Policy* 9, 205–216 (2006).

124. Pizer, W. Adler, M., Aldy, J., Anthoff, D., Cropper, M., Gillingham, K., Greenstone, M., Murray, B., Newell, R., Richels, R., & Rowell, A. Using and improving the social cost of carbon. *Science* 346, 1189–1190 (2014).

125. Ricke, K., Drouet, L., Caldeira, K. & Tavoni, M. Country-level social cost of carbon. *Nat. Clim. Change* 8, 895–900 (2018).

126. Rennert, K. Errickson, R., Prest, B.C., Rennels, L., Newell, R.G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., & Smith, D. Comprehensive evidence implies a higher social cost of CO2. *Nature* 610, 687–692 (2022).

127. Hammer, M. S., Swinburn, T. K. & Neitzel, R. L. Environmental noise pollution in the United States: developing an effective public health response. *Environ. Health Perspect.* 122, 115–119 (2014).

128. National Academies of Engineering of the National Academies. *Technology for a Quieter America*. (National Academies Press, 2010).

129. Goines, L. & Hagler, L. Noise pollution: a modem plague. *South Med J* 100, 287–94 (2007).

130. California Department of Transportation. Typical Noise Levelshttps://dot.ca.gov/programs/maintenance/pavement/noise-levels (2022).

131. Miedema, H. M. & Vos, H. Exposure-response relationships for transportation noise. *J. Acoust. Soc. Am.* 104, 3432–3445 (1998).

132. Swinburn, T. K., Hammer, M. S. & Neitzel, R. L. Valuing quiet: an economic assessment of US environmental noise as a cardiovascular health hazard. *Am. J. Prev. Med.* 49, 345–353 (2015).

133. Hong, T., Ji, C., Park, J., Leigh, S.-B. & Seo, D. Prediction of environmental costs of construction noise and vibration at the preconstruction phase. *J. Manag. Eng.* 31, 04014079 (2015).

134. Jung, S. Kang, H., Choi, J., Hong, T., Park, H.S., & Lee, D.E. Quantitative health impact assessment of construction noise exposure on the nearby region for noise barrier optimization. *Build. Environ.* 176, 106869 (2020).

135. Swärdh, J.-E. & Genell, A. Marginal costs of road noise: Estimation, differentiation and policy implications. *Transp. Policy* 88, 24–32 (2020).

136. Kaddoura, I., Kröger, L. & Nagel, K. An activity-based and dynamic approach to calculate road traffic noise damages. *Transp. Res. Part Transp. Environ.* 54, 335–347 (2017).

137. Cucurachi, S., Heijungs, R. & Ohlau, K. Towards a general framework for including noise impacts in LCA. *Int. J. Life Cycle Assess.* 17, 471–487 (2012).

138. Virani, S. S. *et al.* Heart disease and stroke statistics—2021 update: a report from the American Heart Association. *Circulation* 143, e254–e743 (2021).

139. Bureau of Transportation Statistics. National Transportation Noise Map. https://www.bts.gov/geospatial/national-transportation-noise-map (2022).

140. Piemonte, A. & Masera, S. opeNoise — QGIS Python Plugins Repository. https://plugins.qgis.org/plugins/opeNoise/ (2022).

141. Bureau of Transportation Statistics. BTS Port Performance Freight Statistics Program. https://data.bts.gov/stories/s/Home-BTS-Port-Performance-Freight-Statistics-Progr/mign-rc8p/ (2022).

142. Bureau of Transportation Statistics. U.S. Ports Work Through Daunting Challenges to Deliver the Goods . https://www.bts.gov/data-spotlight/us-ports-work-through-daunting-challenges-deliver-goods (2022).

143. Richardson, B. Air pollution from Port of Long Beach increased amid pandemic congestion, report shows. *Long Beach Business Journal*. https://lbbusinessjournal.com/news/air-pollution-from-port-of-long-beach-increased-amid-pandemic-congestion-report-shows (2022).

144. Port of Oakland. Facts & Figures. https://www.oaklandseaport.com/performance/facts-figures/ (2022).

145. Bay Area Air Quality Management District. AB 617: Community Health Protection Program. https://www.baaqmd.gov/community-health/community-health-protection-program (2022).

146. Praetzellis, A., Praetzellis, M., Gutman, M., Mullins, P. R. & Wlaker, M. Putting the "There in There." *Historical Archaeologies of West Oakland*. (2004).

147. California Air Resources Board. West Oakland https://ww2.arb.ca.gov/our-work/programs/community-air-protection-program/communities/west-oakland (2022).

148. Fujita, E. M., Campbell, D. E., Patrick Arnott, W., Lau, V. & Martien, P. T. Spatial variations of particulate matter and air toxics in communities adjacent to the Port of Oakland. *J. Air Waste Manag. Assoc.* 63, 1399–1411 (2013).

149. Dallmann, T. R., Harley, R. A. & Kirchstetter, T. W. Effects of diesel particle filter retrofits and accelerated fleet turnover on drayage truck emissions at the Port of Oakland. *Environ. Sci. Technol.* 45, 10773–10779 (2011).

150. Kuwayama, T., Schwartz, J. R., Harley, R. A. & Kleeman, M. J. Particulate matter emissions reductions due to adoption of clean diesel technology at a major shipping port. *Aerosol Sci. Technol.* 47, 29–36 (2013).

151. Preble, C. V. Dallmann, T.R., Kreisberg, N.M., Hering, S.V., Harley, R.A., & Kirchstetter, T.W. Effects of particle filters and selective catalytic reduction on heavy-duty diesel drayage truck emissions at the Port of Oakland. *Environ. Sci. Technol.* 49, 8864–8871 (2015).

152. Joe, D. K. Zhang, H., DeNero, S.P., Lee, H.H., Chen, S.H., McDonald, B.C., Harley, R.A., & Kleeman, M.J. Implementation of a high-resolution Source-Oriented WRF/Chem model at the Port of Oakland. *Atmos. Environ.* 82, 351–363 (2014).

153. Sathaye, N., Harley, R. & Madanat, S. Unintended Environmental Impacts of Nighttime Metropolitan Freight Logistics Policies. (2010)

154. West Oakland Environmental Indicators Project. Owning Our Air. https://woeip.org/featured-work/owning-our-air/ (2022).

155. Tao, L., Fairley, D., Kleeman, M. J. & Harley, R. A. Effects of switching to lower sulfur marine fuel oil on air quality in the San Francisco Bay area. *Environ. Sci. Technol.* 47, 10171–10178 (2013).

156. Southerland, V. A. Anenberg, S.C., Harris, M., Apte, J., Hystad, P., van Donkelaar, A., Martin, R.V., Beyers, M., & Roy, A. Assessing the distribution of air pollution health risks within cities: a neighborhood-scale analysis leveraging high-resolution data sets in the Bay Area, California. *Environ. Health Perspect.* 129, 037006 (2021).

157. Port of Oakland. Seaport Air Emissions Inventory. https://www.portofoakland.com/community/environmental-stewardship/seaport-air-emissions-inventory-2005/ (2021).

158. National Oceanic and Atmospheric Administration. Shoreline Mapping Program of Port of Oakland, CA. CA1503B-CS-N | InPort. https://www.fisheries.noaa.gov/inport/item/61368 (2022).

159. California Department of Parks and Recreation. Spatial Database. https://www.parks.ca.gov/ (2022).

160. United States Army Corps of Engineers Geospatial. https://geospatial-usace.opendata.arcgis.com/ (2022).

161. Port of Oakland. About the Port of Oakland. https://www.portofoakland.com/interactive-map/fact-sheet/ (2022).

162. Smith, D. R. Interlocking Concrete Pavement for the Port of Oakland, California, Berths 55-59. (2003).

163. California Air Resources Board. Ocean-Going Vessels at Berth Regulation. https://ww2.arb.ca.gov/our-work/programs/ocean-going-vessels-berth-regulation/about (2022).

164. Port of Oakland. Clean Trucks. https://www.portofoakland.com/port/seaport/comprehensive-truck-management-program/clean-trucks/ (2022).

165. California Department of General Services (DGS). Buy Clean California Act. https://www.dgs.ca.gov/PD/Resources/Page-Content/Procurement-Division-Resources-List-Folder/Buy-Clean-California-Act (2022).

166. California Department of Transportation. Special Route Restriction History – Route 580. https://dot.ca.gov/programs/traffic-operations/legal-truck-access/restrict-route-580 (2022).

167. Greer, F., Bin Thaneya, A., Apte, J. and Horvath, A. (2022), “Pavement Resurfacing and Supply Chains Are Significant Contributors to PM2.5 Exposure from Road Transportation: Evidence from the San Francisco Bay Area.” Environmental Research Letters, 17(12), 124014, https://doi.org/10.1088/1748-9326/aca2bc