Near-Roadway Indoor Air Pollution:
Assessing Health Effects and Mitigation Strategies

An Evidence Review for the California State Legislature

CalSPEC – January 2024

About CalSPEC

The California State Policy Evidence Consortium (CalSPEC) is a University of California (UC) initiative administered through the UC Center Sacramento (UCCS). In alignment with the UC mission, CalSPEC leverages UC expertise in research and commitment to public service to support evidence-based policymaking at the state level. Specifically, CalSPEC seeks to build an evidence pipeline to the State Legislature that enhances policy decision-making through rapid evidence and policy reviews on complex topics of concern or interest to the State Legislature. CalSPEC engages a team of expert UC faculty and staff who collaborate with legislative committee staff to determine the key analytic questions and ultimately produce balanced, nonpartisan, evidence-based reports within a California legislative cycle.

More detailed information about CalSPEC is available at https://uccs.ucdavis.edu/calspec.

Acknowledgement of Subject Matter Expert Review

The authors and editors of this report gratefully acknowledge the assistance of the following subject matter experts: Deborah Bennett, PhD UC Davis Department of Public Health Sciences; Christopher Cappa, PhD, UC Davis Department of Civil and Environmental Engineering; Bart Croes, California Energy Commission, Cooperative Institute for Research in Environmental Sciences, (CIRES) at the University of Colorado-Boulder; and Amanda Goodrich, PhD, MS, UC Davis Department of Public Health Sciences. Note that the analysis and opinions rendered herein are the sole responsibility of the authors and not their respective employers or affiliates.

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Suggested citation: California State Policy Evidence Consortium (CalSPEC). Near-Roadway Indoor Air Pollution: Assessing Health Effects and Mitigation Strategies. January 2024. Sacramento, CA.

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EXECUTIVE SUMMARY

This report responds to an inquiry from the California Senate Committee on Environmental Quality and Assembly Committee on Natural Resources for information about the impact of near-roadway air pollution (NRAP) on indoor air quality, its likely adverse health effects, and strategies for reducing NRAP effects among people who live, work, or go to school near California's major roadways. This report seeks to inform discussions at the California state level but may also help other jurisdictions in and outside of California.

This research was done by the California State Policy Evidence Consortium (CalSPEC), an independent program housed within the University of California Center Sacramento (UCCS) that collaborates with faculty, staff, and graduate student researchers across UC campuses to evaluate evidence to inform public policy deliberations.

This report addresses three overarching questions:

1. How do traffic-related air pollutants get indoors, and what is the relative contribution of roadway pollutants to indoor air quality?
2. What are the human health effects of the exposure to near-roadway air pollution, and are there populations that are disproportionately affected?
3. Are there specific prevention and mitigation strategies that are effective in reducing near-roadway indoor air pollution?

Summary Findings: NRAP Composition and Contribution to Indoor Air Quality

- Vehicles produce traffic-related air pollution from tailpipes; brake, tire, and road wear; and resuspended roadway dust.
- NRAP is defined by the Environmental Protection Agency (EPA) as occurring "within a few hundred meters — about 500-600 feet downwind from the vicinity of heavily traveled roadways or along corridors with significant trucking traffic or rail activities." California code defines heavily trafficked roadways as 100,000 vehicles/day (urban) and 50,000 vehicles/day (rural).
- NRAP concentration and indoor migration vary greatly geographically, seasonally, hourly, and according to local atmospheric and meteorologic conditions as well as by the natural and built environment and type of pollutant.
- There are greater concentrations of the following unregulated pollutants near high-traffic roadways: ultrafine particles (UFP) sized < 0.1 microns; particles sized between 1–10 microns (PM_1-PM_{10}) containing heavy metals, polyaromatic hydrocarbons, and black carbon (BC); nitrogen oxides (NO & NO_2); carbon monoxide (CO); and some volatile organic compounds (VOCs), including air toxics such as benzene and 1,3-butadiene.
- Outdoor-originated air pollutants penetrate indoors through active air exchange (e.g., ventilation systems) and passive air exchange (e.g., building cracks, doors, and windows). Therefore, building location, design, and operation are important determinants of near-roadway indoor pollutant concentrations.

- Particle size matters, as intermediate particles (fine or $PM_{2.5}$) penetrate indoors more efficiently than smaller (ultrafine) and larger (PM_{10}) particles.
- On average, the contribution of outdoor air pollution sources to indoor pollution concentrations is significant even when indoor sources are present. Depending on the situation, outdoor air pollution is responsible for 30%–90% of the indoor pollutant concentrations and near-roadway environments contribute to greater cumulative indoor pollutant concentrations than environments farther away from major roadways.

Summary Findings: Health Effects

CalSPEC performed a rapid overview of systematic reviews to evaluate the evidence concerning known health effects of near-roadway air pollutant exposure. Due to extremely limited evidence on the health effects of near-roadway *indoor* air pollution and consistent evidence showing that outdoor air pollution levels help drive indoor exposures, CalSPEC evaluated exposure to near-roadway air pollutants overall, rather than only exposure through indoor air. Based on two systematic reviews meeting inclusion criteria, CalSPEC found there is:

- *Established evidence* that NRAP increases the risk of:
  - Asthma in children
  - Diabetes
  - All-cause mortality
  - Lung cancer mortality
  - Heart disease mortality
- *Likely evidence* that NRAP increases the risk of:
  - Hypertensive disorders of pregnancy
  - Heart disease and incidence of coronary events
  - Term low birth weight
  - Circulatory mortality
  - Respiratory mortality
  - Stroke mortality
- *Suggestive evidence* that NRAP increases the risk of:
  - Stroke
  - Decreased term birth weight
  - Preterm birth
  - Chronic obstructive pulmonary disease (COPD) mortality

Additionally, California census tracts with higher proportions of Latino, Black, and Asian Americans and Pacific Islanders (AAPI) are more likely to have high traffic pollution, while census tracts with a higher proportion of Whites are less likely to have high traffic pollution. Similarly, census tracts with high levels of linguistic isolation and uninsured residents are most likely to have higher traffic pollution in California. Thus, NRAP is an environmental justice concern due to inequitable distribution of exposures.

Summary Findings: Mitigation Strategies

Based on a review of six systematic reviews meeting inclusion criteria, CalSPEC found sufficient and suggestive evidence of multiple effective mitigation strategies that reduce NRAP exposures and related health effects in California settings.

SUMMARY OF MITIGATION STRATEGY EVIDENCE		
On-Road Source Control Strategies	**Near-Roadway (Ambient) Air Pollution Control Strategies**	**Indoor NRAP Control Strategies**
Sufficient Evidence of Effectiveness • Advancement in vehicle technologies (especially those that comply with tightened fuel and emission standards)	**Sufficient Evidence of Effectiveness** • Obstacles and sinks, especially roadside barriers (e.g., soundwalls) that block or inhibit pollution movement	**Sufficient Evidence of Effectiveness** • Indoor removal through filtration
Moderate Evidence of Effectiveness • Clean vehicle policies • Traffic management (road congestion pricing, vehicle operation restrictions, low emission zones, lower speed limits, intersection controls with roundabouts and signal timing, and eco-driving)	**Moderate Evidence of Effectiveness** • Green infrastructure (tree/hedge barriers, vegetation walls/roofs) • Non-vegetation obstacles (parked cars and artificial sink devices) • Optimized design of built environment including street canyons, building architecture, and land use planning	**Moderate Evidence of Effectiveness** • Retrofits • Phytoremediation

Note: **Sufficient evidence**: Research shows the strategy is effective overall based on diverse study methods in different settings. **Moderate evidence**: Research shows the strategy could be effective in certain settings, but CalSPEC is less confident in the overall effectiveness due to several study limitations (see **Appendix D** for methods details).

Conclusion and Policy Options

This report has three main conclusions:

- First, near-roadway air pollution composition and prevalence varies significantly within and between locales, which highlights the need for flexible mitigation strategies to ensure local "fit."
- Second, adverse health effects of NRAP are well-documented and the inequitable distribution of exposure among vulnerable socioeconomic and racial/ethnic groups raises environmental justice concerns. Although evidence to date indicates the increased risk may be relatively small per person or per measured location, the cumulative exposures occurring to millions of people over multiple years results in substantial public health impact.

- Third, evidence-based mitigation strategies exist that California has yet to fully implement and, for strategies supported by less rigorous evidence, opportunities remain for additional research. Known and potential unintended consequences of these strategies (such as increased electricity/operational costs or behavior-dependent effectiveness of interventions) are important considerations for policy discussions.

Policy Strategies to Explore

Based on moderate to high certainty of adverse health effects of NRAP, CalSPEC recommends taking immediate action to mitigate and/or prevent exposures from NRAP, particularly for vulnerable populations living and working near highly trafficked roadways. In particular, policy discussions about the following evidence-based strategies would continue to help develop California's transportation, housing, and environmental health policies:

- Consider increasing NRAP permanent outdoor and rotating indoor monitoring in densely populated areas for neighborhoods 100–500 feet (or more) from high-traffic roads to improve baseline data and measure effectiveness of mitigation strategies that may be implemented locally or statewide.
- Due to unequal distribution of exposures, which contribute to health disparities, prioritizing health equity as a criterion when evaluating mitigation strategies can help reduce disparities. For example, creating urban housing infill/refill policies to increase affordable housing units, and reduce traffic emissions and travel time may have unintended consequences if policies incentivize low-income/affordable housing infill near highly trafficked roads without a simultaneous effort to mitigate traffic-generated pollutants and/or improve new structure placement, building envelopes, and ventilation systems.
- Concurrent with adoption of infill policies, NRAP interventions to consider include incentivizing clean vehicles, and improving traffic management through intersection design and traffic restrictions in and around these communities. Additionally, appropriate built-environment design for infill housing would preserve enough ground-level open space for urban ventilation and reduced NRAP accumulation.
- For buildings in close proximity to highly trafficked roads, controlled indoor ventilation and improved filtration systems are effective methods to reducing contributions of outdoor pollutants to indoor air.
- Diesel trucks are the primary source of black carbon and NO_x, which drive adverse health outcomes; thus, exploring policies to restrict diesel truck traffic and/or incentivize electrification of truck fleets would likely improve indoor air quality among structures near high-trafficked roads, and may have a positive impact on reducing disparities among vulnerable populations.
- Consider cost-effective mitigation strategies with the most evidence of effectiveness such as portable air cleaners for indoor filtration, which do not require additional costly construction and can be deployed quickly among priority communities.
- Consider prioritizing various mitigation strategies as pilot projects across California based on local needs and constraints such as population density and vulnerability to NRAP health effects, built environment, local weather patterns, and traffic volume. Strategies should be well planned and rigorously evaluated over several years to account for seasonal and meteorological variations.

- Monitor federal activities for future funding opportunities for mitigation pilot projects, research evaluations, and strategy implementation and deployment. The National Academy of Sciences, Engineering and Medicine will release a consensus study report in early 2024 entitled Health Risks of Indoor Exposures to Fine Particulate Matter and Practical Mitigation Solutions, which may stimulate new federal funding opportunities.

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GLOSSARY

Air changes/hour: One air change/hour means that a volume of air equal to the interior volume of the building is replaced with outdoor air once each hour. Typically, mixing is not perfect, so some air will not be replaced in this process.

Apical outcomes: Observable outcomes in an organism (such as a clinical sign or pathological state) that indicate disease; outcomes observed at an organ level or higher.

Arcade design: Implemented as a half-open space by creating an outside corridor on the side of the main building.

Black carbon (BC): One component of fine particulate matter ($PM_{2.5}$) composed of the incomplete combustion of fossil and wood fuels. It lasts days to weeks in the atmosphere and has significant negative environmental and human health effects. Related to elemental carbon.

Category: Refers to type of mitigation strategy (source, ambient, or exposure) along the full process chain of events.

Clinical outcomes: Measurable change in symptoms, overall health, ability to function, quality of life, or survival outcomes.

Cordon pricing: A fee or tax paid by users to enter a restricted area, usually within a city center, as part of a demand management strategy to relieve traffic congestion within that area.

Data review or meta-analysis: Review articles that collect published quantitative results of a topic and/or conduct meta-analysis and synthesis. This type of review is typically quantitative but does not necessarily have a clear search strategy or keywords defined.

Elemental Carbon (EC): Dark-colored soot-like material in particles emitted by some types of combustion sources and tire wear. While any type of vehicle can emit particles containing elemental carbon, it is most commonly associated with diesels; thus**,** elemental carbon is commonly used as a marker for roadway or diesel pollution. Elemental carbon and black carbon are measures of the same material. Because this component of particulate matter strongly absorbs sunlight, it also contributes to global warming.

Lift-up design: Creates a semi-open space underneath the first floor of a high-rise residential buildings. Also called elevated design or void decks.

Literature review: A review and synthesis of available evidence relevant to a specific research question that does not include an evaluation of the quality of the evidence; may also be referred to as a narrative review.

Meta-analysis: When the results of individual studies are combined to produce an overall statistic. This provides a more precise estimate of the health effects of an exposure and reduces uncertainty. Meta-analyses may not be appropriate if the designs of the studies are too different, if the outcomes measured are not sufficiently similar, or if there are concerns about the quality of the studies.

Mitigation strategy: Broad term within source, ambient, or exposure categories that covers reducing NRAP (e.g., vehicle technology-related policies, travel and traffic management).

Near-roadway air pollution (NRAP): Air pollution "within a few hundred meters — about 500-600 feet downwind from the vicinity of heavily traveled roadways or along corridors with significant trucking traffic or rail activities. This distance will vary by location and time of day or year, prevailing meteorology, topography, near land use, traffic patterns, as well as the individual pollutant" (EPA, 2014).

Non-systematic review: Review articles that do not report a detailed, comprehensive plan and search strategy derived a priori and do not meet the systematic review criteria. The quality of these review articles varies. For example, some are mostly narrative, and some contain quality evaluation and summary or synthesis of the evidence. These articles need further screening before they can be included.

Overview of reviews: Also referred to as "overviews," "umbrella reviews," "reviews of reviews," and "meta-reviews," follow the steps of a full systematic review; however, instead of an evaluation of primary studies, overviews evaluate systematic reviews.

Particulate matter (PM): Particulate matter refers to tiny liquid or solid particles suspended in air. While particulate matter is a general term, this report refers to health-relevant particles, which are particles smaller than 10 microns in diameter; this is the range that is small enough to be respirable.

PM_{10}: Al particles smaller than 10 microns in diameter.

$PM_{2.5}$: All particles smaller than 2.5 microns in diameter.

Protocol: Document that is made publicly available to outline the steps of a systematic review (including rapid reviews) before the review is completed.

Rapid systematic review (rapid review): A truncated form of a systematic review that is used when there is a time-sensitive question to address, and quality systematic reviews are not available.

Risk of bias: A critical assessment of whether the design or conduct of a study could systematically change the reported association between exposure and outcome. Sometimes referred to as internal study validity.

Subcategory of mitigation strategy: Further categorization of mitigation strategy (e.g., clean vehicle policies, operating restrictions, and pricing).

Systematic review: Identifies, appraises, and synthesizes all the empirical evidence that meets pre-specified eligibility criteria to answer a specific research question. Researchers conducting systematic reviews use explicit, systematic methods that are selected with a view aimed at minimizing bias, to produce more reliable findings to inform decision making.

Traffic-related air pollution: "Ambient air pollution resulting from the use of motorized vehicles such as heavy-duty and light-duty vehicles, buses, coaches, passenger cars, and motorcycles" (Khreis et al., 2020).

Ultrafine particles (UFP): All particles smaller than 0.1 microns in diameter.

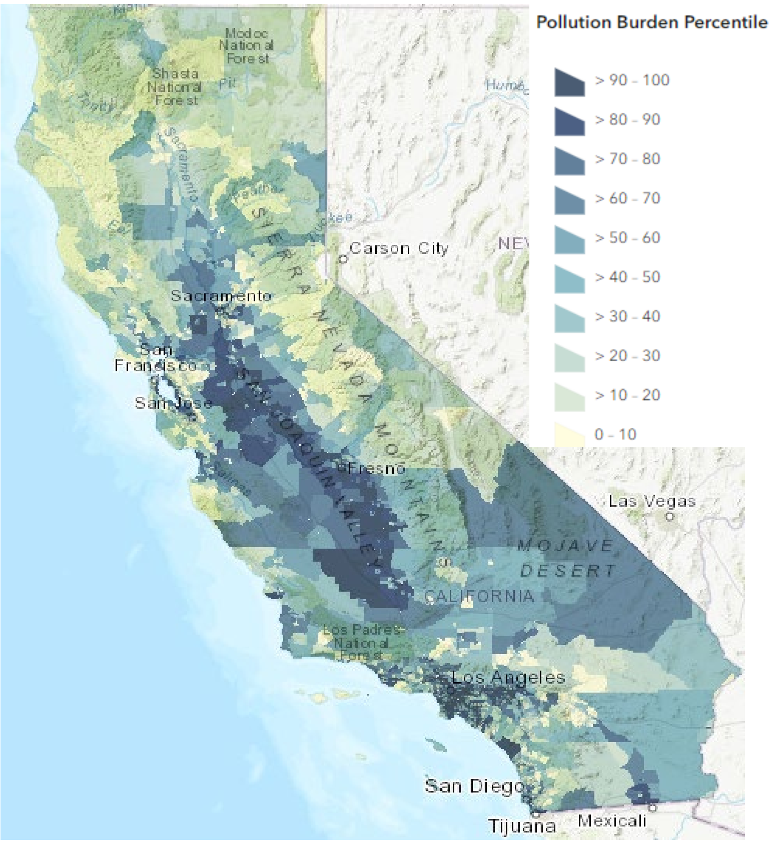
Volatile organic compounds (VOCs): Chemical compounds with a carbon backbone, present in the gas phase in the air. VOCs includes thousands of compounds. VOCs from vehicles is dominated by the portion of fuel that evaporates, and includes light alkanes, alkenes and aromatics such as benzene and toluene and incomplete combustion products such as formaldehyde. In indoor air, common VOCs include fragrances from consumer products, solvents and cooking vapors.

ZEV: Zero emission vehicles, such as battery electric, plugin hybrid, and hydrogen fuel cell vehicles.

CHAPTER 1: INTRODUCTION

Despite substantial progress over the last 50 years in reducing air pollution, more than 90% of Californians breathe unhealthy air at some time each year (CARB, 2023b). The California Air Resources Board (CARB) estimated that reduction or removal of major air pollutants could avoid thousands of premature deaths annually and reduce hundreds to thousands of hospitalizations and emergency room visits (CARB, 2023b). This is especially true for the 7.8 million California residents living in census tracts with high traffic volumes (Zeise and Blumenfeld, 2021). There are further concerns of disproportionate health impacts among specific populations due to racial, ethnic, and income disparities in air pollution exposure and related adverse health outcomes across the U.S. (Jbaily et al., 2022; Lui et al., 2021). In California, people of color are more likely to live in census tracts with high traffic corridors and have a higher prevalence of adverse health conditions from traffic-related air pollution and near-roadway air pollution (NRAP) (Zeise and Blumenfeld, 2021).

Figure 1. Map of Traffic Density by Census Tract in California



Source: OEHHA, 2021.
Traffic impact indicator defined as the amount of traffic on major as well as some local roads and the length of the roads in or near each census tract; impacts are calculated by dividing the traffic volume by the total road length for the year 2017.

Report Purpose

This report responds to an inquiry from the California Senate Committee on Environmental Quality and the Assembly Committee on Natural Resources for information about NRAP, including its influence on indoor air quality, adverse health effects, and strategies for preventing or mitigating adverse effects for people who live, work, or go to school near California's roadways. The report is intended to inform discussions at the California state level but may also aid other jurisdictions in and out of California. It addresses three overarching questions:

1. How do traffic-related outdoor pollutants get indoors, and what is the relative contribution of roadway pollutants to indoor air quality?
2. What are the human health effects of the exposure to near-roadway air pollution, including disproportionate effects on selected populations?
3. To what extent have specific prevention and mitigation strategies been proven effective in reducing near-roadway indoor air pollution?

What is near-roadway air pollution?

Near-roadway air pollution (NRAP) occurs "within a few hundred meters — about 500-600 feet downwind from the vicinity of heavily traveled roadways or along corridors with significant trucking traffic or rail activities. This distance will vary by location and time of day or year, prevailing meteorology, topography, near land use, traffic patterns, as well as the individual pollutant" (EPA, 2014).

The questions were developed through a collaboration between California state legislative committee staff and University of California (UC) researchers. A UC librarian searched the literature based on specifications from the research team. Using results from literature searches, a multi-campus UC research team (part of the California State Policy Evidence Consortium, or CalSPEC) evaluated available evidence to inform stakeholder discussions about the magnitude and nature of the near-roadway indoor air pollution and potential policy solutions. To the extent possible, CalSPEC uses systematic and reproducible methods to obtain, review, and summarize published evidence. However, owing to the short timeframe available for this report, each of its three substantive chapters uses different methods. External subject matter experts, unaffiliated with the research team, reviewed the report for accuracy. The CalSPEC Consortium Advisory Council reviewed the report for clarity, neutrality, and responsiveness to the legislative request.

Background

Outdoor air pollution is a major environmental and health problem and is estimated to cause millions of premature deaths worldwide each year (Fuller et al., 2022; GBD 2019 Risk Factor Collaborators, 2020). However, indoor air can be up to 2 to 5 times more polluted than outdoor air (EPA, 2023a), depending on several factors discussed in this chapter. **This section provides contextual information about the sources and types of near-roadway pollution, how those pollutants migrate indoors, and how outdoor pollution may exacerbate preexisting indoor air pollution. This material also highlights the challenges of measuring the contribution of NRAP to indoor air quality.**

Indoor air pollution refers to pollutants inside homes, schools, offices, or other building environments. Examples of indoor air pollutants include particulate matter ($PM_{2.5}$), carbon monoxide, pet dander, mold, pesticides, lead, asbestos, ozone, and various volatile organic compounds (VOCs). Indoor air quality is affected by both indoor and outdoor sources of pollution (CARB, 2005b; EPA, 2023a).

Residents exposed to elevated levels of traffic and NRAP are at higher risk of a wide variety of air pollution-induced adverse respiratory conditions, cardiovascular events such as heart attacks and strokes, and developmental, metabolic, cancer, neurological, and immunological disorders (Boogaard et al., 2022; NTP, 2019). Children, the elderly, pregnant women, and individuals with preexisting conditions such as disease, asthma, or a metabolic disorder are more likely to suffer ill effects of air pollution exposure.

Researchers estimate that 90%–95% of primary exposure to air pollution occurs indoors (Klepeis et al., 2001).[1] A major reason is that most people spend the majority of time indoors. However, indoor air ultimately comes from outside. People who live or work near high-volume roadways (>100,000 vehicles/day) may experience additional pollution burden from near-roadway sources, particularly vehicle emissions (CARB, 2017b).

California code defines "high-volume roadways" as:
>100,000 vehicles/day (urban areas)
>50,000 vehicles/day (rural areas)

Near-Roadway Air Pollution Composition and Sources

Near-roadway environments have all the pollutants common in urban areas, plus higher levels of pollutants freshly emitted from vehicles. Vehicles traveling along roads produce primary and secondary pollutants via four paths:

- Tailpipe emissions
- Mechanical generation of particulates from brake, tire, and road wear
- Resuspension of existing roadway dust
- Evaporative emissions of volatile organic compounds (VOCs)

Most notable are particulate matter (PM_{10}, and $PM_{2.5}$, both inhalable), black/elemental carbon (BC/EC), oxides of nitrogen (NO_x), and some volatile organic compounds (VOCs) (Choi et al., 2012; Oroumiyeh et al., 2022; Ranasinghe et al., 2019). Secondary pollutants are created through chemical and photochemical reactions of primary pollutants. Each pollutant type has implications for prevention and mitigation strategies. **Table 1** defines the most common pollutants found near roadways together with their indoor and outdoor sources.

Table 2 reorganizes this information, emphasizing the roadway sources of common pollutants and how they are regulated.

Table 1. Common Roadway Pollutants, Definitions, Descriptions and Sources (Including Non-roadway Sources) in Urban Areas

Roadway-Associated Pollutant	Definition	Source(s)	Description
Airborne particulate matter (PM)	PM is a complex mixture of small liquid droplets and dry solid fragments	All types of combustion, secondary formation from reactions of NO_x, VOCs, SO_2, and other gasses in the atmosphere, sprays, and mechanical processes — grinding, windblown dust, etc.	Particles vary widely in size, shape, and chemical composition, and may contain inorganic ions, organic and metallic compounds, black carbon, and compounds from the earth's crust. The chemical composition allows researchers to determine how much each source contributed to particles at each location.

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[1] https://www.epa.gov/indoor-air-quality-iaq

Roadway-Associated Pollutant	Definition	Source(s)	Description
Ultrafine particles (UFP/PM$_{0.1}$)	Particles smaller than 0.1 microns in diameter. (See Figure 2)	Essentially all combustion processes produce UFP, including engines, cooking, heating, etc. Brake and tire wear also produce UFP.	UFPs are similar in size to viruses; they are small enough to directly pass through cell membranes, increasing concern about their health impacts. UFP particles move more rapidly through the air than do larger particles, causing them to quickly collide and stick to other particles. As a result, they disappear within ~30 minutes in urban air, although the material they contain becomes incorporated into larger particles within the PM$_{2.5}$ size range.
PM$_{2.5}$	Particles smaller than 2.5 microns in diameter	Vehicle tailpipes; brake, tire, and road wear; industry; biomass burning; heating and cooking; some dust and sea spray; and secondary formation from reactions of NO$_x$, VOCs, SO$_2$, and other gasses in the atmosphere.	Because PM$_{2.5}$ particles are suspended in the air for ~1 week, they build up and disperse throughout urban areas. They are more uniformly distributed than UFP or PM$_{10}$ particles, although PM$_{2.5}$ particles include UFP.
PM$_{10}$	Particles smaller than 10 microns in diameter (PM$_{10}$ includes PM$_{2.5}$)	PM$_{10}$ ("coarse" particles between 2.5 and 10 microns), plus PM$_{2.5}$. Most PM$_{2.5}$ particles come from combustion or reactions of gasses, while coarse particles come from mechanical breakup of material (wind, grinding, etc.).	Coarse and PM$_{2.5}$ particles come from different sources and have different health impacts, and thus require separate standards. PM$_{2.5}$ particles penetrate deeper into lungs than coarse particles.
Black carbon (BC), elemental carbon (EC)	Light-absorbing, carbon-based sooty material found in particulate matter	Combustion — particularly of diesel and biomass — tire wear, and road dust.	Black carbon (BC) and elemental carbon (EC) are both soot-like carbon-based material in particles but they are measured with different instruments. Unlike most particles, which are light-colored and reflect light, BC strongly absorbs sunlight, which warms the air and significantly contributes to climate change.
Nitrogen oxides (NO/NO$_2$)	Nitric oxide (NO) and nitrogen dioxide (NO$_2$)	Combustion, including tailpipe emissions, gas stoves, industrial burners and biomass burning.	The combustion process creates NO (colorless/odorless) which is rapidly converted to NO$_2$ (reddish-brown color with pungent smell) in the atmosphere.
Volatile organic compounds (VOCs)	Gas phase compounds consisting of carbon and hydrogen; may	The gasoline vehicle fleet, industrial processes, consumer products, solvents,	There are thousands of VOCs in the air, and their toxicity, odors, and other characteristics vary widely. Many VOCs have higher concentrations indoors than outdoors.

Roadway-Associated Pollutant	Definition	Source(s)	Description
	also contain oxygen, sulfur, nitrogen, chlorine, etc.	paints and coatings, trees, and other plants.	Benzene, Toluene, Ethylbenzene, and Xylene — collectively called BTEX — from vehicle exhaust are commonly studied as contributors to adverse health outcomes.
Carbon monoxide (CO)	Gas with the formula CO	All combustion. Vehicles with catalytic converters emit very little CO.	Odorless, colorless, and poisonous gas formed by the combustion of fossil fuels such as gasoline and is emitted primarily from cars and trucks. It is also emitted from appliances using natural gas.
Ground-level ozone (O_3)	Gas with the formula O_3	In the presence of sunlight, VOCs, and NO_x react and form ground-level ozone.	Producing high concentrations of ozone takes several hours, which also allows the ozone to mix and spread over large areas; therefore, ozone is unlikely to be elevated near roadways relative to areas further away.
Sulfur dioxide (SO_2) and ammonia (NH_3)	Gasses with the formula SO_2 and NH_3	(SO_2) Combustion of fuels containing sulfur (NH_3) This is largely a byproduct of catalytic converters.	SO_2: If fuel contains sulfur, the sulfur will leave the tailpipe primarily as sulfur dioxide gas or sulfuric acid in UFP. NH_3: Small amounts of ammonia are also found in tailpipe emissions.

Source: CalSPEC, 2024, based on Bein et al., 2022; CARB, 2023b; EPA, 2023b; Seinfeld and Pandis, 1998; Zhang and Wexler, 2004; Zhang et al., 2004.

Table 2. Primary Pollutants from Roadway Source and Overview of their Regulations

Source	Emissions	Description	Regulations
Gasoline tailpipe emissions	Ultrafine particles (UFP), oxides of nitrogen (NO_x), volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), and ammonia (NH_3)	UFPs are present in very high numbers (up to around 100,000/cm^3 near roadways; more in the exhaust plume of poorly maintained vehicles). Tailpipe VOCs include alkanes, and some alkenes and aromatics, including the air toxics such as benzene, toluene and xylenes.	Tailpipe emissions, subject to numerous regulatory controls, have dropped rapidly over recent years.
Diesel tailpipe emissions	NO_x and UFP, black carbon (BC)	Diesel PM typically has high black carbon content. Diesel engines produce only low levels of VOCs.	Substantial innovations and regulations, including California's ultra-low sulfur diesel and particle trap technology have reduced tailpipe emissions.
***Tailpipe tracers*: UFP and NO_x and BC are considered good indicators for tailpipe emissions because traffic is the dominant source of these pollutants at most locations/times.**			

Source	Emissions	Description	Regulations
Brake and tire wear	Particulate matter (PM) — mostly in the PM_{10} size range; some $PM_{2.5}$	Particles are created by the mechanical action of surfaces grinding against one another. These “non-exhaust” particles are mostly larger, falling between about 1 and 10 microns in diameter, with some UFP. Due to increased vehicle miles travelled and vehicle weights, the quantity of particles emitted by brake and tire wear and resuspended road dust (below) are increasing and are believed to have surpassed tailpipe emissions in many locations, including California.	Regulations to reduce emissions from brake and tire wear are in their very early stages.
Road Dust	PM — mostly in the PM_{10} size range; some $PM_{2.5}$	The action of vehicles moving over roadways, and wind, resuspends dust, which can also be a substantial source of airborne particulate matter near roadways.	Regulations to reduce road dust emissions are in their very early stages.
***Brake, tire, and road wear tracers*: While some specific chemical tracers are being developed, researchers rely on other methods such as aerosol trace metal “fingerprints” to measure the contribution of these sources to particulate matter.**			
Evaporative emissions	VOCs, consisting largely of the more volatile compounds in fuel.	VOC emissions are released into the air as fuel and oil leaking from the engine/fuel system evaporates. The VOCs include alkanes, together with some alkenes and aromatics, including the air toxics such as benzene, toluene and xylenes.	In the 1990s, California addressed tailpipe unburned fuel and evaporative emissions by reformulating gasoline, targeting the most volatile, toxic and/or ozone-forming VOCs in the fuel. The fuel continues to deliver substantial air quality benefits today.
	Other VOCs	Additional VOCs are released by other vehicular sources as well, notably from ethanol and other components of windshield wiper fluid.	Likely minor; not regulated.

Source: CalSPEC, 2024, based on Birmili et al., 2006; Bondorf et al., 2006 ; CARB, 2017a; Gietl et al., 2010; Habre et al., 2021; Harrison et al., 2021; Luo et al., 2022; Matthaios et al., 2022; Pang et al., 2014; Piscitello et al., 2021.

Standards Regulating Ambient Air Quality

The federal Environmental Protection Agency (EPA) created National Ambient Air Quality Standards (NAAQS) to set general exposure limits for six principal air pollutants: PM ($PM_{2.5}$, PM_{10}), airborne lead, carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone. California also has parallel ambient air quality standards (CAAQS) that include four additional pollutants[2]; however, these additional pollutants are not typically higher in near-roadway environments.

Although many studies report associations between living/working near heavily trafficked roadways and increased incidence of health problems, near-roadway environments rarely exceed the NAAQS. Of the pollutants with elevated concentrations in near-roadway environments (ultrafine particles [UFP], black carbon [BC], CO, NO_2, and others), only CO and NO_2 are regulated. (Note that $PM_{2.5}$, PM_{10}, and ozone[3] –which form partly or come from roadway emissions — typically affect large areas of tens of square miles or more, do commonly exceed limits, but that issue is beyond the near-roadway focus of this report [CARB, 2023c; Goldberg et al., 2015; Seinfeld and Pandis, 2016]).

National and State Ambient Air Quality

National Ambient Air Quality Standards (NAAQS)

- Sulfur dioxide (SO_2)
- Carbon monoxide (CO)
- Nitrogen dioxide (NO_2)
- Ground level ozone
- Airborne lead
- PM ($PM_{2.5}$ and PM_{10})

California Ambient Air Quality Standards (CAAQS) are similar to NAAQS. They include NAAQS plus four additional pollutants:

- Sulfate aerosols
- Hydrogen sulfide
- Visibility reducing particles
- Vinyl chloride

Source: EPA, 2023b; CARB, 2023a.

Pollutant Concentrations Near Roadways

NRAP composition, dilution, dispersion, and rates of indoor migration vary greatly within and between locales (EPA, 2014). **Table 3** lists factors that increase or decrease NRAP concentrations.

Table 3. Factors that Increase or Decrease Roadway Air Pollution Concentrations

Factors That Usually Lead to Higher Concentrations	Factors That Usually Lead to Lower Concentrations
• High levels of traffic • Fleets with higher emissions, such as older, poorly maintained, or heavier vehicles • Roadways with inclines or other features that lead to more braking • Depressed or at-grade roadways • Taller buildings, although upper floors of buildings often experience lower outdoor concentrations • Buildings surrounded by minimal open space at ground level, which blocks ventilation • Weak winds from the roadway to the neighborhood • Mornings	• Sound walls along the roadway • Trees around the roadway • Trees in the neighborhood • Elevated roadways • Shorter buildings, which allow more ventilation • More green space around buildings, which improves ventilation • Winds carrying the air from the neighborhood toward the freeway; when a neighborhood is upwind, the impact of the freeway is typically not detectable • Sunny daytime conditions • Windy weather

Source: CalSPEC, 2024, based on Abhijith et al., 2017; Baldauf, 2017; Baldauf et al., 2008; Choi et al., 2012; Choi et al., 2013a; Choi et al., 2013b; Choi et al., 2014; Choi et al., 2016; Finn et al., 2010; Lee et al., 2018; Li et al., 2016; Ranasinghe et al., 2019; Tong et al., 2016; Zhu et al., 2021.

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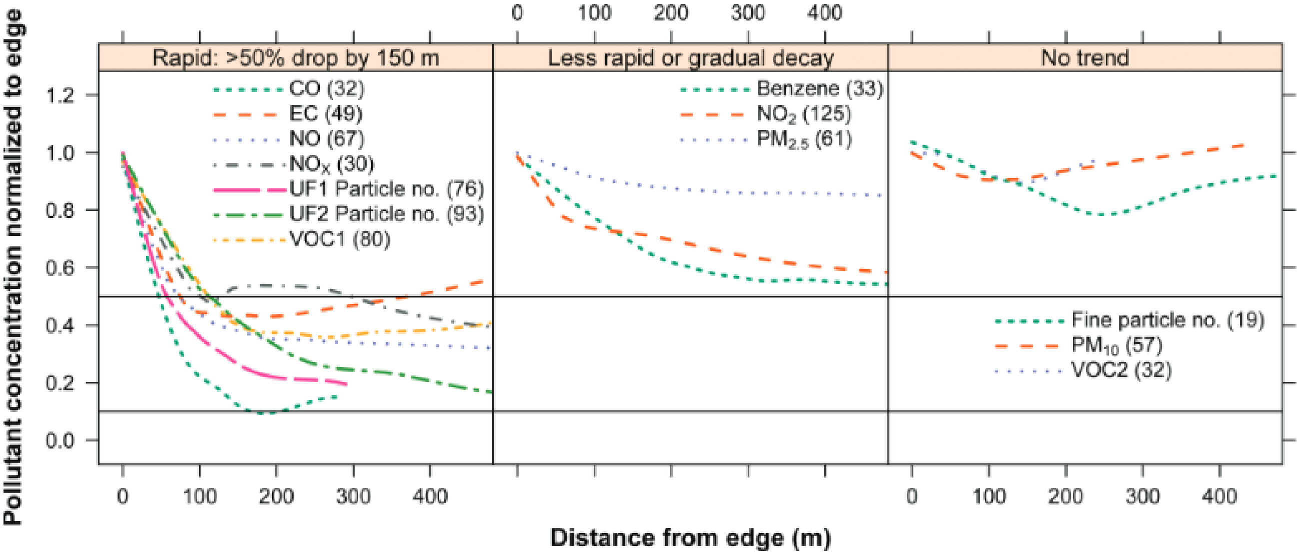
[2] https://ww2.arb.ca.gov/resources/california-ambient-air-quality-standards

[3] https://ww2.arb.ca.gov/resources/documents/maps-state-and-federal-area-designations

One particularly influential factor is time of day. During daytime, the sun warms the ground and the air just above it. The warm air rises, causing vertical mixing and diluting the pollution. At night, the opposite happens; the ground cools more rapidly than the air, creating a layer of colder air near the ground. In this situation, pollution is trapped near the surface, concentrations increase, and the area impacted by NRAP also increases (Choi et al., 2012; Hu et al., 2012; Ranasinghe et al., 2019).

Figure 2 illustrates how certain pollutants dissipate spatially faster than others. Based on a meta-analysis of 41 studies of air pollutant concentrations near roadways (1978-2008), Karner et al. show how pollutant concentrations decay with distance from the edge of the roadway during daytime. Concentrations of UFP, CO, NO, NO_2, elemental carbon (EC) and several other pollutants drop by 10%–60% at the roadway edge within 200 meters. In contrast, no significant drop in concentration is seen for $PM_{2.5}$ and PM_{10} (middle and right panels) within the same distance (Karner et al., 2010).

Figure 2. Spatial Variability of Air Pollutants during Daytime



Source: Karner et al., 2010.

Key: CO = carbon monoxide; EC = elemental carbon; NO = nitric oxide; NO_2 = nitrogen dioxide; PM = particulate matter; UF = ultrafine; VOC = volatile organic compounds.

How Do Outdoor Pollutants Migrate Indoors?

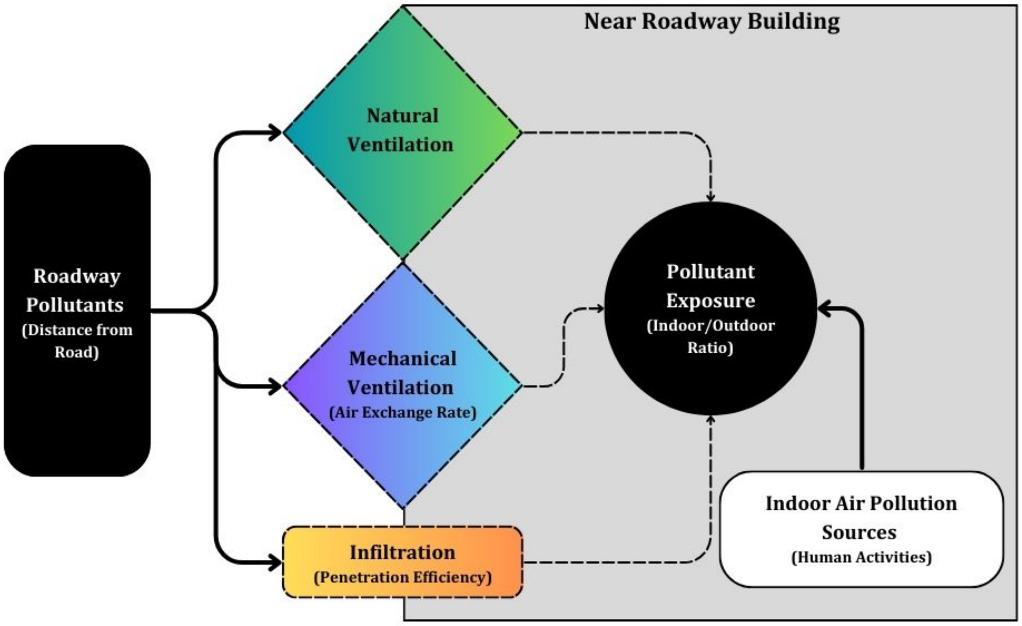
The continual exchange of indoor and outdoor air occurs as a result of both natural and mechanical ventilation and infiltration processes that prevent buildup of pollutants from indoor sources (building materials, cooking, cleaning and personal care products, furniture, plastics in appliances, carpeting, fabrics, humans, and pets) as well as outdoor sources (Isaacs et al., 2013; Murray and Burmaster, 1995). Indoor air may have higher or lower concentrations of VOCs and PM than outdoor air due to indoor source emissions; the infiltration of near-roadway–associated pollutants, including PM, can exacerbate indoor source pollutants thus amplifying the health impacts of those pollutants on residents (Farmer et al., 2019; Goldstein et al., 2021; Masters and Ela, 2007; Nazaroff, 2023).

Figure 3 shows the three primary air change routes for outdoor air:

- Natural ventilation
- Mechanical ventilation
- Infiltration

Natural ventilation (i.e., open doors and windows) and *infiltration* (e.g., building cracks and door/window joints) are passive air exchange pathways through the building envelope. *Mechanical ventilation* involves active exchange through heating, ventilation, and air conditioning systems (Chen and Zhao, 2011). There are two types of mechanical ventilation — spot ventilation and whole-building ventilation (EPA, 2010). Examples of spot ventilation systems are localized exhaust fans such as those above cooking ranges and/or bathrooms whereas whole building ventilation includes HVAC systems.

Figure 3. Major Pathways that Influence Indoor Air Composition



Source: CalSPEC, 2024.

Both ventilation rates and pollutant removal rates depend on the type of ventilation (natural or mechanical), the behavior of occupants (use of HVAC, windows open or closed), and the quality and age of housing stock (Isaacs et al., 2013). Gases and particles ‘stick’ to surfaces, in the cracks, or in the HVAC filtration systems as they pass through. These removal mechanisms do not completely clean the air, but they commonly reduce concentrations by 10%–50% for infiltration of $PM_{2.5}$ and 50%–80% for coarse PM, if HVAC is installed and operating properly (Chen and Zhao, 2011). Often particles that are the smallest (ultrafine) and largest (coarse) are removed more thoroughly than the particles in the intermediate size range (fine, but not ultrafine) (Goldstein et al, 2021; Long et al., 2001; Riley et al., 2002).

Challenges with Measuring Outdoor Pollutant Contribution to Indoor Air Quality

It would be extremely useful for the purposes of this report to confidently and consistently isolate and estimate the *average* contribution of outdoor air pollution (especially NRAP) to indoor air quality. Unfortunately, these measurements are highly sensitive to multiple factors including spatial proximity to roadways, building age and structure, occupant behavior, ventilation, and the factors listed in **Table 3**. The most common measure that estimates near-roadway indoor air pollution is the indoor/outdoor (I/O) ratio, which has its limitations. The I/O ratio studies so far fail to address all the variability and consistently provide a measure of the NRAP contribution to indoor air quality.

The I/O ratio is the ratio of concentration of pollutants inside compared with the concentration of pollutants outside of a building. The ratio is calculated separately for each pollutant. Because it is a ratio of two concentrations (e.g., micrograms per cubic meter/micrograms per cubic meter), the I/O ratio has no units. For example, if the I/O ratio is 0.5, the indoor pollutant concentration is half of that outside.

An I/O ratio below 1 is expected for pollutants with minimal indoor sources, and windows closed. A value greater than 1 generally indicates either a significant indoor source of that pollutant, **or** a high penetration from outdoors (combined with a low-to-modest indoor source). An I/O ratio of 0.5 could be achieved if the pollutant had no significant indoor sources and if about half of the outdoor pollutants were removed on the way in. On the other hand, an I/O ratio of 2 implies that outdoor pollutants have easy ingress if there are few indoor sources of that pollutant. Indoor sources alone, without contribution from outdoor, can cause a high I/O ratio if the spaces are very poorly ventilated leading to accumulation of pollutants inside.

Multiple factors influence the I/O ratio, including the factors that contribute to daily and seasonal fluctuations of NRAP generally; the characteristics of the pollutant; the mode of ventilation; and contributions from aforementioned indoor sources. For particulate matter, the size of a particle affects its ability to penetrate through the building envelope. Aspects of the building structure also influence I/O ratio. In buildings with only natural ventilation, the structure's age is correlated with the gaps in building envelope that provides pathways to pollutants. The duration and times when windows are open also affect indoor-outdoor exchanges and subsequent ratios (Chen and Zhao, 2011; Farmer et al., 2019; Goldstein et al., 2021; Masters and Ela, 2007; Nazaroff, 2023).

Air Exchange Rate

The air exchange rate measures the frequency of outdoor air entering an indoor space and mixing with existing air. The ASHRAE engineering standards 62.1 (commercial buildings) and 62.2 (residential buildings) recommend "ventilation rates by space type, occupancy, and other measures to provide indoor air quality 'that is acceptable to human occupants and that minimize adverse health effects'" (Traube and Spies, 2018). Specifically, it recommends residential spaces to have at least 0.35 air changes per hour (EPA, 2024). The California Energy Commission also sets standards that refer back to ASHRAE 62.2 and 62.1, with some modifications (California Energy Commission, 2022.

One air change/hour means that a volume of air equal to the interior volume of the building is replaced with outdoor air once each hour. Typically, mixing is not perfect, so some air may remain during this process. This measure does not calculate the NRAP contribution to indoor air quality, but it is a common measure frequently used in ventilation studies (see Chapter 3).

Studies measuring the I/O ratio for particles and gaseous pollutants across different building types and geographies suggest a high level of penetration of outdoor air pollutants, especially in absence of high-efficiency air filtration systems. For example, a meta-analysis of combined 89 studies for schools and offices found an average NO_2 I/O ratio of 0.9 in the schools and office buildings studied (Salonen et al., 2019). Another study, focused on three retirement homes in the Los Angeles Basin (situated at 150m, 300m, and 3 km from major freeways) found that the contribution of traffic-related air pollution was higher at the sites close to the freeway and that the average I/O ratio for EC (a tracer for traffic originated PM) to be 0.8 with high correlation (0.83) between outdoor and indoor concentrations (Hasheminassab et al., 2014). The high correlation indicates that regardless of the outdoor concentration, it is having a major impact on indoor concentrations.

Ultimately, penetration of outdoor pollutants (in the absence of a major indoor source) result in modestly lower (10%–40%) indoor concentrations compared with their respective outdoor concentrations (Chen and Zhao, 2011; Farmer et al., 2019; Goldstein et al., 2021; Masters and Ela 2007; Nazaroff, 2023; Salonen et al., 2019). Total indoor concentration is the sum of the outdoor pollutants penetrating inside and the indoor sources. Based on the evidenced reviewed, CalSPEC estimates that outdoor air pollution is responsible for approximately 30%–90% of the pollutant concentrations indoors. Values at the lower end tend to be in locations where there are more indoor sources and/or cleaner outdoor air; values at the higher end tend to be situations with lower indoor sources and/or higher outdoor pollutant concentrations (Chen and Zhao, 2011; Farmer et al., 2019; Goldstein et al., 2021; Masters and Ela, 2007; Nazaroff, 2023; Salonen et al., 2019).

Conclusion

The traffic-related pollutants that are most likely to be elevated out to at least 500 feet from highly trafficked roads (NRAP) are NO_x, ultrafine and larger particles, and VOCs. These pollutants come from tail pipes; brake, tire, and road wear; and evaporated leaking fuel. Of these, ultrafine particles are most elevated relative to the urban background (average); however, they are not subject to state or federal regulations. All outdoor pollutants enter through mechanical ventilation systems or pass through cracks and joints; the entry paths have a wide range of effectiveness at removing pollutants from the air as it moves inside. Outdoor pollutant concentrations vary widely both spatially and temporally; their concentrations depend on the local topography, infrastructure design, time of day or season, weather, traffic patterns, etc.

It is very challenging to generalize the proportion of outdoor pollutants that contribute to poor indoor quality, because of the large number of contributing variables (e.g., housing stock, outdoor concentrations, indoor sources) discussed herein. Nevertheless, research indicates that on average, the contribution of outdoor sources to indoor concentrations is significant even when indoor sources are present. Depending on the situation, outdoor air pollution is responsible for around 30%–90% of the indoor pollutant concentrations with near-roadway environments, being subject to particularly higher pollutant concentrations indoors. These NRAP concentrations can have significant health impacts (Chapter 2) but may be reduced through a variety of mitigation strategies (Chapter 3).

CHAPTER 2: HEALTH EFFECTS OF NEAR-ROADWAY AIR POLLUTANTS

Introduction

Outdoor air pollution levels unequivocally predict indoor exposures (Baxter et al., 2007; Brody et al., 2009; Klepeis et al., 2001; Naumova et al., 2002). However, few studies have investigated the health effects experienced by *residents living and working closest to high-traffic roadways from the outdoor, traffic-related pollution contribution to indoor air pollution* (Magalhaes et al., 2018). This is partly due to the challenges of accurately assessing the contribution of near-roadway air pollution (NRAP) to the overall composition of indoor air (Brody et al., 2009; European Commission, 2007). Identifying the relative contribution of NRAP is challenging because indoor air composition is a function of intrinsic (indoor) sources such as off-gassing from paints and synthetic fabrics and extrinsic sources such as automobile exhaust (Cosselman et al., 2020).

Near-roadway air pollution (NRAP)

Air pollution "within a few hundred meters - about 500-600 feet downwind from the vicinity of heavily traveled roadways or along corridors with significant trucking traffic or rail activities. This distance will vary by location and time of day or year, prevailing meteorology, topography, near land use, traffic patterns, as well as the individual pollutant" (EPA, 2014).

As a result of these challenges, no studies have directly assessed the health effects of near-roadway *indoor* air pollution. Therefore, CalSPEC reviewed the human health effects of exposure to NRAP more generally. Prior research links NRAP with various dimensions of human health, including reproductive, cognitive, respiratory, and cardiovascular health (Cosselman et al., 2020; Frutos et al., 2015; Kim et al., 2004; Kim et al., 2008; Laumbach and Kipen, 2010; Peters et al., 2019; Power et al., 2016; Siegel et al., 2023). Several systematic reviews have assessed the health effects of NRAP. Thus, CalSPEC used an *overview of systematic reviews* of human health studies to summarize the evidence on health effects of NRAP. The findings can then be extrapolated to estimate the burden of health effects of near-roadway *indoor* air pollution (Garritty et al., 2021; Lam et al., 2014; Pollock et al., 2022).

This chapter also explores the extent to which specific groups of Californians (identified by age, race/ethnicity, socioeconomic status, and health history) have greater exposure to NRAP and may therefore be at higher risk of suffering pollution-related adverse health effects. Prior research conducted in the United States has documented the presence of racial and ethnic disparities in NRAP exposure and consequent health effects (Park and Kwan, 2020; Valencia et al., 2023). Children, older adults, and individuals with preexisting cardiovascular and respiratory disease are particularly susceptible to the health impacts of air pollution (EPA, 2023b; Gasana et al., 2012; Tong, 2019). Other research shows that communities with low socioeconomic status experience higher pollutant exposure and are more susceptible to pollution's ill effects (EPA, 2023c). Understanding the disproportionate human health effects of NRAP and the populations most at risk from exposure in California can inform more equitable policies and programs to protect public health.

Methods

CalSPEC developed a protocol for the overview of systematic reviews and meta-analyses related to the effects of NRAP on human health. Details of the method are provided in **Appendix A** (also published online as a protocol) and **Appendix B1.**

Following guidelines for such "overviews of reviews," key elements of the method included:

- Publication of a prespecified protocol, which describes how the authors transparently completed the below steps;
- Specification of a search strategy designed to identify all systematic reviews assessing the relationship of NRAP (or the closely related concept of "traffic-related air pollution") to human health effects;
- Development of specific inclusion and exclusion criteria;
- Evaluation of the quality of each included review, based on 16 validated criteria;
- Exclusion of reviews assigned critically low quality ratings;
- Formation of overall conclusions about the health effects of NRAP exposure, based on the authors "certainty in the body of evidence" and the size and precision of the effect.

Exposures Measured

Epidemiological studies commonly rely on elemental carbon (EC), nitrogen dioxide (NO_2), and particulate matter (PM) as key indicators of NRAP. CalSPEC included systematic reviews evaluating NRAP exposure through exposure to NO_2 and EC measured near roads and excluded studies on PM, as sources other than traffic significantly contribute to PM concentrations (HEI, 2022). The reported effects of EC and NO_2 are *representative of general NRAP health effects overall.* In this sense, EC and NO_2 are proxy measures for the broader set of near-roadway air pollutants; when EC and NO_2 are elevated, one can expect other near-roadway pollutants to be increased as well. Similarly, CalSPEC identified systematic reviews that reported NRAP health effects related to distance to roadway and traffic density. All things equal, one would expect NRAP to increase as distance of the dwelling, office, or school to the roadway decreases and as traffic density increases.

Health Effects and Outcomes Measured

The included systematic reviews evaluated clinical outcomes (clinically meaningful outcomes, including mortality) and apical effects (observable features predictive of or related to disease, including cancer) with respect to the respiratory, cardiovascular, reproductive, nervous, and endocrine systems.

Drawing Conclusions

Because the systematic reviews summarized associations between NRAP exposures and outcomes using various metrics, CalSPEC used the following categories to consistently convey the strength of evidence supporting an association:

- *Established Evidence of an Association*:* Overall body of evidence high or moderate with a positive association (risk ratio [RR] or Odds Ratio [OR]) ≥ 1.01, and lower bound CI ≥ 1.01; e.g., RR 1.03; 95% CI: 1.01 to 1.09, High or Moderate certainty evidence.

- *Likely Evidence of an Association*:* Overall body of evidence low with a positive association (RR or OR) ≥ 1.01, and lower bound CI ≥ 1.01; e.g., RR 1.03; 95% CI: 1.01 to 1.09, Low certainty evidence. Or, overall body of evidence high or moderate with a positive association (RR or OR) ≥ 1.01, and lower bound CI ≥ 0.95.; e.g., RR 1.03; 95% CI: 0.97 to 1.09, Moderate certainty evidence.
- *Suggestive Evidence of an Association*:* Overall body of evidence low with a positive association (RR or OR) ≥ 1.01, and lower bound CI ≥ 0.95.; e.g., RR 1.03; 95% CI: 0.97 to 1.09, Low certainty evidence.
- *Uncertainty of an Association:* Overall body of evidence high, moderate, low, or very low and with a negative association (RR or OR) ≤ 1.00, and/or a lower bound CI ≤ 0.95.; e.g., RR 0.99; 95% CI: 0.97 to 1.09, Moderate certainty evidence. Or, overall body of evidence very low when there is a positive association (RR/OR ≥ 1.01), and precise estimate (CI) ≥ 1.01.

*CalSPEC recommends taking action to mitigate or prevent exposure from NRAP based on findings with established, likely, or suggestive evidence of an association.

Systematic Review Evaluation and Findings

Nine systematic reviews, focused on three exposures (NO_2, EC, and NRAP proxy measures using distance from building to roadway and/or traffic density) were selected for quality evaluation. The reviews were published between 2016 and 2023 and included primary studies published between 1993 and 2022. Additional characteristics of these reviews can be found in **Appendix C4.** Among these systematic reviews, CalSPEC sought certainty ratings that assess the overall body of evidence (high, moderate, low, or very low). Certainty ratings are based on the risk of bias, indirectness, inconsistency, imprecision, publication bias, magnitude of effects, dose response, and the extent to which controlling for potential confounders reduced any observed associations.

Ultimately, two systematic reviews (reflecting 32 exposure-outcome pairs) met inclusion and quality criteria because they contained certainty assessments (HEI, 2022; NTP, 2019). These are classified as "Tier 1" evidence. Specifically, CalSPEC rated the first systematic review, National Toxicology Program (2019), as "moderate" quality. The second review, Health Effects Institute report (2022), was rated low quality despite covering numerous health outcomes, largely because the review lacked a comprehensive search strategy and failed to provide details regarding funding and conflict of interest. Detailed evaluation results can be found in **Appendix C8**.

Based on its full review, CalSPEC downgraded to "second tier" seven systematic reviews of exposure-outcome associations that lacked certainty assessments. The lack of certainty assessments makes it difficult to establish confidence in the overall body of evidence. Many of the studies relied on roadway distance or traffic density as exposure metrics. For context, **Appendix C9** summarizes these Tier 2 study findings. **Table 4** provides an overview of all "Tier 1" exposure-outcome associations along with their source (published systematic review).

Table 4. Summary of Included Systematic Reviews Reporting on Associations Between Near-Roadway Air Pollution (NRAP) Exposure and Health Outcomes

	Health Outcome	Exposure	Systematic Review
Mortality measures			
All-cause mortality		NO_2, EC	HEI, 2022
Cause-specific mortality	Circulatory	NO_2, EC	HEI, 2022
	Respiratory	NO_2, EC	HEI, 2022
	Lung cancer	NO_2, EC	HEI, 2022
	Ischemic heart disease (IHD)	NO_2, EC	HEI, 2022
	Stroke	NO_2	HEI, 2022
	Chronic obstructive pulmonary disease (COPD)	NO_2	HEI, 2022
Body systems			
Cardiovascular	Hypertensive disorders of pregnancy	Traffic measures, NO_2	NTP, 2019
	IHD	NO_2, EC	HEI, 2022
	Incidence of coronary events	NO_2	HEI, 2022
	Stroke	NO_2, EC	HEI, 2022
Endocrine	Diabetes	NO_2, EC	HEI, 2022
Reproductive	Term low birth weight	NO_2, EC	HEI, 2022
	Decreased Term birth weight	NO_2, EC	HEI, 2022
	Small for gestational age	NO_2, EC	HEI, 2022
	Preterm birth	NO_2, EC	HEI, 2022
Respiratory	Prevalence of asthma ever in children	NO_2, EC	HEI, 2022
	Incidence of COPD	NO_2	HEI, 2022

Source: CalSPEC, 2024, based on HEI, 2022; NPT, 2019.
Note: Individual pollutants nitrogen dioxide (NO_2) and elemental carbon (EC) are used as indicators of exposure to NRAP. The listed health conditions are not directly attributed to individual components (e.g., EC, NO_2) of NRAP.

Mortality Effects of NRAP Exposure

Based on seven mortality outcomes from 24 primary studies included in one systematic review (HEI, 2022) (**Table 5**), CalSPEC found:

- ***Established evidence of an association*** **between NRAP and all-cause mortality, lung cancer mortality, and IHD mortality** based on High certainty in the body of evidence. Risks ranged from 1.04 to 1.05 (4%–5% increased risk of harm per unit increase of NRAP).
- ***Likely evidence of an association*** **between NRAP and circulatory mortality, respiratory mortality, and stroke mortality** based on High and Moderate certainty in the body of evidence. Risks ranged from 1.01 to 1.05 (1%–5% increased risk of harm per unit increase

of NRAP, generally defined as 10 micrograms per cubic meter for NO_2 and 1 microgram per cubic meter for EC).

- ***Suggestive evidence of an association*** **between NRAP and COPD mortality** based on Low certainty in the body of evidence. Risk of 1.03 (3% increased risk of harm per unit increase of NRAP).

Table 5. Association Between NRAP Exposure and Mortality

Exposure	Contributing Review	Number of Contributing Primary Studies* (Date range)	Relative Effect	Certainty in the Body of Evidence†
		All-cause mortality		
NO_2	HEI, 2022	11 (2008–2019)	RR 1.04; 95% CI: 1.01–1.06 per 10μg/m^3	High
EC	HEI, 2022	11 (2008–2019)	RR 1.02; 95% CI: 1.00–1.04 per 1μg/m^3	High
		Cause-specific mortality – circulatory		
NO_2	HEI, 2022	10 (2007–2019)	RR 1.04; 95% CI: 1.00–1.09 per 10μg/m^3	High
EC	HEI, 2022	9 (2008–2019)	RR 1.02; 95% CI: 1.00-1.04 per 1μg/m^3	High
		Cause-specific mortality – respiratory		
NO_2	HEI, 2022	8 (2008–2019)	RR 1.05; 95% CI: 1.00–1.09 per 10μg/m^3	High
EC	HEI, 2022	8 (2008–2019)	RR 1.01; 95% CI: 0.98-1.05 per 1μg/m^3	Moderate
		Cause-specific mortality – lung cancer		
NO_2	HEI, 2022	5 (2007–2013)	RR 1.04; 95% CI: 1.01–1.07 per 10μg/m^3	High
EC	HEI, 2022	3 (2008–2012)	RR 1.02; 95% CI:0.88–1.19 per 1μg/m^3	Low
		Cause-specific mortality – IHD		
NO_2	HEI, 2022	6 (2013–2018)	RR 1.05; 95% CI: 1.03–1.08 per 10μg/m^3	High
EC	HEI, 2022	6 (2012–2018)	RR 1.05; 95% CI: 0.99–1.11 per 1μg/m^3	Moderate
		Cause-specific mortality – stroke		
NO_2	HEI, 2022	6 (2013-2018)	RR 1.01; 95% CI: 0.98–1.04 per 10μg/m^3	Moderate
		Cause-specific mortality – COPD		
NO_2	HEI, 2022	3 (2007-2018)	RR 1.03; 95% CI: 1.00–1.05 per 10μg/m^3	Low

Source: CalSPEC, 2024.

Key: CI = confidence interval (a range of values that describes the uncertainty around an estimate); EC = elemental carbon; NO_2 = nitrogen dioxide; RR = Relative Risk ratio (the % of increased risk of harm for every unit increase of NRAP in the exposed population).

*The included studies (with sample sizes) are available in **Appendix C8.**

†Certainty in the body of evidence is based on the systematic review author assessment of the evidence.

Cardiovascular Effects of NRAP Exposure

Based on evaluation of four cardiovascular outcomes from 31 primary studies included in two systematic reviews (**Table 6**), CalSPEC found:

- ***Likely evidence of an association*** between NRAP and hypertensive disorders of pregnancy, ischemic heart disease, and incidence of coronary events based on Moderate certainty in the body of evidence. Risks ranged from 1.01 to 1.03 (1%–3% increased risk of harm per unit increase of NRAP).
- ***Suggestive evidence of an association*** **between NRAP and stroke** based on Low certainty in the body of evidence. Risk of 1.03 (3% increased risk of harm per unit increase of NRAP).

Table 6. Association Between NRAP Exposure and Cardiovascular Effects

Exposure	Contributing Review	Number of Contributing Primary Studies* (Date Range)	Relative Effect	Certainty in the Body of Evidence†
		Hypertensive disorders of pregnancy		
NO_2	NTP, 2019	7 (2011–2018)	RR 1.03; 95% CI: 0.97 to 1.09 per 10µg/m^3	Moderate
Traffic measures	NTP, 2019	9 (2011–2018)	**Traffic density**‡**:** 4 of 4 studies reported a harmful effect (100% [95% CI: 0.40–1.0], P=0.125). Two studies were statistically significant, OR ranging from 1.02 to 1.10. **Traffic proximity**‡**:** 4 of 5 studies reported a harmful effect (80% [95% CI: 0.28–0.99], P=0.375) Three studies were statistically significant, OR ranging from 0.98 to 1.30.	Low
		Ischemic heart disease (IHD)		
NO_2	HEI, 2022	5 (2011–2018)	RR 0.99; 95% CI: 0.94–1.05 per 10µg/m^3	Low
EC	HEI, 2022	5 (2011–2018)	RR 1.01; 95% CI: 0.99–1.03 per 1µg/m^3	Moderate
		Incidence of coronary events		
NO_2	HEI, 2022	7 (2004–2019)	RR 1.03; 95% CI: 0.95–1.11 per 10µg/m^3	Moderate
		Stroke		
NO_2	HEI, 2022	7 (2013–2019)	RR 0.98; 95% CI: 0.92–1.05 per 10µg/m^3	Low
EC	HEI, 2022	6 (2012–2019)	RR 1.03; 95% CI: 0.98–1.09 per 1µg/m^3	Low

Source: CalSPEC, 2024.
Key: CI = confidence interval (a range of values that describes the uncertainty around an estimate); EC = elemental carbon; NO_2 = nitrogen dioxide; OR = odds ratio (the ratio of the odds of an event); RR = relative risk ratio (the % of increased risk of harm for every unit increase of NRAP in the exposed population) .

*The included studies (with sample sizes) are available in **Appendix C8.**
†Certainty in the body of evidence is based on the systematic review authors assessment of the evidence.
‡CalSPEC utilized vote counting based on direction of effect because a meta-analysis was not conducted. A two-sided p-value from a binomial probability test is presented, testing if the true proportion of studies showing harm is equal to 0.5. Due to the small number of contributing studies, there is large uncertainty in this estimated proportion (McKenzie and Brennan, 2023).

Endocrine Effects from NRAP Exposure

Based on the evaluation of two endocrine effects from 16 primary studies included in one systematic review (HEI, 2022) (**Table 7**)**,** CalSPEC found:

- ***Established evidence of an association* between NRAP and diabetes** based on Moderate certainty in the body of evidence. Risk of 1.09 (9% increased risk of harm per unit increase of NRAP).

Table 7. Association Between NRAP Exposure and Endocrine Effects

Exposure	Contributing Review*	Number of Contributing Primary Studies (Date range)	Relative Effect	Certainty in the Body of Evidence†
		Diabetes		
NO_2	HEI, 2022	7 (incidence) 7 (prevalence) (2010–2019)	RR 1.04; 95% CI: 0.96–1.13 per 10µg/m^3 (incidence) RR 1.09; 95% CI: 1.02–1.17 per 10µg/m^3 (prevalence)	Moderate
EC	HEI, 2022	3 (incidence) (2010–2018)	RR 1.16; 95% CI: 0.57–2.36 per 1µg/m^3 (incidence)	Low

Source: CalSPEC, 2024**.**
Key: CI = confidence interval (a range of values that describes the uncertainty around an estimate); EC = elemental carbon; NO_2 = nitrogen dioxide; RR = relative risk ratio (the % of increased risk of harm for every unit increase of NRAP in the exposed population;.
*The included studies (with sample sizes) are available in **Appendix C8.**
†Certainty in the body of evidence was based on the systematic review authors assessment of the evidence.

Reproductive Effects of NRAP Exposure

Based on the evaluation of four reproductive effects from 40 primary studies included in one systematic review (HEI, 2022) **(Table 8),** CalSPEC found there is:

- ***Likely evidence of an association* between NRAP and term low birth weight** based on High certainty in the body of the evidence. Risk of 1.01 (1% increased risk of harm per unit increase of NRAP).
- ***Suggestive evidence of an association* between NRAP and decreased term birth weight** based on Low certainty in the body of evidence. MD −2.6 grams (decrease of −2.6 grams/bw per unit increase of NRAP).

- ***Suggestive evidence of an association*** **between NRAP the risk of preterm birth** based on Low certainty in the body of evidence. Risk of 1.02 (2% increased risk of harm per unit increase of NRAP).
- ***Uncertainty of an association*** between NRAP and small for gestational age.

Table 8. Association Between NRAP Exposure and Reproductive Effects

Exposure	Contributing Review	Number of Contributing Primary Studies* (Date Range)	Relative Effect	Certainty in the Body of Evidence†
Term low birth weight				
NO_2	HEI, 2022	12 (2003–2017)	RR 1.01; 95% CI: 0.99–1.03 per 10μg/m^3	High
EC	HEI, 2022	5 (2008–2017)	RR 1.01; 95% CI: 0.99–1.04 per 1μg/m^3	Moderate
Decreased term birth weight				
NO_2	HEI, 2022	8 (2011–2017)	MD −3.2 grams; 95% CI: −11.0 to 4.6 per 10μg/m^3	Low
EC	HEI, 2022	4 (2011–2017)	MD −2.6 grams; 95% CI: -6.1 to 0.9 per 1μg/m^3	Low
Small for gestational age				
NO_2	HEI, 2022	11 (2008–2018)	RR 1.00; 95% CI: 0.98-1.02 per 10μg/m^3	Moderate
EC	HEI, 2022	3 (2008–2017)	RR 1.02; 95% CI: 0.92-1.14 per 1μg/m^3	Very Low
Preterm birth				
NO_2	HEI, 2022	14 (2002–2019)	RR 1.00; 95% CI: 0.96–1.04 per 10μg/m^3	Low
EC	HEI, 2022	5 (2011–2017)	RR 1.02; 95% CI: 0.97–1.07 per 1μg/m^3	Low

Source: CalSPEC, 2024.
Key: CI = confidence interval (a range of values that describes the uncertainty around an estimate); EC = elemental carbon; MD = mean difference; NO_2 = nitrogen dioxide; RR = relative risk ratio (the % of increased risk of harm for every unit increase of NRAP in the exposed population).
*The included studies (with sample sizes) are available in **Appendix C8.**
†Certainty in the body of evidence was based on the systematic review authors assessment of the evidence.

Respiratory Effects from NRAP Exposure

Based on evaluation of two respiratory effects from 28 primary studies included in one systematic review (HEI, 2022) (**Table 9**) CalSPEC found there is:

- ***Established evidence of an association*** **between NRAP and prevalence of ever having asthma in children** based on High certainty in the body of evidence. Risk of 1.09 (9% increased risk of harm per 10μg/m^3 increase of NRAP).
- ***Uncertainty of an association*** between NRAP and incidence of COPD.

Table 9. Association Between NRAP Exposure and Respiratory Effects

Exposure	Contributing Review	Number of Contributing Primary Studies* (Date Range)	Relative Effect	Certainty in the Body of Evidence†
Prevalence of asthma ever in children				
NO_2	HEI 2022	21 (1999–2019)	RR 1.09; 95% CI: 1.01–1.18 per 10μg/m^3	High
EC	HEI 2022	3 (2003–2015)	RR 1.30; 95% CI 0.56–3.04 per 1μg/m^3	Moderate
Incidence of COPD				
NO_2	HEI 2022	7 (2011–2018)	RR 1.03; 95% CI: 0.94–1.13 per 10μg/m^3	Low

Source: CalSPEC, 2024.
Key: CI = confidence interval (a range of values that describes the uncertainty around an estimate); EC = elemental carbon; NO_2 = nitrogen dioxide; RR = relative risk ratio (the % of increased risk of harm for every unit increase of NRAP in the exposed population).
*The included studies (with sample sizes) are available in **Appendix C8**.
†Certainty in the body of evidence was based on the systematic review authors assessment of the evidence.

Effects of NRAP Exposure on Health Conclusion

There is **well-established evidence** that NRAP increases the risk of asthma in children, diabetes, all-cause mortality, lung cancer mortality, and ischemic heart disease mortality; **likely evidence** that NRAP increases the risk of hypertensive disorders of pregnancy, ischemic heart disease, low birth weight at term, circulatory mortality, respiratory mortality, and stroke mortality; and **suggestive evidence** that NRAP increases the risk of stroke, decreased term birthweight, COPD mortality, and preterm birth.

Disproportionate Health Impacts of NRAP Exposure in California

In addition to evaluating and summarizing peer-reviewed evidence on health effects of NRAP, CalSPEC also investigated variations in exposure to NRAP to help assess health equity impacts. CalEnviroScreen is a tool that maps the distribution of environmental, public health, and socioeconomic conditions to identify communities that are more highly burdened by, or more vulnerable to, environmental pollutants (Zeise and Blumenfeld, 2021). The spatial distribution of traffic volume across California is concentrated in the most populated (urban) areas (see **Figure 1**).

CalSPEC used CalEnviroScreen 4.0 to assess which subpopulations of Californians have greater exposure to NRAP based on living in census tracts with the top 10, 20, and 50 percentiles of traffic volume. Traffic Impact Percentile is defined as the “sum of traffic volumes adjusted by road segment length (vehicle kilometers per hour) divided by total road length (kilometers) within 150 meters of the census tract (Zeise and Blumenfeld, 2021). **Table 10** displays the demographic and health characteristics of Californians living in census tracts experiencing the highest traffic volume compared with the average state volume. In this unadjusted analysis, the most striking associations are between high-traffic-volume areas and census tracts with a higher-than-average proportion of

Latinos, Asian-Americans, adults lacking a high school diploma, and households with limited English proficiency (**Table 10**).

Table 10. Demographic and Health Characteristics of Californians Living in Census Tracts with High Traffic Volume

	Census Tracts by Traffic Volume			
	State*	Top 10%	Top 20%	Top 50%
Number of census tracts	8,035	801	1,601	4,001
Population	39,283,497	3,717,192	7,781,247	19,606,016
Race/ethnicity (%)				
Asian American	14	17	18	17
Black	6	6	6	6
Latino	38	46	40	39
Native American	0.4	0.2	0.3	0.3
Pacific Islander	0.3	0.4	0.4	0.4
White	39	28	32	35
Other/Multiple	3	3	3	3
Age				
Median age of the population (5-year estimate, 2015–2019)	38	37	37	38
Percent of the population under age 10	12	12	12	12
Percent of the population aged 10–64	73	75	74	74
Percent of the population over 65	15	13	14	14
Poverty Percent of the population living below two times the federal poverty level† (5-year estimate, 2015–2019)	31	32	30	31
Uninsured Percent of the civilian noninstitutionalized population that does not have health insurance (5-year estimate, 2015–2019)	8	9	8	8
Educational attainment Percent of the population over age 25 with less than a high school education (5-year estimate, 2015–2019)	18	21	18	17
Linguistic isolation Percent of limited English-speaking households, (5-year estimate, 2015–2019)	10	12	11	11

Source: OEHHA, 2021

*The top 99% of census tracts is being used to describe state-level trends, as available in CalEnviroScreen.

†The Census Bureau uses income thresholds that are dependent on family size to determine a person's poverty status. For example, if a family of four with two children has a total income less than $25,465 during 2018, everyone in that family is considered to live below the federal poverty line. CalEnviroScreen uses a threshold of twice the federal poverty level because California's cost of living is higher than many other parts of the country (Ziese & Blumenfeld, 2021).

CalSPEC also examined *adjusted* associations between population characteristics and NRAP exposure using multivariate logistic regression (**Table 11**). Covariates that were significantly associated with NRAP exposure were retained in adjusted models. This analysis was restricted to census tracts in California with complete data on all covariates (n=7,650). Demographic variables that were evaluated include age, race/ethnicity, linguistic isolation, and sex. Socioeconomic variables included poverty, health insurance status, and educational attainment. These factors have been associated with air pollution exposure in the United States. For these analyses, data from the American Community Survey were merged with data from CalEnviroScreen 4.0.

Table 11. Odds of Census Tracts Having High Traffic Pollution* by Sociodemographic Composition

	Odds Ratios (95% CIs) (adjusted)
Race/Ethnicity†	
Latino	1.02 (0.98 - 1.07)
African American	1.18 (1.11 - 1.25)‡
AAPI	1.19 (1.15 - 1.24) ‡
White	0.83 (0.81 - 0.86)‡
Age	
Median age	1.00 (0.99 - 1.01)
Percent of the population under age 10	0.71 (0.63 - 0.81)‡
Percent of the population aged 10–64	1.13 (1.05 - 1.23) ‡
Percent of the population over 65	1.00 (0.93 - 1.08)
Socioeconomic measures	
Poverty Percent of the population living below two times the federal poverty level (5-year estimate, 2015–2019)	0.88 (0.84 - 0.92)‡
Education Percent of the population over age 25 with less than a high school education (5-year estimate, 2015–2019)	0.64 (0.59 - 0.69)‡
Uninsured Percent of the civilian noninstitutionalized population that does not have health insurance (5-year estimate, 2015–2019)	1.75 (1.53 - 2.01)‡
Linguistic isolation Percent of limited English-speaking households, (5-year estimate, 2015–2019)	1.42 (1.31 - 1.53)‡

Source: CalSPEC, 2024.

*Census tracts in the top 50% of traffic volume.

†Race/ethnicity models were adjusted for percent urban, median age, poverty, education, percent uninsured, and linguistic isolation. All other logistic regression models included percent urban, median age, poverty, education, percent uninsured, percent White, and linguistic isolation.

‡Statistical significance ($p<0.05$).

Note: All ORs (except for median age) were converted to a 10% increase before analysis. Example interpretation: For every 10% increase in the percent of the population that is linguistically isolated, a census tract has 42% higher odds of being in the top 50% of census tracts with high traffic volume.

Census tracts with higher proportions of Latino, African Americans, and Asian Americans and Pacific Islanders (AAPI) were more likely to have high traffic pollution, while census tracts with a higher proportion of Whites were less likely to have high traffic pollution after adjustment. This finding is consistent with prior research demonstrating racial and ethnic disparities in exposure to traffic pollution in California (Gunier et al., 2003; Lu et al., 2022; Weaver and Gauderman, 2018). Historically, infrastructure policies placed major roadways in Black and Brown communities. Census tracts with higher rates of linguistic isolation were also more likely to have high traffic pollution.

CalSPEC also found that census tracts with higher proportions of uninsured Californians were the most likely to have high traffic pollution, whereas census tracts with higher rates of poverty and lower levels of education were less likely to have high traffic pollution (all adjusted ORs are statistically significant). Though this finding contradicts much of the literature on this topic (Gunier et al., 2003; Houston et al., 2004; Lu et al., 2022; Ponce et al., 2005; Tian et al., 2013), other U.S. studies have found evidence for no income-based disparity or a positive association between income and exposure to NRAP (Houston et al., 2014).

Evidence of more disparities in NRAP exposure by race/ethnicity than by socioeconomic status could reflect patterns of residential segregation, with neighborhoods more segregated by race than income (Reardon et al., 2016). This finding also aligns with previous studies on environmental injustice in exposure to NRAP in the United States. (Clark et al., 2017).

These findings provide context when considering the burden of health effects from NRAP on Californians. Although the analysis is limited by use of ecological data, wide variation in the geographical size of census tracts, and focus on place of residence rather than place of work (where exposures may be higher) (Park and Kwan, 2020), the results underscore the need to center equity in the design and implementation of mitigation strategies around NRAP.

Disproportionate Health Impacts Conclusion

CalSPEC found that communities of color (Black, Latino, and AAPI), those experiencing linguistic isolation, and the uninsured are more likely to live in areas with higher traffic pollution.

Near roadway air pollution might be exacerbating health inequities.

Conclusion

Based on the available evidence from the included systematic reviews, CalSPEC concludes:

- There is *Established Evidence* that NRAP increases the risk of ever having asthma in children, diabetes, all-cause mortality, lung cancer mortality, and ischemic heart disease mortality.
- There is *Likely Evidence* that NRAP increases the risk of hypertensive disorders of pregnancy, ischemic heart disease and coronary events, low birth weight at term, circulatory mortality, respiratory mortality, and stroke mortality.
- There is *Suggestive Evidence* that NRAP increases the risk of stroke, COPD mortality, decreased term birth weight, and preterm birth.
- People of color, those experiencing linguistic isolation, and those lacking health insurance are most likely to live in areas of California with high traffic pollution.
- Though reviews categorized as Tier 2 evidence (shown only in **Appendix C9**) are limited due to the absence of a rigorous evaluation of the certainty of evidence, these results

nevertheless demonstrate strong evidence that NRAP is associated with other diseases and mortality because of their magnitude of effect and consistent direction of effect. There is an opportunity for future research to evaluate the certainty of the evidence for additional health effects from NRAP exposure.

In summary, many serious adverse health effects of near-roadway air pollution are well established. These findings support continued efforts to reduce NRAP levels as much as possible consistent with economic feasibility and other societal values.

CalSPEC was unable to specifically assess the health impacts of near-roadway *indoor* air pollution. However, because outdoor air pollution is a major source of indoor air pollution, it is reasonable to assume that curtailing traffic-related air pollution through source control (e.g., reducing traffic volume, increasing use of low-emission vehicles) will result in less indoor air pollution and fewer adverse human health effects (given that most Californians spend most of their time indoors). In addition, as described in Chapter 3 of this report, other outdoor controls such as barriers or “sinks” as well as indoor controls such as enhanced building design or filtering may help mitigate the effects of traffic-related pollution by preventing pollutants from entering buildings or removing them once they enter.

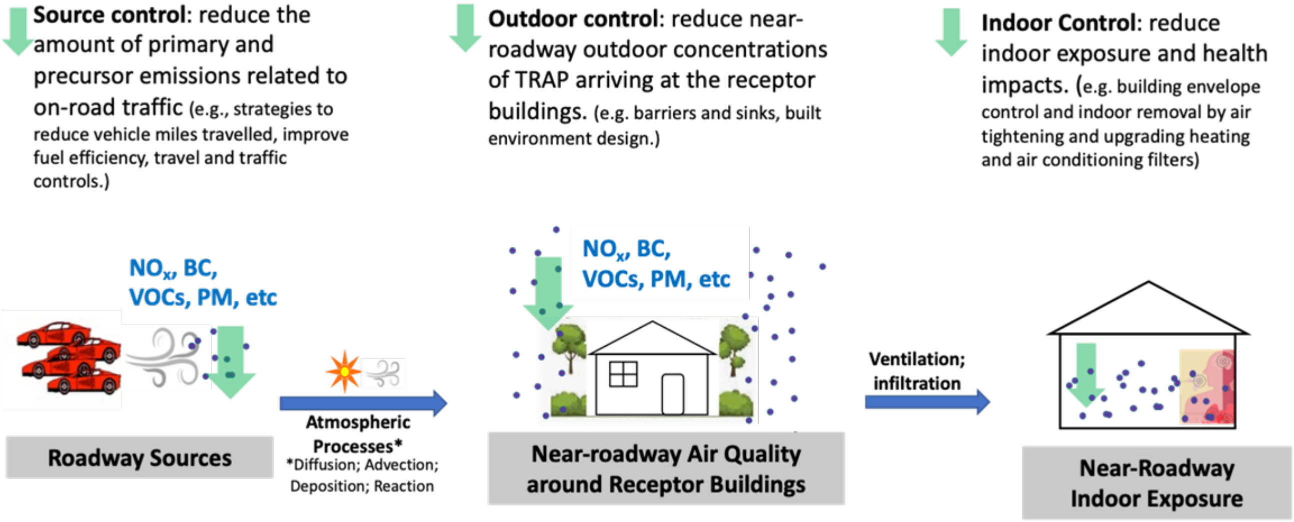
CHAPTER 3: MITIGATION STRATEGIES

Introduction

Broadly speaking, there are only three ways to reduce near-roadway indoor air pollution: (1) reduce the production of pollutants by vehicles on roadways (source control); (2) prevent near-roadway pollutants from getting close to or inside of buildings (outdoor control); and (3) diminish indoor concentrations of pollutants (indoor control). These strategies are depicted schematically in **Figure 4**.

Source control strategies aim to reduce the emissions of near-roadway air pollution (NRAP) or its precursors at the source from vehicular traffic. *Outdoor NRAP control strategies* aim to reduce outdoor concentrations of traffic-related air pollution after they have already been emitted into the air outside and before they have entered indoors. *Indoor NRAP exposure control strategies* include preventing NRAP from entering residences, schools, and offices as well as reducing human exposure and health risks after pollutants have made their way indoors.

Figure 4. Overview of the Near-Roadway Indoor Air Pollution Exposure Continuum and Points of Pollution Control



Source: CalSPEC, 2024.

Key: BC = black carbon; NO$_x$ = nitrogen oxides; PM = particulate matter; VOCs = volatile organic compounds.

This chapter addresses two key questions:

1. To what extent have specific mitigation strategies (source control, outdoor control, and indoor control) been effective in reducing near-roadway indoor air pollution?
2. What is the relative cost (or when available, cost-effectiveness) of these strategies?

Literature Search and Evaluation Methods

Working with a research librarian, CalSPEC used keywords to search relevant databases to identify systematic and narrative reviews assessing the effectiveness or cost-effectiveness of the three broad control strategies. Twenty-six of 718 articles met the inclusion criteria (9 assessing on-road source control strategies, 10 outdoor NRAP control, and 12 indoor NRAP exposure control). Studies were selected for inclusion based on their use of empirical data (systematic review or data synthesis) or unique contributions (coverage of interventions not touched upon in the systematic reviews and/or focus on cost-effectiveness). Further details of the article selection process are provided in **Appendix D**.

Rating the Evidence

CalSPEC rated near-roadway air pollution (NRAP) mitigation strategies based on the systematic review authors' assessments of the quality of the body of evidence; direction and magnitude of effect estimates (consistently positive results among many studies would receive greater weight than conflicting results among the same number or fewer studies); and confidence in the effect estimates (e.g., diverse methods converging on a single result). Additionally, other compelling attributes of the data were sometimes used in assigning a weight of evidence grade. Based on these factors, CalSPEC rated the evidence as sufficient, moderate, or insufficient (See **Appendix D**).

Cost and Cost Effectiveness Assessment

The cost of mitigation strategies is sparsely reported in the literature. CalSPEC found 16 relevant cost-related review articles that met inclusion criteria. Each included qualitative and subjective cost assessments, mostly focused on the cost and complexity of *implementation.* Additional details are provided below and in **Appendix E.**

On-Road Source Control Strategies to Improve Near-Roadway Air Quality — Findings

CalSPEC assessed the effects of source control strategies by summarizing the changes in on-road emissions and resulting NRAP concentrations associated with the interventions reported in the nine systematic reviews meeting inclusion criteria. These reviews rarely reported changes in health outcomes. A summary of the evidence rating and size/direction of effects for each mitigation strategy category is presented in tabular form followed by descriptive text and a conclusion box.

This report addresses **two broad sets of source control strategies:**

1) Vehicle technology advances and adoption driven by policy and regulations; and
2) Travel and traffic management.

Vehicle Technology Advances and Adoption Driven by Policy and Regulations

Vehicle technology advances are driven by policies and regulations that seek to shift the composition of vehicle fleets and freight systems to improve the environmental performance of vehicles. These improvements can be achieved through the use of alternative powertrains (e.g., electric motors), alternative fuel content or type, or exhaust treatment technologies. These source control strategies target the types of vehicles used by travelers and the types of fuel used to power them.

Clean Vehicle Technologies for Reducing Emissions

Various state- and federal-level policies and regulations have provided incentives for the manufacture, sale, and use of *clean vehicle technologies.*[4] Important examples include zero emission vehicle (ZEV) sales mandates (e.g., California's 2035 Zero Emission Vehicle Mandate[5]), ZEV purchase incentives (e.g., California Clean Vehicle Rebate Project;[6] Federal Inflation Reduction Act 2022), and alternative fuel regulation (e.g., Energy Independence and Security Act of 2007). These initiatives, and others (CARB, 2023d) seek to promote the adoption of low emission or zero emission alternative fuel vehicles (such as battery electric, plug-in hybrid electric, hydrogen fuel cell, and renewable fuel vehicles) to decarbonize the transportation sector as well as reduce on-road emission rates.

In assessing the potential for clean vehicle technologies to mitigate near-roadway air pollution, CalSPEC considered both the generation of *on-road emissions* and their diffusion and persistence in the near-roadway environment. **There is moderate evidence that clean vehicle technologies can reduce *on-road source* emissions.** The rating is moderate rather than sufficient, as the effects varied greatly depending on the types of pollutants, ZEV market penetration, baseline emission rates, and lack of diversity in the assessment methods.

Most of the included systematic reviews evaluated emission changes from the *lifecycle perspective*. The lifecycle emissions of clean vehicles account for vehicle manufacturing, on-road source emissions, and induced emissions from power grid for charging. However, this CalSPEC evaluation is focused on the *on-road source* portion as these emissions are most relevant to NRAP. The current fleet share of clean vehicles is low. As a result, most of the primary studies summarized in the included reviews used modeling approaches (emission modeling and/or air quality modeling) instead of real-world measurement to evaluate the changes in emissions and/or ambient concentrations. Only one primary study (Kim and Shon, 2011) measured the local air quality change (i.e., concentrations) due to a real-world intervention (Burns et al., 2020).

CalSPEC's findings concerning on-road source emissions are summarized here and in **Table 12**. Additional information may be found in **Appendix E.**

- Requia et al. (2018) found greater potential of clean vehicles to reduce gaseous pollutant emissions (by 20% to 50%) than to reduce particulate matter pollutants. Variation in reductions is attributable to the type of clean vehicles, countries with different baseline emissions, and market penetration levels. While EVs can eliminate on-road tailpipe and evaporative emissions entirely, they are generally 24% heavier than conventional vehicles and thus require more braking power and produce more tire and road wear particulate pollutants (Timmers and Achten, 2016). Requia et al. (2018) found zero emission vehicles (ZEVs) may also have negative effects under conditions of high penetration (i.e., as ownership of ZEVs increases) due to pollution produced by powerplants and brake- and tire-wear particulates.

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[4] https://ww2.arb.ca.gov/our-work/programs/advanced-clean-cars-program/advanced-clean-cars-ii

[5] https://www.energy.gov/lpo/inflation-reduction-act-2022#:~:text=The%20President's%20Inflation%20Reduction%20Act,energy%20manufacturing%2C%20and%20putting%20the

[6] https://www.epa.gov/greeningepa/energy-independence-and-security-act-2007#:~:text=Signed%20on%20December%2019%2C%202007,and%20improve%20vehicle%20fuel%20economy.

- Machado et al. (2021) reported lifecycle emission changes in the medium and heavy-duty vehicle sectors without isolating the effects on on-road emissions. Overall, Machado et al. (2021) found an ambiguous direction of effect in reducing PM emissions.

Additionally, CalSPEC found insufficient evidence as to whether emerging clean vehicle technologies (e.g., electric vehicles) reduce pollutant concentrations and improve ambient air quality (i.e., the concentration of pollutants in the air near roadways). Considerable uncertainty remains due to gaps in existing research. The evidence derived from included reviews is moderate due to: (1) lack of specification of the spatial context (whether the concentration changes were measured near roadways or regionally) and (2) mixed and varying effects depending on the types of pollutants and scenario assumptions. Although generally insufficient, existing evidence suggests that adoption of clean vehicles reduces gaseous pollutants (NO_2 being the most studied) but may marginally worsen the concentration of particulate pollution. For example, Burns et al. (2020) found a 14.7% increase in PM_{10} concentrations and no clear change for NO_2 associated with the Natural Gas Vehicle Supply program that led to the introduction of natural gas-powered buses in South Korean cities.

In terms of cost, a review by Ayodele and Mustapa (2020) indicated the total life cycle cost of EVs (including tangible and intangible costs) is approximately $100,000 across makes and models of EVs studied. Although ZEVs are currently more expensive on average than internal combustion engine vehicles, purchase costs of EVs are declining rapidly, driven in part by declining battery costs. Between 2007 and 2014, industry-wide costs of lithium-ion battery packs fell by more than 50% (Nykvist and Nilssom, 2015). The situation will likely continue to improve as market penetration for EVs increases (Ayodele and Mustapa, 2020).

Long-Term Policies to Improve Fuel and Emission Standards

Vehicle fuel content, internal combustion process, and exhaust treatment may have a significant influence on tail-pipe emissions of conventional vehicles. Air pollution control policies, such as fuel/emission standards, may reduce on-road emission rates by regulating fuel content, improving combustion efficiency, and treating tail-pipe exhaust (**Table 12**).

- CalSPEC found sufficient evidence that these long-term air pollutant control policies are effective at reducing *on-road* emissions. Several primary studies included in Rawat and Kumar (2023) and Henneman et al. (2017) indicate that improved fuel and emission standards are associated with a decrease in on-road emissions. In particular, car tailpipe emissions have been reduced by up to 99% since 1970 when the Clean Air Act was implemented (Rawat and Kumar, 2023). Enforcement of emission control devices installed on vehicles, such as diesel particle filters and diesel oxidation catalysts, reduced truck PM emissions by up to 87%. Ultra-low sulfur diesel coupled with diesel oxidation catalysts reduced the ultra-fine particle emissions by 40% to 50% from buses.

Despite these clear-cut effects on tailpipe emissions, the evidence that fuel and emission standards reduce *near-roadway* air pollution specifically is rated moderate because studies did not specify where measurements were taken (i.e., samples obtained close to roadways versus samples obtained from the broader local environment). Burns et al. (2020) included two real-world interventions and reported an 8% decrease in CO concentrations after restricting oxygen content of gasoline in winter months in California and a 22.5% reduction in NO_2 after the NO_x/PM law was enforced in designated areas in Japan. Henneman et al. (2017) concluded that a decrease in NRAP was observed after the enforcement of various air pollution control policies (8 primary studies conducted internationally, see “Source Control Detailed” tab in **Appendix E1**). However, no quantitative data were reported. Again, it is unclear in these review articles whether these effects were measured near roadways or at regional scales. Although these vehicle technology-related interventions, which rely on regulatory drivers, can reduce long-term on-road emissions, the cost of implementation (from installation to operation and maintenance) is high (Rawat and Kumar, 2023). This is due in part to impacts on automakers and their upstream suppliers. Some of these costs are likely to diminish with time due to economies of scale.

Vehicle Technology Advances and Fuel/Emission Standards: Summary of Findings on Effectiveness and Weight of Evidence

Evidence for effectiveness of emerging clean vehicle technologies is rated moderate for tailpipe emission reductions and insufficient for improving near-roadway air quality. The evidence for long-term policies that enforce improved fuel and emission standards is more robust (**Table 12**).

Table 12. Evidence Rating of the Effectiveness of Vehicle Technology Advances*

Strategies	Evidence Rating		Effects of Strategy on Reducing:	
	On-road source emissions	Near-roadway concentrations	Total on-road source emissions	Near-roadway concentrations
Emerging vehicle technology advances and adoption	Moderate	Insufficient	From <20% to >50% fleet reduction in gaseous pollutants. Inconclusive for PM pollutants.	Inconclusive
Long-term policies that improve fuel and emission standards	Sufficient	Moderate	Reduction up to 99% measured long-term.	Reduces near-roadway concentrations†

Source: CalSPEC, 2024.

Notes on effects: **Inconclusive***:* both positive and negative effects are found or effects are inconclusive due to confounding factors. **N/A:** speculative or not evaluated.

Note: Emerging vehicle technology refers to powertrain type, fuel, and exhaust emission control devices that are part of the vehicle itself.
*Effects of Strategy were quantitative, inconclusive, speculative, or not available (N/A).
†Due to lack of quantitative assessment in the review articles included; nevertheless, the directionality is clear.

Conclusions about Emerging Vehicle Technology Advances and Adoption Driven by Policy and Regulations

Across the interventions assessed, CalSPEC found (1) **moderate evidence** that emerging vehicle technology adoption to decarbonize the transportation sector is effective reducing on-road emissions for gaseous pollutants, while their effects on particulate matter pollution were inconclusive, and (2) **sufficient evidence** that long-term interventions such as tightened fuel/emission standards are effective in reducing on-road vehicular emissions.

Travel and Traffic Management

Travel and traffic management strategies aim to reduce on-road vehicular emissions by reducing motorized travel in each region or improving vehicle dynamics (e.g., speed management leading to lower emission rates). As depicted in **Table 13**, CalSPEC grouped these strategies into the following categories:

- Operating restrictions and pricing
- Lane and speed management
- Traffic flow control
- Eco-driving and eco-routing
- Vehicle miles traveled and trip reduction

Operating Restrictions and Pricing

Mandatory restrictions (such as vehicle restrictions during major events and access restrictions) and pricing incentives (such as congestion pricing, parking supply and pricing), or combination of the two (low emission zones) are intended to reduce roadway traffic in a given area or region. The working principles of these interventions are described in **Table 13**.

Table 13. Descriptions of Key Operation Restrictions and Pricing Interventions

Intervention	Description
Vehicle operation restrictions	Vehicle operating restrictions limit vehicle access to certain areas or facilities, potentially at certain times. One common type of restriction in the literature is single-weekday driving restrictions in a city or zone based on license plate number. Facility-oriented restrictions include street closures to create pedestrian zones.
Low emission zones	An area-based pricing and operation restriction in which vehicle operations and road usage fees are determined by the emission class of the vehicle. Low emission zones typically involve the banning of high-emitting vehicles or differential cordon pricing.
Road and congestion pricing	Includes various types of road pricing strategies, including facility tolling, distance pricing, area pricing, or pricing based on time of day or congestion levels. Cordon area congestion pricing is a fee or tax paid by users to enter a restricted area, usually within a city center, as part of a demand management strategy to relieve traffic congestion within that area. These strategies are intended to reduce the number of vehicles by increasing the cost of operation in these regions.
Parking management	Parking management strategies impact emissions primarily through parking search activity and travel mode choices related to the cost and availability of parking.

Source: CalSPEC, 2024.

CalSPEC found moderate evidence that pricing and vehicle restriction strategies reduce on-road emissions. The evidence is rated moderate because available studies were largely based on modeling, only assessed short-term effects, and did not consider the consequences of congestion relief (e.g., the traffic volume and dynamics in and around the restricted zones may include both positive and negative spillover effects (Bigazzi and Rouleau, 2017)). The reduction in emissions found in the primary studies in Bigazzi and Rouleau (2017) is less than 50% under the pricing interventions and varies from less than 20% to greater than 50% under the operation restriction interventions.

There is also moderate evidence that low emission zones and congestion pricing interventions reduce near-roadway air pollution.

- Burns et al. (2020) and Bigazzi and Rouleau (2017) found near-roadway pollution reductions up to 25%; however, the evidence is entirely based on studies conducted in European cities with validity yet to be verified in U.S. locations.

CalSPEC found insufficient evidence for operation restriction and parking management due to the lack of primary studies or inconsistent effects.

- In the review by Burns et al. (2020), Davis (2008) observed a significant increase in NO_x and NO_2 concentrations after even-odd license plate restrictions, which was likely due to the confounding of meteorological factors during the evaluation period.

Lane and Speed Management

Lane management strategies

High occupancy vehicle lane/toll/eco-lanes, truck and/or bus lanes, and lane capacity changes (“road diets,” peak shoulder running) are designed to help reduce overall vehicle miles traveled as well as alleviate congestion and therefore reduce average emission rates. **These types of interventions are insufficiently studied, and their effects on emissions and roadway air quality are uncertain.**

Speed management strategies

High speeds (>55 mph) on highways are associated with increased per-vehicle tailpipe emission rates. These increases result from power outputs as well as increased non-tailpipe emissions due to greater tire wear and resuspension of road dust (CARB, 2017b). Speed interventions such as lower speed limits, variable speed limits, and speed enforcement devices and programs are designed to limit the vehicle speed to an optimal range of 35 to 55 mph, within which per-mile traffic emissions and fuel consumption are minimized (CARB, 2017b).

Vehicle Miles Traveled is primarily affected by the number of trips taken, the length of those trips, and the mode of transportation (e.g. car, bus, train). In contrast, emission rates are affected by vehicle type, as vehicles differ by powertrain, fuel, and emission control technologies. Emission rates are also affected by traffic dynamics such as the speed and volume of vehicles that affect driving cycles (e.g., stop-and-go motion, acceleration, idling).

Strategies to reduce roadway vehicular emissions generally operate by reducing the amount of travel, average emission rates, or both. Total emissions are equal to the product of these factors.

Lowering speed limit is the most studied intervention under this category (8 primary studies) with varying effects on reducing *on-road source emissions*. On-road vehicle emissions can be reduced by up to 27% across the primary studies reviewed by Bigazzi and Rouleau (2017) and CARB (2017b). Although both modeling and field measurement studies have suggested an effect on emissions, the evidence is rated moderate because the studies were concentrated in European cities with effects varying greatly by the level of enforcement. U.S. studies have not been identified in these two included review articles for assessment of this strategy. Other types of interventions (variable speed limits, etc.) each had fewer than three primary studies included in the review articles in Bigazzi and Rouleau (2017) and CARB (2017b) and therefore had insufficient data to evaluate the effects on emissions.

CalSPEC found insufficient evidence regarding the effects on *ambient concentrations* for this type of intervention. According to Bigazzi and Rouleau (2017), existing primary studies are inconsistent and provide insufficiently clear statistical evidence. Both positive and negative effects were observed on PM_{10} and NO_x concentrations in primary studies review by Burns et al. (2020), depending on site-specific traffic conditions and country.

Traffic Flow Control

Traffic flow interventions modify the vehicle volume passing specific parts of the road each minute, aiming to reduce traffic congestion and stop-and-go motions associated with an increase in emission rates.

CalSPEC found that intersection control devices and traffic signal timing were the most studied interventions (with 3 and 5 primary studies, respectively), while other types, such as ramp metering, toll collection, and tunnels have been studied less (fewer than 3 primary studies).

Intersection control device interventions use arterial intersection controls to improve traffic flow and reduce emissions, for example, using roundabouts to replace stop signs. Traffic signal timing interventions aim to improve the performance of signalized intersections, most often in terms of delay and travel time, along with other objectives including transit operations and emissions.

CalSPEC found moderate evidence that intersection control devices (roundabouts) or signal timing reduce *roadway emissions*. While several studies suggested roundabouts can be effective in reducing per vehicle emissions by up to 50%, the results were not consistent across site-specific conditions with different road speed and vehicle volume (Bigazzi and Rouleau, 2017; CARB, 2017b). Both CARB (2017b) and Bigazzi and Rouleau (2017) indicated that more comprehensive and long-term research and evaluation were needed.

CalSPEC found insufficient evidence of traffic flow controls to reduce *ambient concentrations* of pollutants due to an insufficient number of primary studies.

Eco-Driving/Eco-Routing

Eco-driving/routing is a type of behavioral intervention that seeks to optimize emission-related driving cycles (e.g., by lowering speed, making speed more consistent speed, avoiding idling, avoiding rapid braking and acceleration, and reducing hauling weight) and/or driving routes by influencing drivers' behavior. It is often considered a more cost-effective intervention because it does not require upgrades of vehicle powertrains or any new infrastructure (Bigazzi and Rouleau, 2017).

CalSPEC found moderate evidence for beneficial effects of eco-driving/routing on emissions. The real-world scalability of behavioral changes is uncertain, and the long-term effects (> 1 year) have yet to be fully evaluated.

- Five primary studies included in Bigazzi and Rouleau (2017) indicated less than 20% reduction of traffic emissions, while Tu et al. (2022) reported that one on-road study showed up to a 65% NO reduction in immediate response to dynamic eco-driving guidance, with no long-term effects reported.

CalSPEC found no evidence about eco-driving effects on *near-roadway* ambient pollution concentrations.

VMT/Trip Reduction Strategies

VMT/trip reduction strategies aim to reduce the amount of motorized travel through shared-ride programs, telework programs supported by employers, better public transit, more extensive walking/biking paths, and increased outreach and marketing to promote change in consumer behavior.

CalSPEC found insufficient evidence regarding the effects on emissions or ambient concentrations due to the lack of primary studies (fewer than 3 primary studies were found across all interventions: 2 for employer programs, 1 for transit improvement, and 0 for the rest).

Summary of Evidence about Travel and Traffic Management Strategies

Like the technological innovations of the prior section, the evidence for effectiveness of travel and traffic management strategies is more robust for on-road source emissions than for near-roadway pollution concentrations. Based on the available literature, the most promising strategies appear to be road congestion pricing, vehicle operation restrictions, lower speed limits, intersection control devices such as roundabouts, and traffic signal timing (**Table 14**).

Table 14. Summary of the Evidence Ratings and Effectiveness of Travel and Traffic Management Strategies

Strategies		Evidence Ratings		Effects of Strategy on Reducing	
		On-road source emissions	Near-roadway concentrations	On-road source emissions	Near-roadway concentrations
Operating restrictions and pricing	Road congestion pricing	Moderate	Moderate	<50%	<25%
	Low emission zones	Moderate	Moderate	<50%	<25%
	Vehicle operation restrictions	Moderate	Insufficient	Varies from <20% to >50%	Inconclusive
	Parking management	Insufficient	Insufficient	N/A	N/A
Lane management	High occupancy lanes, bus lanes, etc.	Insufficient	Insufficient	N/A	N/A
Speed management	Lower speed limits	Moderate	Insufficient	<27%	Inconclusive
	Variable speed limit; speed timing; speed	Insufficient	Insufficient	N/A	N/A

Strategies		Evidence Ratings		Effects of Strategy on Reducing	
		On-road source emissions	**Near-roadway concentrations**	**On-road source emissions**	**Near-roadway concentrations**
	enforcement programs				
Traffic flow control	Intersection control device	Moderate	Insufficient	<50%	N/A
	Traffic signal timing	Moderate	Insufficient	<50%	N/A
	Ramp meters, toll collection, incident management systems	Insufficient	Insufficient	N/A	N/A
Eco-driving/ eco-routing	Eco-driving/ eco-routing	Moderate	Insufficient	<20%	N/A
VMT/trip reduction strategies	Employer programs, transit improvement, etc.	Insufficient	Insufficient	N/A	N/A

Source: CalSPEC, 2024.

Notes on effects: **Inconclusive***:* both positive and negative effects are found or inconclusive due to confounding factors. **N/A:** speculative or not evaluated.

Cost Effectiveness of Travel and Traffic Management Strategies

Among the travel and traffic management strategies, lower speed limits and eco-driving are the top-ranking strategies in terms of their cost effectiveness for improving air quality, largely because they do not require costly investment in infrastructure or significant technology improvements (**Table 15**). Road congestion pricing, low emission zones, and traffic signal timing management were considered less cost-effective than speed management and eco-driving strategies.

Table 15. Cost Considerations Related to Traffic Management Interventions (Excluding Strategies with Insufficient Evidence) (Extracted from Bigazzi and Rouleau, 2017)

Strategies Assessed	Cost and Complexity of Implementation	Effectiveness
Operation restrictions and pricing		
Road and congestion pricing (RCP)	**Medium.** Costs depend on scale of application and level of enforcement; potential for revenue to offset costs; public acceptance can be an obstacle but can be surprisingly high if the public perceives benefits in traffic operations.	**Medium.** Depends greatly on administration and price levels and how revenues are used.

Strategies Assessed	Cost and Complexity of Implementation	Effectiveness
Operation restrictions and pricing		
Low emission zones	**Medium.** Like RCP strategies, costs depend on scale of application and level of enforcement; public acceptance can be a major obstacle.	**Medium.** Moderate ex ante estimates are available; generally similar to effects of area RCP strategies.
Vehicle operating restrictions	**High.** Public opposition and enforcement are major challenges to implementation.	**Low.** Potentially not cost-effective in the long-run due to vehicle ownership effects and lack of efficacy in air quality improvements. Strong VOR may be subject to high levels of non-compliance, which can significantly reduce effectiveness.
Speed management		
Lower speed limits	**Low-medium.** Potentially strong public opposition from travelers and freight companies; costs depend on enforcement.	**High.** Most costs are generated by enforcement, some of which can be offset through fines.
Eco-driving/eco-routing		
Eco-driving	**Low.** Unlikely to generate public opposition and potentially inexpensive, depending on the type of implementation.	**High.** Costs and effectiveness are both highly uncertain, but cost effectiveness is likely high relative to more infrastructure-based interventions.
Traffic flow control		
Intersection control devices (such as roundabout)	**High.** Roundabouts and signalized intersections are costly; public acceptance of roundabouts in North America can be a challenge.	**Low.** Highly uncertain.
Traffic signal timing	**Low-medium.** Much can be done using existing expertise and systems; new hardware for adaptive and coordinated systems is widely used and well proven.	**Medium.** Variations with amount of new hardware required.

Source: CalSPEC, 2024, based on Bigazzi and Rouleau, 2017; Anas and Lindsey, 2011; Eliasson and Jonsson, 2011; Gallego et al., 2013; Kalra et al., 2012; Porter et al., 2010; Puckett et al., 2015; Wang et al., 2014.
Note: Cost data are sparsely reported in the literature. No clear quantitative definitions of the cost scales were provided; therefore, cost data and cost effectiveness are described in a qualitative and narrative fashion, relying mostly on the assessment by the included review papers.

Travel and Traffic Management Conclusion

Across the interventions assessed, CalSPEC found **moderate evidence** that the following interventions are effective in reducing on-road source emissions: road congestion pricing, vehicle operation restrictions, lowering speed limits, intersection controls with roundabouts, traffic signal timing, and eco-driving/routing, with more restrictive speed limits and eco-driving/routing being the most cost-effective. CalSPEC found overall **insufficient evidence** on whether these interventions might result in an improvement in near-roadway air quality. The **most cost-effective strategies** were lower speed limits and eco-driving. Road congestion pricing, low emission zones, and traffic signal timing management were found to be **less cost-effective**.

Outdoor NRAP (Ambient) Control Strategies — Findings

Once pollutants have moved from roadways into the atmosphere, outdoor NRAP (also known as ambient) control strategies aim to reduce concentrations around buildings (including residences, schools, and offices). As detailed in **Appendix E**, major strategies adopted to address ambient control include:

- Obstacles and sinks, including green infrastructure and non-vegetation barriers; and
- Built environmental design, including configuration of street canyons, building architecture, and land use buffers.

Obstacles and Sinks

Obstacle: provides a barrier to pollution
Sink: natural or artificial reservoir (e.g., plants, bodies of water, or soil) that absorbs, stores, or breaks down pollutants

Constructing obstacles and sinks within the built environment can mitigate localized traffic-related air pollution in three ways (adapted from Li et al., 2021):

- Creating barriers between the pollution source (roadway) and receptor (building) (e.g., sound walls, parked cars, roadside hedges, and low boundary walls);
- Increasing pollutant dispersion or dilution through improved ventilation and turbulence control (e.g., wind catchers, solar chimneys); and
- Reducing pollutant levels by introducing pollutant sinks (green walls/roofs, green spaces).

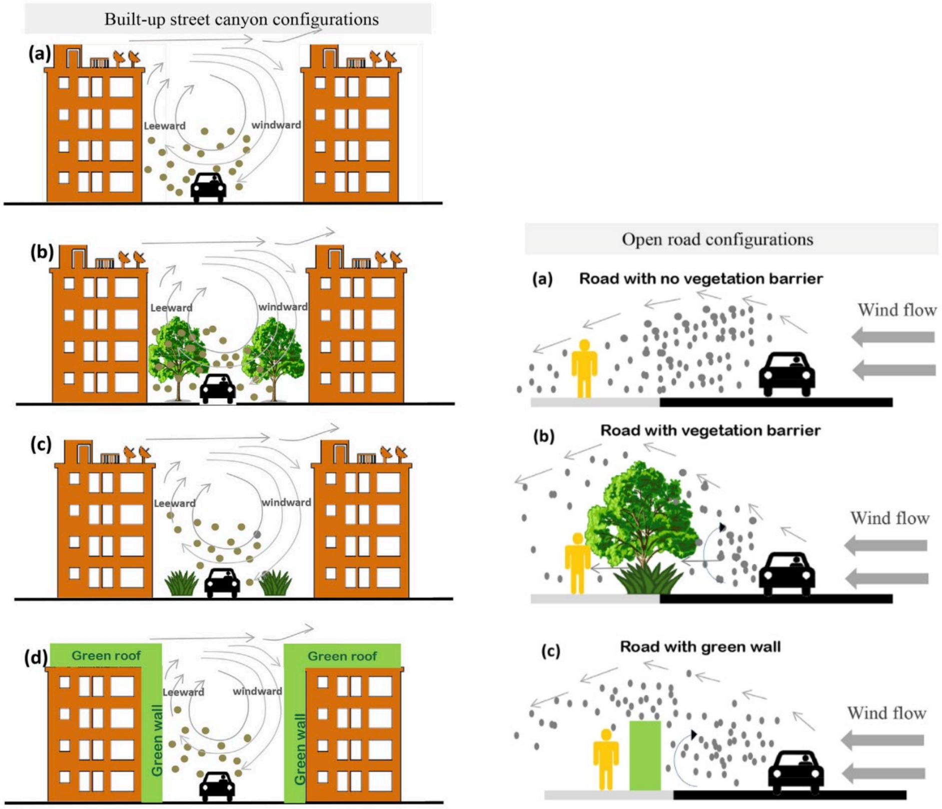
Green/Vegetation Obstacle and Sink Infrastructure

Roadside green infrastructure (GI) can serve both as a barrier and a pollutant sink that removes pollutants by absorption through leaf stomata or by deposition to plant surfaces. **CalSPEC concludes that there is moderate evidence that green infrastructure improves ambient air quality.** The weight of evidence is rated moderate rather than sufficient because available studies have produced highly varied effect estimates, influenced by site characteristics, street canyon geometry, meteorological conditions, measurement locations, and season. Most studies were conducted on the East Coast and in Europe where vegetation types and densities differ from what is found in California (CARB, 2017b). Further research is needed to accurately determine the effects of this type of strategy in California in terms of climate, vegetation types, and typical built environment.

Although the evidence is rated moderate, this type of strategy can be effective, potentially reducing ambient pollution by more than 50% when implemented appropriately and under the right conditions:

- As reviewed by Abhijith et al. (2017), high-level GI, such as trees, results in a ***reduction*** in pollutants of at least 50% in open streets but an ***increase*** in street canyons. In street canyons, tree species with lower heights and thin tree trunks are recommended in order to allow wind penetration (Voordeckers et al., 2021). More generally, the effects of street canyon geometry and building architecture are depicted in **Figure 5**.

Figure 5. Green Infrastructure in Street Canyon and Open Road Settings (Adapted from Abhijith et al., 2017)



- Low-level GI, such as hedges, deliver more consistent effects: a 24% to 61% pollution reduction in the footpath areas within street canyons and a 15% to 60% reduction around open streets. The review by Rawat and Kumar (2023) also found that installing GI as a physical barrier around schools reduced concentrations of near-roadway pollutants PM_{10}, NO_2, BC, and other particle number concentrations by up to 60%, 59%, 63%, and 77%, respectively as compared to control conditions.

- The meta-analysis conducted by Abhijith et al. (2017) revealed that green walls reduced air pollutants up 95% compared with the green-wall-free scenario. In the case of green rooftops, the reduction ranged from 2% to 52%. However, green walls and roofs were not as effective overall as trees and hedges.
- Trees and hedges have lower installation and maintenance costs than fully grown green walls (Rawat and Kumar, 2023). Generally green walls require a greater initial investment and more ongoing maintenance (Teotónio et al., 2021) making them a less attractive investment for building owners.

Non-Vegetation Obstacle and Sink Infrastructure

Non-vegetation obstacles and sinks include solid roadside barriers, parked cars, solar chimneys, and artificial sinks such as electrostatic precipitators that can be installed in high NRAP areas.

Based on a diverse set of field measurements and modeling studies, CalSPEC found **sufficient evidence to conclude that solid roadside barriers such as sound walls can reduce near-roadway downwind pollutant concentrations**. Similar to vegetation barriers, the effects vary greatly depending on site characteristics such as street canyon aspect ratio, wind directions, etc. (Buccolieri et al., 2022; CARB, 2017b; Li et al., 2021).

- Solid roadside barriers act as baffle plates that both redirect air flow and increase vertical air dispersion, and subsequently improve the air quality downwind of the traffic. As reviewed by Li et al. (2021) and CARB (2017b), the effectiveness of solid barriers on flow patterns and pollutant dilution has been widely researched including the use of noise barriers (over 4–5 m tall) along highways and low bound walls (1–2 m or less in height) adjacent to low-speed roadways in urban areas. Solid barriers generally result in a reduction of road-side pollution by up to 50% (CARB, 2017b). Simulation studies indicate that the number can vary further by wind directions (Li et al., 2021).

There is **moderate evidence that parked cars, artificial pollutant sinks, and solar chimneys may reduce ambient pollution;** however, the evidence is rated "moderate" because the effects were quantified based on modeling studies with no field measurements reported.

- Modeling showed the presence of parked cars led to a 15% to 49% reduction in roadside pollutant concentrations under varying wind conditions and urban geometries (Li et al., 2021).
- Artificial pollutant sinks, such as electrostatic precipitators, reduce near-roadway air pollution. Three modeling studies (Li et al., 2021) estimated that electrostatic precipitators can reduce particulate matter by 40% to 50% close by and up to 10% downstream.
- Solar chimneys are a new area of research. They represent a passive intervention and have excellent potential to remove pollutants at regional scales. Two primary studies included in Li et al. (2021) found that solar chimneys reduce pollution levels by 10% to 19% region-wide. Despite promising evidence, CalSPEC rated the evidence as insufficient due to the lack of primary studies to date.

Among these interventions, parked cars are among the least costly obstacle strategies (though they come with aesthetic and ecological downsides), and solar chimneys are currently very expensive (Buccolieri et al., 2022).

Summary of Evidence about Obstacles and Sinks

Evidence for the effectiveness of roadside structural barriers is judged sufficient, with studies suggesting decreases in pollutant exposure of up to 50% based on a diverse set of assessment methods. Evidence for the effectiveness of green infrastructure, parked cars, and artificial sinks is moderate and contingent on local architectural and airflow conditions (**Table 16**). Green infrastructure may reduce ambient pollution by 50% or more when implemented properly.

Table 16. Summary of the Effectiveness of Obstacles and Sinks Strategies

Strategies	Intervention Assessed	Evidence Rating	Effects of Strategy on Reducing Ambient Concentrations
Green infrastructure	Vegetation barriers	Moderate	**Trees:** >50% reduction near open streets; *worsen* NRAP in street canyons
			Hedges: Reduction by 15%–60% near open streets and 24%–61% in street canyons
	Green walls/roofs		**Green walls:** Reduction up to 95%, 50%, and 46% in ultra-fine particles, PM$_{10}$, and NO$_2$, respectively
			Green roofs: Reduction by 2%–52%.
Non-vegetation obstacles	Roadside barriers	Sufficient	Reduction <50%
	Parked cars	Moderate	Reduction by 15%–49%
	Artificial sinks	Moderate	Reduction by 40%–50%
	Solar chimneys	Insufficient	N/A

Source: CalSPEC, 2024.

Obstacles and Sinks Conclusion

Across the interventions assessed, CalSPEC found **sufficient evidence** that roadside barriers were effective improving local air (ambient) quality near roadways. CalSPEC found **moderate evidence** that green infrastructure such as vegetation barriers, green walls and roofs, and non-vegetation obstacles such as parked cars and artificial sink devices were effective reducing ambient pollution. CalSPEC found in general, the size of the effects, if implemented properly, was greater for green infrastructure interventions (> 50%) than non-vegetation obstacle interventions (generally < 50%).

Built Environment Design

In addition to modifying existing roadside features with obstacles and sinks, another approach to ambient control is to incorporate environmental design into future city planning processes. These interventions include innovations related to:

- Street canyon configuration

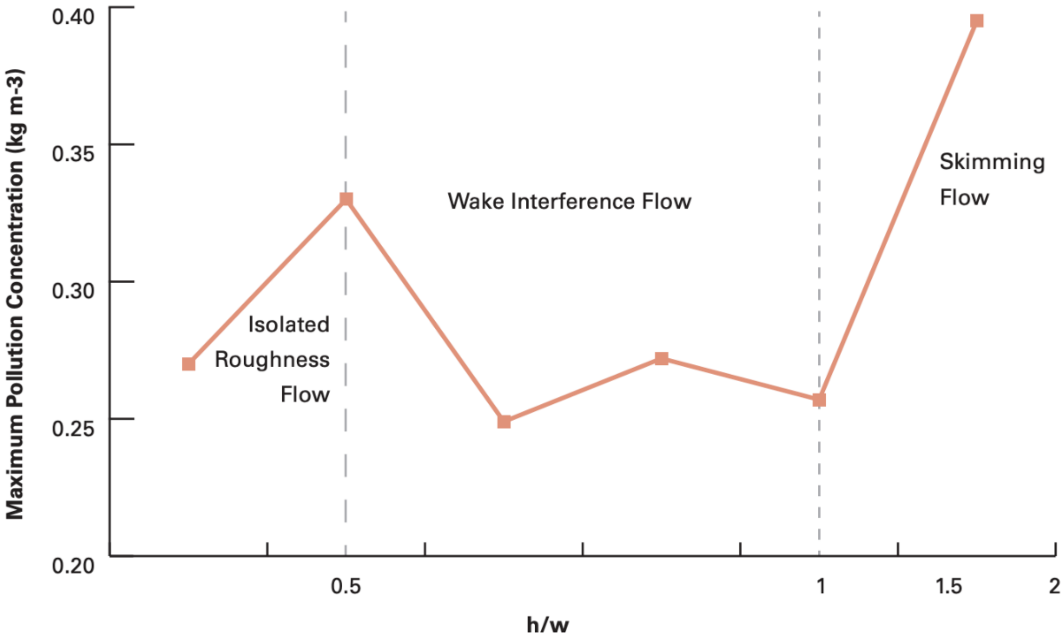
- Building architecture
- Land use buffers

Street Canyon Configuration

The physical layout of urban streetscapes influences air flow and pollution movement. Near-roadway *indoor* air pollution may potentially be reduced by optimizing street-canyon orientation, depth, and length, as well as street canyon aspect ratio (or height-to-width ratio) in order to increase the canyon ventilation and reduce the accumulation of traffic pollutants. Key findings related to this subgroup of interventions are:

- Several engineering studies support the effectiveness of smart street canyon design; CalSPEC found moderate evidence on the magnitude of resulting effects (CARB, 2017b; Voordeckers et al., 2021).
- In general, streets in parallel to the prevailing wind direction with aspect ratios that describe canyons that are wider relative to their height (i.e., with height-to-width ratios <0.65) promote better pollutant dispersion because they provide more space for ventilation flow to reach the street level Error! Reference source not found..

Figure 6. Variation of Maximum Pollutant Concentrations with Street Canyon Height-to-Width Ratio, Indicating a General Increase of Pollutant Levels with Height-to-Width Ratio When It Is Greater than 1



Source: CARB, 2017b.

Building Architecture

Architectural design of buildings such as height, setback within street canyons, roof shape, and building permeability can help with pollutant dispersion. **There is moderate evidence of**

architecture improving ambient air quality. The rating is moderate rather than sufficient because the effects of building geometry vary by canyon aspect ratio, affect small areas, and have been evaluated based on model simulations or wind tunnel experiments rather than field measurements. Key findings include:

- Sloped and pitched roofs increase ventilation and dispersion more than flat roofs in street canyons with a height less than its width (Li et al., 2021).
- Lift-up designs (elevated building design or void decks that create a semi-open space underneath the first floor of a high-rise residential buildings) can increase wind circulation and reduce daily pollutant exposure by 34%–50%. Similarly, building setbacks or arcade designs, which are implemented as a half-open space by creating an outside corridor on the side of the main building, can increase air exchange rates and reduce pollutant levels by 6%–13% depending on the canyon aspect ratios.
- Multiple buildings of varying heights can result in significant increases in turbulence and reduce pollution levels by up to 40%, and adding bike lanes and sidewalks not only reduces car traffic, but also creates space for dispersion, resulting in up to a 45% reduction in pollutant concentrations (CARB, 2017b).

The reviewed studies focused on modeling air flow rather than pollutant concentrations, and more research involving real-world measurements is needed.

Land Use Zoning and Building Placement ("Siting")

These strategies involve locating sensitive buildings (such as schools or residences) a certain distance from busy roads. Evidence from the spatial gradient of near-roadway concentrations is needed to support policy decisions on the optimal buffering distance. The current buffering distance designated by California regulators is generally 150–400 meters (Karner et al., 2010).

CalSPEC found moderate evidence for the effectiveness of land use buffers in reducing ambient pollutant levels. The determination of safe distances is complicated by site-specific conditions and varies by time of day. Pertinent findings include:

- Pollutants of traffic origin are mostly reduced to background levels around 500 meters away from the edge of the roads (Karner et al., 2010). However, these estimates vary depending on time of day and site-specific conditions.
- The report by CARB (2017b) reviewed time-of-day dependence of near-roadway concentration gradients and found the concentration of ultrafine particles decreased with distance at a much slower rate at night than during the daytime. In fact, during the pre-sunrise period, elevated pollutant levels can be observed up to 2,600 meters (8,530 feet) from the freeway (Choi et al., 2012).

Based on these and similar findings, California has implemented a number of zoning and building placement polices over the years to reduce roadway air pollution exposure, especially among sensitive populations. For example, SB 352 (Escutia) requires that new schools be sited no less than 500 feet from freeways or other busy corridors.[7] CARB issued a series of setback recommendations (CARB, 2005; CARB, 2017b) based on field measurement and modeling evidence; however, the

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[7] Schoolsites: sources of pollution. Cal Senate B 352 (2003-2004), California Education Code § 17213; California Public Resources Code § 21151.8. Available at: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200320040SB352. Accessed December 19, 2023.

number of locales adopting these recommendations for new or retrofitted construction is unknown. In 2020, CARB also updated California's 2017 General Plan with environmental justice requirements related to roadway proximity (California OPR, 2020).

Summary of Evidence about Built Environmental Design Strategies

Although available evidence points to the effectiveness of innovations in street canyon configuration, building architecture, and zoning, the evidence is moderate in each case and requires further research to determine optimal buffering zones (**Table 17**). No cost data was found in the evidence reviewed by CalSPEC.

Table 17. Summary of Evidence About Built Environment Design Strategies

Strategies	Design Parameter	Recommended Design	Evidence Rating	Effects of Strategy on Ambient Concentrations
Street canyon configuration	Canyon orientation	Streets parallel to wind directions	Moderate	Increased ventilation and reduced pollutant levels*
	Aspect ratio (AR)	Lower aspect ratio, preferably with height-to-width less than 0.65		
Building architecture	Roof shape	Pitched roofs rather than flat roofs in canyons with AR <1	Moderate	Increased ventilation and reduced pollutant levels*
	Building height	Variable building heights preferred		Reduced 40%–45%
	Building setback	Half open space outside on the side of the building is recommended		Reduced 6%–13%
	Building permeability	Lift-up design with void decks underneath the first floor		Reduced 34%–50%
Land use buffers/ siting	Separation distance from roadways	500 meters away from the roadways	Moderate	Reduce concentration from roadway edge level to background level

Source: CalSPEC, 2024.
*Directionality is reported here due to lack of a reference level to compare with or lack of quantitative results for changes in pollutant levels.

Built Environment Design Conclusion

Across the interventions assessed, CalSPEC found **moderate evidence** that the proper design of street canyon configuration, building architecture, and land use buffers/siting can_reduce the ambient pollutant levels near roadways.

Indoor Control Strategies for Near-Roadway Air Pollution — Findings

Strategies to reduce exposures to and concentrations of indoor near-roadway air pollution include building envelope control and indoor removal. These strategies seek to limit the amount of near-roadway indoor air pollution that residents and building occupants are exposed to (See **Appendix E** for more details).

Building Envelope Control

Building envelope control limits the air exchange between outdoor and indoor settings. Specifically, it refers to reducing traffic-related air pollution entering buildings through infiltration or uncontrollable ventilation.

Retrofits

Retrofits are infrastructural improvements of existing buildings and homes often implemented to improve energy efficiency (Rawat and Kumar, 2023). Retrofits seek to tightly seal air leakage pathways (e.g., windows, doors, roofs, walls, HVAC ducts) in building envelopes to reduce the rate of uncontrolled air exchange between indoors and outdoors (Fisk, 2020). Note that retrofits may not only trap indoor-generated pollutants (e.g., NO_2), but also introduce new indoor pollutants from sealant and insulation materials.

CalSPEC found insufficient evidence that retrofits reduced indoor pollutant concentrations (Fisk, 2020). There is moderate evidence that retrofits improve health outcomes. The general trend toward reported improvements in respiratory outcomes after retrofits was not explained by the measured changes in pollutant concentrations because the concentrations did not decrease (Fisk, 2020).

Ventilation Schedules and Ventilation Rates

In the near-roadway context, ventilation schedule and ventilation rates refer to keeping windows and doors closed during high traffic times and decreasing rate of indoor-outdoor air exchange to reduce ingress of polluted outdoor air. Ventilation rates vary according to frequency and timing of open windows and doors, how tightly sealed they are, and the age and seal of HVAC systems. **CalSPEC found moderate evidence for this group of interventions**. For example, some strategies (e.g., operating the HVAC system in schools one hour before the onset of rush hour) can reduce both fine particles (by 43%) and ultrafine particles (by 34%) (Fernandes et al., 2023).

Summary of Evidence about Building Envelope Control Strategies

CalSPEC found moderate evidence that changing ventilation schedules can reduce indoor pollutant concentrations. Evidence for the effectiveness of retrofits in reducing pollutant concentrations is insufficient (**Table 18**).

Table 18. Review of the weight of evidence and effectiveness of building envelope control strategies

Strategies	Evidence Rating		Effects of Strategy on Reducing:	
	Exposure/ concentrations	Health risks	Exposure/ concentrations	Health risks
Retrofits	Insufficient	Moderate	Inconclusive	Decreasing
Ventilation schedule and rates	Moderate	Insufficient	34%–43%	N/A

Source: CalSPEC, 2024.

Note: Health risks refer to whether the negative health risks increased, decreased, were mixed, or not applicable because of the subcategory of the mitigation strategy. *Notes on effects:* **Inconclusive***:* both positive and negative effects are found or inconclusive due to confounding factors. **N/A:** speculative or not evaluated.

Building Envelope Control Conclusion

CalSPEC found **insufficient evidence to support the use of retrofits or changes in** ventilation schedules and rates in the near-roadway setting.

Indoor Air Pollution Control

Indoor removal refers to removing traffic-related air pollution once inside using filtration, such as air cleaners and purifiers, and phytoremediation, such as green walls.

Filtration

Filtration includes portable high-efficiency air cleaners and air purifiers, mechanical filtration including HEPA (high-efficiency particulate air) filtration, and heating, ventilation and air conditioning (HVAC) systems with high efficiency filters in residences, schools, and offices. Filters are available in Minimal Efficiency Reporting Value (MERV) ratings ranging from 1 to 16. HEPA filters offer slightly higher filtration efficiencies than MERV 16 (Azimi et al., 2014).

To ensure the highest filtration efficiency, regular operation and maintenance is necessary (CARB, 2017b). Filtration lowers particle concentrations indoors and is effective even when the outdoor concentrations of particles are high (Rawat and Kumar, 2023). Although air purifiers are effective in removing particles and aerosols, they do not supply fresh air to the room, so they work better with pre-installed HVAC systems when possible (Rawat and Kumar, 2023). Mechanical ventilation contains in-duct filters that remove some air pollutants (CARB, 2017b).

CalSPEC found sufficient evidence that filtration reduces pollutant concentrations within buildings.

Across studies, filtration reduced 20% to 90% of particulate matter concentrations depending on the setting (residences, schools, offices), type of filter, and ambient concentrations of outdoor pollutants (CARB, 2017b; Cheek et al., 2021; Fernandes et al., 2023; Rajagopalan et al., 2020; Rawat and Kumar, 2023; Walzer et al., 2020). HVAC systems with high MERV filters (13–16) are more efficient than those with low MERV filters (Rajagopalan et al., 2020; Rawat and Kumar, 2023). Because field testing reveals that filters with the same MERV rating from different manufacturers can deliver significantly different results, using filtration with the highest MERV HEPA rating possible is recommended. See detailed findings in the “Exposure Control Detailed” tab in **Appendix E1.**

Findings regarding filtration effects on health were mixed, with some studies suggesting benefits of filtration with respect to systolic blood pressure (Rajagopalan, 2020), allergies and asthma (Cheek, 2021; Kelly and Fussel, 2019), respiratory symptoms (Rajagopalan et al., 2020), and microvascular function (Kelly and Fussell, 2019).

The cost of filtration interventions ranges from moderately low for portable or wall mount air purifiers to high for installation of HVAC systems with efficient filters (Rawat and Kumar, 2023). The average cost of a low-power portable air cleaner with the capacity to clean a middle-sized living room costs less than $250 using portable air cleaners exceeded intervention expenditures ($445 million in benefits vs. $368 million in costs) (Kelly and Fussell, 2019). Although the cost of portable air filter installation is relatively low, operation and maintenance costs may be high depending on the size of the room to be cleaned and frequency of filter changes with higher rated MERV filters costing more than lower rated filters (Rawat and Kumar, 2023). In comparison with portable filters, HVAC systems with high efficiency filters cost more to install, operate, and maintain. Cost-effectiveness may increase by prioritizing retrofits of the homes of vulnerable populations, such as the elderly (Kelly and Fussell, 2019).

Phytoremediation

Phytoremediation refers to reduction of indoor pollutants by indoor plants, green walls, and other forms of vegetative pollutant sinks that purify indoor air**.** These interventions can complement the role of outdoor vegetation. **CalSPEC found moderate evidence that phytoremediation strategies reduce indoor air pollution** (Fonseca et al., 2023; Kumar et al., 2023). Several studies confirmed plant efficiency for removing different types of VOCs and other indoor pollutants; efficiency varied according to plant species and placement (e.g., pots or living walls). Reported concentration reductions ranged from less than 30% to more than 90% depending on the type of phytoremediation, room size, and type of pollutant. Effects on VOCs were especially pronounced, and vertical greenery systems seemed particularly efficient.

Summary of Evidence about Indoor Air Pollution Control Strategies

Indoor filtration and phytoremediation appear effective in reducing exposure to particulate pollutants and to VOCs (**Table 19**). The practicality of these two approaches has been questioned, because they rely on individual households and building managers for implementation.

Table 19. Summary of evidence about indoor air pollution control strategies

	Evidence Rating		Effects of Strategy on Reducing:	
Strategies	Exposure/ concentrations	Health risks	Exposure/ concentrations	Health risks
Filtration	Sufficient	Moderate	Air purifiers: 22.6%–92% reduction Air purifiers with HEPA: 30%–90% reduction HVAC systems with high efficiency filters: 30%–99% reduction	Mixed
Phytoremediation	Moderate	Moderate	28%–93%	Low

Source: CalSPEC, 2024.

Indoor Air Pollution Control Conclusion

CalSPEC found **sufficient evidence** that indoor air filtration reduces pollutant concentrations, but mixed evidence of its effectiveness on intermediate health outcomes. There is **moderate evidence** that phytoremediation can reduce indoor air pollution.

Conclusion

Based on this review of reviews, CalSPEC identified broad strategies covering on-road source, outdoor, and indoor exposure control. Strategies supported by the *most rigorous studies and demonstrating the greatest effects* include:

- **Advancements in vehicle technologies,** especially long-term improvements to comply with tightened fuel and emission standards
- **Roadside obstacles and sinks**, especially roadside barriers, such as soundwalls
- **Indoor removal through filtration**

Among these three strategies, the indoor removal strategy does not require additional costly construction and deployment and can be applied locally. In particular, the installation, operation, and maintenance costs for portable air cleaners are relatively low, making them a feasible option at a household level. The obvious disadvantage is that the use and maintenance require individual initiative, which could be difficult to sustain at scale. To improve cost-efficiency, priority deployment of these interventions should target subpopulations most at risk as identified in Chapter 2. However, these populations will likely require considerable support to access and successfully use and maintain filtration devices.

Additionally, CalSPEC found *moderate evidence* that a range of interventions may be effective in reducing on-road emissions, improving near-roadway air quality, or improving indoor air quality or health under the three categories below:

- **On-road source control strategies**: Clean vehicle policies, traffic management via road congestion pricing, vehicle operation restrictions, low emission zones, lower speed limits, intersection controls with roundabouts and signal timing, and eco-driving.
- **Outdoor NRAP (ambient) control strategies**: Green infrastructure including vegetation barriers, green walls/roofs, non-vegetation obstacles including parked cars, and artificial sink devices, and optimized design of built environment including street canyon configuration, building architecture, and land use buffering/siting.

REPORT CONCLUSION

California has made significant progress in reducing air pollution over the last 50 years despite its population growth (Warneke et al., 2012); however, opportunities remain for continued improvement. There is substantial evidence of adverse respiratory, cardiovascular, and reproductive health effects from near-roadway air pollution (NRAP). With an estimated 7.8 million Californians living and/or working in areas exposed to high traffic volume, this CalSPEC report identifies a significant ongoing public health concern, which intersects with several key public policy issues; particularly California's housing crisis and health inequities. As noted previously, there is a focus on urban housing infill/refill to increase the number of affordable housing units in areas with substantial or potential economic activity. Such developments can reduce travel and resulting emissions. However, infill/refill policy implementation could have unintended consequences across the state if road proximity and health effects are not considered for new or retrofit building or road construction. Similarly, health inequities are likely exacerbated by the propensity of lower income people and people of color to live closer to high traffic volume roads and, therefore, experience higher rates of NRAP-related health conditions than their higher-income, White counterparts.

This report identifies multiple mitigation strategies that are effective in reducing indoor air pollution sourced from traffic-related pollution; policy options to explore and debate are suggested below. There are several key strengths and limitations to this report. Limitations include adopting a rapid review approach, which may have inadvertently overlooked evidence from newer, individual studies. However, CalSPEC used scientifically rigorous methods to evaluate the health effects of NRAP and included multiple outcomes related to different biological systems. In its review of mitigation literature, CalSPEC used a process-oriented approach that distilled a diverse set of interventions into concise and interpretable categories; however, the results are limited by the state of the science including the lack of assessment of effects on indoor air pollution and health outcomes from the source and ambient control strategies as well as a lack of cost-effectiveness studies.

Policy Strategies to Explore

Based on moderate to high certainty of adverse health effects of NRAP, CalSPEC recommends taking immediate action to mitigate and/or prevent exposures from NRAP, particularly for vulnerable populations living and working near highly trafficked roadways. In particular, policy discussions about the following evidence-based strategies would continue to help develop California's transportation, housing, and environmental health policies:

- Consider increasing NRAP permanent outdoor and rotating indoor monitoring in densely populated areas for neighborhoods 100–500 feet (or more) from high-traffic roads to improve baseline data and measure effectiveness of mitigation strategies that may be implemented locally or statewide.
- Due to unequal distribution of exposures, which contribute to health disparities, prioritizing health equity as a criterion when evaluating mitigation strategies can help reduce disparities. For example, creating urban housing infill/refill policies to increase affordable housing units, and reduce traffic emissions and travel time may have unintended consequences if policies incentivize low-income/affordable housing infill near highly trafficked roads without a simultaneous effort to mitigate traffic-generated pollutants and/or improve new structure placement, building envelopes, and ventilation systems.

- Concurrent with adoption of infill policies, NRAP interventions to consider include incentivizing clean vehicles, and improving traffic management through intersection design and traffic restrictions in and around these communities. Additionally, appropriate built-environment design for infill housing would preserve enough ground-level open space for urban ventilation and reduced NRAP accumulation.
- For buildings in close proximity to highly trafficked roads, controlled indoor ventilation and improved filtration systems are effective methods to reducing contributions of outdoor pollutants to indoor air.
- Diesel trucks are the primary source of black carbon and NO_x, which drive adverse health outcomes; thus, exploring policies to restrict diesel truck traffic and/or incentivize electrification of truck fleets would likely improve indoor air quality among structures near high-trafficked roads, and may have a positive impact on reducing disparities among vulnerable populations.
- Consider cost-effective mitigation strategies with the most evidence of effectiveness such as portable air cleaners for indoor filtration, which do not require additional costly construction and can be deployed quickly among priority communities.
- Consider prioritizing various mitigation strategies as pilot projects across California based on local needs and constraints such as population density and vulnerability to NRAP health effects, built environment, local weather patterns, and traffic volume. Strategies should be well planned and rigorously evaluated over several years to account for seasonal and meteorological variations.
- Monitor federal activities for future funding opportunities for mitigation pilot projects, research evaluations, and strategy implementation and deployment. The National Academy of Sciences, Engineering and Medicine will release a consensus study report in early 2024 entitled Health Risks of Indoor Exposures to Fine Particulate Matter and Practical Mitigation Solutions, which may stimulate new federal funding opportunities.

APPENDIX A HEALTH EFFECTS CHAPTER PROTOCOL

NRAP Rapid Overview Protocol

This publicly available protocol outlines the processes for this rapid overview of reviews. Developing a protocol prior to initiating a review is an important step in an overview as it increases transparency in the methods used and reduces the potential for bias. The protocol is available on Open Science Framework website at: https://osf.io/wvukp

APPENDIX B HEALTH EFFECTS CHAPTER METHODS

Appendix B1: Comprehensive Summary of Rapid Overview Methods: This document contains a more in-depth summary of the methods CalSPEC used to conduct a rapid overview on the human health effects of exposure to NRAP.

APPENDIX C HEALTH EFFECTS CHAPTER FINDINGS

Study Screening and Selection

Appendix C1. CONSORT Diagram: This flow diagram displays the number of reviews included and excluded at each stage of the overview process.

Appendix C2. Full Text Exclusion Rationale: This document outlines the 320 reviews that were excluded after reviewing the full text and presents the rationale for their exclusions.

Appendix C3. Evaluation Exclusion Rationale: This document outlines the 3 reviews that were excluded at the evaluation stage and presents the rationale for their exclusions.

Appendix C4. Study Characteristics: This evidence table contains additional information about each included systematic review, including the author's country, study objectives, PECO (population, exposure, comparator, outcomes) statement, conflict of interest information, etc.

Primary Study Overlap

CalSPEC utilized the established GROOVE (Graphical Representation of Overlap for OVErviews) tool to assess overlap of primary studies when multiple reviews evaluated the same exposure/outcome pairs (Pérez-Bracchiglione et al., 2022). Below we present the tools utilized for studies exploring the association between distance to roadway and diabetes (**Appendix C5**) and NRAP and dementia (**Appendix C6**).

Appendix C5. GROOVE Tool for Diabetes/Distance to Roadway: This evidence matrix displays *very high overlap* in primary studies between Zhao et al. (2016) and HEI (2022). CalSPEC chose to prioritize Zhao et al. (2016) as the authors conducted a meta-analysis, while HEI (2022) narratively summarized study findings.

Appendix C6. GROOVE Tool for Dementia/NRAP: This evidence matrix displays *very high overlap* in primary studies between Peters et al. (2019) and Tang et al. (2022). CalSPEC chose to prioritize Tang et al. (2022) as it included more recent primary studies.

Quality of Systematic Reviews

Appendix C7. AMSTAR Quality Assessment Results: This document contains the results of the modified AMSTAR (A MeaSurement Tool to Assess systematic Reviews) tool CalSPEC used to evaluate the quality of the 9 systematic reviews.

Systematic Review and Primary Study Results

Appendix C8. Review Results and Primary Study Results by Outcome/Exposure: This collection of tables contains detailed systematic review and primary study results for each exposure/outcome pair. Tables and figures from the systematic reviews are also included. Tier 1 exposure/outcome pairs are shaded blue, while Tier 2 are shaded white.

Tier 2 Results

Appendix C9. **Tier 2 Results:** This document contains 6 tables with narrative summaries of the Tier 2 exposure/outcome pairs. Though limited in that they have not had a rigorous evaluation of the certainty of evidence, these results provide additional insight into the research that has been conducted on the health effects of NRAP exposure and opportunity for future research to evaluate the certainty of the evidence for additional exposure/outcome pairs.

APPENDIX D MITIGATION CHAPTER METHODS

Appendix D1. **Detailed Methods:** This document includes the search guide provided to the librarian from the CalSPEC team to inform the literature search, the librarian's full search strategy while conducting the literature search, and diagrams outlining the process of screening articles for source, outdoor, and indoor exposure pollution control evidence synthesis.

Appendix D2. **Study Screening and Selection Details:** This table outlines the further down select process of the included papers.

APPENDIX E MITIGATION CHAPTER SUMMARY OF EVIDENCE

Appendix E1. **Evidence Tracker:** This evidence tracking table includes cost synthesis and detailed categorization of source control, outdoor control, and indoor pollution exposure control strategies.

Appendix E2. **Summary of Systematic Reviews Included in Mitigation Chapter:** This document includes several tables summarizing systematic reviews included in the mitigation chapter, organized by source control, outdoor control, and indoor pollution exposure control strategies.

Appendix E3. **Evidence on Person-level Interventions to Reduce Exposure to NRAP:** CalSPEC also reviewed and evaluated evidence on person-level interventions. This document provides a narrative summary and evaluation on the effectiveness of person-level interventions on reducing exposure to NRAP.

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