Research Division

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY | AIR RESOURCES BOARD

TECHNICAL ADVISORY

Strategies to Reduce Air Pollution Exposure Near High-Volume Roadways

April 2017

Acknowledgements

ARB staff would like to acknowledge the exceptional contributions made to this document by several stakeholders and contributors. Individuals from various state, national, and international agencies; local and regional governments; academic institutions; and other organizations were especially instrumental in compiling the information contained herein and in providing comments and reviews. ARB thanks individual reviewers from the following agencies, organizations, and institutions:

Bay Area Air Quality Management District (BAAQMD)

California Air Pollution Control Officers Association (CAPCOA)

California Association of Councils of Governments (CalCOG)

California Department of Forestry and Fire Protection (CAL FIRE)

California Department of Housing and Community Development (HCD)

California Department of Public Health (CDPH)

California Department of Transportation (Caltrans)

California Planning Roundtable

California State Transportation Agency (CalSTA)

California Strategic Growth Council (SGC)

Environmental Investigation Agency (EIA)

European Comission (EC)

Governor's Office of Planning and Research (OPR)

Mutual Housing California

Netherlands National Institute of Health and the Environment (RIVM)

Sacramento Metropolitan Air Quality Management District (SMAQMD)

Santa Barbara County Air Pollution Control District

Santa Barbara County Association of Governments (SBCAG)

Shasta Regional Transportation Agency (SRTA)

Southern California Association of Governments (SCAG)

Stanislaus Council of Governments (StanCOG)

Tahoe Regional Planning Agency (TRPA)

Umwelt Bundesamt (UBA, Germany's environmental agency)

University of California, Berkeley (UCB)

University of California, Davis (UCD)

University of California, Los Angeles (UCLA)

University of California, Riverside (UCR)

University of Southern California (USC)

U.S. Environmental Protection Agency

Ventura County Air Pollution Control District (VCAPCD)

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Executive Summary

This advisory is a technical supplement to ARB's *Air Quality and Land Use Handbook: A Community Health Perspective* (hereafter referred to as the Land Use Handbook).[1] Published in 2005 under the auspices of ARB's Environmental Justice Stakeholders Group, the Land Use Handbook provides information for local elected officials and land use agencies to consider regarding the siting of new sensitive uses near pollution sources, including (but not limited to) freeways and high-volume roadways, when site-specific air quality information is not available. Since its publication, research has demonstrated the public health, climate, financial, and other benefits of compact, infill development along transportation corridors. Moreover, new research has demonstrated promising strategies to help decrease pollution exposure near their sources. These strategies are the focus of this Technical Advisory.

ARB intends for this Technical Advisory to provide planners and other stakeholders involved in land use planning and decision-making with information on scientifically based strategies to reduce exposure to traffic emissions near high-volume roadways in order to protect public health and promote equity and environmental justice. Many communities in California exist near high-volume roadways. This is both because freeways and other busy traffic corridors have been built adjacent to and through existing neighborhoods in California, and because new developments have been built near existing roadways. Near-roadway development is a result of a variety of factors, including economic growth, demand for built environment uses, and the scarcity of developable land in some areas.

This Technical Advisory demonstrates that planners, developers, and local governments can pursue infill development while simultaneously reducing exposure to traffic-related pollution by implementing the strategies identified here and in other statewide guidance and policies that promote sustainable communities. The State Planning Priorities[2] emphasize infill development, since this pattern of development can help attain goals to promote equity, strengthen the economy, protect the environment, and promote public health and safety. ARB acknowledges that there are many existing developments near high-volume roadways and other sources of air pollution throughout the state, and many of these strategies apply in those situations, as well.

Strategies to reduce exposure include practices and technologies that reduce traffic emissions, increase dispersion of traffic pollution, or remove pollution from the air. Recent research documents the effectiveness of a variety of strategies. Based on a review of this body of research, ARB staff compiled a list of recommended strategies, which this document describes in detail.

This document does not include all potential pollution reduction measures, but rather the options that are well supported by scientific findings and which meet all of the following criteria:

1. Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, or emissions rates, or improving air flow to disperse pollutants.
2. The scientific literature documents evidence of significantly effective exposure reduction.
3. Diversity in the study methods supports consistent findings (such that strategy efficacy does not exclusively rely on one method of investigation).

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1 *http://www.arb.ca.gov/ch/handbook.pdf*
2 California Government Code Section 65041.1.

Appendix A outlines strategies that did not meet the ARB's three criteria, but were nonetheless identified in ARB's literature review. In some cases, these strategies represent nascent technologies or designs that require more study before ARB can recommend them for general application. In other cases, studies do not present consistent results or strategies have only been studied via modeling or simulation, and it is uncertain if these strategies will perform similarly in real world settings.

Benefits of compact, infill development

Infill and compact development characterizes many communities located near freeways and other busy traffic corridors. This development pattern has many benefits. It promotes physical activity by facilitating active transportation (biking and walking) and by shortening the distances that people must travel for their daily activities [1]. It also provides density of development that helps support transit operations [2]. The car trips that are shortened or replaced by these other modes result in greenhouse gas (GHG) emissions reductions, and GHGs are further reduced in these communities because they are also associated with reduced energy and water use [3]. Importantly, compact and infill development can also improve people's quality of life by facilitating community connectivity. For these reasons, planners often favor infill and compact development and other stakeholders involved in land use planning and real estate development. Additionally, these types of developments are encouraged by regions striving to achieve greenhouse gas emissions reductions from land use and transportation planning in accordance with Senate Bill (SB) 375.

The foremost strategy for reducing pollution exposure near high-volume roadways is to minimize traffic pollution in the first place. A key mechanism for this is the reduction of vehicle miles traveled (VMT). State legislation including Senate Bills 375 and 743, are specifically designed to facilitate VMT reductions from passenger cars by encouraging and facilitating the replacement of vehicle trips with walk, bike, and transit trips. There is evidence from research and real-world measurement that,

KEY TERMS

traffic emissions

Primary emissions/pollution from motor vehicles, including carbon monoxide, hydrocarbons, nitrogen oxides, particulate matter, toxic air contaminants, brake dust, and tire wear.

high-volume roadways

Roadways that, on an average day, have traffic in excess of 50,000 vehicles in a rural area and 100,000 vehicles in an urban area (Source: California Public Resources Code Section 21151.8).

at-risk populations/communities

Children, pregnant women, the elderly, and those with serious health problems affected by air pollution.

sensitive uses

Land uses where sensitive individuals are most likely to spend time include schools and schoolyards, parks and playgrounds, daycare centers, nursing homes, hospitals, and residential communities.

sustainable communities

Communities that foster conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations.

disadvantaged communities

Communities that score at or above the 75th percentile in the CalEnviroScreen Tool. The tool scores tracts according to their proximity to multiple sources and their vulnerability to the effects of pollution and also account for socioeconomic characteristics and underlying health status.

dispersion (of air pollution)

Distribution of air pollution into the atmosphere.

when vehicle miles and trips are greatly reduced—for example, when streets are temporarily closed to motorized vehicles for car-free open-streets or “ciclovia” events—air quality is significantly improved [4, 5].[3]

Coordinated land use and transportation planning that results in more compact neighborhoods can help reduce VMT by making transit and active transportation viable and reducing the need for personal cars. Travel demand management strategies that improve the efficient use of transportation resources (e.g., teleworking, car-sharing, and carpooling) also reduce vehicle trips. ARB’s partners also promote other innovative ideas for increasing the availability and appeal of alternative modes of transportation. At Caltrans, for example, the newly created Active Transportation Program focuses on making California a national leader in active transportation[4] and one Caltrans district is studying freeway capping as an innovative way to better connect people to destinations via parks, paths, and transit constructed atop existing freeways.[5]

In addition to reducing VMT, there are many efforts underway to reduce emissions via other mechanisms. These include more stringent emissions and fuel standards for cars, trucks, and buses; state regulations for zero emission vehicle (ZEV) adoption; and California’s Sustainable Freight Transport Initiative. Other state efforts that will reduce emissions, and therefore complement this document, include the AB 32 Scoping Plan and the State Implementation Plan, and the Mobile Source Strategy.

More and more, planners are designing land use developments to make alternatives to automobile travel more attractive. These changes are important because of their long-term significance, as changes in the built environment mean changes in land use patterns that will last for decades. Land use development patterns in some California jurisdictions already contribute to reductions in the use and ownership of cars because of land use planning strategies and active transportation investments. However, change is slow, and many existing and planned developments—including important infill and compact development projects—place sensitive individuals in close proximity to high-volume roadways. In these instances, there is a need for developers, local governments, and other entities to consider pollution reduction strategies to ensure that residents of both new and existing developments breathe air that is as clean as possible.

Need for this Technical Advisory

The primary public health concern regarding roadways near existing and future developments is the possibility that at-risk populations/communities—like children, pregnant women, the elderly, and those with serious health problems affected by air pollution—will be exposed to traffic emissions. In California, there are several instances of schools and other sensitive locations such as daycare facilities located near major roadways, particularly in non-white and economically disadvantaged neighborhoods [6, 7]. Studies show that these populations can experience serious health impacts, including worsening of asthma and cardiovascular disease and adverse birth outcomes because of exposure to traffic-related air pollution. Additionally, studies show that poor and minority communities are more likely to live near busy roadways, and therefore may be more at-risk for the health effects related to exposure to traffic emissions [8, 9].

Scientific evidence indicates that implementing the strategies contained in this document would decrease exposure to air pollution in a variety of locations and contexts, so these strategies are applicable in a broad range of developments, not just those located near high-volume roadways. ARB’s motivation for emphasizing these strategies in near-roadway environments is a reflection of the potentially serious health impacts that at-risk populations/communities may experience when they spend significant time in such environments, absent appropriate design measures.

3 “Ciclovias,” Open Streets, and Sunday Streets are events whereby roadways are closed to automobiles but open to cyclists and pedestrians. Many cities around the world have implemented these events, including several cities in California: Los Angeles (*http://www.ciclavia.org/*), San Francisco (*http://sundaystreetssf.com/*), San Jose (http://*www.vivacallesj.org/*). Albany, Long Beach, Oakland, Redding, and San Mateo. Visit the California Bicycle Coalition’s Web site for more information: *http://www.calbike.org/open_streets*.

4 *http://www.dot.ca.gov/hq/LocalPrograms/atp/index.html*

5 *http://www.dot.ca.gov/dist11/departments/planning/planningpages/capstudy.htm*

In addition, these strategies are likely to yield the greatest public health benefit when applied in near high-volume roadway contexts.

Planners, developers, and others can implement these strategies where existing sensitive uses are already located near high-volume roadways. The strategies are also relevant for new developments. When planners and other decision makers consider these strategies during the planning phase, they may be less expensive to implement than if they are added via retrofits after construction.

How to use this Technical Advisory

ARB envisions that this document will be used by planners and other stakeholders to identify combinations of strategies that can be implemented to reduce exposure at specific developments or to recommend the consideration of these strategies in policy or planning documents. For example, local governments may refer to it or use portions of it in their general plans. The contents may also be helpful in the development or updating of environmental justice policies in general plans, as required by Senate Bill (SB) 1000. Readers interested in learning more about the requirements of SB 1000 should consult OPR's General Plan Guidelines.

It is important to note that this Technical Advisory is not intended as guidance for any specific project, nor does it create any presumption regarding the feasibility of mitigation measures for purposes of compliance with the California Environmental Quality Act (CEQA). Instead, it is meant as guidance for planners weighing options for reducing exposure to traffic emissions.

Strategies to reduce exposure, weighed alongside overarching considerations

The table that follows this executive summary describes the research findings supporting each recommended strategy, the appropriate land use context, and other considerations. These additional items were revealed either through the research or through consultation with experts and stakeholders. This table can be used for quick reference, but readers should also refer to *Section II* for an expanded discussion of these strategies, including details about co-benefits and potential drawbacks.

In addition to the considerations outlined in Section II, readers should be mindful of the following important overarching considerations that were identified by ARB staff and other experts who were consulted during the development of this document:

Changes in land use patterns and the built environment persist for decades

Land use patterns, once established, remain fixed for decades. Increasing density through infill development helps to transform low-density neighborhoods to ones that can support alternative modes. When developing new plans and projects, planners should carefully consider the ongoing influence of those plans and projects on the creation of accessible and livable neighborhoods.

Holistic and comprehensive planning practices

Stakeholders involved in public health, air quality, and community planning efforts must weigh a variety of factors and issues when making policy decisions. At-risk populations/communities' exposure to traffic is just one of many considerations, but it is an important piece that planners and others should weigh alongside other local goals and priorities. Thus, ARB recommends that exposure to traffic emissions and strategies to reduce exposure be considered holistically, within planning processes at the scale of a neighborhood or community plan or ordinance, general plan, sub-regional or regional plan, depending on the geographic impact and regulatory context of the issue. Additionally, ARB recommends that planners consider leveraging holistic and combined practices, policies, and strategies to achieve local goals. Real-world evidence from the Atlanta 1996 Summer Olympic Games showed that a suite of coordinated strategies reduced ozone pollution and childhood asthma events significantly (*see textbox on page 16 for details*).

Site-specific considerations

Site-specific factors may play a significant role in whether or not an exposure reduction strategy will be effective without resulting in negative, unintended consequences. In some cases, it may be possible for planners and other stakeholders to use site-specific information to estimate the reduction in pollution concentration associated with a specific strategy or combination of strategies. When exposure reduction strategies—such as those presented in this document—are incorporated into large-scale policy documents like jurisdiction-wide general plans, a menu of strategies and language about the usefulness of site-specific analysis to assist in choosing the right strategies for specific projects may be appropriate, since not all strategies are necessary or appropriate in all cases.

Changing vehicle fleets and impacts on air quality

California's vehicle fleets and freight system are becoming cleaner and this trend will continue into the future, given existing and forthcoming policies and transformations underway in the automobile market (see more information in *Section I. Introduction*). This fact should be carefully considered in local decision-making, particularly when long-term, durable strategies are being considered, such as urban design changes or standards. It is worth noting, however, that while transitioning to ZEVs eliminates tailpipe emissions, it does not eliminate all traffic emissions. Non-tailpipe particulate matter emissions from road dust, brake dust, and tire wear are likely to continue to impact public health, particularly for sensitive individuals. Furthermore, ZEVs do not eliminate upstream emissions from non-renewable energy sources or sources linked to their manufacture and production [10].

On-roadway exposure to traffic emissions

The more time people spend on roadways, the greater their exposure to emissions that are harmful to their health [11]. This fact should also be considered as planners weigh strategies for reducing near-roadway pollution exposure, since it is crucial that they avoid making land use decisions that would result in longer commutes. In other words, planners should not push new development farther from urban centers because this could induce longer vehicle trips and thus increased on-roadway exposure. Additionally, it should be noted that, in some cases, exposure reduction strategies may increase on-road pollution concentrations. If in-vehicle filtration is inadequate or if drivers travel with the windows down, this could translate into increased exposure for people driving in cars.

Translating research into practice

Putting research into practice can be challenging since research studies often seek to address a narrowly defined question and control for factors that are commonly observed in the real world. The way that research is conducted may not be reflective of real world conditions, so users of this Technical Advisory should consider how the research applies to the specific context being considered. Also, even when data is collected in the real world, the data may be several years old by the time that researchers are able to digest, analyze, and summarize findings and conclusions. Thus, users of this document may need to consider how changes in the local context may have affected the variables that researchers considered in their analyses.

Executive Summary conclusion

The identification of strategies described herein is intended to provide stakeholders involved in public health, air quality, and land use planning efforts (including city and county planners, planning commissioners, developers, planning consultants, and other local government staff and decision makers) with options for reducing exposure to traffic pollution in near-roadway environments, both for existing and new developments. We envision that this document will be used as a resource to:

1. Identify strategies that can be employed on a site-specific basis to reduce exposure to traffic emissions at existing and future developments and;
2. Help shape local policies aimed at reducing exposure to traffic emissions and therefore associated public health impacts.

As California grows, we have the collective opportunity to shape the future of the built environment to be both protective of public health and supportive of environmental goals. ARB hopes that the content of this Technical Advisory will assist the efforts of planners and other practitioners and decision makers to promote healthy, safe, equitable, and sustainable communities. Furthermore, ARB will continue to investigate options to mitigate air pollution exposure in many contexts and related to different sources of air pollution in addition to high-volume roadways.

Table 1: Summary of strategies to reduce air pollution exposure near high-volume roadways

Strategy	Description of research findings	Appropriate context and other considerations
Strategies that reduce traffic emissions		See *Section II*, page 20.
Speed reduction mechanisms, including roundabouts	Vehicle speed reduction mechanisms change the design and operating speed of the road by altering the physical characteristics of the road. These features can reduce stop-and-go driving and hard accelerations and thereby reduce emissions rates. Some of these features, like the roundabout intersection, can be used as an alternative to stop-controlled and signalized intersections. Studies show that roundabouts can reduce localized pollutant concentrations compared to intersections with stop and signal control by 20 percent or more (depending on context and site-specific conditions).	Transportation planners and engineers should carefully consider the potential direct and indirect effects of implementing speed reduction mechanisms to determine if they will reduce vehicle emissions and other impacts to the environment as well as to traveler safety and delay. When guidance is needed to estimate emissions and air quality-related effects, planners and engineers may consult with MPOs or traffic modeling experts.

Strategy	Description of research findings	Appropriate context and other considerations
Traffic signal management	Traffic signal management systems can reduce stop-and-go driving and vehicle idling, resulting in reduced localized pollutant concentrations of up to 50 percent compared to corridors that do not implement these systems. Studies show that site-specific conditions dictate the magnitude of reductions.	Many different types of signal management are available, and planners should identify what is best for air quality, vulnerable road user safety, and transit and active mode throughput and comfort.
Speed limit reductions on high-speed roadways (>55 mph)	Research studies have identified an optimal average speed range of ~35-55 mph within which per-mile traffic emissions and fuel consumption are minimized. Generally, speed limit reductions on high-speed roadways can reduce tailpipe emission rates up to 30 percent, depending on the change in speed, the pollutant measured or modeled, and the roadway characteristics.	Speed limit reductions are appropriate on roadways where speed limit and design speeds exceed 55 mph.
Strategies that increase dispersion of traffic emissions		See *Section II*, page 26.
Design that promotes air flow and pollutant dispersion along street corridors	The physical layout of urban streetscapes influences air flow and pollution movement. Research studies show that street corridors characterized by buildings with varying shapes and heights, building articulations (street frontage design elements like edges and corners that help break up building mass), and spaces that encourage air flow (e.g., parks) benefit from better pollutant dispersion and air quality. For example, buildings of varying heights can result in significant increases in turbulence (e.g., up to doubling), and adding bike lanes and sidewalks not only reduces car traffic, but also creates space for more dispersion (up to a 45 percent reduction in particulate concentrations).	Wider sidewalks, bicycle lanes, dedicated transit lanes, and other features that benefit alternative modes of transportation can also create space for better air flow and pollutant dispersion along with increasing active transportation and mode shift. This strategy should be considered in the context of the overall need to increase development density.

Strategy	Description of research findings	Appropriate context and other considerations
Solid barriers, such as sound walls	Measurement and modeling studies consistently find that solid barriers reduce near-road downwind concentrations by increasing vertical **dispersion** of pollutants emitted by vehicles. The magnitude of the reduction and its spatial extent depend on the height of the barrier, the width of the road, and micrometeorology. Studies have consistently found that pollution concentrations downwind of the barrier range from a 10 percent to 50 percent reduction compared to concentrations measured on or directly adjacent to high-volume roadways.	Solid barriers should only be considered for installation along freeways, because they have the negative effect of dividing neighborhoods and obscuring sightlines.
Vegetation for pollutant dispersion	Studies indicate that vegetation has the potential to alter pollutant transport and **dispersion**. In some studies, specific locations and conditions translated to air quality benefits (e.g., pollution concentration reductions of up to 20 percent on the leeward side of the tree line). It should be noted that most studies were conducted on the East Coast and in Europe where vegetation types and densities differ from what is found in California.	Online tools are available to assist with the selection of appropriate vegetation considering allergen impacts, watering needs, and other factors. Maximum benefits have been shown to occur when vegetation is combined with solid barriers.
Strategies that remove pollution from the air		See Section II, page 36.
Indoor high efficiency filtration	Studies show that particle filtration systems and devices, specifically high-efficiency filtration with mechanical ventilation or portable high efficiency air cleaners, can be highly effective for reducing indoor pollution concentrations. High efficiency filters in ventilation systems can remove from 50-99 percent of particles in the air. However, research shows that filtration technologies for gaseous pollutants (VOCs) are variable in their effectiveness; some remove certain VOCs well, but not others.	Planners should be aware of current state and local building codes and their respective air filtration requirements, including requirements for amending code standards. Regular operation and maintenance is necessary for highest filter and ventilation efficiency, and is required by regulation in commercial buildings.

Introduction

State programs to improve air quality and reduce exposure to traffic emissions

California has a long and successful history of reducing air pollution to protect public health. Gasoline sold in California contains less pollution-forming compounds than most gasoline sold elsewhere in the nation[6], and the low carbon fuel standard is continuing to reduce the carbon content of fuels[7]. California now has more than 100,000 plug-in electric vehicles on its roads, and today's new cars pollute 99 percent less than their predecessors did thirty years ago. ARB's Advanced Clean Cars program will continue to drive reductions in emissions from light-duty vehicles[8]. Emissions from trucks and buses are declining[9], and ambient diesel particulate matter (PM) concentrations in California dropped 68 percent between 1990 and 2012 [12]. These emissions reductions have resulted in significant public health benefits, including the reduction of cancer risk associated with diesel PM.

Reducing traffic emissions

The primary mission of ARB is to protect public health through the improvement of air quality. ARB has many policies and programs to improve near-roadway air quality and to protect public health. These policies and programs primarily rely on technologies or strategies that reduce traffic emissions at the source, which is more effective than attempting to clean up the air after emissions have already been released into the environment. ARB policies and programs focus on traffic emissions because regulation of emissions from stationary sources occurs at local and regional air pollution control authorities known as Air Pollution Control Districts (APCD) or Air Quality Management Districts (AQMD). The following describes State programs that are important for reducing traffic emissions.

The sustainable communities program at ARB focuses on ways to reduce traffic emissions by reducing vehicle miles traveled (VMT). VMT can be reduced through a variety of strategies. Research shows that people tend to drive less when trip origins and destinations can be easily accessed via walking, biking, and transit. Dense, mixed use development is a common way that communities can achieve improved accessibility and mobility without relying on cars.

ARB is responsible for the implementation of the Sustainable Communities and Climate Protection Act of 2008, or SB 375[10]. In accordance with the law, ARB sets regional targets for GHG emissions reductions from passenger vehicle use. In 2010, ARB established targets for 2020 and 2035 for each of the state's metropolitan planning organizations (MPO). To comply with the law, MPOs prepare a "sustainable communities strategy" (SCS) to be included in their regional transportation plans (RTP). The SCS contains land use, housing, and transportation strategies that, if implemented, would allow the region to meet its GHG emission reduction targets. Once adopted by the MPO, the RTP/SCS guides the transportation policies and investments for the region. ARB must review the adopted SCS to confirm and accept the MPO's determination that the SCS, if implemented, would meet the regional GHG targets. As of the writing of this Technical

6 *http://www.arb.ca.gov/fuels/gasoline/gasoline.htm*
7 *http://www.arb.ca.gov/fuels/lcfs/lcfs.htm*
8 *http://www.arb.ca.gov/msprog/consumer_info/advanced_clean_cars/consumer_acc.ht*
9 *http://www.arb.ca.gov/msprog/onrdiesel/onrdiesel.htm*
10 *http://www.leginfo.ca.gov/pub/07-08/bill/sen/sb_0351-0400/sb_375_bill_20080930_chaptered.pdf*

Advisory, all MPOs in California have completed their first SCS/RTP, and most have at least begun the process of completing their second. ARB's Sustainable Communities Web page provides links to SCSs along with ARB staff's technical evaluation. These documents are a useful place for planners to gather information about what is happening at a regional level to reduce VMT and thus air pollution from cars generally.[11]

ARB partners closely with many other state agencies to promote sustainable communities and reductions in VMT and to provide MPOs and local governments with resources that can be used in the development of SCSs and in the implementation of land use and transportation policies at the local level. Partners include Caltrans, the California State Transportation Agency (CalSTA), the Governor's Office of Planning and Research (OPR), the California Department of Housing and Community Development (HCD), and the Strategic Growth Council (SGC). These partners are actively engaged in various programs to reduce VMT. OPR is actively working on promoting VMT reduction by changing the metric used to assess transportation impacts under CEQA, per SB 743[12]. Caltrans is also encouraging shifts from passenger car use toward alternative modes of transportation. The Strategic Management Plan: 2015-2020 contains a statewide VMT reduction target of 15 percent by 2020 relative to 2010 levels and targets to triple biking and double walking and transit by 2020, compared to the 2010-2012 California Household Travel Survey Baseline.[13] Additionally, Caltrans's Active Transportation Program facilitates active transportation programs and infrastructure throughout the state. Caltrans's District 11 (San Diego and Imperial Counties) is also studying freeway capping as a way to use land atop freeways to better connect communities and make walking and biking viable and attractive, and has engaged the local community to consider a future cap over State Route 94.[14]

ARB is responsible for developing statewide programs and strategies to reduce the emission of smog-forming pollutants and toxics by mobile sources. These include both on- and off-road sources such as passenger cars, motorcycles, trucks, buses, heavy-duty construction equipment, recreational vehicles, marine vessels, lawn and garden equipment, and small utility engines.

Looking to the future, ARB's Mobile Source Strategy[15] contains a suite of measures that are being considered to simultaneously meet air quality standards, achieve GHG emission reduction targets, reduce petroleum consumption, and decrease health risk from transportation emissions over the next 15 years. California's Sustainable Freight Action Plan[16] is part of the broader mobile source strategy for on-road heavy-duty vehicles, and includes efforts to reduce nitrogen oxide (NO_x) emissions at the state and federal levels and to encourage freight electrification. Figures 1 and 2 below illustrate both past emission reduction trends and projected future reductions as a result of elements of the Mobile Source Strategy (and based on EMFAC2014[17]).

11 *https://www.arb.ca.gov/cc/sb375/sb375.htm*
12 *https://www.opr.ca.gov/s_sb743.php*
13 *http://www.dot.ca.gov/perf/library/pdf/Caltrans_Strategic_Mgmt_Plan_033015.pdf*
14 *http://www.dot.ca.gov/dist11/departments/planning/planningpages/capstudy.htm*
15 *http://www.arb.ca.gov/planning/sip/2016sip/2016mobsrc_dd.pdf*
16 *http://www.arb.ca.gov/gmp/sfti/sfti.htm*
17 ARB's EMFAC2014 model assesses emissions from on-road vehicles including cars, trucks, and buses in California, and represents ARB's current understanding of motor vehicle travel activities and their associated emission levels.

Figure 1: Statewide annual NO_x emissions (tons/day) between 2000 and 2030 based on EMFAC2014.

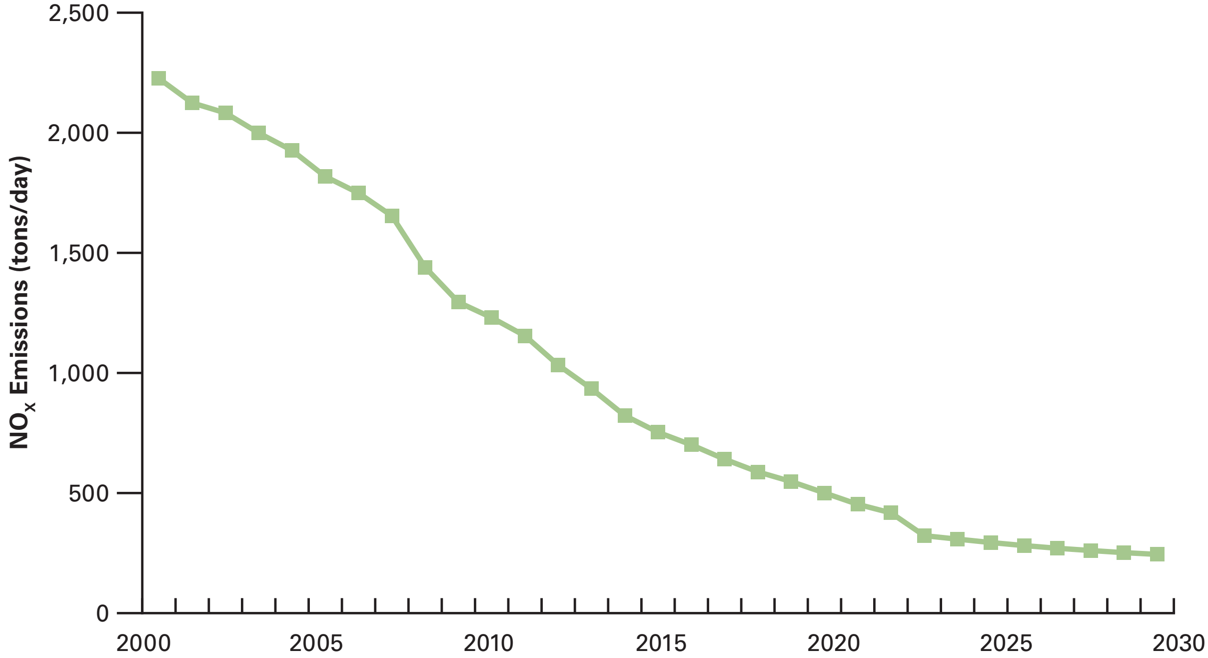
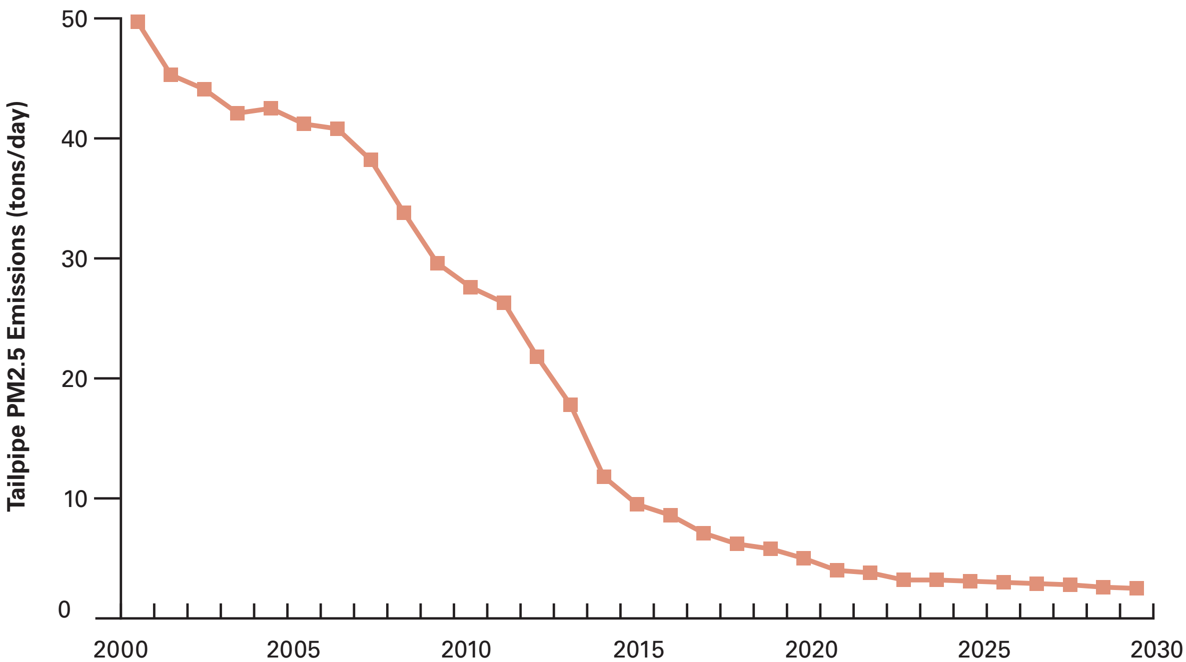


Figure 2: Statewide annual PM2.5[18] tailpipe emissions (tons/day) between 2000 and 2030 based on EMFAC2014.



18 PM2.5 is particulate matter with a diameter of 2.5 micrometers or less.

Reducing exposure to traffic emissions

ARB sponsors research and develops programs and regulations to improve Californians' health by identifying and reducing exposure to air pollutants in both indoor and outdoor environments. Research, sponsored by ARB and others, has revealed a variety of strategies that can be used to reduce exposure when traffic emissions cannot be avoided. These strategies are of great interest to ARB, but it is beyond the authority of ARB to regulate or require that they be implemented. Instead, ARB has historically provided guidance—based on scientific studies and peer-reviewed literature—to agencies with land use authority. In this capacity, ARB has provided guidance on the following, related to reducing the exposure of at-risk populations/communities to traffic emissions.

The 2005 Land Use Handbook recommends that health protective distances (500 feet at minimum, if there is no site-specific information available) be implemented to separate sensitive uses from freeways, urban roads with 100,000 vehicles/day, or rural roads with 50,000 vehicles/day.[19] This recommendation is based on research showing that pollutant concentrations decline significantly as you move farther away from pollution sources, including freeways and other busy traffic corridors [13-15] and epidemiological studies that indicate that spending time in proximity to traffic emissions sources may lead to adverse health effects beyond those associated with regional air pollution in urban areas [16-21].

Much research has taken place since the publication of the Land Use Handbook, and while vehicle emissions rates have declined because of increasingly stringent emissions standards for cars and trucks, recent studies continue to show high near-roadway concentrations and serious health impacts linked to traffic emissions [22-24]. Studies also show that these pollutant concentration gradients can change with traffic patterns, meteorology, and time of day [25, 26, 27-30]. Pollution concentrations near high-volume roadways decline with distance more sharply during the daytime than during the night and the very early morning (i.e., 1-2 hours before sunrise), largely as a result of diurnal meteorological patterns [25, 26, 27, 31]. These research findings—explained in more detail in the text box "*Time-of-day and air pollution concentrations*" (page 20)—highlight the possibility that near-roadway pollution exposure had been previously underestimated and that people living as much as 1,000 feet from freeways were being adversely impacted by poor air quality at night and in the early morning. However, additional research demonstrates that there are alternative strategies that can protect public health while not dictating development patterns.

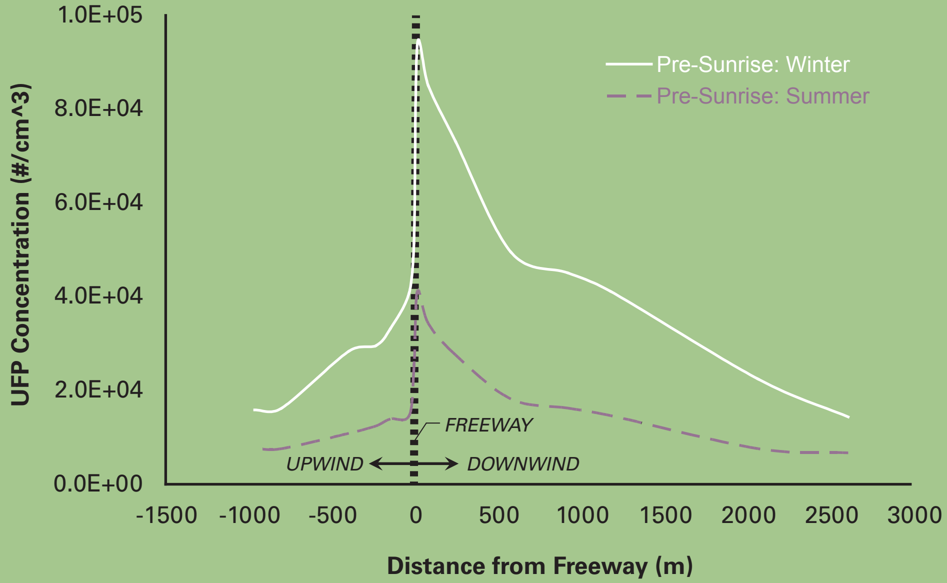
19 *http://www.arb.ca.gov/ch/landuse.htm*

Time-of-day and air pollution concentrations

In a study measuring near-roadway ultrafine particulate matter (UFP) size distributions and concentrations along the Interstate 405 freeway, Zhu et al. [25] found that UFP concentrations decreased with downwind distance from the freeway at night, but at a slower rate than is typically observed during the day.

This finding sparked additional studies to characterize night-time and pre-sunrise pollution concentrations. These studies were motivated by concerns that near-roadway pollution exposure had been previously underestimated and that many people living more than 300 meters (984 feet) from freeways were being adversely impacted by poor air quality at night and in the early morning. Like Zhu et al., these studies found both seasonal and diurnal differences in the rate of decline for pollution concentrations with increasing distance from pollution sources. Winer et al. [32] found that, before sunrise, UFP concentrations did not return to background levels until 2,600 meters (8,530 feet) from the freeway. Later in the morning and afternoon, pollutant concentrations exhibited the typical daytime downwind decrease to background levels within 300 meters (984 feet) downwind of the freeway.

Figure 3: UFP concentrations and gradients along the pre-sunrise route by season. Positive distances are downwind and negative distances are upwind from the I-10 freeway. Image: Winer et al.



Choi et al. [26] observed significant extensions of freeway plumes (~2 kilometers or 1.2 miles) in the stable pre-sunrise periods, much longer than typical daytime plumes measuring ~150-300 meters (~493-984 feet). Also, the researchers calculated a pre-sunrise dilution rate coefficient that is about 10 times lower than dilution coefficient measured during the daytime.

These recent studies highlight the importance of protecting at-risk populations/communities from traffic emissions and indicate that exposure reduction strategies may be needed to protect people that live and spend time in environments that are more than 500 feet from high-volume roadways. This does not mean that nothing should be developed within this distance. In fact, as previously discussed, a compact development pattern is a key strategy in reducing GHG emissions and improving public health through physical activity and it has many other benefits. Instead, planners and developers may want to consider siting non-sensitive uses and developments that will be primarily used and occupied during the daytime—such as commercial uses and offices. In addition to optimizing land use when near-roadway pollution concentrations drop off more sharply with distance, commercial and office buildings are often equipped with indoor filtration systems that can remove particulates from the air inhaled by building occupants, and these buildings are more likely to have permanently closed or sealed windows. This means that, when these buildings are sited close to roads, people that spend time in them are less likely to breathe harmful pollutants and experience negative health impacts. Plus, people typically spend less time at work than at home, meaning that the duration of exposure at work is shorter. These approaches, along with strategies to reduce traffic emissions, disperse pollution and clean indoor air—all discussed in this Technical Advisory—will reduce exposure.

Strategies to reduce air pollution exposure near high-volume roadways

In spite of past successes and ongoing efforts to improve near roadway air quality in California, exposure to traffic pollution is still a concern because pollution concentrations and exposure levels near high-volume roadways continue to indicate that there is a lingering public health concern. In addition, the Office of Environmental Health Hazard Assessment (OEHHA) recently revised its methodology for risk assessment in order to estimate more accurately the health impacts of exposure. This reanalysis has resulted in a revision of cancer risks from exposure to toxic air contaminants, including those emitted by transportation-related sources, to significantly higher levels.[20] ARB forecasting models also indicate that air quality issues will persist even with changes in vehicle technologies and increasingly stringent emissions and fuel regulations. Finally, ARB does not currently regulate non-tailpipe emissions—like tire- and brake-wear—and noise. Scientific literature links these to health effects. Therefore, despite existing efforts they are likely to continue to impact near-roadway public health.

For these reasons, ARB recommends that strategies to reduce emissions, increase dispersion, and remove pollution from the air be implemented to reduce health risks. Many such strategies have been studied and published in peer-reviewed scientific literature. Results can vary based on the specifics of the studies performed, but comprehensive literature reviews conducted by ARB have identified several strategies that consistently and effectively improve air quality and reduce exposure to traffic-related air pollution, particularly where people spend time near high-volume roadways. The specific criteria that ARB used in its evaluation of potential exposure reduction strategies includes the following.

1. Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, or emissions rates, or improving air flow to disperse pollutants.
2. Evidence of significantly effective exposure reduction is documented in the scientific literature.
3. Diversity in the study methods supports consistent findings (such that strategy efficacy does not exclusively rely on one method of investigation).

If literature reviews revealed that all criteria were met, ARB staff included the strategy in this document. In Section II, readers will find a comprehensive discussion of each strategy, including scientific findings and "appropriate context and other considerations."

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20 *https://oehha.ca.gov/air/crnr/notice-adoption-air-toxics-hot-spots-program-guidance-manual-preparation-health-risk-0*

Important overarching considerations in selecting strategies

In addition to the strategy-specific considerations outlined in Section II, readers should be mindful of important overarching considerations that were identified by ARB staff and others consulted in the process of compiling these strategies. All of these should be considered regardless of the types of exposure reduction strategies being considered by planners and other users of this document.

Changes in land use patterns and the built environment are changes that last

The durability of the built environment means that land use patterns, once established, remain fixed for decades. This can both help and hinder compact and infill development and the promotion of alternative transportation. In cities like New York, Boston, and Philadelphia, which developed prior to the widespread use of personal cars, established land use patterns have facilitated density and the viability of transit, biking, and walking. Conversely, where a majority of development occurred when personal cars were prevalent, low-density development and separated land uses necessitate driving to access key destinations [3].

Increasing density through infill development helps to transform low-density neighborhoods to ones that can support alternative modes. When developing new plans and projects, planners should carefully consider the ongoing influence of those plans and projects on public health, sustainability, and community goals to support accessible and livable neighborhoods. Some of the exposure reduction strategies listed in this document will have long-term effects on the built environment. In the case where durable changes will be made to the urban fabric, planners should consider how long-run variables might influence their selection from the exposure recommendations strategies recommended by ARB.

Holistic and comprehensive planning practices

Stakeholders involved in public health, air quality, and community planning efforts must weigh a variety of factors and issues when making policy decisions. Vulnerable populations' exposure to traffic is just one of many considerations, but it is an important piece that should be weighed alongside other local goals and priorities. For this reason, it is recommended that exposure to traffic emissions and strategies to reduce exposure be considered within planning processes at the scale of a neighborhood or community plan or ordinance, general plan, and sub-regional or regional plan, depending on the geographic impact and regulatory context of the issue. In this way, planners and other local officials can proactively consider near-roadway factors in their broader, holistic planning processes.

Another important part of holistic planning is considering how combinations of practices, policies, and strategies can be leveraged to achieve local goals. Few scientific studies examine the combined effect of strategies to reduce air pollution exposure, but there is real-world evidence that a suite of strategies yields better results than those implemented in isolation. For example, when multiple strategies were employed to reduce downtown traffic congestion in Atlanta during the 1996 Summer Olympic Games, ozone pollution and childhood asthma events decreased significantly (*see textbox on the next page for more details*).

Additionally, there is evidence that increasing density and urbanization should be implemented in combination with efforts to expand transit, walking, and biking in order to ensure that mobility needs are met without necessitating the use of a vehicle [33-39].

Site-specific considerations

Site-specific factors may play a significant role in whether or not an exposure reduction strategy will be effective without resulting in negative, unintended consequences. Specific factors that are important to consider include topographical, meteorological, and time-of-day factors (e.g., roadway versus development height, wind direction, and pollutant concentration). For example, both traffic management and high efficiency filtration for indoor air may be particularly important

Case study of the 1996 Summer Olympic Games in Atlanta: The impact of changes in transportation and commuting behaviors on air quality

The 1996 Summer Olympic Games in Atlanta, Georgia provided a unique, real-world opportunity to study the traffic, air quality, and public health outcomes of a holistic, integrated alternative transportation strategy. This strategy was developed in preparation for the Games by the City of Atlanta to mitigate anticipated traffic congestion and to enable travel between Olympic events for the more than 1 million visitors. Moreover, Atlanta hoped that the strategy would avoid additional summertime ground-level ozone-related air quality violations. The strategy included a suite of travel-demand management measures, including the following: (1) a 24-hour public transportation system, (2) the addition of 1,000 buses for park-and-ride services, (3) use of alternative work hours and telecommuting by local businesses, (4) the closure of the downtown sector to private cars, (5) alterations in downtown delivery schedules, and (6) public notifications of potential traffic and air quality problems.

Researchers studied the effect of this alternative transportation strategy by comparing the 17 days of the Olympic Games (July 19 – August 4, 1996) to a baseline period consisting of 4 weeks before and 4 weeks after the Games. They looked at citywide acute care visits and hospitalizations for asthma and non-asthma events, concentrations of major air pollutants, meteorological variables, and traffic counts. Results showed decreased traffic density, especially during the critical morning period. This was associated with a prolonged reduction in ozone pollution and significantly lower rates of childhood asthma events [40].

to employ in development along a high-volume roadway where there will be a cumulative pollution burden. Local context is also important; some strategies herein work better in urban environments than in suburban or rural contexts. Drawbacks associated with some strategies may make them unacceptable for a specific site. For example, while stop signs may mean increased emission rates at some intersections, planners may determine that they are more appropriate than implementing a roundabout at that particular location, for a variety of reasons. Also, local planners may wish to eliminate from consideration any strategy that, in the local context, would increase VMT and therefore overall emissions. If such factors are considered as part of a detailed planning process, such as the development of a specific plan, a project-specific or parcel-specific analysis may be avoided.

When strategies are incorporated into large-scale policy documents, such as jurisdiction-wide general plans that direct planning processes for new developments, a menu of strategies and language about the usefulness of site-specific analysis to assist in choosing the right strategies for specific projects may be appropriate, since not all strategies are necessary or appropriate in all cases.

Changing vehicle fleets and impacts on air quality

California's vehicle fleets and freight system are becoming cleaner, and this trend will continue into the future, given existing and forthcoming policies and transformations underway in the automobile market. ARB programs, like those previously noted in the section "State programs to improve air quality and reduce exposure to traffic emissions" (*page 9*), are helping to usher in this transition. This fact should be considered in local decision-making, particularly when long-term, durable strategies are being considered, such as urban design changes or standards.

However, while transitioning to ZEVs eliminates tailpipe emissions, it does not eliminate all traffic emissions. Non-tailpipe particulate matter emissions—like road dust, tire wear, and brake wear—currently account for more than 90 percent of PM10 and 85 percent of PM2.5 emissions from traffic. Both epidemiological and toxicological studies show an association between these pollutants and cardiovascular and pulmonary effects [41]. In a review of published literature examining how the transition to EVs may effect PM10 and PM2.5 emissions, researchers confirmed a positive relationship between vehicle weights and non-exhaust PM emission factors, and also found that ZEVs are, on average 24 percent heavier than equivalent internal combustion engine vehicles (ICEVs) [42]. This makes PM10 emissions from ZEVs roughly equivalent to PM10 emissions from modern ICEVs. PM2.5 emissions from ZEVs are about 1-3 percent less than PM2.5 emissions from conventional cars. This study concludes that, absent efforts to reduce vehicle weights and otherwise mitigate PM emissions, PM10 and PM2.5 levels could remain steady with the EV transition.

Furthermore, ZEVs do not eliminate upstream emissions from non-renewable energy sources or sources linked to their manufacture and production [10]. Using a life cycle approach, some studies have found a modest increase in emissions associated with ZEV production compared to the production of ICEVs [43, 44]. Other studies emphasize the importance of the energy sources used to produce the electricity for ZEVs. They demonstrate that, in some cases, carbon-intense grid mixes can actually translate to greater per-mile CO_2 equivalent emissions from ZEVs relative to conventional cars [44-46].

On-roadway exposure to traffic emissions

Exposure to vehicle emissions also occurs when people use the roadways, whether or not they live or work near them, and past studies show that on-road pollution concentrations can far exceed ambient concentrations. On-road ultrafine particulate matter (UFP) concentrations, for example, typically range from 10,000 to 500,000 particles/cm^3, which is 1-2 orders of magnitude greater than typical ambient levels [15]. These high on-road concentrations mean that people may experience a large proportion of their total daily UFP exposure while driving, depending on where and how long they drive. Based on data from Los Angeles, Fruin et al. [47] found that 36 percent of total daily exposure to ultrafine particulate matter (UFP) resulted from drive time even though only 6 percent of the day (~90 minutes) is spent driving on these roadways by the average Californian. These exposures can be reduced three ways: (1) by reducing on-road concentrations and (2) by reducing time spent driving on roadways, and (3) via in-vehicle air filtration. Reducing time spent driving is an important point for planners to consider, since it is crucial that they avoid making land use decisions that would result in longer commutes. In other words, planners should avoid new development farther from key destinations because this could induce longer vehicle trips and thus increased on-roadway exposure.

Users of this document should also be aware that it is possible that some of the exposure reduction strategies herein—specifically solid barriers and vegetation—could have the effect of increasing on-road pollution concentrations, but study results are mixed [48, 49]. Some field studies that have found increased on-road concentrations attribute this to the possibility that barriers block air flow across the roadway that would, in the absence of a barrier, carry pollution off the roadway. When meteorological conditions and windspeed and direction create the conditions for the entrapment of on-road pollution, some modeling studies also demonstrate this phenomenon. Hagler et al. found that on-road pollution concentrations may increase as barriers grow taller, too [50]. On the other hand, there is also research that contradicts these results. In field studies in Phoenix, AZ, Bauldauf et al. found that concentrations on the highway upwind of the barrier were similar to those measured in the absence of the barrier [51]. These studies suggest that it is very important for planners and others to consider local meteorology when deciding if and how to design certain exposure reduction strategies, which is consistent with the abovementioned overarching consideration regarding the use of site-specific information when it is available and when issues like elevated on-road pollution concentrations are a relevant concern.

While on-road pollution concentrations are concerning, it is also worth noting that many new passenger vehicles are equipped with on-board air filtration that helps to remove particles from the air breathed by the people traveling in the cabin of the car. Xu et al. found that typical commercially available filters exhibit a range of particle removal efficiencies (up to 60 percent), and some thicker filters are even more effective [52]. A study by Zhu et al. found that maximum in-cabin protection from UFPs (approximately an 85 percent reduction in UFP concentration) could be achieved when the in-cabin fan and recirculation settings were on [15]. There are many variables that influence filter efficacy, however, including age, maintenance, and driver behavior when it comes to operating their vehicles. When old filters are not replaced or when windows are open while traveling on roadways, for example, exposure concentrations may be very high [15].

Translating research into practice

Putting research into practice can be challenging since research studies often seek to address narrowly defined questions and control for factors that are commonly observed in the real world. For this reason, research findings may not always be entirely reflective of real world conditions, so users of this Technical Advisory should consider how the research applies to the specific context being considered.

Additionally, even when research is based on data collected in the real-world, the data may be several years old by the time that researchers are able to digest, analyze, and summarize findings and conclusions. For this reason, it may be necessary for planners and the users of this document to consider how changes in the local context may have affected the variables that researchers considered in their analyses. For example, improvements in vehicle technology and controls for diesel emissions from trucks may mean that concentrations of some pollutants are lower today than they were when the data were collected. However, ARB cautions against making assumptions about how health outcomes may be affected by these changes, since health effects are related to a suite of variables, not just emission rates and pollution concentrations.

Ongoing research and other resources

New studies are currently underway and results are constantly emerging from the literature. Appendix A, "Strategies not meeting ARB's criteria at this time" (*page 42*), includes exposure reduction strategies that did not meet all three ARB's following criteria required for inclusion: (1) consistent findings from multiple studies, (2) evidence of significantly effective exposure reduction, and (3) diversity in the study methods used.

In the years to come, these strategies may emerge as promising exposure reduction strategies as a result of additional investigation or updated techniques for more successful implementation.

ARB collaborated with many partner agencies and organizations to produce this Technical Advisory, and in the process, learned of many additional resources that stakeholders will find useful, including the following:

- The United States Environmental Protection Agency (U.S. EPA) sponsors research related to near-roadway air pollution exposure, and as such, recently published a report outlining strategies for reducing exposure at schools. Many of the strategies found in the U.S. EPA document, titled "Best Practices for Reducing Near-Road Air Pollution Exposure at Schools" complement strategies found in this Technical Advisory. To access the U.S. EPA report, visit: *https://www.epa.gov/schools/best-practices-reducing-near-road-air-pollution-exposure-schools.*
- The Bay Area Air Quality Management District (BAAQMD) provides tools, guidance, and information to promote "healthy infill development" from an air quality perspective. The guidance is also intended to encourage Bay Area local governments to consider and address local air quality issues in the planning and development stages. In 2016, BAAQMD published "Planning Healthy Places," which provides recommended best practices for reducing emissions from and exposure to local air pollution sources. BAAQMD's guidebook is accompanied by an interactive web-based mapping tool that illustrates where best practices are recommended and where "further study" is recommended to assess the local concentrations of TACs and fine PM, and therefore the health risks from air pollution" (pg. 12). To access BAAQMD's document and interactive map, visit: *http://www.baaqmd.gov/plans-and-climate/planning-healthy-places.*

ARB encourages users of this Technical Advisory to consult with local air quality experts as they weigh the options presented in this document. Air districts, like BAAQMD may also have useful localized information to aid in the decision-making process. Finally, given the evolving nature of the science, ARB will continue to update documents and websites with the most current information, which can be found at: *https://www.arb.ca.gov/ch/landuse.htm*.

Detailed Description of Strategies to Reduce Air Pollution Exposure Near High-Volume Roadways

This section details strategies to reduce air pollution exposure near high-volume roadways identified by ARB staff from academic literature and ARB-funded research. These strategies are organized into three categories:

1. Strategies that reduce traffic emissions,
2. Strategies that increase dispersion of traffic pollution, and
3. Strategies that remove pollution from the air .

Each strategy presented below includes a description of relevant research findings as well as a summary of the "appropriate context & other considerations" that planners and policy makers should be take into account as they make decisions about which exposure reduction strategies they might include in policy-level documents or on a case-by-case basis. The "other considerations" portion for each strategy also includes a discussion of potential co-benefits and drawbacks.

Strategies that reduce traffic emissions

1: Speed reduction mechanisms, including roundabouts

FINDING: Vehicle speed reduction mechanisms change the design and operating speed of the road by altering the physical characteristics of the road. These features can reduce stop-and-go driving and hard accelerations and thereby reduce emissions rates. Some of these features, like the roundabout intersection, can be used as an alternative to stop-controlled and signalized intersections. Studies show that roundabouts can reduce localized pollutant concentrations compared to intersections with stop and signal control by 20 percent or more (depending on context and site-specific conditions).

APPROPRIATE CONTEXT & OTHER CONSIDERATIONS: Transportation planners and engineers should carefully consider the potential direct and indirect effects of implementing speed reduction mechanisms to determine if they will reduce vehicle emissions and other impacts to the environment as well as to traveler safety and delay. When guidance is needed to estimate emissions and air quality-related effects, planners and engineers may consult with MPOs or traffic modeling experts.

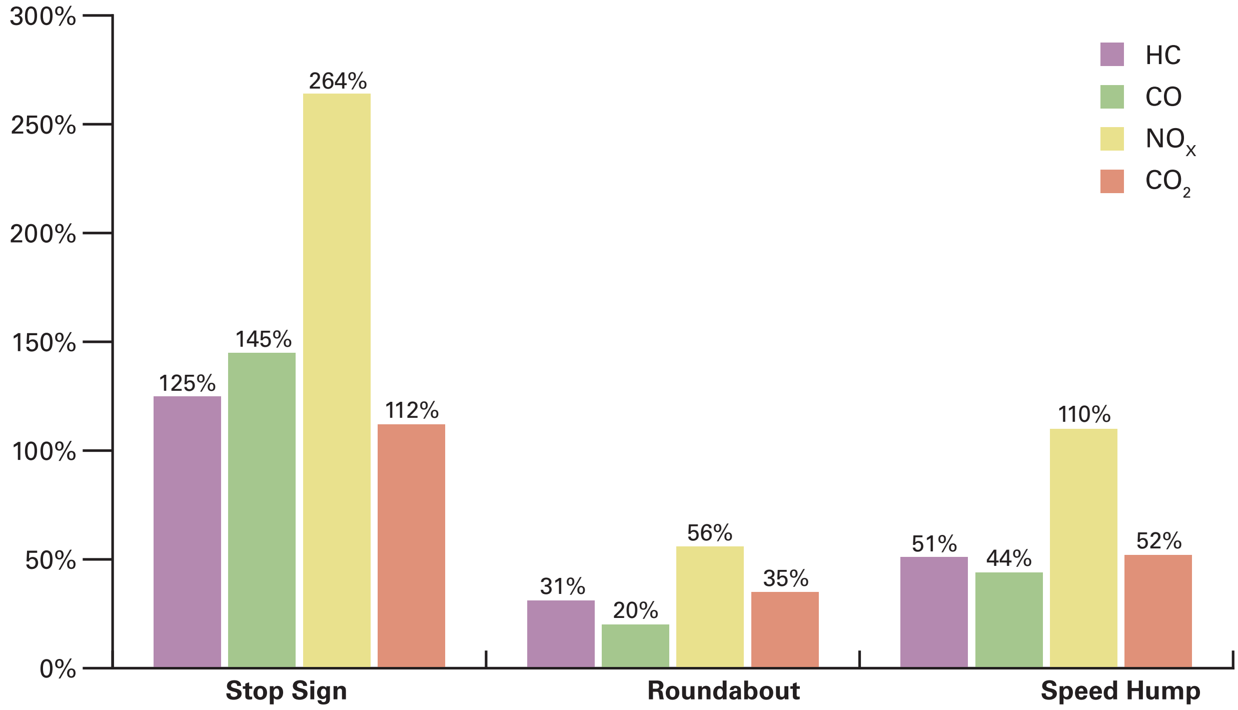
Street, highway, and freeway ramp intersections have been found to be pollution hot spots. This is mainly due to frequent deceleration and acceleration and the increased frequency and duration of idling at intersections. As a result, intersection alternatives that reduce the frequency of stops, acceleration, and idling can generally benefit air quality at and around intersections.

Speed reductions mechanisms, such as roundabouts, can be implemented to smooth traffic flow. Roundabouts can be used in lieu of stop signs or signal controls in order to decrease hard accelerations and decelerations and encourage driving speeds that fall within the optimal range for minimizing emissions rates and fuel consumption. A roundabout is an example of an intersection-specific speed reduction mechanism that can be implemented to reduce pollution concentrations, and produce other transportation system benefits.

Roundabouts

Several studies have found that roundabouts generate substantially less air pollution from vehicles than stop-controlled intersections. Ahn and Rakha [53] found that roundabouts reduce emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxide (NO_x), and carbon dioxide (CO_2) by 75, 86, 79, and 69 percent respectively, compared to stop-controlled intersections. Figure 4 shows how emissions levels changed compared to a no-control scenario and illustrates how roundabouts and speed humps—another speed reduction measure—compare to a two-way stop controlled intersection (with stop signs on the minor leg approaches). These data were produced using a mathematical model that estimates emission rates using second-by-second speed and acceleration measurements collected by researchers at a specific intersection located in Arlington, VA.

Figure 4: Relative increases in emissions for various intersection treatments (compared to no treatment) as measured at an experimental site in Arlington, VA. Image derived from: Ahn and Rakha 2009.



Höglund [54] found when a traffic signal intersection was changed to a roundabout, the HC emission per vehicle per kilometer travelled decreased by 36 percent. Várhelyi [55] used the "car-following" method and showed that replacing a signalized junction with a roundabout decreased CO emissions from vehicles by 29 percent, NO_X emissions by 21 percent, and fuel consumption by 28 percent. Mandavilli et al. [56] found a statistically significant decrease in the emissions from vehicles when a modern roundabout replaced a stop-controlled intersection for six sites with different traffic volumes. In particular, the reductions were 21-42 percent for CO, 16-59 percent for CO_2, 20-48 percent for NO_X and 17-65 percent for HC.

While the research literature shows mostly positive performance results for roundabouts from the emissions and air pollution perspective, some studies illuminate their limitations. Ahn et al. [57] find that, at the intersection of a high-speed road with a low-speed road, an isolated roundabout does not necessarily reduce vehicle fuel consumption and emissions compared with other forms of intersection control (stop sign and traffic signal control). In fact, the case study found that the roundabout in this context results in a significant increase in vehicle fuel consumption and emission levels compared with a two-way stop. The researchers attribute this finding to the fact that, as demand increases, traffic at the roundabout experiences a substantial increase in geometric delay (the increase in travel time as vehicles must navigate the roundabout more slowly) in comparison with the use of signal control.

Appropriate context & other considerations

It is important that speed reduction mechanisms and roundabouts be evaluated with site-specific conditions and context in mind in order to ensure that these road design elements achieve sought-after emissions reductions and other benefits. Many resources are available to assist with the selection, planning, and design of speed reduction mechanisms and roundabouts, including (but not limited to) the following:

- FHWA Roundabout Website: *http://safety.fhwa.dot.gov/intersection/roundabouts/*
- Roundabouts: An Informational Guide, Second Edition (NCHRP Report 672):
- *http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_672.pdf*
- National Association of City Transportation Officials Urban Street Design Guide: *http://nacto.org/publication/urban-street-design-guide/design-controls/design-speed/*
- AASHTO's Strategic Highway Safety Plan: *http://safety.transportation.org/htmlguides/speeding/section01.htm*
- FHWA Roundabout Outreach and Education Toolbox: *http://safety.fhwa.dot.gov/intersection/roundabouts/roundabouttoolbox/*

Depending on site-specific conditions, speed reduction mechanisms can result in improved safety; specifically, fewer fatal crashes and less serious injuries when crashes occur. The FHWA Office of Safety identified roundabouts as a Proven Safety Countermeasure because of their ability to substantially reduce the types of crashes that result in injury or loss of life. Roundabouts reduce vehicle speed and the number of conflict points at the intersection, which provides safety benefits for vehicles, pedestrians, and bicycles. Single lane roundabouts produce the lowest vehicle speeds and fewest number of conflict points compared to multi-lane roundabouts and traditional signal and stop-controlled intersections. The FHWA document, "Roundabouts: An Information Guide,"[21] states, "While overall [and especially severe] crash frequencies have been reduced, the crash reductions are most pronounced for motor vehicles, less pronounced for pedestrians, and equivocal for bicyclists, depending on the study and bicycle design treatments" [58-60].

While roundabouts are not expected to reduce vehicle emissions at all intersections (refer to above mentioned case study by Ahn et al.), [57] roundabouts have been proven to be effective at freeway interchange ramp terminals. FHWA guidance indicates that roundabouts can help create a transition area that moves traffic from a high-speed to a lower-speed environment.

Regarding design and engineering requirements for roundabouts, Caltrans and FHWA provide guidance to help local planners and engineers, including the following:

- The California Manual of Uniform Traffic Control Devices (MUTCD) provides standard guidance on roundabouts as an alternative to traffic signal control; see Part 4, Chapter 4C, Section 4C.01 Studies and Factors for Justifying Traffic Control Signals.[22]
- The Caltrans Intersection Control Evaluation (ICE) Policy Directive (TOPD13-02) and website provide direction and guidance on the evaluation of highway project proposals that create new, and expand or modify existing, intersections and interchanges. Caltrans established ICE to ensure the objective consideration, evaluation, and comparison

21 *https://www.fhwa.dot.gov/publications/research/safety/00067/index.cfm*
22 *http://www.dot.ca.gov/trafficops/camutcd/*

of roundabouts with traditional and other innovative intersection solutions.[23]

In all cases, roundabouts should be designed to satisfy the engineering principles outlined in the FHWA Informational Guide on Roundabouts, published as NCHRP Report 672.[24] This will generally produce the range of vehicle speeds that are capable of reducing vehicle emissions and the potential for crashes (as described above). Local and other agencies responsible for the operation of streets and highways are advised to employ qualified traffic analysts and engineers to evaluate, design and oversee their first roundabouts. Roundabout implementation in some communities may require consultation with local agencies that may be affected by these intersections, including (but not limited to) operators of transit, waste disposal, delivery, and emergency response vehicles. Planners should also consult with their local air quality management district to see if it provides additional recommendations for this type of strategy.

It is advisable to establish an education campaign for communities that are planning to construct roundabout intersections for the first time to accelerate understanding and acceptance of roundabouts in communities that do not yet have a modern roundabout intersection. This can inform travelers and others who will be affected by a roundabout of other advantages and co-benefits attributed to roundabouts (e.g., roundabouts can improve aesthetics and reduce operating & maintenance costs compared to signalized intersections).

2: Traffic signal management

FINDING: Traffic signal management systems can reduce stop-and-go driving and vehicle idling, resulting in reduced localized pollutant concentrations of up to 50 percent compared to corridors that do not implement these systems. Studies show that site-specific conditions dictate the magnitude of reductions.

APPROPRIATE CONTEXT & OTHER CONSIDERATIONS: Many different types of signal management are available, and planners should identify what is best for air quality, vulnerable road user safety, and transit and active mode throughput and comfort.

Traffic lights are widely used at intersections to reduce traffic speed, avoid traffic accidents and crashes, and improve safety for road users. However traffic lights can also increase idling, deceleration, and acceleration of vehicles, and therefore increase air pollutant emissions from vehicles. Coelho et al. [61] found the presence of traffic signals can increase CO, NO, and HC emissions from vehicles by about 15 percent, 10 percent, and 40 percent, respectively. Different traffic signal schemes may have different impacts on vehicle emissions [62]. Signal strategies that prioritize enforcement of the speed limit may result in more stops for all traffic, and therefore lead to higher emissions from vehicles. Signal strategies that are more tolerant on speed enforcement may achieve lower emissions.

Traffic signal coordination has been found to be a potentially effective strategy to reduce vehicle emissions by several modeling studies. Rakha et al. [63] found a well-timed green wave (all vehicles only need to stop at the first traffic signal along a road section) can reduce the emissions of HC, CO, and NO_X from vehicles by 50 percent, compared with extreme cases of all vehicles having to stop at all signals. De Coensel et al. [64] simulated vehicle emissions for an urban arterial road with a speed limit of 50 kph, and five consecutive traffic signals spaced at a distance of 200 m from each other. This study found that the introduction of a green wave could reduce the emissions of CO_2, NO_X, and PM10 by 10-40 percent. The largest reduction of vehicle emissions may be achieved when traffic intensities are close to road capacity and the green split (the ratio between the amount of green light time and the traffic light cycle time) is high. The introduction

23 *http://www.dot.ca.gov/trafficops/ice.html*
24 *http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_672.pdf*

of a green wave also reduced noise levels near traffic signals; however, noise levels between intersections increased. A study in China showed that, by increasing the green split of the major direction by 5 percent, the emissions of CO, HC, and NO_X of different vehicle categories decreased in the range of 2.6-14.6 percent [65].

Positive environmental impacts of traffic signal coordination have also been confirmed in measurement studies. Unal et al. [66] performed on-board air pollutant emission measurements along two signalized arterial roads in North Carolina and found that, depending on the type of vehicles and the level of congestion, the implementation of traffic signal coordination reduced the HC, NO, and CO emissions per unit of distance by 10-20 percent. Similarly, Zhang et al. [67] measured the NO_X, HC, and CO emissions from a single vehicle driven on two roads that were similar except one had coordinated traffic signals. The results showed that the emissions of HC and CO per kilometer travelled decreased 50 percent and 30 percent, respectively, along the road with coordinated signals, but the emission of NO_X per kilometer travelled was 10 percent higher.

Appropriate context & other considerations

It is important that planners consider site-specific factors and consult with guidance material and traffic experts before deciding to implement traffic signal management strategies. The following resources (and others) are available to assist with the selection, planning, and design of traffic signal management systems:

- FHWA Traffic Signal Timing Manual: *http://ops.fhwa.dot.gov/publications/fhwahop08024/fhwa_hop_08_024.pdf*
- Signal Timing Manual: Second Edition (NCHRP Report 812): *http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_812.pdf*

When implemented with site-specific context and other goals in mind, traffic signal management can improve safety and enable efficient movement of transit vehicles and bicycles. Regarding safety, several studies have found that coordinated signals can reduce the frequency and severity of automobile crashes. A field evaluation in Scottsdale, Arizona found that coordinated traffic signals resulted in a crash risk reduction of 6.7 percent [68] and studies from Europe found that network coordinated signals were associated with a 20 percent reduction in injury accidents at intersections [69]. Based on data from 1,345 crashes at three arterial intersections in Indiana, Li and Tarko [70] used a mixed logit model to find that crashes and severe crashes are less likely at intersections with signal coordination. Finally, a study in Phoenix, Arizona assessed five years of crash data (1993-1997) and found that crash rates at coordinated traffic signals were less than those for uncoordinated traffic signals by 14 to 43 percent.

Coordinated signals can also be designed to more efficiently move transit vehicles and other modes. With the technological infrastructure in place, coordinated traffic signals can be programmed to work in concert with transit vehicles. Recent advances in intelligent transportation system technology have made it possible for transit vehicles to communicate with signal timing infrastructure, so coordinated signals could be dynamically adjusted to allow more efficient movement of transit vehicles which not only makes them more attractive to transit riders but also reduces diesel particulate emissions from these heavy-duty vehicles. Coordinated signals can also be timed to accommodate cyclists and to give them a "green wave" along with motorists.

It is important for planners and others to consider potential effects of traffic signal management strategies when deciding if and where this exposure reduction strategy may make sense. For example, this strategy loses effectiveness when implemented where traffic volumes on cross-streets are comparable with those on the managed section. This will result in increased idling on these perpendicular sections and thus accumulating traffic emissions.

Additionally, it is possible that coordinated signals will increase vehicle throughput and VMT on the road section where it is implemented, since this strategy increases the "effective" capacity of the roadway section. Some models have shown that increased throughput is VMT shifted from elsewhere while others attribute increased VMT to new trips generated by the increased effective capacity. Dowling [71] analyzed the net effects of a 0.5 mile long arterial signal coordination project and found that, regionally, VMT is actually reduced by -0.01 percent and emissions by 0.02-0.04 percent as a result of the project. More studies are needed to understand the broad and long-term impacts of traffic signal synchronizations, and local traffic engineers may have information that will make it possible for planners to implement this without offsetting air quality gains with increased vehicle use.

Finally, pedestrian crossings are an important consideration for traffic signal management projects. The FHWA Traffic Signal Timing Manual indicates that the time needed to serve vehicle volume is usually commensurate with a reasonable amount of wait-time for pedestrian calls, but planners should evaluate this on a site-specific basis to ensure that traffic signal coordination and the resultant timings for pedestrian crossings do not curb overall pedestrian activity.

Planners should also consult with their local air quality management district to see if it provides additional recommendations for this type of strategy.

3: Speed limit reductions on high-speed roadways (>55 mph)

FINDING: Research studies have identified an optimal average speed range of ~35-55 mph within which per-mile traffic emissions and fuel consumption are minimized. Generally, speed limit reductions on high-speed roadways can reduce tailpipe emission rates up to 30 percent, depending on the change in speed, the pollutant measured or modeled, and the roadway characteristics.

APPROPRIATE CONTEXT & OTHER CONSIDERATIONS: Speed limit reductions are appropriate on roadways where speed limit and design speeds exceed 55 mph.

Studies show that high speeds encountered on highways require high power output from vehicles, and this is associated with increased per-vehicle tailpipe emissions rates. Several studies have evaluated the role that speed limits play in vehicle speeds and air quality. Keller et al. [72] conducted a modeling simulation to investigate the emission impact of lowering the maximum speed limit on Swiss motorways from 120 to 80 kph (75 to 50 mph). The models predicted current total NO_X release from road traffic would decrease around 4 percent, peak ozone levels may decrease by less than 1 percent, and no significant change in emissions of VOCs. Similarly, Gonçalves et al. [73] simulated the effects on vehicle emissions of the 80 kph (50 mph) speed restriction planned for the Barcelona Metropolitan area, and found the reductions on NO_2, NO_2, and PM10 levels on the affected roads reached up to 5.7 percent, 5.3 percent, and 3.0 percent on 24-h average concentration, respectively. Field measurements also confirmed the reductions of traffic-related air pollutant levels with lower speed limits. A Netherlands study monitored the changes of traffic related air pollutant levels in the direct vicinity of a highway after lowering the maximum speed limit from 100 to 80 kph (62 to 50 mph) [74]. This study found the adjusted traffic contribution to air pollutant concentrations in the vicinity of the intervention site significantly decreased by 27 percent, 11 percent, and 21 percent, for PM10, PM2.5, and black smoke, respectively.

Additionally, studies indicate that higher vehicle speeds are also associated with increased non-tailpipe emissions, including higher rates of tire wear and associated PM emissions and greater resuspension of road dust [75, 76]. Related to tire wear, researchers have measured increased PM emissions with increasing vehicle speed and have hypothesized that, as tire temperature increases with faster speeds, tires break down more readily [77]. Studies also show that more road dust tends to be re-suspended into the air when vehicles travel faster [76]; Kuhns et al. found that road dust emissions increase exponentially with increasing vehicle speeds [78].

Appropriate context & other considerations

Planners should consider the direct and indirect effects—including benefits and drawbacks—involved in reducing posted speed limits on high-speed roadways to less than 55 mph. Planners should also consult with their local air quality management district to see if it provides additional recommendations for this type of strategy.

Higher vehicle speeds are associated with increased risk of severe crashes and injury or death when crashes occur [79, 80]. Thus, reducing speed limits to 55 mph or less on freeways could result in safety benefits for roadway users. This assumes, however, that drivers respond to speed limit reductions. In actuality, changing the speed limit does not necessarily translate to a change in vehicle speed, as the majority of drivers drive at speeds at which they feel comfortable. This means that speed limit reductions may need to be implemented in conjunction with additional enforcement in order to ensure that drivers adhere to new speed limits. Enforcement can be implemented via police, radar, camera, or aircraft, but this comes with associated costs.

Research also indicates that the ratio of in-cabin to on-roadway pollution concentration ratios—or I/O ratios—increase with increasing vehicle speed because faster driving speed creates a larger pressure differential between the in-cabin and outside air. This causes more air exchange into the cabin from outside, and therefore exposes the people traveling in the cabin to higher pollution concentrations [81]. Xu et al. measured in-cabin I/O ratios for UFP and found that the largest UFP penetration factor and the largest I/O ratios were measured at the fasted driving speeds [52]. Thus, reducing in-cabin exposure to traffic related pollution may be a co-benefit of reducing speed limits for near-roadway exposure reduction purposes.

Strategies that increase dispersion of traffic pollution

To date, several studies and literature reviews have evaluated how urban design in the built environment influences air pollutant levels in streetscapes [82-92]. While the majority of these are modeling studies conducted to understand air flow and pollutant dispersion in urban street canyons, they also show that urban design characteristics—including building geometry, architectural design, street canyon dimensions, and building siting—are important parameters that influence pollutant dispersion, concentration, and exposure [82, 86]. Also, a select few have identified urban design guidelines to reduce pollutant exposure [91, 93-95].

4: Design that promotes air flow and pollutant dispersion along street corridors

FINDING: The physical layout of urban streetscapes influences air flow and pollution movement. Research studies show that street corridors characterized by buildings with varying shapes and heights, building articulations (street frontage design elements like edges and corners that help break up building mass), and spaces that encourage air flow (e.g., parks) benefit from better pollutant dispersion and air quality. For example, buildings of varying heights can result in significant increases in turbulence (e.g., up to doubling), and adding bike lanes and sidewalks not only reduces car traffic, but also creates space for more dispersion (up to a 45 percent reduction in particulate concentrations).

APPROPRIATE CONTEXT & OTHER CONSIDERATIONS: Wider sidewalks, bicycle lanes, dedicated transit lanes, and other features that benefit alternative modes of transportation can also create space for better air flow and pollutant dispersion along with increasing active transportation and mode shift. This strategy should be considered in the context of the overall need to increase development density.

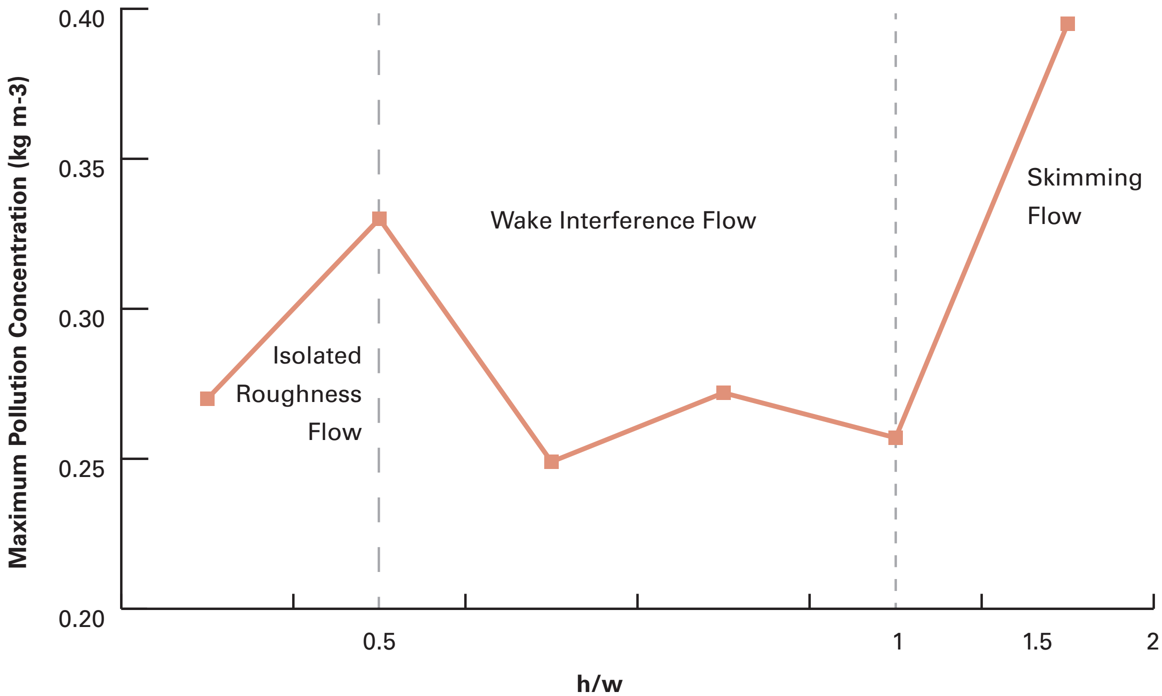
Research shows that the physical layout of urban streetscapes influences how air flows and pollutants move, and thus, planners can use this to their advantage to design buildings and streets to facilitate pollution dispersion [83, 84, 96, 97]. Key variables that planners can consider include the size, shape, and location of building and streets. This section outlines findings from modeling studies (e.g., wind tunnel simulations, computational fluid dynamics modeling, etc.) and field and measurement studies that shed light on the influence of these variables.

Many studies focus on evaluating pollutant behavior in "urban street canyons" characterized by narrow streetscapes continuously lined with buildings because they often experience "hot spots" of gaseous and particulate pollutants due to high levels of vehicular traffic and reduced ventilation flow created by the street canyon configurations themselves [98, 99]. In California, there are very few cities with traditional urban street canyons, and as such, concerns about pollution hot spots that have been raised in other cities—like Hong Kong and Manhattan—may not be relevant for current California cities. Nevertheless, the studies discussed herein can inform design choices that reduce pollutant exposures by maintaining or increasing ventilation and air flow as California's cities continue to grow and develop.

Developing uniform characterizations of pollutant dispersion and concentration in urban street canyons is challenging because differences in canyon geometry, traffic intensity and fleet mix, and local meteorological conditions translate to an almost infinite set of combinations and air quality outcomes [82, 89, 100]. While arriving at rigid guidelines for altering urban design to reduce air pollution is extremely difficult given this complexity, researchers have endeavored to identify various critical configurations to avoid when concerned about pollution concentrations [84, 100, 101]. These recommendations align with findings from studies that model the flow of pollutants through urban areas.

Numerous studies have investigated the close link between air vortex circulations that develop within the canyons and pollutant dispersion. Modeled and measured research confirms that when roof-level wind flows perpendicular to the street, a vortex circulation develops, resulting in much higher pollution levels on the downwind side of the street canyon [82, 87, 100, 102-108]. These circulation vortices are also influenced by street canyon geometry, and one variable used to measure this geometry is called the "aspect ratio" [89]. In canyon flow studies, the aspect ratio—the ratio of the building height to the width between buildings—is generally accepted as the key factor determining wind flow characteristics [83, 85, 93, 109]. Research shows that aspect ratios that describe canyons that are wider relative to their height promote better pollutant dispersion because they provide more space for ventilation flow to reach the street level [84, 100, 110-113]. This is not to say that tall buildings necessarily promote blockage, however. Using dispersion modeling validated against measurements from wind tunnels, Chan et al. [100] found that—with a fixed reference speed and fixed building height—as the street width is increased, pollutant concentrations decrease on both the upwind and downwind sides of the street. As long as the canyon aspect ratio creates a turbulence pattern that falls between stagnation flow and leeward blockage, ventilation will be promoted [84]. Figure 5 below demonstrates this concept by showing how pollution concentrations change with varying height-to-width ratios (h/w).

Figure 5: There are three air flow regimes in urban areas that are denoted in the figure: isolated roughness flow (generally more ventilation), wake interference flow (some ventilation), and skimming flow (little to no ventilation). The figure demonstrates that street canyons with higher height-to-width ratios tend to have higher pollutant concentration. To avoid this, ARB suggests that street canyons have space for better ventilation and/or implement strategies to reduce emissions produced. Image: Chan et al. 2001.



Studies also show that open space can increase ventilation over the city fabric [91, 114, 115]. Kaur et al. [114] found that particulate concentrations are two times higher at intersections surrounded by buildings compared to intersections adjacent to open space. Hess et al. [115] examined pollutant concentrations inside and outside seven bus stop locations in Buffalo, New York and found that the presence of undeveloped areas without vehicle access on both sides of the bus shelter or without a building on one side provide statistically significant reductions compared to a bus stop site with buildings on both sides of the street.

In addition to canyon geometry, building variables—including height, width, and roof shape—also influence air flow and pollutant dispersion. Some studies find that building uniformity (e.g., height and breadth) decreases air flow [83, 84, 89], and others find that gaps between adjacent buildings facilitate air flow and ventilation [116-118]. Roof shape and height can also influence air flow [30, 106, 119, 120]. Xie et al. used both 2D and 3D modeling to simulate the effects of different roof shapes and building geometries on vehicle emissions dispersion [106]. They found that different roof shapes lead to different circulation vortices and thereby influence air quality in the urban canyon. Huang found similar results when investigating the impact of wedge-shaped roofs on pollutant dispersion [30].

Boarnet et al. studied the effect of both canyon geometry and building characteristics on pollutant concentrations in five cities in Southern California [111]. The researchers measured PM2.5 concentrations near arterials in five cities that exhibit different development patterns, ranging from low-density auto-oriented development to dense urban areas with mid- and high-rise buildings. A regression analysis of the measurements indicated that—after accounting for meteorology, time of day, and location—higher concentrations were associated with lower wind speeds, higher temperatures, higher adjacent passenger vehicle traffic, higher ambient concentrations, and street canyons with buildings over five stories.

While there is a large body of research that explores the interaction between building and street design and air flow, only a few studies quantify the pollution reduction. Chan et al. applied the urban form guidelines they developed through their modeling efforts to a hypothetical situation and modeled the effect of these building configuration modifications in a small district in Hong Kong [83]. These modifications included (1) altering the relative building heights—including by adding height to some buildings—to create differential heights and (2) altering the building breadth ratio. The modeled pollution levels dropped by 40 percent and 30 percent, respectively.

Acero et al. used dispersion models to calcuate NO_2 concentrations associated with three different urban design features—a park with trees, an open space with obstacles, and a building—in the medium-sized town of Durango, Spain [121]. The study found that removing the park with trees to leave an open space reduced NO_2 concentrations on the eastern part of the street by about 6.1 percent. On the other hand, the presence of a 16 meter (52 foot) building instead of trees created a recirculation vortex. This dispersed local traffic pollutants to the western side of the street, close to the new building, with the wind direction influencing the spatial variation of pollutants. This study illustrates the importance of local wind direction and orientation to the dispersion of polluants.

Schulte et al. [113] developed and evaluated a semi-empirical dispersion model to estimate surface concentrations of NO and NO_2. This was accomplished using empirically collected data from street canyons in Hanover, Germany to evaluate dispersion models and identify the variables that best describe the observed data. The researchers concluded that the ratio of effective building height to street width governs the dispersion of vehicle emissions. The researchers also presented three possible methods for mitigating street-level pedestrian exposure to vehicle emissions: (1) limiting vehicle traffic within streets with large aspect ratios when there is high pedestrian traffic, (2) limiting the street aspect ratio based on expected pedestrian exposure, and (3) in new developments, or where such design can be implemented, separate pedestrian and heavy vehicle traffic into different streets.

Appropriate context & other considerations

The research literature demonstrates that design that promotes air flow and pollutant dispersion along street corridors can take many forms. Implementing complete streets design concepts—which are characterized by wider sidewalks, bike routes or paths, and transit lanes or infrastructure—is an option that both facilitates air flow and encourages active transportation and alternative modes. Complete streets designs also have the potential to reduce VMT and therefore emissions along a corridor, particularly when vehicle lanes are converted to provide the infrastructure for alternative modes.

A recent ARB study that compared existing complete streets and "incomplete streets (streets that did not exhibit the characteristics of complete streets) found that the former may be positively associated with reductions in UFP, lower vehicle traffic volume, and more pedestrians and cyclists [122]. The research concluded, however, that these outcomes are not always a given with complete streets; context and design play an important role in influencing the direction and magnitude of the benefits. The researchers recommend prioritizing construction of complete streets in downtowns, business areas, and locations that create a contiguous network of bike, pedestrian, and transit infrastructure.

Other valuable sources of information on how to maximize the desired benefits of complete streets implementation are available from the National Association of City Transportation Officials (NACTO). Several NACTO publications provide guidance on how to design urban streets, transit streets, and urban bikeways, and include case study examples.[25] Planners should also consult with their local air quality management district to see if it provides additional recommendations for this type of strategy.

25 *http://nacto.org/*

Increasing active transportation may lead to additional health benefits that are associated with increased physical activity [123]. Also, complete streets can improve the street aesthetic, increase property values, and promote business visibility.

The literature also shows that siting or preserving parks can also improve air quality along street corridors, but care should be taken when deciding what park facilities will be installed and where these facilities should be located. For example, playgrounds or recreation fields should be located away from heavily-trafficked routes to protect children and others from concentrated emissions.

Lastly, this strategy should be considered in the context of the overarching goals to increase development density and infill. Planners should consider how this strategy can be used without spurring more dispersed development, which is associated with more vehicle travel and thus more emissions, which would undercut the environmental and health benefits. In some cases, it may be necessary to implement this strategy in specific areas in concert with other measures that will ensure that broader goals are still supported.

5: Solid barriers, such as sound walls

FINDING: Measurement and modeling studies consistently find that solid barriers reduce near-road downwind concentrations by increasing vertical dispersion of pollutants emitted by vehicles. The magnitude of the reduction and its spatial extent depend on the height of the barrier, the width of the road, and micrometeorology. As reference, studies have consistently found a concentration deficit downwind of the barrier, ranging from a 10 percent to 50 percent reduction compared to concentrations measured on or directly adjacent to high-volume roadways.

APPROPRIATE CONTEXT & OTHER CONSIDERATIONS: Solid barriers should only be considered for installation along freeways because they have the negative effect of dividing neighborhoods and obscuring sightlines.

Field measurement studies generally show that solid barriers, such as sound walls, can effectively and significantly reduce near-road pollution concentrations for a variety of traffic air pollutants [48, 51, 124-127]. Baldauf et al. measured concentrations of NO_X, PM, and air toxics behind a 1 km long barrier along Interstate I-440 in Raleigh, NC using a mobile platform and fixed sampling instruments. The study revealed that CO and PM number concentrations generally decreased between 15-50 percent behind the barrier [48]. Ning et al. also measured lower pollution concentration reductions where barriers were present along I-710 and I-5 in Southern California, compared to where they were not present [125]. Finally, a more recent field study in Phoenix, AZ—which measured NO_2, CO, UFP, and black carbon (BC) using both a mobile platform and fixed sites—found that pollutant concentrations behind the roadside barriers were significantly lower relative to those measured in the absence of barriers. The reductions ranged from 50 percent within 50 meters (~164 feet) from the barrier to about 30 percent as far as 300 meters (984 feet) from the barrier [51].

Modeling and wind tunnel studies, like the field studies mentioned above, also consistently find that barriers result in reduced concentrations beyond the barrier [50, 127-129]. Heist et al. conducted a wind tunnel experiment that modeled 12 configurations with and without barriers and found that all with-barrier configurations reduced the downwind ground-level concentrations compared to no-barrier configurations, though the magnitude of the reduction varied depending on the specific conditions [129]. Hagler et al. created a model to mimic the wind tunnel experiments conducted by Heist et al. and used it to observe the effect of changing variables—like the barrier height and wind direction—to test how near-roadway concentrations of pollutants might change with these different variables. The model found decreased concentrations downwind of the barrier and estimated that higher barriers would result in greater downwind reductions [50].

The South Coast Air Quality Management District recently funded a study to investigate the effect of roadside barriers on dispersion from roadways [49, 130]. Using semi-empirical modeling approaches, the study found that barrier height, freeway width, and atmospheric turbulence were key factors determining pollutant dispersion. Results from Schulte et al. are consistent with the studies above that look specifically at varying barrier heights and atmospheric stability [130].

Appropriate context & other considerations

Research shows that solid barriers can be effective at reducing near-roadway pollution concentrations, but many other considerations should be taken into account before deciding to implement these as a means to reduce near-roadway pollution exposure. Local planners should consider consulting with highway experts at FHWA or Caltrans and referencing some of the many resources that are available to assist with the selection, planning, and design of solid barriers, including (but not limited to) the following:

- FHWA Highway Noise Barrier Design Handbook: *http://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/design/index.cfm*
- FHWA Guide to Visual Quality in Noise Barrier Design *http://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/visql/index.cfm*
- FHWA Brochure, "Keeping the Noise Down: Highway Traffic Noise Barriers" *http://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/keepdown.pdf*
- Caltrans Highway Design Manual, Chapter 1100 Highway Traffic Noise Abatement *http://www.dot.ca.gov/hq/oppd/hdm/pdf/english/chp1100.pdf*
- Caltrans Project Development Procedures Manual, Chapter 30 Highway Traffic Noise Abatement: *http://www.dot.ca.gov/hq/oppd/pdpm/chap_pdf/chapt30.pdf*

Solid barriers are only appropriate for installation along freeways. When implemented in non-freeway settings, solid barriers can increase vehicle miles traveled, disrupt community connectivity, and counteract planners' efforts to encourage walking, biking, and complete streets designs.

Research shows that there are design features of solid barriers that should be avoided in order to maximize their effectiveness in reducing pollutant concentrations near high-volume roadways. For example, gaps and edges are places where pollutants can concentrate and creep around barriers, so gaps should be avoided and edges should occur where sensitive uses will not be exposed to elevated pollution levels [50].

Some studies indicate that barriers may result in increased on-road pollution concentrations, as was discussed previously under "*Important overarching considerations in selecting strategies*" that users of this Technical Advisory should take into account. This is not observed in all cases, but it is worth considering whether or not the site-specific conditions will result in very high on-road concentrations and additional exposure reduction strategies that could be implemented in concert to reduce them. Possibilities include other strategies that would reduce roadway volumes and thereby bring down the emissions rates of the roadway segment where a barrier may be implemented.

Before implementing solid barriers, planners should inform nearby residents and the public to ensure that the community is involved in the proposal and planning of the barrier before it is implemented. FHWA finds that people's reactions to noise barriers can be mixed. In the past, residents that live near roadways reported that solid barriers make conversations and sleeping easier in their homes and that, as a result of the barrier, they are more likely to open windows and spend time outdoors. Others have complained that solid barriers restrict views, contribute to a sense of confinement, reduce circulation, and can create an eyesore if the barrier is not maintained or designed with aesthetics in mind. Additionally, if solid barriers disrupt existing network connectivity, they could also result in an increase in vehicle miles traveled [131]. Planners should also consult with their local air quality management district to see if it provides additional recommendations for this type of strategy.

In addition to mitigating pollution exposure, solid barriers benefit near-roadway populations by reducing noise from roadways or freeways. Several studies have shown an association between roadway noise to a variety of physical and psychological health outcomes. Because noise can cause stress in humans, it may be linked to a variety of stress-related diseases, including hypertension, anxiety, and heart disease [132]. The negative health outcomes of stress are particularly serious if noise causes disruption in sleep cycles [133]. One survey of residents near a sound wall found that most felt that sleeping conditions were improved after the barrier was built [134]. Solid barriers and sound walls can reduce the loudness of traffic noise by as much as 50 percent [135].

6: Vegetation for pollutant dispersion

FINDING: Studies indicate that vegetation has the potential to alter pollutant transport and dispersion. In some studies, specific locations and conditions translated to air quality benefits (e.g., pollution concentrations of up to 20 percent on the leeward side of the tree line). It should be noted that most studies were conducted on the East Coast and in Europe where vegetation types and densities differ from what is found in California.

APPROPRIATE CONTEXT & OTHER CONSIDERATIONS: Online tools are available to assist with the selection of appropriate vegetation considering allergen impacts, watering needs, and other factors. Maximum benefits have been shown to occur when vegetation is combined with solid barriers.

Vegetation, including plants and trees, has been studied as a means of improving air quality by assisting in the dispersion of near-roadway pollution. Jeanjean et al. [136] modeled the effectiveness of trees at dispersing road traffic emissions and found that they can reduce ambient pollutant concentrations by increasing turbulence. Other studies have included the effect of urban parks and green belts. Experimental studies measured reductions of PM (and gases) attributable to urban parks and forests by measuring within, near and away from urban parks, finding reduced levels of PM and other pollutants (NO_2, SO_2) within and near park areas [137, 138]. Similarly, strategies such as creating green belts have been used as an environmental management strategy and appear to be successful in reducing air pollution [139, 140].

An emerging area of study examines the potential air quality impact of vegetation as a barrier and vegetation combined with solid barriers. Brantley et al. found that black carbon on the leeward side of the tree line was reduced up to 22 percent compared to the BC levels measured on the traffic adjacent side of the tree line, indicating that trees may provide some air quality improvement [141]. Baldauf et al. conducted a field study at a site in Raleigh, North Carolina that provided an opportunity to evaluate near-road air quality with no barriers, with a noise barrier only, and with a noise barrier and vegetation adjacent to the road. The study results suggested that the presence of mature trees (~10 m tall) in addition to the barrier lowered PM number concentrations beyond what was observed in the barrier-only scenario. Researchers attributed this additional reduction to increased turbulence and mixing created by the presence of the trees [48]. However, a subsequent study by Hagler et al. showed mixed results for vegetative barriers. UFP concentrations were sometimes higher and sometimes lower at the two vegetative barrier sites, which were characterized by relatively thin tree stands, one evergreen, and one deciduous (all sites were in central North Carolina). The researchers posit that study and site-specific conditions may have influenced these results, including the relative sparseness of the tree stands that acted as vegetative barriers [124].

Modeling studies also support the air quality improvement potential of vegetative barriers [128, 142, 143]. Fuller et al. [143] modeled a vegetation screen separating a freeway in Davis, California from a nearby elementary school. The modeling showed that—with the tree configurations studied—74 percent of PM impacted a tree surface. This means that the particles did not merely pass by the tree, but rather impacted and may have deposited on the tree itself. The modeling study also found that installing multiple rows of trees maximized the potential for impaction. The most recent modeling study, by Tong et al., found that the greatest reduction in downwind particle concentration was associated with a vegetation-solid barrier combination, whereby trees are planted next to a solid barrier [144]. However, the modeling for this configuration also showed significant increases in on-road particle concentrations.

A recent study has also investigated the effect of tree stands on indoor PM levels. While being indoors provides some protection from pollution exposure, Maher et al. [145] found that trees planted outside the home can provide substantial reductions in PM inside the home (>50 percent reduction).

It is worth noting that these measurement studies take advantage of existing tree stands or vegetative barriers with various densities, plant species, leaf shapes, and other variables, and it is difficult to isolate the variables that most strongly contribute to potential air quality improvement. In addition, these studies have been mostly conducted in the U.K. or on the east coast of the U.S., and the greatest effectiveness has been observed with extremely dense vegetative stands that provide a solid barrier (with no gaps, from ground-level to top of the canopy) between roadways and people that live or spend time in near roadway environments.

A recent ARB-funded study examined vegetation in combination with solid barriers in California. At the time of the writing of this Technical Advisory, the final report on the study was not yet available, but upon finalization, it will be published at the associated ARB Research webpage.[26] Measurements from the study show that the combination of vegetation (trees) and soundwalls is associated with a reduction in BC, UFP, PM2.5, and NO_x concentrations, when ideal or perpendicular wind conditions are present. The concentration reductions vary from 4.8 percent to 28 percent, depending on the location and wind conditions. The study looked at many wind conditions outside of the simple perpendicular wind pattern and found that the soundwall/tree combination barrier may have little or no effect in very high wind cases and in parallel wind cases. A useful table summarizing conditions and measured values will appear in the final report. Additionally, the research project included the development of a model to estimate the reduction in pollution concentrations for combined soundwall and vegetation barriers. This model will also be made publicly available when this project is finalized later in 2017.

Appropriate context & other considerations

While much research is still underway to assess the effectiveness of vegetative barriers and solid barriers plus vegetation as a means for reducing near-roadway pollution concentrations, the U.S. EPA has synthesized research to date into a recent publication, "Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality."[27] The document summarizes research findings on the best practices for building roadside vegetative barriers to improve air quality, and includes examples of effective and ineffective vegetative barrier designs and also discussions of vegetation characteristics and how these may affect exposure reduction potential. Specifically, the document emphasizes that higher and thicker vegetation results in the greatest downwind pollution reduction. Research has shown that pollutants can meander around edges and through gaps, so vegetation should be densely planted and well-maintained to prevent gaps created by dead or dying trees. Figure 6, from U.S. EPA's publication provides examples of (a) effective barriers that have full coverage from ground to top of canopy and (b) ineffective vegetation barriers that may result in increased pollutant concentrations because of gaps and edge effects.

26 *https://www.arb.ca.gov/research/single-project.php?row_id=65195*

27 *https://www.epa.gov/air-research/recommendations-constructing-roadside-vegetation-barriers-improve-near-road-air-quality*.

Figure 6: Examples of effective and ineffective vegetative barriers. Image: U.S. EPA 2016.

This document also highlights a variety of non-air quality related considerations that should be weighed when considering planting trees or vegetation to mitigate pollution near high-volumes roadways. One important consideration is what to install and where to install it order to minimize potential negative impacts, including allergen production, water need, cost, and safety hazards. The overarching best management practice for urban forestry is to plant a diversity of species in accordance with the 30/20/10 rule: no more than 30 percent of trees should be species within the same family, no more than 20 percent should be from the same genus, and no more than 10 percent should be the same species. Diversity not only reduces concentrations of allergens, but also protects against pests, invasive species, climate change, and severe weather.

In February 2017, the Sacramento Metropolitan Air Quality Management District released a draft document, "Landscaping Guidance for Improving Air Quality near Roadways."[28] The document translates findings and recommendations from the above mentioned U.S. EPA document so that they can be applied in the unique conditions and circumstances found in the Sacramento region.

For tree installations, CAL FIRE and the USDA Forest Service have funded the Urban Forest Ecosystems Institute website, which includes a tree selection software tool called Selectree.[29] This online tool allows users to search for low allergen and drought resistant trees and to select for other characteristics that best fit the context of where they will be planted. To avoid over- or under-watering trees, "Save Our Water and Our Trees" guidance can be consulted.[30] Planners should also consult with their local air quality management district to see if it provides additional recommendations for this type of strategy.

As stated in the research summary above, wind conditions—including wind speed and direction—influence the effect of adding vegetation to a solid barrier. The local meteorological conditions displayed in a wind rose can help planners decide how much of an air quality benefit can be realized from the addition of trees to a soundwall. Some communities prefer to plant low growing vegetation near soundwalls or near freeways out of concerns for pedestrian safety, to reduce shelter for vermin, and to discourage illegal camping.

A potential co-benefit is the possibility that this action may help to mitigate the urban heat island effect.[31] If trees or vegetation replace or are installed over non-reflective, heat-absorbing surfaces, they can reflect light that may have otherwise been converted into heat. This reduction in heat can have important air quality and energy use benefits, since it may translate to reductions in the use of electricity for air conditioning. Additionally, trees and vegetation can encourage outdoor activity, walking and other non-vehicle modes, and improve the street aesthetic.

While trees and vegetation can increase pollutant dispersion and thereby improve air quality, some studies show that they can increase street-level pollutant levels under certain circumstances. The effectiveness of trees in mitigating pollution in urban street canyons depends on three major factors: (1) ventilation, (2) tree planting density/size of canopy, and (3) street width to building height ratio. In street canyons, roadside vegetation may lead to increased pollutant levels in the street canyon at the street level, as the presence of trees can reduce ventilation, effectively trapping pollutants in the canyon; this aerodynamic effect has been shown to be much stronger than the pollutant removal from trees [146]. Increasing tree planting density reduces the effect of ventilation and can result in increased pollutant concentrations under the tree canopy [117, 147-149]. Larger tree crowns were associated with increasing concentrations [150]. However, increased ventilation can mitigate these effects [117, 149]. In addition to ventilation, the ratio of building height to street width (h/w) also is an important variable in describing the effect of trees in an urban canyon. Large h/w ratios reduce the trapping effect of trees by increasing ventilation in the local area [147, 149]. Finally, some tree species may contribute to the worsening of air quality by producing VOCs that can lead to ozone formation [151]. These species should be avoided, and online tools and expert consultations are helpful resources for planners as they choose tree species for installation.

28 *http://www.airquality.org/Residents/CEQA-Land-Use-Planning/Roadway-Protocol*

29 *http://ufei.calpoly.edu/index.lasso*

30 *http://saveourwater.com/what-you-can-do/tips/landscaping/save-our-water-and-our-trees/*

31 Urban air temperature is elevated compared to rural areas because of the prevalence of roofs and pavements that absorb heat and radiate it back into the ambient environment.

Strategies that remove pollution from the air

7: Indoor high efficiency filtration

FINDING: Studies show that particle filtration systems and devices, specifically high-efficiency filtration with mechanical ventilation or portable high efficiency air cleaners, can be highly effective for reducing indoor pollution concentrations. High efficiency filters in ventilation systems, for example, can remove 50-99 percent of particles in the air. However, research shows that filtration technologies for gaseous pollutants (VOCs) are variable in their effectiveness; some remove certain VOCs well, but not others.

APPROPRIATE CONTEXT & OTHER CONSIDERATIONS: Planners should be aware of current state and local building codes and their respective air filtration requirements, including requirements for amending code standards. Regular operation and maintenance is necessary for highest filter and ventilation efficiency, and is required by regulation in commercial buildings.

Reducing the entry of air pollutants into indoor environments from nearby roadways is critical for mitigating adverse health impacts. Research shows that both high efficiency filtration in central ventilation systems and portable air cleaners can effectively remove particles in most circumstances. Depending on particle size and other factors, central ventilation systems with high efficiency filtration remove about 50-99 percent and portable air cleaners remove about 30-90 percent of the particles in the air. Unlike particle filtration, filtration technologies for gaseous pollutants can be useful in some circumstances but generally are not as effective as particle filters.

Filter efficiency is rated using several scales, the most common of which is the minimum efficiency reporting value (MERV) rating system. A table illustrating the features and characteristics of MERV rated filters can be found in Appendix B. Flat, one-inch fiberglass filters are the most commonly used filters in residential heating and air systems. They remove only a portion of the largest particles in the airstream that passes through the filter and are typically rated no higher than MERV 4. MERV 5 to MERV 8 filters are medium efficiency filters that remove some additional types of particles such as mold spores and cat and dog dander, but they still do not remove the finer particles produced on roadways. MERV 9 to MERV 12 filters begin to remove particles in the smaller fraction of PM2.5. Higher efficiency MERV 13 to MERV 16 filters remove a portion of the ultrafine and submicron particles emitted from vehicles. True HEPA (high efficiency particulate arrestance) filters—equivalent to MERV 17 to MERV 20—remove 99.97 percent to 99.999 percent of particles less than 0.3 microns (μm). HEPA filters are available for use in residential applications, but they are not yet in widespread use in residences.

High efficiency filtration with mechanical ventilation

Mechanical ventilation integrated with in-duct filters removes some air pollutants when outdoor air passes through the filters and through deposition in the ducts. The amount of air pollutants removed depends on the air flow passing through the filters and the filtration efficiency of the filters. The performance of high efficiency filtration with mechanical ventilation has been evaluated by both field measurements and modeling simulations for residences, schools, and commercial buildings.

In residences, field studies of high efficiency filtration with mechanical ventilation have found that these systems can reduce air pollutants of outdoor origin by 50-98 percent [152-154]. In a seven-home study in northern California, Bhangar et al. [152] found that when filtration was active (systems turned on) at the two homes with active filtration in a mechanical system, the portion of indoor particles from outdoors was lower by 54 percent and 74 percent respectively, than when they were turned off (no filtration). In the most recent ARB-funded study in a test home, Singer et al. [154] measured indoor reductions of incoming outdoor PM2.5 particles up to 97-98 percent with MERV 16 filtration on a supply ventilation system and one central ventilation system configuration. MacIntosh et al. [155] measured particle removal rates of various in-duct filters that varied in thickness and found that, compared to a 1-inch filter, using a 5-inch MERV 8 filter increased the PM2.5 removal rates by 4.6 times. Stephens et al. [156] used four different methods to estimate the particle removal efficiencies of filters in the heating, ventilation, and air conditioning (HVAC) system of a test house, and found that all methods showed significantly higher removal efficiencies for MERV 11 filters than MERV 7 or lower filters across the size range (0.3-10 μm) measured, by about 20-50 percent. Modeling simulations show similar results. Brown et al. [157] found that, compared to a MERV 1 fiberglass filter, a MERV 12 or higher filter can effectively remove 63-76 percent more PM2.5 of outdoor origin. Using the same model as Brown et al., MacIntosh et al. [158] found an indoor/outdoor ratio of 0.1 for PM2.5 (a reduction of 90 percent) for homes with a high efficiency electrostatic air cleaner in the HVAC systems. This was significantly lower than the ratio of 0.35 (65 percent reduction) found in homes with a one-inch media filter and 0.57 (43 percent reduction) for homes with natural ventilation.

Although the MERV rating system does not specify removal efficiencies for particles smaller than 0.3 μm in diameter, a few studies have evaluated the performance of high efficiency filtration on UFPs. In a recent study of various filtration levels and types of mechanical ventilation in a test home, Singer et al. found good removal of UFP, including up to 99 percent removal of incoming UFP from the outdoors with a MERV 16 filter on either a supply ventilation system or a central system [154]. The researchers also measured air flow resistance for the highest MERV filters tested, and found that it was not an issue; a deep pleat MERV16 filter reduced airflow by just 2.7 percent and a 1-inch MERV13 filter reduced airflow by 4.9 percent. Stephens and Siegel [159] found that achieving substantial removal of UFPs in real residential environments (>50 percent removal efficiency) requires higher efficiency filters (e.g., MERV 13 or higher) than those typically used in homes. A field study in a radio station surrounded by busy roads in Australia showed that adding a MERV 7-8 equivalent pre-filter and a MERV 14-15 equivalent filter to the HVAC system increased overall removal efficiency for UFPs by 48 percent [160]. In a modeling study, Azimi et al. [161] used about 200 outdoor particle size distributions and the single-pass filter removal efficiencies obtained from the literature to estimate the removal efficiencies for UFPs of outdoor origin. This study found that, assuming an HVAC system operates with 100 percent outdoor air, the UFP removal efficiencies for MERV 16 or higher filters were over 98 percent, compared to 12 percent for MERV 7 or lower filters.

Similar findings on high efficiency filtration with mechanical ventilation were also reported in schools and other commercial buildings. In a study of a single school in Utah, indoor submicron particle counts were reduced to just one-eighth of the outdoor levels in a building with a mechanical system using a MERV 8 filter, indicating substantial protection of air filtration in the HVAC system against exposure to outdoor submicron particles [162]. In a pilot study in three southern California schools, a combination of MERV 16 filters used as a replacement for the normal panel filter in the ventilation system and in a separate filtration unit reduced indoor levels of outdoor-generated black carbon, UFPs and PM2.5 by 87-96 percent [163]. Use of the MERV 16 panel filter alone in the HVAC system achieved average particle reductions of nearly 90 percent. Wu et al. [164] found that in small and medium commercial buildings, indoor/outdoor ratios of black carbon were lower for those with MERV 6-8 filters in the HVAC systems, compared to the building with MERV 4 or lower filters, although the difference was not statistically significant. Zaatari et al. [165] estimated that the removal efficiencies of PM2.5 for the rooftop HVAC units in commercial buildings increased by 2.9-3.8 times after upgrading filters from MERV 8 to MERV 13-14.

High efficiency portable air cleaning devices

For homes and schools without forced air HVAC systems, portable or stand-alone air cleaning devices can be used to provide filtration. When portable air cleaners use high efficiency or HEPA filters and are appropriately sized for the space to be treated, they can typically achieve 30-60 percent removal of particles and sometimes up to 90 percent removal [166-169]. In the pilot study conducted in three southern California schools (discussed above), a large stand-alone air cleaner with MERV 16 filters reduced black carbon, UFP and PM2.5 by 90 percent or more, and PM2.5 mass by 75 percent, when the HVAC system was not running [163]. However, portable air cleaning devices are generally not as capable as in-duct air cleaners and those associated with mechanical ventilation systems for cleaning large areas. The review by Sublett [170] indicated that portable air cleaners with HEPA filters can lower particle levels indoors, but their effectiveness is limited to a single room and not the entire dwelling. The results from the field study by MacIntosh et al. [155] showed that five portable HEPA air cleaners operating at the same time were needed to achieve the same PM2.5 removal rate of an in-duct MERV 8 filter in a test house.

Appropriate context & other considerations

There are several California state building codes that relate to indoor air filtration in residences and commercial buildings, including offices. For workplaces, State regulation (California Labor Code, Title 8, Section 5142) requires that mechanical ventilation systems be operated as designed to provide the required amounts of outdoor air exchange during occupied periods. This includes properly servicing and maintaining filtration equipment. For residences, California building codes [2016 California Energy Code, Section 150.0 (m)(12)(B)] require mechanical ventilation in new construction; however, the current building code only requires a minimum filtration efficiency of MERV 6, which is rated lower than what is likely needed to adequately protect residents' health when homes are located near roadways. Local jurisdictions and planners should consider opportunities to revise local codes to include recommendations that filtration with a higher efficiency rating be installed when new housing is planned near roadways. Installation at the time of construction involves minimal incremental costs (equal to a two-inch or larger filter slot vs. the typical one-inch slot) and costs less than retrofitting existing buildings. Airflow resistance issues can be avoided by using deeper pleat filters, and there are high efficiency filters on the market that do not produce airflow resistance issues. This is true for retrofitting existing buildings as well, although costs may be higher depending on the nature and extent of the retrofit. The 2016 California Energy Code [Section 150.0 (m)(12)(C)] also requires mechanical systems, including heating and air conditioning systems, to be designed to accommodate the system's air filter media rated pressure drop for the system design airflow rate. Planners should also consult with their local air quality management district to see if it provides additional recommendations for this type of strategy.

Stand-alone air cleaners are less relevant for new homes which are now required to include mechanical ventilation, but good quality high-efficiency portable models can be useful in reducing indoor exposure to pollutants in existing homes that do not have mechanical ventilation. Also, they can be useful in homes that use bathroom exhaust type mechanical ventilation systems, which by their design cannot incorporate filtration of the incoming air because the supply air enters through leakage points throughout the building.

In general, particles are typically of greatest concern and pose the highest health risk, so HEPA filtration is likely to provide the highest degree of public health protection in near-roadway buildings. However, when VOC levels are of concern for a specific site, planners should consider additional options and consult with filtration experts. As described in more detail in Appendix A, adsorption using activated charcoal, sometimes with a catalyst such as potassium permanganate, is most commonly used, and while its effectiveness varies, it generally reduces VOCs, including VOCs commonly emitted from vehicles such as benzene and xylenes. Other methods may effectively reduce gaseous pollutants, but they also present the possibility of producing harmful byproducts. These technologies should be used with caution and in consultation with indoor air quality and filtration experts. Those seeking information on air cleaning devices can also consult the ARB document, "Air Cleaning Devices for the Home: Frequently Asked Questions."[32] The document discusses situations where an air cleaning device can help improve indoor air quality describes central system filtration and portable air cleaning technologies and the benefits of each.

Indoor high efficiency filtration is linked to a number of co-benefits. First, filtration can help reduce the dust and soot that collects in building interiors, making it easier to maintain a clean and hygienic environment. Additionally, some studies have shown improved employee health and reduced absences with reduced exposure to pollution. Indoor filtration is among a very small number of exposure reduction strategies that can be implemented in existing buildings.

32 *https://www.arb.ca.gov/research/indoor/acdsumm.pdf*

III. Conclusions

The implementation of SB 375 and other long-range land use and transportation planning efforts are important for California to meet its greenhouse gas emission reduction goals, to reduce pollution, to protect natural and working lands, and to promote equity and environmental justice. Many of these efforts focus on increasing development density as a means to reduce the frequency and length of automobile trips. In addition, greater density facilitates alternative modes of transportation, including transit, biking, and walking.

In some parts of the state, efforts to increase development density may result in infill development located near high-traffic roadways. The people that spend time in and around buildings located on these infill parcels will likely experience heightened exposures to traffic emissions, even as the vehicle fleet gets cleaner over time. Decades of research show an association between exposure to traffic emissions and serious health impacts, including cardiovascular and respiratory impacts. For new development, setbacks and buffers separating roadways from housing, offices, and other uses have been the primary defense against traffic emissions exposure and its public health impacts. This is largely because the distance-decay gradients for traffic-related pollutants is well studied and understood, and setbacks and buffers are effective ways to protect against the public health impacts of traffic pollution. However, given the significant population already living near high-volume roadways, and with the growing need to develop infill parcels to meet other state goals, ARB has funded and examined research that assesses other ways to reduce pollution exposure in near-roadway developments.

As this document shows, there are a variety of scientifically supported strategies to reduce near-roadway pollution exposure. Not only are these strategies well-studied and consistently effective, but they also fall into diverse categories. Urban design characteristics, roadside features, street design and traffic management strategies, and pollutant removal technologies outlined in this document give local planners and decision-makers options and thus the opportunity to find a strategy that best fits the local context.

As emphasized throughout this document, however, it is important that planners and decision-makers consider a variety of variables and tradeoffs when deciding which exposure reduction strategies make the most sense. Important points for consideration include (but are not limited to) the following:

- Site specific factors and conditions;
- Potential co-benefits, drawbacks, and direct and indirect effects;
- Interaction of the exposure reduction strategy with other local, regional, and state goals and policies;
- Community well-being and concerns, including safety and equity;
- Long-term effects of implementing strategies;
- Importance of implementing strategies in concert to enhance their effectiveness; and
- Other policies may need to be implemented concurrently to counter any potential drawbacks of the near-roadway strategy.

Many resources are available to assist local governments and other stakeholders to help them determine which exposure reduction strategies are appropriate for their community, including documents and guidance mentioned throughout this report. Various public and nongovernmental agencies may also be able to provide expert assistance, including ARB, Caltrans, the Office of Planning and Research, CA Department of Housing and Community Development, CAL FIRE, CA Department of Public Health, FHWA, U.S. EPA, MPOs, regional air districts, and local community groups.

Finally, many studies exploring this topic are currently underway and more will be published in the years to come. ARB will continue to review and analyze this research on a periodic basis. Updates to this document will be posted to ARB's website at: *https://www.arb.ca.gov/ch/landuse.htm*.

Appendix A: Strategies not meeting ARB's criteria at this time

This appendix contains a summary of findings for other potential exposure reduction strategies that ARB evaluated in its review of scientific, peer-reviewed literature. The following are not included in the main section of this document because they did not meet all of the following criteria at the time of the 2016 literature review.

1. Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations or emissions rates or for improving air flow to disperse pollutants.
2. Significant evidence of effective emissions reductions is documented in the scientific literature.
3. Diversity in the study methods supports consistent findings (such that strategies do not exclusively rely on one method of investigation).

The table that precedes each strategy indicates the criteria that were (þ) and were not (o) met.

Strategies that reduce traffic emissions

Onboard traffic signal system

☐	Criterion 1	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
☑	Criterion 2	Significant evidence of effective emissions reductions is documented in the scientific literature.
☐	Criterion 3	Diversity in the study methods supports consistent findings (such that strategies do not exclusively rely on one method).

To reduce the stop-and-go activities at intersections, in-vehicle signal systems that help drivers anticipate signals and speed limit have been introduced. One in-vehicle advanced driving alert system (ADAS) which provides real time information on traffic signal status to help drivers avoid hard braking at intersections was investigated for its potential to change drivers' behavior and reduce vehicle emissions [171]. A modeling simulation shows that ADAS can help reduce vehicle fuel consumption and CO_2 emissions both by 26-40 percent in a single vehicle in the tested hypothetical conditions. Another in-vehicle signal system which had been studied for its effect on traffic emissions is Intelligent Speed Adaptation (ISA) system [172]. ISA consists of a GPS navigation system that locates a vehicle on a digital map with speed limits for each street, and a device that can control fuel supply. It provides speed limit warnings and can cap the maximum driving speed automatically to comply with speed limits. This study found that with an ISA on board, there was a significant reduction in averge speed, but no statistically significant change in NO_X and PM emissions, and even a small increase in volatile organic compound (VOC) emissions.

Road pricing

☐	**Criterion 1**	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
☑	**Criterion 2**	Significant evidence of effective emissions reductions is documented in the scientific literature.
☑	**Criterion 3**	Diversity in the study methods supports consistent findings (such that strategies do not exclusively rely on one method).

For a few decades, road pricing has been considered to be an effective way to manage traffic demand and generate revenue. In 1975, Singapore implemented the world's first congestion pricing scheme and since then, pricing schemes have been adopted in many cities worldwide. Road pricing programs, including the London Congestion Charging Scheme (CCS) and the Stockholm Congestion Tax Scheme, have been studied for their roles in reducing vehicular emissions.

Implemented in February 2003, the London Congestion Charging Scheme (CCS) assesses a single charge for vehicles entering a central London zone between 07:00–18:30 on weekdays, with several vehicle types exempt from the charge. Since the program's inception, vehicle kilometers travelled within the zone reduced by 15 percent and the average speed increased by 20 percent. Based on the measurements from a single roadside monitor within the CCS Zone, roadside levels of NO_X and NO dropped by 5 percent and 9.5 percent, respectively, but concentrations of NO_2 and PM10 increased by 2.1 percent and 5.6 percent, respectively [173]. Interestingly, similar changes were observed during the same hours during weekends when the scheme was not operating. This may be due to the exceptional meteorological conditions of 2003, when concentrations of PM10, NO_2 and O_3 were higher than those in 2002, perhaps causing the impacts of the implementation of the CCS zone to be concealed. In an attempt to understand the role meteorology might have played in the observations, a modeling simulation was conducted and found that total NO_X and PM10 emissions in the CCS zone were reduced by 12.0 percent and 11.9 percent, respectively [174]. Furthermore, Tonne et al. [175] conducted more extensive air pollution concentration modeling combining exposure-response relationships from the literature to predict the life expectancy impact of the CCS. This study estimated that 183 years of life per 100,000 people would be gained within the CCS zone.

The Stockholm Congestion Tax Scheme was employed between January 3 and July 31, 2006. Vehicles travelling into and out of the affected area were charged for every passage during weekdays. Based on measured and modelled changes in road traffic, this scheme resulted in a 15 percent reduction in total road use within the affected area. Total traffic emissions of NO_X and PM10 in this area fell by 8.5 and 13 percent, respectively [176]. It was estimated that with a permanent congestion tax system, the annual average NO_X concentrations would drop up to 12 percent and PM10 concentrations would drop up to 7 percent along the most densely trafficked streets.

Low emission zones

☐	**Criterion 1**	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
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☑	**Criterion 3**	Diversity in the study methods supports consistent findings (such that strategies do not exclusively rely on one method).

Low Emission Zones (LEZ) vary in terms of their parameters, but usually involve limiting vehicles into part or all of an urban area. Generally, there are three types of LEZs. An air quality based LEZ triggers action when air quality in the LEZ exceeds or is predicted to exceed a certain threshold. A technology based LEZ restricts certain vehicle types (i.e., vehicles that do not meet certain emission standards) from entering the designated zone. A transport-based LEZ usually aims to restrict, prioritize, and optimize traffic flow in order to reduce emissions.

A London-based study used empirical prediction models to evaluate the impacts of different LEZ scenarios on annual mean NO_2 concentrations in central London [177]. By reducing all road traffic in central London by 10 percent or 20 percent, the concentrations of NO_2 were decreased by 1.4-3.4 percent or 2.9-7.1 percent, respectively. Removing all pre-Euro I cars and light-goods vehicles reduced NO_2 level in London by 1.8-5.2 percent. Further removing all pre-Euro III heavy-goods vehicles and buses reduced NO_2 by 3.6-11.1 percent. A similar regulation implemented in Amsterdam excluded Euro 0, I and II heavy-duty vehicles from entering Amsterdam's Low Emission Zone (LEZA). Data from two monitoring sites within the LEZA showed that the traffic-contributed concentrations decreased by 4.9 percent for NO_2, 5.9 percent for NO_X, 5.8 percent for PM10, 7.7 percent for absorbance, and 12.9 percent for elemental carbon (EC) [178]. Boogaard et al. [179] investigated air pollution at street level before and after implementation of LEZ in the inner-city of five Dutch cities. The Dutch LEZ restricts old heavy-duty vehicles entering the LEZ, including all Euro-0, I, II trucks and Euro-III trucks if older than 8 years or not retrofitted with particle filters. The results showed that the traffic-related pollutants monitored, including 'soot', NO_X, and elemental composition (Cr, Cu, Fe), did not decrease significantly. Only PM2.5 reductions, which fell 30 percent, were large compared to the observed reductions at the corresponding suburban control location (22 percent). While overall, the Dutch study did not find reductions in soot, NO_X, and NO_2, in one urban street where traffic intensity was reduced 50 percent, they were found to be reduced by 41, 36, and 25 percent, respectively, compared to reductions at the suburban control location (22, 14, and 7 percent, respectively). Acero et al. [180] studied the emission reductions related to a minor extension of a pre-existing LEZ. This LEZ is around 0.1 kilometer^2 with 60 percent of the area occupied by buildings. Only resident and commercial vehicles can operate within this LEZ during certain hours. The modeling simulation showed that if the LEZ is extended to include a 170 meter street during weekend, there will be a reduction of 6.4 percent for PM10 and 6.6 percent for NO_2 within the LEZ. But the impact outside the LEZ was negligible.

An extreme case of LEZ is called a pedestrianization scheme, which forbids any vehicles entering a small region, usually a commercial or residential area. Chiquetto [181] analyzed the influence of a pedestrianization scheme in Chester, UK on total vehicle exhaust emissions, local levels of air pollution concentration, and noise from traffic. The results showed that the pedestrianization scheme reduced air pollution in the pedestrian area 70-80 percent. However, the subsequent re-routing of traffic increased average air pollutant concentrations in the city as a whole by 6 percent.

Road surface designs

☐	**Criterion 1**	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
☑	**Criterion 2**	Significant evidence of effective emissions reductions is documented in the scientific literature.
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Special road surface designs, including speed humps and bumps, pavement treatments, chicanes, and raised crosswalks and speed tables have been used for decades to reduce driving speed and improve pedestrian safety. Most drivers will slow down when driving over these structures, which results in a series of accelerations and decelerations, and are anticipated to have adverse impact on vehicle emissions. A few studies have investigated the impacts of some road surface designs on emissions from vehicles driving on roadways. A case study in Gothenburg, Sweden used a simulation model to investigate the environmental impacts of speed humps for different traffic intensities and driving speed limits and found that speed humps increased fuel consumption estimates by 3-19 percent. Accordingly, the introduction of speed bumps increased the emissions from a singular vehicle by 7-62 percent for HC, 0.4-32 percent for CO, and 5-26 percent for NO_X [182]. Similarly, Ahn and Rakha [53] simulated vehicle emissions using vehicle driving data and energy and emission modeling, and found the installation of speed humps and bumps increased fuel consumption by 53 percent, and the emissions of HC, CO, NO_X, and CO_2 by 51, 44, 110, and 52 percent, respectively.

Strategies that increase dispersion of traffic pollution

Taller buildings/pollution dispersion along vertical gradients

☐	**Criterion 1**	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
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☑	**Criterion 3**	Diversity in the study methods supports consistent findings (such that strategies do not exclusively rely on one method).

A handful of studies have examined how pollution concentrations change along a vertical gradient with increasing distance from ground-level. These studies help to shed light on exposure levels that may be experienced by people that spend prolonged periods of time above ground-level along street corridors (e.g., in offices, homes, etc.).

Morawska et al. [183] examined both horizontal and vertical pollutant concentration gradients near busy roadways in Brisbane, Australia (not an urban canyon site). The researchers found that fine and ultrafine particle concentrations outside buildings with 9 to 26 stories were not significant and can be highly variable, depending on other local sources and local meteorological conditions. Also, they found no correlation between particle concentration and height for buildings 15 meters or more from the freeway. For buildings in the immediate proximity of the roadway, pollutant concentrations throughout the building envelope were very high, comparable to those in the immediate vicinity of the road, indicating that undiluted concentrations drawn directly from the freeway encircled the buildings.

In contrast, several studies from urban areas in Asia show statistically significant reductions in pollutant concentrations with increasing distance from ground-level [184-186]. However, for some pollutants (e.g. polycyclic aromatic hydrocarbons, PAHs, and PM2.5), the attenuation rate slows above a certain threshold, indicating that concentrations drop off more sharply closer to pollution sources. In a study conducted in Macao, China, Wu et al. [184] found that the mass concentrations of PM10, PM2.5, and PM1 decreased by 40, 38, and 20 percent respectively at 79 meters (~26 floors) above ground level, and maximum mass concentrations were measured at 2 meters above the ground. Li et al. [185] studied changes in PM2.5 and PAH concentrations along a vertical gradient at a residential building adjacent to a busy roadway in Guangzhou, China. The study found that both pollutants decreased significantly at heights above ground level at an urban study site. At 24 meters (~8 stories), PM2.5 concentrations had decreased by 36 percent from the maximum, but the rate of decrease slowed at a height of 36 meters (~12 stories). PAH concentrations showed a similar vertical tapering off; at a height of 33 meters (~11 stories), PAH concentrations had fallen to 51 percent of the maximum. Tao et al. [186] confirmed these prior results via measurements collected along a meteorological tower in Beijing during the winter.

Recent studies in the U.S. agree with the directionality of these Asian studies but differ in the magnitude of the pollutant concentration reductions observed. Wu et al. [187] studied particle number concentration and particulate matter mass concentration by hoisting instruments up the vertical face of an 11-story (35 meter) building in Boston's Chinatown. The researchers found that particle number concentration decreased by 7.7 percent and PM2.5 concentration decreased 3.6 percent with increasing height from 0 to 35 meters. Another study in New York found that outdoor black carbon and polycyclic aromatic hydrocarbons were significantly reduced for floors 6 through 32 during the non-heating season only [188]. Researchers also measured the highest median concentrations for outdoor pollutants at floors 3 to 5, but this trend was not statistically significant and the elevated pollutants were believed to come from nearby rooftop exhausts.

Finally, in a modeling study, Zhou and Levy [189] found that—in a street canyon with a height of 60 meters and a width of 30 meters—approximately 30 percent of the ground-level concentrations of PM10, PM2.5, CO, and NO remains at the top of the street canyon. For NO_2, 50 percent of the ground-level concentration remains at the top of the street canyon. Overall, the sharpest decline in pollutant concentration occurred within 15 meters (~50 feet) of the ground.

While the research literature shows that transportation related pollutants may decline with increasing distance from the roadway along a vertical gradient, there are many other factors at play, including local meteorological conditions, seasonal differences, and other local pollution sources. Studies that observed higher concentrations several floors up attributed these to other pollution sources, like exhaust vents on adjacent buildings. Thus, while multi-story housing may reduce exposure in some situations, further research is needed to determine conditions under which tall buildings might provide a reliable approach to reduce exposure near busy roadways.

Air intake location

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Although locating air intakes for mechanical ventilation systems on the opposite side of the building from the nearby outdoor source and prevailing wind direction seems logical, there is little scientific evidence that this practice results in significant indoor air quality improvement, and the limited research indicates that many site-specific factors influence effectiveness. Specifically, the reduction of pollutant entry depends on the distance of the intake from the outdoor source, the consistency of the prevailing wind direction, and any local geographical or structural objects that might produce wind turbulence or eddies near the building and the air intake. It is likely that moving the air intake would be somewhat beneficial if the outdoor source is very near the intake and the intake is moved fairly far away. Otherwise, because particles tend to disperse quickly and particle plumes "flow" around buildings, elevated particle concentrations around the building will be fairly consistent. Also, according to the abovementioned Australian study, researchers found consistently high submicron particle concentrations enveloping a building located within 15 meters of the roadway [183]. Thus, while there may be some benefit to moving the intake in certain circumstances, that benefit likely will be very small, and is not reliable or quantifiable at this time.

Roadway elevation

☐	**Criterion 1**	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
☐	**Criterion 2**	Significant evidence of effective emissions reductions is documented in the scientific literature.
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Elevation of the road surface plays an important role in the transport and dispersion of traffic-emitted air pollutants in the near-road environment [190]. A wind tunnel study indicates that at-grade roadways experience the least amount of pollutant mixing if no other structures exist near the road, while depressed or elevated roadways result in higher pollutant mixing and dispersion, and therefore lower near-road concentrations of air pollutants [129]. Field measurements have also evaluated the impact of road grade on local air pollution, finding depressed configurations are associated with lower pollutant levels for downwind near-road environments. For instance, size-resolved PM samples collected upwind and downwind of five urban freeways in Los Angeles, CA with different road configurations (i.e., at-grade, sloped depressed section, and elevated fill section) indicated that depressed sections resulted in lower downwind concentration [191]. Similarly, a study in Santa Monica, CA investigated particulate dispersion from highways located along depressed sections, and found lower near-road pollutant concentrations compared with theoretical dispersion model predictions for at-grade roadways [192]. By monitoring PM2.5, NO_x, elemental carbon, and particle number concentration, one study in Antwerp, Belgium found that taking into account confounding parameters (i.e., time of day, day of the week, distance to the road and wind speed), the contribution of traffic to air pollutant concentrations in the near-roadway environment is significantly higher for a ground level motorway than a motorway flyover [193]. Similarly, a study by Nikolaou et al. [194] found that elevated freeways had slightly lower levels of near-road pollution while depressed freeways were similar to at-grade roads.

Sidewalk and bicycle lane placement

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☑	**Criterion 2**	Significant evidence of effective emissions reductions is documented in the scientific literature.
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The separation of a pedestrian or cyclist from the roadway may be an effective mitigation measure for walkers and bikers, but not necessarily for people that dwell in buildings near-roadways.

Studies have shown that route choice (walking or biking on less trafficked roads) or location of a walkway or bike lane with respect to a busy roadway (at or below grade, roadside boundary wall or parked cars separating street from foot path) can significantly reduce exposure to air pollution [126, 195-198]. McNabola et al. [126] found that PM2.5 levels on a boardwalk 1-3 meters from the road were almost three times lower than PM2.5 levels on a sidewalk immediately adjacent to the road. Kendrick et al. [196] conducted a similar study in Seattle with bicycle lanes adjacent to the roadway or a few meters away, separated by parked cars. They found up to 40 percent reduction in UFP concentrations when the bicycle lane was further away from the road.

Proper route choice and time of commute can also reduce exposure. In Copenhagen, Hertel et al. [195] not only found that low trafficked routes were beneficial in terms of air pollutant exposure, travel during non-rush hour commutes also reduced exposures by 5-20 percent. In Australia, a study showed UFP concentrations that are two times higher on average on routes with high traffic [197]. Such studies suggest alternate routes and commute times may reduce exposure to traffic-related pollutants. Hatzopoulou et al. [198] developed a web-based planning tool to reduce such exposures for cyclists in Montreal and found that decreased exposure could be achieved with only a small increase in overall route length.

Truck rerouting

☐	**Criterion 1**	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
☑	**Criterion 2**	Significant evidence of effective emissions reductions is documented in the scientific literature.
☑	**Criterion 3**	Diversity in the study methods supports consistent findings (such that strategies do not exclusively rely on one method).

Field measurements before and after local traffic rerouting interventions were in place agree that these interventions improve local air quality [199, 200]. After a by-pass was operational in North Wales, PM concentrations decreased between 23-29 percent in nearby residential streets as heavy-duty traffic decreased almost in half [200]. Similarly, opening of a tunnel in Australia led to a redistribution of NO_2 concentrations with the greatest decrease occurring along the bypassed main road [199]. Modeling studies have confirmed that rerouting traffic decreases localized air pollution [201, 202]. For example, rerouting trucks weighing over 5 tons away from residential streets in San Diego, CA is estimated to have decreased diesel particulate matter by 99 percent near residences and schools [201]. Truck restrictions in the Philippines were also shown to have decreased CO, NO_X, and PM in the zone closest to the restrictions [202]. Despite local improvements in air quality, regional emissions increased because trucks were required to drive longer distances [199-202]. Because air pollutant concentrations decline with distance as one moves away from heavily trafficked roads [17], the improvements from these local interventions are expected to be limited to about 500 feet from the intervention site. Therefore, these local traffic interventions could have a significant impact in areas with a high density of residences, schools, or hospitals nearby. However, results from a health questionnaire indicate that health improvements of residents were fairly modest after trucks were rerouted off the local streets through a by-pass [200].

A microscopic modeling study of freeway traffic emissions determined that hydrocarbon, CO, and NO_X emissions from heavy-duty vehicles during road-work congestion were highest followed by rush-hour congestion compared with periods of free-flowing traffic [203]. External parameters that impact CO_2 truck emissions include travel speed, road gradient, whether congestion is present, temperature, wind, and road surface [204].

Strategies that remove pollution from the air

Removal of gaseous pollutants by filtration

☐	**Criterion 1**	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
☐	**Criterion 2**	Significant evidence of effective emissions reductions is documented in the scientific literature.
☑	**Criterion 3**	Diversity in the study methods supports consistent findings (such that strategies do not exclusively rely on one method).

As pointed out in the review by Zhang et al. [205], mechanical filters can efficiently remove particles, but are not as effective for gaseous pollutants. Many technologies have been developed to address indoor air quality issues related to gaseous pollutants. One of the most common methods is adsorption whereby the pollutant is transferred from a gaseous phase to a solid phase, usually via activated carbon. Because a wide range of gaseous pollutants with different attractive forces to different sorbents are present indoors, and testing conditions such as temperature and relative humidity differed, the removal efficiencies of adsorption reported in the literature vary greatly. In the study by Batterman et al. [206], a portable air cleaner with an activated carbon pre-filter and a HEPA filter removed 30-70 percent of particles in cigarette smokers' houses, but did not change the concentration of volatile organic chemicals (VOCs). Chen et al. [207] tested the initial performance of 15 air cleaners with a mixture of 16 representative VOCs in a chamber study, and found that sorption filtration removed some but not all VOCs (light and very volatile gases such as aldehydes and dichloromethane were not well removed). However, devices that included sorption media such as activated alumina impregnated with potassium permanganate showed better VOC removal efficiencies. Using a modeling analysis, Sidheswaran et al. [208] estimated that the combination of using activated carbon fiber filters for air cleaning in HVAC systems and a 50 percent reduction in ventilation could decrease indoor concentrations of VOCs by 60-80 percent and reduce formaldehyde concentrations by 12-40 percent. In the southern California schools study discussed above, the stand-alone unit used in one of the schools included charcoal sorbent for removal of gaseous pollutants; it removed 52 percent of the benzene indoors and 15 percent of total VOCs when operated with the HVAC turned off [163]. In addition to activated carbon, various adsorbents for VOC removal had been studied, but their removal efficiencies under real world conditions were not conclusive [209-212].

Other available technologies for gaseous pollutant removal include photocatalytic oxidation (PCO), ozone-oxidation, non-thermal plasma, and other technologies. PCO systems combine ultraviolet rays with a catalyst, usually a titanium oxide-coated filter. This interaction produces highly reactive electrons that in turn combine with and break down VOCs and other pollutants in the air. Hodgson et al. [213] found that, when challenged with complex VOC mixtures, ultraviolet PCO systems achieved 20-80 percent VOC conversion efficiencies. However, due to incomplete mineralization of common VOCs, this device also produced formaldehyde, acetaldehyde, acetone, formic acid and acetic acid as by-products. The formation of secondary air pollutants was also reported in a recent ARB-funded study [214]. Ozone oxidation is generally not recommended as a means for removing gaseous pollutants in indoor environments because the oxidation process can produce other air pollutants like formaldehyde and UFPs, which also have serious adverse health impacts [215-217]. To protect Californians from adverse health effects related to ozone-emitting air cleaning devices, ARB adopted a regulation in September 2007 to limit the ozone emissions from indoor air cleaning devices to no more than 50 ppb.[33] Non-thermal plasma has been found to effectively remove VOCs in some laboratory studies. Quoc An et al. [218] reported that the toluene removal efficiencies were in the 55-60 percent range with non-thermal plasma only, and increased to 96 percent when combined with a catalyst. But removal efficiencies of

33 *https://www.arb.ca.gov/regs/regs-17.htm*

this technology were much lower under real world conditions, and like PCO, the process can also produce harmful byproducts, including aldehydes and ketones. The ARB-funded study discussed above [219] also tested a plasma generator. While the device removed 29 percent of VOCs from the chamber, small amounts of ozone and formaldehyde were emitted.

Overall, the literature shows highly variable removal efficiencies for gaseous pollutants, ranging from 0 to 80 percent. Some technologies have been found to generate harmful by-products during the removal process. Specifically, they either re-emit VOCs that have been removed over time, or emit potentially harmful reaction products from the process during which VOCs are removed. Thus, these VOC removal technologies are not always reliable, and caution should be taken when using these technologies for indoor environments.

Removal of air pollution via vegetation

☑	**Criterion 1**	Consistent findings from multiple studies support the strategy as a means for reducing pollution concentrations, etc.
☐	**Criterion 2**	Significant evidence of effective emissions reductions is documented in the scientific literature.
☑	**Criterion 3**	Diversity in the study methods supports consistent findings (such that strategies do not exclusively rely on one method).

The ability of plants to remove pollutants from the atmosphere depends on absorption and deposition onto vegetative material. The scientific literature contains both modeling and measurement studies that characterize this removal process. An early study indicated that vegetation could effectively absorb gaseous air pollutants including NO_2 and ozone [220]. Later studies have investigated the ability of trees to act as an effective particle sink. A review of the literature [221] and measurement studies [222] found that coniferous species had the greatest potential to capture particles compared to their deciduous counterparts, although the deposition of PM on surfaces by particle size varies with different plant species [223]. For UFPs, the capture efficiency of vegetation tends to decrease with increasing particle size, increasing wind speed, and decreasing packing density, which in wind tunnel studies is the volume fraction of the wind tunnel occupied by the branches [224].

Many studies have modeled the application and effectiveness of vegetation in urban areas to remove pollution by deposition [225-228]. These studies have shown that trees and other vegetation have the ability to remove pollutants from the atmosphere in urban contexts. Separate from such processes; however, some trees can also emit volatile organic compounds (VOCs) that can lead to the formation of ozone [151]. As such, some tree species may be more advantageous than others, in terms of air quality. In the United Kingdom one study suggests an index to rank trees in order of their potential to improve air quality using an atmospheric chemistry model [229]. In this study, researchers used species-specific VOCs emission rates, pollutant deposition rates, and tree cover data to develop an urban tree air quality score. Conifers and silver birch were found to have the highest potential to improve air quality while several deciduous tree species such as oak and poplar had the greatest potential to worsen air quality when planted in large numbers. These results are consistent with other studies discussed previously.

The application of trees and vegetation to remove air pollutants have been studied from a city-wide [230, 231] to microscale (e.g., street canyon) level [232, 233]. Although trees and vegetation have the potential to remove large quantities of air pollutants from ambient air, the process of pollutant removal through dry deposition alone can only improve air quality by a small fraction (<5 percent), particularly in urban areas [225-228, 231, 234, 235]. However, Pugh et al. [236] found that, in the street canyon microenvironment, pollutant removal through green walls and roofs reduced levels of NO_2 and PM by 40-60 percent, respectively. Another study by Baik et al. [232] used computational fluid dynamics (CFD) modeling to illustrate how greening cools surrounding air to strengthen air flow in a street canyon, thereby reducing pollutant concentrations. These two studies suggest vegetation in the form of green walls and roofs is an effective mitigation measure for reducing exposure to traffic-related pollutants in urban street canyons. However, it is important to note that pollutant removal effectiveness increases as dispersion decreases, so these two mitigation goals may be at odds with one another (e.g., green walls and roofs may be less effective if mitigation to improve pollutant dispersion has been successfully implemented).

Appendix B: Characteristics of MERV-Rated Filters

<table>
<tr><th rowspan="2">MERV rating</th><th colspan="3">Removal rate according to average particle size</th><th rowspan="2">Typical controlled contaminant or material sources (ASHRAE 52.2)</th><th rowspan="2">Typical building applications</th></tr>
<tr><th>0.3-1.0</th><th>1.0-3.0</th><th>3.0-10.0</th></tr>
<tr><td>1-4</td><td>—</td><td>—</td><td>< 20%</td><td>> 10 μm
textile fibers, dust mites dust, pollen</td><td>Window AC units, common residential, minimal filtration</td></tr>
<tr><td>5</td><td>—</td><td>—</td><td>20-35%</td><td rowspan="2">3.0-10.0 μm
cement dust, mold spores, dusting aids</td><td rowspan="2">Industrial workplace, better residential, commercial</td></tr>
<tr><td>8</td><td>—</td><td>—</td><td>> 70%</td></tr>
<tr><td>9</td><td>—</td><td>< 50%</td><td>> 85%</td><td rowspan="2">1.0-3.0 μm
legionella, some auto emissions, humidifier dust</td><td rowspan="2">Hospital laboratories, better commercial, superior residential</td></tr>
<tr><td>12</td><td>—</td><td>> 80%</td><td>> 90%</td></tr>
<tr><td>13</td><td>< 75%</td><td>> 90%</td><td>> 90%</td><td rowspan="2">0.3 to 1.0 μm
bacteria, droplet nuclei (sneeze), most tobacco smoke, insecticide dust</td><td rowspan="2">Superior commercial, smoking lounge, hospital care, general surgery</td></tr>
<tr><td>16</td><td>> 95%</td><td>> 95%</td><td>> 95%</td></tr>
<tr><td>17**</td><td colspan="3">> 99.97%</td><td rowspan="3"><0.3 μm
(HEPA/ULPA filters)**, viruses, carbon dust, fine combustion smoke</td><td rowspan="3">Clean rooms, carcinogenic & radioactive materials, orthopedic surgery</td></tr>
<tr><td>18**</td><td colspan="3">> 99.99%</td></tr>
<tr><td>19, 20**</td><td colspan="3">> 99.999%</td></tr>
</table>

* Adapted from EPA 2009; originally from ANSI/ASHRAE Standard 52.2-2007.
** Not part of the official ASHRAE Standard 52.2 test, but added by ASHRAE for comparison purposes.

Acronyms

ARB	Air Resources Board
APCD	Air Pollution Control District
AQMD	Air Quality Management District
BAAQMD	Bay Area Air Quality Management District
BC	black carbon
CCS	Congestion Charging Scheme
CFD	computational fluid dynamics
CO	carbon monoxide
CO_2	carbon dioxide
DPM	diesel particulate matter
EC	elemental carbon
FHWA	Federal Highway Administration
GHG	greenhouse gas
HC	hydrocarbon
HDV	heavy-duty vehicle
HEPA	high-efficiency particulate arrestance
HVAC	heating, ventilation, and air conditioning
ICE	Intersection Control Evaluation
ICEV	internal combustion engine vehicle
I/O	ratio of in-cabin to on-roadway pollution concentrations
kph	kilometers per hour
LDV	light-duty vehicle
LEZ	low emission zone
MERV	minimum efficiency reporting value
mph	miles per hour
MPO	metropolitan planning organization
MUTCD	California Manual of Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NO_X	mono-nitrogen oxides (NO and NO_2)
OEHHA	Office of Environmental Health Hazard Assessment
PAH	polycyclic aromatic hydrocarbon
PCO	photocatalytic oxidation
PHEV	plug-in electric hybrid vehicle

PM10	particulate matter with an aerodynamic diameter of 10 micrometers or less
PM2.5	particulate matter with an aerodynamic diameter of 2.5 micrometers or less
ppb	parts per billion
ppm	parts per million
RTP	regional transportation plan
SB 375	Senate Bill 375
SCS	Sustainable Communities Strategy
TAC	toxic air contaminants
UFP	ultrafine particulate matter with an aerodynamic diameter of 0.1 micrometers or less
U.S. EPA	United States Environmental Protection Agency
VMT	vehicle miles traveled
VOC	volatile organic compound
ZEV	zero emission vehicle

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