STATUS OF RESEARCH ON POTENTIAL MITIGATION CONCEPTS TO REDUCE EXPOSURE TO NEARBY TRAFFIC POLLUTION

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Introduction

Air Resources Board (ARB) staff has prepared this document to provide information on scientific research that has been conducted on various building-related and site mitigation concepts suggested as potentially effective approaches for reducing the traffic-related exposures of those living near high traffic roadways. While it provides useful information for consideration of potential mitigation approaches, this paper is not intended as guidance for any specific project, and does not provide a methodology for determining appropriate mitigation measures for purposes of compliance with the California Environmental Quality Act. This review looked only at the current status of air pollution research, and does not address other potential community benefits of the concepts, such as the aesthetic and noise reduction benefits of adding vegetation or sound walls.

The State's current set-back requirement for schools (500 feet [ft]; PRC 21151.8) and the ARB's recommendations on siting for housing and other sensitive uses (e.g., 500 ft from major roadways and 1000 ft from busy distribution centers and rail yards; ARB 2005a) are intended to help protect the public from exposure to traffic emissions. Such emissions have been associated with a variety of serious health impacts in epidemiological studies, including exacerbation of respiratory and cardiovascular diseases and conditions, increased asthma and bronchitis in children, and increased risk of premature death. Traffic pollutant concentrations near high traffic roadways have been found to be 2 to 10 times higher than levels at a distance from the roadways. Also, recent studies have shown elevated traffic pollutant levels at greater distances from the roadway than previously measured.

ARB and the U.S. EPA continue to adopt increasingly stringent regulations limiting emissions from vehicles of all types, which have substantially reduced, and will continue to reduce, vehicle emissions. However, recently adopted regulations have compliance dates extending as far as 2025 for full implementation, and fleet turnover to zero or near-zero technologies will take 20 to 30 years. New reductions in vehicle emissions are improving regional air quality throughout California, including near roadways. As the ARB and the air districts work to reduce emissions from diesel PM and other pollutants, the impact of proximity will also be reduced. However, the differential exposure to high air pollution near high traffic roadways compared to other locations makes the siting of housing in those locations a continuing health concern. Recognizing that unhealthful levels of air pollution is a long term problem, ARB is funding research to identify advanced technologies to further reduce vehicle emissions, to better understand traffic related air pollution exposures, and to explore the benefits of high efficiency filtration in California homes.

As communities plan for more compact development, the potential health impacts of infill projects will need to be considered. Infill development can reduce urban sprawl and has other potential health and environmental benefits. It also has the potential to increase exposure to traffic pollution due to the proximity of the infill areas to established traffic routes.

Status of Research on Traffic Exposures and Health Impacts

Measurements of air pollutants near roadways show a consistent finding of elevated levels based on proximity. Black carbon, often used as an indicator of diesel exhaust, and ultrafine particles (particles less than 0.1 microns in size), which are emitted in very high numbers from vehicles, are often 2 to 10 times (or more) higher near roadways and freeways (Zhu et al., 2002a, 2002b, 2006; Kuhn et al., 2005; Westerdahl et al., 2005; Ntziachristos et al., 2007; Kozawa et al., 2009a). Concentrations of PM2.5 (particles 2.5 microns or less in diameter) near busy roadways can be about 20% higher than levels at a distance (Zhu et al., 2002a; Kim et al., 2004; Janssen et al., 2001). Nitrogen oxides also are elevated near roadways, usually about 2 to 3 times the levels measured at a distance from the roadway (Kim et al., 2004; Singer et al., 2004; Kozawa et al., 2009a; Durant et al., 2010).

Previous studies of near roadway pollutant levels showed that concentrations of pollutants emitted from vehicles were highest right at the roadway and decreased substantially in the first 300-500 feet from the roadway (Zhu et al., 2002b; Knape 1999). These results were consistent with health studies that showed a stronger association of health impacts for those living within 300-500 ft of the roadway compared to those living farther than 500 ft from the roadway (Brunekreef et al., 1997; Venn et al., 2001; English et al., 1999). More recent studies have shown a somewhat longer plume of increased pollutant concentrations farther from the roadway. Using data collected mostly during the day and near roadways, a meta-analysis of many studies found that for almost all pollutants, elevated levels of pollutants caused by the increased contributions from roadways returns to background levels at 160 - 570 meters (m; 525 – 1870 ft; Karner et al., 2010). The range of distances needed to reach background is usually a result of local meteorological conditions, which can vary significantly; however, a more constant observation is a steep concentration gradient observed closest to the roadway, within 500 ft, with a more gradual and extended decline at further distances. Another meta-analysis found that the “spatial extent of impact” of motor vehicles can extend up to 400 m (1312 ft) for black carbon and particles and 500 m (1640 ft) for nitrogen dioxide (NO_2; Zhou and Levy 2007). Levels of traffic pollutants near roadways vary due to many factors, including traffic type and density, wind direction and speed, local and roadway topography, and time of day and season (Zhu et al., 2004; Kuhn et al., 2005; Moore et al., 2007; Ning et al., 2007; Hu et al., 2009; Kozawa et al., 2009a, 2009b).

In a major 2008 review of the scientific literature by the Health Effects Institute (HEI), proximity to busy roadways was found to be associated with a variety of adverse health impacts, the strongest association being exacerbation of asthma, with others including asthma onset in children, impaired lung function, and increased heart disease (HEI, 2010). More recent studies have added to the list of effects and heightened concern regarding exposure to traffic emissions. Respiratory and cardiovascular effects seen in these studies include an increased risk of new-onset chronic obstructive pulmonary disease (Andersen et al., 2010), a faster progression of atherosclerosis in those living within 100 m of highways in Los Angeles (Künzli et al., 2010), increased risk of premature death from circulatory disease (Jerrett et al., 2009), and increased incidence of new heart disease (Kan et al., 2008). Other effects include increased risk of low birth weight (Brauer et al., 2008; Llop et al., 2010) and increased risk of pre-term delivery (Wilhelm and Ritz, 2003; Wilhelm et al., 2011) for mothers living very near heavy traffic, lower immune function in post-menopausal women living within 150 m of arterial roads (Williams et al., 2009), and increased risk of Type 2 diabetes in post-menopausal women (Krämer et al., 2010).

Children appear to be particularly vulnerable to the adverse effects of traffic emissions. Epidemiological studies have found significant associations of children living near high traffic areas with decreased lung function (Brunekreef et al., 1997; Gauderman et al., 2007), increased medical visits and hospital admissions for childhood asthma (English et al., 1999; Lin et al., 2002), increased wheezing (Venn et al., 2001), and increased childhood asthma and bronchitis (Kim et al., 2004; Gauderman et al., 2005; McConnell et al., 2006), including development of new asthma cases (McConnell et al., 2010; Gehring et al., 2010). Children living near busy roadways are especially likely to experience elevated exposures because they would also play outdoors in the neighborhood and typically would attend nearby schools. Their higher breathing rates per unit of body mass relative to adults (Adams, 1993) and their developing immune, neurological, and respiratory systems make them especially susceptible to impacts from air pollution.

ARB’s recommendation to avoid siting sensitive land uses such as new housing within 500 ft of busy roadways was based on the traffic exposure and health studies completed as of 2005. More recent studies confirm the relationship, and indicate that in some situations an elevated risk extends well past 500 ft. A few studies have measured elevated pollutant levels at distances well beyond 1000 ft (305 m; Karner et al., 2010; Zhou and Levy, 2007). For example, Hu and colleagues (2009) found that in the pre-dawn hours in Los Angeles, elevated ultrafine particle number concentration, nitric oxide, and particle-bound polycyclic aromatic hydrocarbons extended at least 1200 m (3937 ft) downwind of the freeway and did not reach background levels until a distance of 2600 m (8530 ft). More importantly, results from the Southern California Children’s Health Study on the association of residential distance to traffic and lung function development, performed in the same general location as the Hu et al. study, found adverse health effects in children living as far as 1500 m (4921 ft) from roads (Gauderman et al., 2007). These are not unique findings; in the HEI (2010) report mentioned above, the authors noted that studies showed that people living up to 500 m (1640 ft) from heavy traffic are most at risk from the health effects of traffic pollution.

Status of Research on Mitigation Concepts

Various building and site mitigation approaches have been suggested as potential means to reduce exposure to traffic pollution near roadways. A review by ARB staff found that there has been limited study of most of these approaches. Building measures examined include high efficiency filtration for residences through either central, in-duct type filtration or portable air cleaners; and external building design measures, such as locating the air intakes for ventilation systems on the opposite side of the building from outdoor sources, reducing the size and number of openable windows on the side of the building nearest the outdoor sources, or housing people in tall buildings. Site mitigation measures examined include the use of sound walls and vegetation as barriers. These measures are all assessed further below. Studies of elevated and below-grade roadways and freeway caps (also called freeway decks, lids or covers), which are covers over a sunken roadway that produce a road tunnel, also were reviewed, but studies were limited and results variable, and these measures are not feasible or are impractical for most new housing developments. Traffic measures such as those to reduce vehicle miles traveled also were considered; most such measures are typically integrated into roadway and community planning for regional benefits.

Building-related Measures: Filtration

No single building-related measure has been identified as adequate to reduce entry of pollutants from nearby roadways to the extent expected from set-back under common conditions. However, the use of high efficiency filtration appears to be relatively effective in most circumstances, as discussed below. It is especially appropriate for new homes because new homes in California must have mechanical ventilation systems [CCR 2008, Title 24, Section 150(o)], and those systems purposely pull outdoor air into the home that often is not filtered at all or is poorly filtered. High efficiency filtration also appears useful in existing homes without mechanical ventilation as discussed below. Mechanical ventilation systems and the Code requirement are discussed further in the Addendum at the end of this paper.

Background for Filtration

Outdoor-generated pollutants enter and leave buildings through three primary mechanisms: mechanical ventilation systems, which actively draw in outdoor air through an intake vent and distribute it throughout the building; natural ventilation (opening of doors or windows), which is the typical ventilation mode for most homes and small commercial buildings in California; and infiltration, which is the passive entry of unfiltered, outdoor air through small cracks and gaps in the building shell. Both natural ventilation and infiltration allow unfiltered air into the building and reduce the effectiveness of any filtration device.

Filter efficiency is rated using several scales, the most common of which is the Minimum Efficiency Reporting Value (MERV) rating system (ASHRAE 52.2-2007 as cited in EPA 2009). Flat fiberglass filters are the most common filters used in residential heating and air systems, and are rated at only MERV 1 to 4; they remove only a portion of the largest particles in the airstream that passes through the filter. MERV 5 to 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 12 filters begin to remove particles smaller than PM2.5. Higher efficiency MERV 13 to 16 filters are rated to remove a portion of the ultrafine and submicron particles emitted from vehicles. True HEPA (high efficiency particle arrestance) filters (equivalent to MERV 17 to 20) remove 99.97% to 99.999% of particles less than 0.3 microns, but these generally have not been available for residential applications. High efficiency filters associated with central heating, ventilating and air conditioning (HVAC) systems must be carefully selected to assure the mechanical system can handle the increased airflow resistance. Additional information on MERV ratings, the size particles they remove, and typical applications are provided in Table 1 in the Addendum at the end of this paper.

High Efficiency Filtration with Mechanical Ventilation

Because mechanical ventilation has not been used in residential buildings until recently, there has been limited assessment of its impact on entry of particles and other pollutants into homes. However, a few recent studies of homes and schools have shown that high efficiency filtration in mechanical ventilation systems can be effective in reducing levels of incoming outdoor particles. In a seven-home study in northern California, Bhangar et al. (2010) found that the two homes with active filtration in a mechanical system had a notably lower portion of indoor particles from outdoors when the systems were on (filtration active) than when they were turned off (no filtration). In a modeling study of Korean residential units with mechanical ventilation, Noh and Hwang (2010) found that filters rated lower than MERV 7 were insufficient for reducing contaminants that enter through the ventilation filter, and concluded that filters should exceed MERV 11. In a school pilot study, 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, ultrafine particles and PM2.5 by 87% to 96% in three southern California schools (SCAQMD, 2009). Use of the MERV 16 panel filter alone in the HVAC system achieved average particle reductions of nearly 90%. 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 (Parker et al., 2008). The investigators noted that the building shell and other mechanical system components appeared to play a significant role in the submicron particle removal as well.

These findings are similar to those from earlier studies of mechanically ventilated office buildings (e.g., Jamriska et al., 2000; Fisk et al., 1998). Fisk et al. (2000) concluded that use of higher efficiency filters instead of normal filters can reduce indoor numbers of submicron particles by 90% and that there is evidence of a large rate of removal of submicron indoor particles by processes (e.g., deposition) other than ventilation and filtration.

Because most of the studies discussed above were conducted in buildings with few or no indoor sources of submicron particles, the measured efficiencies of filters for reducing indoor concentrations of submicron particles from all sources may be overestimated. Many other studies have identified activities such as unvented cooking, cigarette smoking, and use of unvented gas appliances as indoor sources of submicron particles (ARB, 2005b, studies cited). These would only be removed by filtration to the extent the indoor air is re-circulated through the filters.

High Efficiency Portable Air Cleaning Devices

Portable or stand-alone air cleaners are generally not as capable as in-duct air cleaners and those associated with mechanical ventilation systems for cleaning large areas such as an entire home (Consumer Reports, 2007). However, when they are appropriately sized for the space to be treated, and when they use high efficiency or HEPA filters, portable air cleaners can significantly reduce particles in the treated area and serve as an adjunct to other pollutant reduction measures (Hacker and Sparrow, 2005; Shaughnessy et al., 1994; Shaughnessy and Sextro, 2006; Skulberg et al., 2005; Ward et al., 2005). 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, ultrafine particles and PM2.5 counts by 90% or more, and PM2.5 mass by 75%, when the HVAC system was not running (SCAQMD, 2009). Barn et al. (2008) found median removal efficiencies of 55% to 65% for PM2.5 from fires and wood burning by a HEPA air cleaner in 21 winter homes and 17 summer homes. In other work, Fisk et al. (2002) estimated an 80% reduction in outdoor fine mode particles with stand-alone air cleaners using filters in the MERV 11 to 13 range.

Because new California homes are now required to have mechanical ventilation, stand-alone air cleaners are less relevant to the assessment of measures for new California home construction. However, highly efficient portable air cleaners may be useful in reducing indoor exposure to pollutants in existing homes that do not have mechanical ventilation, and 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.

Removal of Gaseous Pollutants

There are limited options for effective removal of gaseous pollutants such as volatile organic chemicals, or VOCs, and NO_2 in central systems, and although the number and variety of technologies are increasing, there has been only limited research to date on their effectiveness. However, a few studies have examined the effectiveness of stand-alone filtration technologies intended to remove gaseous pollutants from the airstream (Shaughnessy and Sextro, 2006). The most comprehensive study was conducted by Chen et al. (2005), who tested the initial performance of 15 air cleaners with a mixture of 16 representative VOCs in a chamber study. Sorption filtration (e.g., activated carbon) 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. In the 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% of the benzene indoors and 15% of total VOCs when operated with the HVAC turned off (SCAQMD, 2009). In a children's daycare center in Finland, Partti-Pellinen et al. (2000) found that up to 50% to 70% of nitrogen oxides could be removed by chemical filtration using a combination of charcoal, aluminum oxide and potassium permanganate, while another study found about 50% NO_2 removal by a HEPA air cleaner with large quantities of carbon in the adsorption bed, but little or no removal by other types of air cleaners (Shaughnessy et al., 1994).

Results from these studies show effectiveness for some technologies but are not conclusive due to their limited number and scope, including a relative lack of real world measurements. Additionally, some investigators have found that some filters re-emit VOCs that have been removed over time, or emit reaction products from the matter collected on the filter (Daisey and Hodgson, 1989; Fisk, 2007; Destaillats et al., 2011; Hyttinen et al., 2006, 2007).

Limitations of High Efficiency Filtration

Although they can substantially reduce indoor concentrations of pollutants, mechanical filtration systems alone are insufficient to fully protect occupants from particles and other emissions from nearby roadways, for several reasons.

- First, most people tend to open their windows or doors at least part of each day (Offermann, 2009; Phillips et al., 1990), and such natural ventilation involves no filtration of incoming air and can diminish any pollutant reductions attained through the use of the mechanical system. The effectiveness of high efficiency filtration in homes whose occupants open their doors and windows regularly has not been quantified.
- Second, as higher MERV filters are used, greater attention must be paid to the increased air flow resistance that occurs with some filter types; mechanical system motors must be sufficiently sized to accommodate the air flow needs.
- Third, studies have shown that homeowners are not provided with sufficient information regarding use and maintenance of their central HVAC systems, or do not read and follow instructions for maintaining their filters (EPA, 2009; Offermann, 2009). Filtration is only effective if filters are well-fitted and are replaced or maintained according to the manufacturer's recommendations, and duct leakage is minimized (Thatcher et al., 2001; Wallace et al., 2004). Older (aged) filters have been associated with increased irritant health symptoms and decreased work performance in studies of filtration maintenance in workplaces (Clausen, 2004; Seppänen and Fisk, 2002; Wargocki et al., 2004).
- Finally, as discussed above, gaseous pollutants are not removed by most particle filters, and the technologies for VOC removal in residential applications are limited and still evolving.

Expected Benefits of High Efficiency Filtration

High efficiency filtration has been used in homes and schools only recently, and there is a range of highly variable building characteristics, filtration technologies, and occupant behaviors that determine the effectiveness of high efficiency filters in reducing the overall levels of pollutants indoors. Accordingly, it is difficult to accurately quantify the actual reduction in particulate matter that would be achieved by introducing high efficiency filtration on a widespread basis across the population of California homes and schools. For example, while filters with a MERV 16 rating remove more than 95% of particles from 0.3 to 3 microns in diameter, only those particles in the airstream actually passing through the filter are removed. Factors that determine the fraction of particles removed from the air in a building include the airflow rate through the unit, the amount of time that the system is "on", the extent to which windows and doors are opened, and other factors. While results from the studies conducted in homes and schools to date appear promising, those studies usually limited the opening of windows and doors or followed other specific protocols. Thus, although a substantial reduction in particles would be expected, the reduction that would be realized across the wide variety of conditions in California homes and schools cannot be confidently estimated.

Two kinds of programs are currently being implemented that will provide critical information needed to help confirm and quantify the effectiveness of high efficiency filtration. First, ARB is funding two key studies of high efficiency filtration in homes. Second, several local air quality management districts and school districts are implementing programs to install high efficiency filtration devices in a substantial number of schools in California, and collecting data regarding the performance of the filtration units. These are discussed below.

ARB's Planned High Efficiency Filtration Research

ARB is funding a project entitled "Reducing In-Home Exposure to Air Pollution" to measure the exposure reduction and energy use of combinations of mechanical ventilation and filtration systems in order to identify compatible, low-energy systems that are effective at reducing indoor exposures to indoor, and incoming outdoor, pollutants. The study will be conducted by Drs. Brett Singer and Iain Walker of Lawrence Berkeley National Laboratory. The investigators plan to evaluate 15 current and new systems, and test seven of the most promising systems in a test home near a major roadway in an area with high ambient ozone and PM2.5 levels. They will measure fine and ultrafine particles, ozone, VOCs, NO_2 and black carbon, both indoors and outdoors, along with energy consumption and the performance of systems as filters age. This project is needed because new California homes are now required to have mechanical ventilation as discussed above, and the most widely used, low energy mechanical ventilation systems, bathroom exhaust systems, do not filter the incoming air; hence, the occupants' indoor exposure to outdoor air pollutants can potentially increase with these systems.

ARB is also funding a second study entitled "Benefits of High Efficiency Filtration to Children with Asthma". Dr. Deborah Bennett from the University of California at Davis will conduct this 4-year study of 200 children with asthma in Fresno and Riverside to quantify the exposure and asthma reduction benefits of high efficiency filtration in their homes. One intervention group will have high efficiency filters or filtration systems installed in their homes' central heating and air conditioning systems. The second group will have high efficiency portable air cleaners placed in the child's bedroom and in the main living area. Filters with a MERV rating of 15 or higher will be used. Improvements in asthma symptoms will be evaluated in a randomized cross-over design, with each participant receiving high efficiency air filtration for a year and no filtration for a year, allowing the investigators to identify the improvements related to the air filtration. During the control periods, "sham" filters with little or no particle removal capability will be used. Half of the homes with portable air cleaners will also have filters that remove ozone and VOCs. The extent to which particulate matter (PM10, PM2.5

and ultrafine particles), ozone, black carbon, and nitrogen oxides are reduced will be measured. Key asthma health endpoints will also be examined, including unplanned utilization of the healthcare system for asthma-related illness, short-term medication use, symptom diaries, peak exhaled flow, spirometry and exhaled nitric oxide.

Current Programs Using High Efficiency Filtration

Several programs have been completed or are underway in the State to install and/or test high efficiency filters, primarily in schools, to reduce exposures to pollutants from heavy traffic and/or port-related emissions. Since 2008, the South Coast Air Quality Management District (SCAQMD) has approved $3 million for installation of high efficiency air filtration devices in a total of 18 schools and one community center in the Long Beach and Los Angeles Unified School Districts, San Bernardino and the Boyle Heights area (Kwon, 2012). SCAQMD also has agreed to oversee implementation of a program to utilize $5.4 million in settlement funds to install and maintain high performance air filtration devices at about 47 schools in Wilmington and San Pedro. Installation of the filtration devices was scheduled to begin in summer 2012. Detailed site assessments of the schools are underway prior to installation in order to determine the best filtration device for each classroom and to facilitate assessment of actual improvements in classroom air.

Also, the Bay Area Air Quality Management District (BAAQMD) is conducting a school air filtration project in five schools for about $300,000 (Smith, 2012). In 2010, a contractor completed installation of high efficiency air filtration equipment at five elementary schools located in the Bay View Hunters Point neighborhood of San Francisco. The filtration equipment is designed to reduce exposure inside the schools to particles from outdoor sources, as well as indoor-based particles such as some allergens. Initial monitoring results indicate that there has been a substantial reduction of particulate matter (up to about 50% to 75% for PM2.5 and higher for very small particles) inside the classrooms as a result of the newly installed high performance filters (IQAir, 2012).

To date, these programs appear successful, but overall cost, changes to the operation of the classrooms' central HVAC systems (such as running the system continuously rather than allowing it to switch on and off based on temperature needs) and other considerations (noise, drafts) may reduce the feasibility of the current technologies for use in all classrooms and require further refinements. However, because of the similarities of schools to homes with mechanical ventilation systems, one would expect comparable reductions in particle levels from high efficiency HVAC filtration in new and retrofitted homes.

Cost of High Efficiency Filtration

About a dozen companies offer high efficiency filtration devices incorporated into, or suitable for, residential mechanical ventilation systems, and most offer just one or two models. The devices are rated from MERV 11 to 16, plus several are true HEPA filters (equivalent to about MERV 17 to 20). Initial costs range from about $200 to $2800 for a very high end system; however, most cost less than $500. This range does not include installation, although in a new home the added cost over the installation of the mechanical system itself would be expected to be minimal. Annual filter replacement and/or maintenance cost ranges from about $25 to $255 per year, depending on MERV rating, number of filter changes needed per year, and whether the system includes a carbon filter for VOCs (which increases the cost of filter replacement, as these typically need to be replaced several times per year).

For existing homes and those that are renovated and do not have a mechanical ventilation system, either higher efficiency filters in the central heating and air system or portable high efficiency filtration devices could be used. High efficiency filters for central systems that can accept them cost about $20. However, the increased airflow resistance may cause the central system to be less efficient. Effective, high efficiency portable units range in purchase cost from about $200 to $1250 depending on the size of the room or space to be treated and the specific technologies included (e.g., MERV rating and charcoal or other VOC removal filters) and would typically not involve any installation costs. Replacement filters and maintenance range from about $75 to $500 per year, again depending on the types of filters included and how dirty the air is, which would determine the frequency of filter changes needed. To adequately treat the living areas of most homes (e.g., bedrooms, family room, living room), two or more portable units may be needed.

External Building Design Measures

Moving Air Intakes

Research focused on assessing external building design measures is generally not readily available. 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. However, the reduction of pollutant entry in such a case would depend 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. One particle expert has noted that moving the intake would likely only be beneficial when 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 (Thatcher, 2010). This view appears at least partially substantiated by an Australian study that found that the concentration of submicron particles was consistently high and relatively undiluted around a building that was within 15 m of the roadway (Morawska et al., 1999). However, because this option has received little scientific study, and because all new California homes are required to use mechanical ventilation, which will often include a supply air intake, this option warrants further study to determine whether there are conditions under which strategic placement of air intakes might provide some benefits.

Reducing Openable Windows

Reducing the size and number of openable windows on the side of the building nearest the outdoor source would likely do little to reduce entry of particles and other pollutants into homes. Furthermore, this potential measure may not be acceptable to homeowners, who often open windows to take advantage of the breeze, from which the benefit arises primarily from opening windows on the prevailing wind side of the building. Windows opened only on the opposite side may result in little air movement in the home. In regions of the State where window opening currently replaces air conditioning in the summer evening and nighttime periods, there could be substantial energy and cost penalties for the increased use of mechanical air conditioning to cool the home. Additionally, increased indoor air stagnation and condensation may occur, which can result in mold issues. Thus, for all of these reasons, this option does not appear practical for single family dwellings. This measure might be acceptable in multi-family dwellings, depending on the specific building design and the ventilation systems used. However, inclusion of a sufficient number of windows (even if unopenable) would allow more daylight into the building, which would reduce energy use for indoor lighting and provide the satisfaction and efficiency benefits that accompany daylighting (Heschong Mahone Group, 2003a, 2003b).

Taller Buildings

Housing people in taller buildings has also been suggested as a possible exposure reduction measure. However, one of the few relevant studies of multi-story buildings near busy roadways found that vertical differences in 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 (Morawska et al., 1999). A second study, conducted in New York, found significant decreases for outdoor black carbon and non-volatile polycyclic aromatic hydrocarbons for floors 6 to 32 during the non-heating season only (Jung et al., 2011). Additionally, floors 3 to 5 showed the highest median outdoor concentrations for all pollutants measured, although the trend was not statistically significant and the elevated pollutants were believed to come from nearby rooftop exhausts. Thus, multi-story housing may reduce exposure in some situations but requires further research to determine conditions under which tall buildings might provide a reliable approach to reduce exposure near busy roadways.

Site-related Measures

The primary site-related measures reviewed by ARB staff were sound walls and vegetation barriers.

Sound Walls

Sound walls appear to reduce pollutant concentrations near the roadway; near-road concentrations (within 15-20 m [49-66 ft]) have shown reductions up to about 50% (Ning et al., 2010; Baldauf et al., 2008; Bowker et al., 2007; Hagler et al., 2012). However, in some studies higher levels of pollution were seen behind the barrier and at a distance from the sound walls and roadways, although in some of these studies the higher levels appear related to other sources of pollution (Ning et al., 2010; Bowker et al., 2007; Hagler et al., 2010; Baldauf et al., 2008). In one of the few field measurement studies of sound walls, conducted along two southern California freeways, Ning et al. (2010) found that concentrations at farther distances (about 80 to 100 m from the roadway) were typically greater for the portions of the roads with sound walls, and background levels behind sound walls were not reached until 250 to 400 m as compared to 150 to 200 m without sound walls. Modeling and tracer studies (Heist et al., 2009; Finn et al., 2009) showed that barriers reduced air pollution downwind of the barrier, although in some cases trapping of pollution and increased levels on the road would occur (Hagler et al., 2011; Finn et al., 2009). Nearby buildings and structural barriers can also affect the attenuation and dispersion of pollution from roadways, but results vary with different meteorological conditions (Bowker et al., 2007; Hagler et al., 2010; Hagler et al., 2012).

Vegetation Barriers

Results for vegetation alone are more variable than those for sound walls. Vegetation can remove some gaseous pollutants by uptake or absorption, and particles are removed primarily by interception (impaction or physical adherence; Nowak et al., 2006; Fujii et al., 2008; Smith, 1990; Pardyjak et al., 2008; Baldauf et al., 2008). However, particles can be resuspended, apparently even at very low wind speeds (Fujii et al., 2008; Smith, 1990). Vegetation may restrict dispersion and increase concentrations on-road in street canyons with closer spacing of trees, particularly in low wind conditions (Gromke, 2011; Gromke and Ruck, 2007, 2009; Buccolieri et al., 2009). Another study has further shown the complexity of the effects of vegetation; investigators found different results depending on particle size and wind speed, and a non-linear increase of particle removal with increased leaf area density, which varies by tree species and season (Steffens et al., 2012). Gaps in vegetation barriers can have a significant negative impact on their effectiveness (Hagler et al., 2012), which needs to be addressed in future California research because California roadside vegetation tends to be less dense than that in the eastern U.S., where most previous field studies have been conducted. Also, some types of vegetation can trigger asthma and allergy attacks, and some emit reactive VOCs that contribute to the formation of ozone.

Sound Walls and Vegetation Combined

A combination of sound walls and vegetation appears to be more effective than either one alone. The two used together have been shown to disperse pollutants more consistently and to greater distances than either alone, with up to about a 60% reduction in near roadway levels (Baldauf et al., 2008; Bowker et al., 2007). While sound walls alone and sound walls combined with vegetation show promise, the increase in concentrations on-road and at a distance seen in some studies can increase exposures of others in the population and thus redistributes, rather than removes, pollutants. Additionally, the complexity of pollutant movement under varying conditions makes accurate prediction of exposure reduction difficult. Specific conditions under which sound walls and vegetation can reliably and consistently reduce exposures to air pollution have not been identified, especially in California.

Reduction of Indoor-generated Pollutants to Reduce Overall Exposure

Particles, NO_2 and other pollutants emitted by vehicles and other outdoor sources also have indoor sources that can produce higher indoor concentrations at times (ARB, 2005b, Section 2, and sources cited). Therefore, a reduction in indoor emissions and exposures can reduce the overall health impact of exposure to outdoor pollutants because the total exposure (indoor plus outdoor) to those pollutants experienced by the building occupants would be reduced. A number of studies have identified unvented cooking, cigarette smoking, the use of unvented gas appliances, burning of candles and incense, and woodburning as indoor sources of fine and ultrafine particles (Bhangar et al., 2010; ARB, 2005b; Fortmann et al., 2001; Wallace, 1996; Wallace, 2005; Wallace et al., 2008). High fine and ultrafine particle counts have been measured from such indoor sources. In homes with such sources, average indoor concentrations and occupants' personal exposures to fine and ultrafine PM are dominated by those indoor sources. Thus, measures to reduce indoor sources can help to significantly reduce occupants' peak and overall daily exposures to key pollutants emitted from both traffic and indoor sources.

Summary of Research Review

ARB has developed and adopted increasingly stringent regulations limiting emissions from passenger cars, trucks and buses, which have substantially reduced, and will continue to reduce, vehicle emissions. However, recently adopted regulations have compliance dates extending as far as 2025 for full implementation, and fleet turnover to zero or near-zero technologies will take 20 to 30 years. The set-back of buildings from high traffic roadways remains the most certain approach for preventing the residual health risk from traffic pollution exposures for those living closest to the roadways because it distances them from the highest pollutant concentrations. Research conducted since the publication of ARB's recommendations in 2005 further supports the use of set-back.

There are two mitigation measures that can be effective for exposure reduction. Increased filtration of air and reduction of indoor pollution sources potentially can reduce the overall pollution burden in homes. These measures warrant consideration especially in light of recent studies showing that the pollutant plumes at times can extend beyond 1000 ft (305 m) from the roadway. For most residential applications near busy roadways, high efficiency (MERV 13 to 16, or higher) pleated particle filters would generally be considered the most effective approach to filtration because they can remove the very small particles emitted by motor vehicles without emitting ozone, formaldehyde, or other harmful byproducts. Based on a limited number of studies, such high efficiency filtration has been shown to reduce indoor PM2.5 and ultrafine particle levels by up to 90% relative to incoming outdoor levels when doors and windows are kept mostly closed. Purchase costs for high efficiency filtration devices or systems that are compatible with residential mechanical ventilation systems (which are now required in new residential construction in California) range from $200 up to $2800, but most are available for under $500. Because Title 24 now requires mechanical ventilation for new residential construction, enhanced filtration can help avoid increased exposures to outdoor pollutants that may occur. The use of high efficiency air filters in central heating and air systems or stand-alone air cleaning devices can also reduce exposures in existing homes and homes that use certain types of mechanical ventilation systems that cannot accommodate central filtration.

While research shows that high efficiency filtration can be effective, it has several limitations. Filtration cannot remove all incoming outdoor pollutants because of normal building leakage and the fact that most people open windows and doors at least a portion of the day, allowing entry of unfiltered air. Additionally, not all pollutants are filtered by the filter media. Moreover, studies show irregular homeowner maintenance of filters and central systems, and regular maintenance is critical for effective removal of pollutants. ARB is funding two studies that should help further identify the approximate reduction in exposure that high efficiency filtration can provide in homes. High efficiency filtration is already being used or is planned for use in over 70 schools in California; these programs should provide comparable information for high efficiency filtration in classrooms.

The benefits are less clear for most of the other potential mitigation measures examined. Studies have shown that the use of sound walls alone, or sound walls and vegetation together, can reduce near roadway concentrations by about 50% and 60%, respectively. However, the extent of exposure reduction is quite variable under different conditions of meteorology and topography, and increased levels of pollutants can occur on-road and at a distance from the roadway. Thus, unlike the situation with filtration, pollutants are primarily redistributed rather than removed; while individuals living near the roadway would benefit, those traveling on the road or living at a distance could experience elevated exposures at times. The effectiveness of vegetation alone is even more variable, and has not been well-quantified. Furthermore, vegetation with low allergenic potential and low reactive VOC formation needs to be identified and tested, and other limitations of vegetation as a pollution barrier need to be better understood. Research is needed that identifies the specific conditions under which sound walls and vegetation can consistently provide a reliable exposure reduction benefit with limited disbenefits. In particular, California field studies are needed because of the significant differences in California meteorology, building practices, and flora from those of the eastern U.S.

The limited studies conducted to date on other potential mitigation concepts are not promising, although further research may identify situations in which they are generally effective. Placement of air intakes on the side of the building opposite the roadway may make little difference in terms of exposure, due to rapid particle movement around buildings. Locating windows only on the side of the building opposite the roadway reduces indoor daylighting, air circulation and cooling, and may do little to reduce exposure. Finally, taller buildings do not necessarily experience substantially reduced pollutant levels at higher floor levels, depending on local meteorology and other nearby sources of pollution. However, further research on placement of air intakes and housing in taller buildings may identify conditions under which these measures reliably reduce exposures. Research is warranted on these measures and the measures discussed above as effective or showing promise in order to further identify cumulative measures that together can assure sufficient exposure reduction and health protection for those living near busy roadways.

References

Adams WC, 1993. Measurement of Breathing Rate and Volume in Routinely Performed Daily Activities. Final Report to the California Air Resources Board, Contract no. A033-205.

Andersen ZJ, Hvidberg M, Jensen SS, Ketzel M, Loft S, Sørensen M, Tjønneland A, Overvad K, Raaschou-Nielsen O. 2010. Chronic Obstructive Pulmonary Disease and Long-Term Exposure to Traffic-Related Air Pollution: A Cohort Study. American Journal of Respiratory and Critical Care Medicine, doi: 10.1164/rccm.201006-0937OC.

ARB, 2005a. Air Quality and Land Use Handbook: A Community Health Perspective. Califiornia Air Resources Board, April 2005. http://www.arb.ca.gov/ch/handbook.pdf

ARB, 2005b. Report to the California Legislature: Indoor Air Pollution in California. California Air Resources Board. Found at http://www.arb.ca.gov/research/indoor/ab1173/rpt0705.pdf.

Baldauf R, Thomas E, Khlystov A, Isakov V, Bowker G, Long T, Snow R, 2008. Impact of noise barriers on near-road air quality. Atmospheric Environment 42: 7502-7507.

Barn P, Larson T, Noulett M, Kennedy S, Copes R, Brauer M, 2008. Infiltration of forest fire and residential wood smoke: an evaluation of air cleaner effectiveness. J. Exposure Sci. and Environ. Epidemiology 18: 503-511.

Batterman SA, Zhang K, Kononowech R. 2010. Prediction and analysis of near-road concentrations using a reduced-form emission/dispersion model. Environmental Health 9: 29, doi: 10.1186/1476-069X-9-29.

Bemis GR, Ranzieri AJ, Benson PE, Peter RR, Pinkerman KO, Squires BT. 1977. Air Pollution and Roadway Location, Design, and Operation – Project Overview. FHWA-CA-TL-7080-77-25. California Department of Transportation. Found at http://www.dot.ca.gov/newtech/researchreports/1976-1977/77-25.pdf.

Bhangar S, Mullen NA, Hering SV, Kreisberg NM, Nazaroff WW. 2010. Ultrafine particle concentrations and exposures in seven residences in northern California. Indoor Air, doi: 10.1111/j.1600-0668.2010.00689.x.

Bowker GE, Baldauf R, Isakov V, Khlystov A, Petersen W. 2007. The effects of roadside structures on the transport and dispersion of ultrafine particles from highways. Atmospheric Environment 41 (37): 8128-8139.

Brauer M, Lencar C, Tamburic L, Koehoorn M, Demers P, Karr C. 2008. A cohort study of traffic-related air pollution impacts on birth outcomes. Environmental Health Perspectives 116 (5): 680-686.

Brunekreef B, Janssen NA, de Hartog J, Harssema H, Knape M, van Vliet P, 1997. Air pollution from truck traffic and lung function in children living near motorways. Epidemiology 8 (3): 298-303.

Buccolieri R, Gromke C, Di Sabatino S, Ruck B, 2009. Aerodynamic effects of trees on pollutant concentration in street canyons. Science of the Total Environment 407 (19): 5247-5256.

Bunn F, Collier T, Frost C, Ker K, Roberts I, Wentz R, 2003. Traffic calming for the prevention of road traffic injuries: systematic review and meta-analysis. Injury Prevention 9:200-204.

CCR 2008. California Code of Regulations, Title 24, Article 1, Energy Building Regulations, Section 150(o), Ventilation for Indoor Air Quality. Found at http://www.energy.ca.gov/2008publications/CEC-400-2008-001/CEC-400-2008-001-CMF.PDF

CEC 2010. Residential Compliance Manual – 2008 Building Energy Efficiency Standards. Publication number CEC-400-2008-016-CMF-Rev1. California Energy Commission. Found at http://www.energy.ca.gov/2008publications/CEC-400-2008-016/CEC-400-2008-016-CMF-REV1.PDF

Chen W, Zhang JS, Zhang Z, 2005. Performance of air cleaners for removing multiple volatile organic compounds in indoor air. ASHRAE Transactions 111 (1): 1101-1114.

Child & Associates, 2004. M5 East Freeway: A review of emission treatment technologies, systems & applications. NSW Roads and Traffic Authority. Found at http://www.rta.nsw.gov.au/constructionmaintenance/downloads/2004_10_childrepfiltration.pdf

Clausen G, 2004. Ventilation filters and indoor air quality: a review of research from the International Centre for Indoor Environment and Energy. Indoor Air 14 Suppl 7: 202-7.

Consumer Reports, 2007. Air Purifiers: Filtering the Claims. December 2007, issue 12: 48-51.

Dabberdt WF, Cagliostro DJ, Meisel WS, Horowitz AJ, Skinner G, 1974. Studies of air quality on and near highways. Interim report No. 1, 1973-74. Report number PB-82-192147. Stanford Research Institute. Found at http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=6854698.

Daisey JM, and AT Hodgson, 1989. Initial efficiencies of air cleaners for the removal of nitrogen dioxide and volatile organic compounds. Atmospheric Environment 23: 1885-1892.

de Nazelle A, Rodriguez DA, Crawford-Brown D, 2009. The built environment and health: Impacts of pedestrian-friendly designs on air pollution exposure. Science of the Total Environment 407 (8): 2525-35.

Destaillats H, Chen W, Apte M, Li N, Spears M, Almonsi J, Brunner G, Zhang J, Fisk W, 2011. Secondary pollutants from ozone reactions with ventilation filters and degradation of filter media additives. Atmospheric Environment 45: 3561-3568.

Durant JL, Ash CA, Wood EC, Herndon SC, Jayne JT, Knighton WB, Canagaratna MR, Trull JB, Brugge D, Zamore W, Kolb CE, 2010. Short-term variation in near-highway air pollutant gradients on a winter morning. Atmospheric Chemistry and Physics Discussions 10: 1-28.

English P, Neutra R, Scalf R, Sullivan M, Waller L, Zhu L, 1999. Examining associations between childhood asthma and traffic flow using a geographic information system. Environmental Health Perspectives 107 (9): 761-767.

EPA 2007. Measuring the air quality and transportation impacts of infill development. EPA 231-R-07-001. Environmental Protection Agency. Found at http://www.epa.gov/smartgrowth/pdf/transp_impacts_infill.pdf.

EPA 2009. Residential Air Cleaners (Second Edition): A Summary of Available Information. EPA 402-F-09-002. Environmental Protection Agency. Found at http://www.epa.gov/iaq/pdfs/residential_air_cleaners.pdf

Finn D, Clawson KL, Carter RG, Rich JD, Eckman RM, Perry SG, Isakov V, Heist DK, 2010. Tracer studies to characterize the effects of roadside noise barriers on near-road pollutant dispersion under varying atmospheric stability conditions. Atmospheric Environment 44: 204-214.

Fisk WJ, Faulkner D, Sullivan D, Dong M, Dabrowski C, Thomas JJ, Mendell MJ, Hines CJ, Ruder AM, Boeniger MF, 1998. The Healthy Building Intervention Study: Objectives, Methods and Results of Selected Environment Measurements. LBNL-41546. Lawrence Berkeley National Laboratory. Found at http://www.osti.gov/bridge/servlets/purl/674933-HRRsOR/webviewable/.

Fisk WJ, Faulkner D, Sullivan D, Mendell MJ, 2000. Particle Concentrations and Sizes with Normal and High Efficiency Air Filtration in a Sealed Air-Conditioned Office Building. Aerosol Science and Technology 32 (6): 527-544.

Fisk WJ, Faulkner D, Palonen J, Seppanen OA, 2002. Performance and costs of particle air filtration technologies. Indoor Air 12 (4): 223-234.

Fisk WJ, 2007. Can Sorbent-based Gas Phase Air Cleaning for VOCs Substitute for Ventilation in Commercial Buildings? Proceedings of IAQ 2007 conference, “Healthy and Sustainable Buildings,” October 15-17, 2007, Baltimore, MD. Sponsored by ASHRAE, Atlanta.

Fortmann R, Kariher P, Clayton R, 2001. Indoor Air Quality: Residential Cooking Exposures. Final report to the California Air Resources Board. Contract number 97-330. Found at http://www.arb.ca.gov/research/abstracts/97-330.htm.

Fujii E, Lawton J, Cahill TA, Barnes DE, Hayes C, Spada N, McPherson G, 2008. Removal Rates of Particulate Matter onto Vegetation as a Function of Particle Size. Final Report to Breathe California of Sacramento-Emigrant Trails' Health Effects Task Force and Sacramento Metropolitan Air Quality Management District. Found at http://www.sacbreathe.org/Local%20Studies/Vegetation%20Study.pdf.

Gauderman JW, Vora H, McConnell R, Berhane K, Gilliland F, Thomas D, Lurmann F, Avol E, Kunzli N, Jerrett M, Peters J, 2007. Effect of exposure to traffic on lung development from 10 to 18 years of age: a cohort study. Lancet 369: 571-577.

Gauderman WJ, Avol E, Lurmann F, Kuenzli N, Gilliland F, Peters J, 2005. Childhood asthma and exposure to traffic and nitrogen dioxide. Epidemiology 16 (6): 737-743.

Gehring U, Wijga AH, Brauer M, Fischer P, de Jongste JC, Kerkhof M, Oldenwening M, Smit HA, Brunekreef B, 2010. Traffic-related air pollution and the development of asthma and allergies during the first 8 years of life. American Journal of Respiratory and Critical Care Medicine 181 (6): 596-603.

Gromke C and Ruck B, 2007. Influence of trees on the dispersion of pollutants in an urban street canyon – Experimental investigation of the flow and concentration field. Atmospheric Environment 41 (16): 3287-3302.

Gromke C and Ruck B, 2009. On the Impact of Trees on Dispersion Processes of Traffic Emissions in Street Canyons. Boundary-Layer Meteorology 131 (1): 19-34.

Gromke C, 2011. A vegetation modeling concept for Building and Environmental Aerodynamics wind tunnel tests and its application in pollutant dispersion studies. Environmental Pollution, 159: 2094-2099.

Hacker DW and Sparrow EM, 2005. Use of air-cleaning devices to create airborne particle-free spaces intended to alleviate allergic rhinitis and asthma during sleep. Indoor Air 15 (6): 420-431.

Hagler GSW, Thomas ED, Baldauf RW, 2010. High-resolution mobile monitoring of carbon monoxide and ultrafine particle concentrations in a near-road environment. Journal of the Air & Waste Management Association 60 (3): 328-36.

Hagler GSW, Tang W, Freeman MJ, Heist DK, Perry SG, Vette AF, 2011. Model evaluation of roadside barrier impact on near-road air pollution. Atmospheric Environment 45: 2522-2530.

Hagler GSW, Lin MY, Khlystov A, Baldauf RW, Isakov V, Faircloth J, Jackson LE, 2012. Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions. Science of the Total Environment 419: 7-15.

Hankey S and Marshall JD, 2009. Impacts of urban form on future US passenger-vehicle greenhouse gas emissions. Energy Policy 38 (9): 4880-4887.

HEI, Health Effects Institute, 2010. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects, Special Report 17. HEI Panel on the Health Effects of Traffic-Related Air Pollution. January 2010.

Heist DK, Perry SG, Brixey LA, 2009. A wind tunnel study of the effect of roadway configurations on the dispersion of traffic-related pollution. Atmospheric Environment 43: 5101-5111.

Heschong Mahone Group, Inc., 2003a. Windows and Offices: A Study of Office Worker Performance and the Indoor Environment. Technical Report to the California Energy Commission, P500-03-082-A-9, October 2003.

Heschong Mahone Group, Inc., 2003b. Windows and Classrooms: A Study of Student Performance and the Indoor Environment. Technical Report to the California Energy Commission, P500-03-082-A-7, October 2003.

Hosking J, Macmillan A, Connor J, Bullen C, Ameratunga S, 2010. Organisational travel plans for improving health. Cochrane Database of Systematic Reviews 3: CD005575, doi: 10.1002/14651858.CD005575.pub3.

Hu S, Fruin S, Kozawa K, Mara S, Paulson S, Winer AM, 2009. A wide area of air pollutant impact downwind of a freeway during pre-sunrise hours. Atmospheric Environment 43: 2541-2549.

Hyttinen M, Pasanen P, Bjorkroth M, Kalliokoski P, 2007. Odors and volatile organic compounds released from ventilation filters. Atmospheric Environment 41: 4029-4039.

Hyttinen M, Pasanen P, Kalliokoski P, 2006. Removal of ozone on clean, dusty and sooty supply air filters. Atmospheric Environment 40: 315-325.

IQAir 2012. Performance Testing & Monitoring Final Report (San Francisco Unified School District), submitted to the Bay Area Air Quality Management District, contract no. 2010-095.

Jamriska M, Morawska L, Clark BA, 2000. Effect of ventilation and filtration on submicrometer particles in an indoor environment. Indoor Air 10 (1): 19-26.

Janssen NAH, van Vliet PHN, Aarts F, Harssema H, Brunekreef B, 2001. Assessment of exposure to traffic related air pollution of children attending schools near motorways. Atmospheric Environment 35 :3875-3884.

Jerrett M, Finkelstein MM, Brook JR, Arain MA, Kanaroglou P, Stieb DM, Gilbert NL, Verma D, Finkelstein N, Chapman KR, Sears MR, 2009. A cohort study of traffic-related air pollution and mortality in Toronto, Ontario, Canada. Environmental Health Perspectives 117 (5): 772-777.

Jung KH, Bernabe K, Moors K, Yan B, Chillrud SN, Whyatt R, Camaan D, Kinney PK, Perera FP, Miller RL, 2011. Effects of Floor Level and Building Type on Residential Levels of Outdoor and Indoor Polycyclic Aromatic Hydrocarbons, Black Carbon, and Particulate Matter in New York City, Atmosphere 2: 96-109.

Kan H, Heiss G, Rose KM, Whitsel EA, Lurmann F, London SJ, 2008. Prospective analysis of traffic exposure as a risk factor for incident coronary heart disease: the Atherosclerosis Risk in Communities (ARIC) study. Environmental Health Perspectives 116 (11): 1463-1468.

Karner AA, Eisinger DS, Niemeier DA, 2010. Near Roadway Air Quality: Synthesizing the Findings from Real-World Data. Environmental Science & Technology 44: 5334-5344.

Kendrick CM, Moore A, Haire A, Bigazzi A, Figliozzi M, Monsere CM, George L, 2011. Impact of bicycle lane characteristics on exposure of bicyclist to traffic-related particulate matter. Transportation Research Record, 2247: 24-32.

Kim JJ, Smorodinsky S, Lipsett M, Singer B, Hodgson A, Ostro B, 2004. Traffic-related air pollution near busy roads: The East Bay Children's Respiratory Health Study. American Journal of Respiratory and Critical Care Medicine 170: 520-526.

Knape M, 1999. Traffic related air pollution in city districts near motorways. The Science of the Total Environment, 235:339-341.

Kozawa K, Fruin S, Winer AM, 2009a. Near-road air pollution impacts of goods movement in communities adjacent to the ports of Los Angeles and Long Beach. Atmospheric Environment 43: 2960-2970.

Kozawa KH, Fruin SA, Winer AM, 2009b. A predictive model to determine near-freeway pollution impacts. Presented at the 2009 Annual Conference for the International Society for Exposure Science, Minneapolis, MN.

Krämer U, Herder C, Sugiri D, Strassburger K, Schikowski T, Ranft U, Rathmann W, 2010. Traffic-related air pollution and incident type 2 diabetes: results from the SALIA cohort study. Environmental Health Perspectives 118 (9): 1273-1279

Kuhn T, Biswas S, Sioutas C, 2005. Diurnal and seasonal characteristics of particle volatility and chemical composition in the vicinity of a light-duty vehicle freeway. Atmospheric Environment 39: 7154-7166.

Künzli N, Jerrett M, Garcia-Esteban R, Basagaña X, Beckermann B, Gilliland F, Medina M, Peters J, Hodis HN, Mack WJ, 2010. Ambient air pollution and the progression of atherosclerosis in adults. PloS One 5 (2): 90-96.

Kwon, 2012. Patricia Kwon, Air Quality Specialist, SCAQMD, personal communication.

Lin S, Munsie JP, Hwang SA, Fitzgerald E, Cayo MR, 2002. Childhood asthma hospitalization and residential exposure to state route traffic. Environmental Research 88 (2): 73-81.

Litman T, 1999. Traffic calming benefits, costs and equity impacts. Victoria Transport Policy Institute, British Columbia, Canada.

Llop S, Ballester F, Estarlich M, Esplugues A, Rebagliato M, Iñiguez C, 2010. Pre-term birth and exposure to air pollutants during pregnancy. Environmental Research 110 (8): 778-785.

Marshall JD, 2008. Environmental inequality: Air pollution exposures in California's South Coast Air Basin. Atmospheric Environment 42 (21): 5499-5503.

Marshall JD, Brauer M, Frank LD, 2009. Healthy neighborhoods: walkability and air pollution. Environmental Health Perspectives 117 (11): 1752-9.

McConnell R, Berhane K, Yao L, Jerrett M, Lurmann F, Gilliland F, Kunzli N, Gauderman J, Avol E, Thomas D, Peters J, 2006. Traffic, susceptibility, and childhood asthma. Environmental Health Perspectives 114 (5): 766-72.

McConnell R, Islam T, Shankardass K, Jerrett M, Lurmann F, Gilliland F, 2010. Childhood incident asthma and traffic-related air pollution at home and school. Environmental Health Perspectives 118 (7): 1021-1026.

Moore KF, Ning Z, Ntziachristos L, Schauer JJ, Sioutas C, 2007. Daily variation in the properties of urban ultrafine aerosol – Part I: Physical characterization and volatility. Atmospheric Environment 41: 8633-8646.

Morawska L, Thomas S, Gilbert D, Greenaway C, Rijnders E, 1999. A study of the horizontal and vertical profile of submicrometer particles in relation to a busy road. Atmospheric Environment 33: 1261-1274.

Nikolaou M, Buffington J, Herrera A, Inkeuk H, 1997. Traffic Air Pollution Effects of Elevated, Depressed, and At-Grade Level Freeways in Texas. Final report FHWA/TX-97/1327-4. Texas Transportation Institute, The Texas A&M University System. Found at http://pubs.chee.uh.edu/faculty/nikolaou/TTIFinalReport.pdf.

Ning Z, Geller MD, Moore KF, Sheesley R, Schauer J, Sioutas C, 2007. Daily variation in chemical characteristics of urban ultrafine aerosols and inference of their sources. Environmental Science and Technology 41: 6000-6006.

Ning Z, Hudda N, Dasher N, Kam W, Herner J, Kozawa K, Mara S, Sioutas C, 2010. Impact of roadside noise barriers on particle size distributions and pollutant concentrations near freeways. Atmospheric Environment 44: 3118-3127.

Noh K-C and Hwang J, 2010. The Effect of Ventilation Rate and Filter Performance on Indoor Particle Concentration and Fan Power Consumption in a Residential Housing Unit. Indoor and Built Environment 19 (4): 444-452.

Nowak DJ, Crane DE, Stevens JC, 2006. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry & Urban Greening 4 (3-4): 115-123.

Ntziachristos L, Ning Z, Geller MD, Sioutas C, 2007. Particle concentration and characteristics near a major freeway with heavy-duty diesel traffic. Environmental Science and Technology 41: 2223-2230.

Offermann F, 2009. Ventilation and Indoor Air Quality in New Homes. Collaborative Report. CEC-500-2009-085. California Air Resources Board and California Energy Commission, PIER Energy-Related Environmental Research Program. Found at http://www.arb.ca.gov/research/apr/past/04-310.pdf

Pardyjak ER, Speckart SO, Yin F, Veranth JM, 2008. Near source deposition of vehicle generated fugitive dust on vegetation and buildings: Model development and theory. Atmospheric Environment 42 (26): 6442-6452.

Parker JL, Larson RR, Eskelson E, Wood EM, Veranth JM, 2008. Particle size distribution and composition in a mechanically ventilated school building during air pollution episodes. Indoor Air 18 (5): 386-393.

Partti-Pellinen K, Marttila O, Ahonen A, Suominen, O. and Haahtela T, 2000. Penetration of Nitrogen Oxides and Particles from Outdoor into Indoor Air and Removal of the Pollutants through Filtration of Incoming Air. Indoor Air 10: 126–132. http://onlinelibrary.wiley.com/doi/10.1034/j.1600-0668.2000.010002126.x/pdf

Phillips TJ, Mulberg EJ, Jenkins PL, 1990. Activity Patterns of California Adults and Adolescents: Appliance Use, Ventilation Practices, and Building Occupancy. Proceedings of the ACEEE 1990 Summer Study on Energy Efficiency in Buildings, Vol. 4.

PRC 21151.8. California Public Resources Code, Division 13, chapter 4, Section 21151.8. See also Education Code Section 17213.

Reich J, 2007. Factors Affecting the Feasibility of Urban Infill Development Over Freeways. Another shade of green: Implementing complex multidisciplinary work. Architecture Department, California Polytechnic State University San Luis Obispo. Found at http://www.arch.calpoly.edu/research/documents/research-0607/Reich_2.pdf.

SCAQMD, 2009. Pilot Study of High Performance Air Filtration for Classrooms Applications. Final Report to the South Coast Air Quality Management District. South Coast Air Quality Management District and IQAir North America. Found at http://www.aqmd.gov/rfp/attachments/2010/AQMDPilotStudyFinalReport.pdf.

Schweitzer L and Zhou J, 2010. Neighborhood air quality, respiratory health, and vulnerable populations in compact and sprawled regions. Journal of the American Planning Association 76 (3): 363-371.

Seppänen OA and Fisk WJ, 2002. Association of ventilation system type with SBS symptoms in office workers. Indoor Air 12 (2): 98-112.

Shaughnessy RJ, Levetin E, Blocker J, Sublette KL, 1994. Effectiveness of Portable Indoor Air Cleaners: Sensory Testing Results. Indoor Air 4 (3): 179-188.

Shaughnessy RJ and Sextro RG, 2006. What is an effective portable air cleaning device? A review. Journal of Occupational and Environmental Hygiene 3 (4): 169-181.

Singer BC, Hodgson AT, Hotchi T, Kim JJ, 2004. Passive measurement of nitrogen oxides to assess traffic-related pollutant exposure for the East Bay Children's Respiratory Health Study. Atmospheric Environment 38: 393-403.

Skulberg KR, Skyberg K, Kruse K, Eduard W, Levy F, Kongerud J, Djupesland P, 2005. The effects of intervention with local electrostatic air cleaners on airborne dust and the health of office employees. Indoor Air 15 (3): 152-159.

Smith WH, 1990. Air pollution and forests. New York: Springer-Verlag.

Smith J, 2012. Information Officer, Bay Area Air Quality Management District. Personal communication.

Steffens JT, Wang YJ, Zhang KM, 2012. Exploration of effects of a vegetation barrier on particle size distributions in a near-road environment. Atmospheric Environment 50: 120-128.

Thatcher TL, 2010. Personal Communication. November 8, 2010.

Thatcher TL, McKone TE, Fisk WJ, Sohn MD, Delp WW, Riley WJ, Sextro RG, 2001. Factors affecting the concentration of outdoor particles indoors (COPI): Identification of data needs and existing data. LBNL-49321. Lawrence Berkeley National Laboratory. Found at http://emc.ornl.gov/CSEPPweb/data/Reports/Berkely%20Reports/LBNL-49321copi.pdf.

U. S. EPA, 2007. Final Rule on the Control of Emissions of Air Pollution from 2007 and Later Model Year Heavy-Duty Highway Engines and Vehicles; Revision of Light-Duty On-Board

Diagnostics Requirements (66 FR 5002, January 18, 2001). Referred to as the “U.S. EPA’s 2007 Final Rule” or “2007 Final Rule.” See http://www.epa.gov/otaq/diesel.htm#hd2007.

Venn AJ, Lewis SA, Cooper M, Hubbard R, Britton J, 2001. Living near a main road and the risk of wheezing illness in children. American Journal of Respiratory and Critical Care Medicine 164 (12): 2177-2180.

Wallace LA, 1996. Indoor particles: a review. Journal of the Air & Waste Management Association 46 (2): 98-126.

Wallace LA, 2005. Ultrafine particles from a vented gas clothes dryer. Atmospheric Environment 39 (32): 5777-5786.

Wallace LA, Emmerich SJ, Howard-Reed C, 2004. Effect of central fans and in-duct filters on deposition rates of ultrafine and fine particles in an occupied townhouse. Atmospheric Environment 38 (3): 405-413.

Wallace LA, Wang F, Howard-Reed C, Persily A, 2008. Contribution of gas and electric stoves to residential ultrafine particle concentrations between 2 and 64 nm: size distributions and emission and coagulation remission and coagulation rates. Environmental Science & Technology 42 (23): 8641-8647.

Ward M, Siegel JA, Corsi RL, 2005. The effectiveness of standalone air cleaners for shelter-in-place. Indoor Air 15 (2): 127-134.

Wargocki P, Wyon DP, Fanger PO, 2004. The performance and subjective responses of call-center operators with new and used supply air filters at two outdoor air supply rates. Indoor Air 14 Suppl 8: 7-16.

Westerdahl D, Fruin SA, Sax T, Fine PM, Sioutas C, 2005. Mobile platform measurements of ultrafine particles and associated pollutant concentrations on freeways and residential streets in Los Angeles. Atmospheric Environment 39: 3597-3610.

Wilhelm M and Ritz B, 2003. Residential proximity to traffic and adverse birth outcomes in Los Angeles County, California, 1994-1996. Environmental Health Perspectives 111 (2): 207-216.

Wilhelm M, Ghosh JK, Su J, Cockburn M, Jerrett M, Ritz B, 2011. Traffic-related air toxics and preterm birth: a population-based case-control study in Los Angeles County, California. Environmental Health 10 (1): 89.

Williams LA, Ulrich CM, Larson T, Wener MH, Wood B, Campbell PT, Potter JD, McTiernan A, De Roos AJ, 2009. Proximity to traffic, inflammation, and immune function among women in the Seattle, Washington, area. Environmental Health Perspectives 117 (3): 373-8.

Zhou Y and Levy JI, 2007. Factors influencing the spatial extent of mobile source air pollution impacts: a meta-analysis. BioMed Central Public Health 7: 89, doi: 10.1186/1471-2458-7-89.

Zhu Y, Hinds WC, Kim S, Shen S, Sioutas C, 2002a. Concentration and size distribution of ultrafine particles near a major highway. Journal of the Air and Waste Management Association 52: 1032-1043.

Zhu Y, Hinds WC, Kim S, Shen S, Sioutas C, 2002b. Study of ultrafine particles near a major highway with heavy-duty diesel traffic. Atmospheric Environment 36: 4323-4335.
Zhu Y, Hinds WC, Kim S, Shen S, Sioutas C, 2004. Seasonal trends of concentration and size distribution of ultrafine particles near major highways in Los Angeles. Journal of Aerosol Science and Technology 38 (S1): 5-13.

Zhu Y, Kuhn T, Mayo T, Hinds WC, 2006. Comparison of daytime and nighttime concentration profiles and size distributions of ultrafine particles near a major highway. Environmental Science and Technology 40: 2531-2536.

ADDENDUM

Current California Building Code Requirements

Section 150(o) of Title 24 of the California Code of Regulations (CCR 2008) requires mechanical ventilation in all new residential construction in California built after January 1, 2010. Section 150(o) allows the requirement to be met through a variety of system types (CEC 2010). "Exhaust only" type systems increase the entry of unfiltered outdoor air through leakage points in the building shell and can result in negative pressure indoors, thus increasing the possibility of backdrafting of combustion emissions from gas water heaters, fireplaces and other combustion appliances. These are the most widely used systems in California. "Supply systems" typically use a small motor to bring outdoor air in through a ducted supply and can include high efficiency filters to filter the air as it is brought in, prior to circulation of the air throughout the home. Combination (supply and exhaust) systems are available, with some linked to the central heating and air system; these include filtration of incoming outdoor air. However, the Code requires only a MERV 6 air filter (an increase to MERV 8 is proposed in the 2012 revisions to Title 24), which does not remove the smaller particles emitted by vehicles which are the particles of greatest concern. In future construction, the type of mechanical system used in new homes will have a major impact on the entry of outdoor pollutants indoors − if filtration is not included or is weak, indoor exposures to outdoor pollutants likely will increase.

Table 1. MERV Ratings*

MERV Rating	**Average Particle Size Efficiency (PSE), microns – % Removal**			**Typical Controlled Contaminant or Material Sources (ASHRAE 52.2)**	**Typical Building Applications**
	0.3-1.0	**1.0-3.0**	**3.0-10.0**		
1-4			<20%	**> 10 Microns** Textile Fibers Dust Mites, Dust, Pollen	Window AC units Common Residential Minimal Filtration
5			20-35	**3.0 to 10.0 Microns** Cement Dust, Mold Spores, Dusting Aids	Industrial Workplace Better Residential Commercial
8			>70		
9		<50	>85	**1.0 to 3.0 Microns** Legionella, Some Auto Emissions, Humidifier Dust	Hospital Laboratories Better Commercial Superior Residential
12		>80	>90		
13	<75	>90	>90	**0.3 to 1.0 Microns** Bacteria, Droplet Nuclei (sneeze), Most Tobacco Smoke, Insecticide Dust	Superior Commercial Smoking Lounge Hospital Care General Surgery
16	>95	>95	>95		
17**	≥ 99.97			**<0.3 Microns (HEPA/ULPA filters)**** Viruses, Carbon Dust, Fine Combustion Smoke	Clean Rooms Carcinogenic & Radioactive Matls., Orthopedic Surgery
18**	≥ 99.99				
19, 20**	≥ 99.999				

* 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.