



Chapter 9
**Near Roadway Exposure and
Ultrafine Particles**

South Coast Air Quality Management District

Cleaning the air that we breathe...



CHAPTER 9

NEAR ROADWAY EXPOSURE AND ULTRAFINE PARTICLES

Introduction

Ultrafine Particles

Other Near-Roadway Pollutants

Ambient Measurements

Health Effects

Future Research and Assessment Needs

Planning and Regulatory Issues

District Future Actions

INTRODUCTION

There is growing concern about the potential health effects as caused by exposure for people living near major roadways to criteria pollutants and air toxics emitted from both gasoline and diesel vehicles (HEI, 2010). Recent toxicological and epidemiological studies have identified living near major roadways as a risk factor for respiratory and cardiovascular problems and other health related issues including: asthma and allergic diseases, reduced lung function and growth, low birth weight and pre-term newborns, lung cancer and premature death (Brugge et al., 2007; Kan et al., 2008; Balmes et al., 2009; Jerrett et al., 2009; Andersen et al., 2010; Hoek et al., 2010).

Motor-vehicle emissions consist of a complex mixture of particulate and gaseous pollutants such as fine particulate matter (PM_{2.5}; particles with a diameter less than 2.5 µm), ultrafine particles (UFPs; diameter < 0.1 µm), metals, organic material, black carbon (BC), volatile organic compounds (VOC), nitrogen oxides (NO_x; mostly NO and NO₂) and carbon monoxide (CO). While PM_{2.5} and NO₂ are currently regulated as criteria pollutants, UFPs have been shown to be toxic and have health impacts, but are not specifically regulated.

In 1998, the California Air Resources Board (CARB) classified diesel exhaust PM as a toxic air contaminant, citing its potential to cause cancer and other health problems. The U.S. EPA concluded that long-term exposure to diesel engine exhaust is likely to pose a lung cancer hazard to humans and can also contribute to other acute and chronic health effects.¹ The International Agency for Research on Cancer (IARC), part of the World Health Organization, recently classified diesel exhaust as a human carcinogen (Benbrahim-Tallaa et al., 2012). A recent study conducted by the District suggested that exposure to diesel PM is the major contributor to the remaining air toxics cancer risk in the South Coast Air Basin (Basin), accounting on average for about 84% of the carcinogenic risk attributable to air pollutants (MATES III; AQMD, 2008).²

While substantial effort has been made to characterize the health risks associated with exposure to diesel PM, information about the health impacts of UFPs is just now emerging. These very minute particles (consisting primarily of organic material, soot,

¹ <http://www.epa.gov/ttn/atw/dieselfinal.pdf>

² <http://www.aqmd.gov/prdas/matesIII/matesIII.html>

and trace elements) have a different chemical composition than the larger PM fractions (PM_{2.5} and PM₁₀). Due to their small size, UFPs can penetrate deeply into the human respiratory tract, into the blood stream, and be transported to other critical organs such as the heart and brain. Furthermore, their large surface area may provide a mechanism for delivering potentially toxic adsorbed material into the lung and other organs. This penetration capability is suspected to have human health implications because UFPs' toxic components may initiate or facilitate biological processes that may lead to adverse effects to the heart, lung, and other organs (HEI, 2010).

UFPs are emitted from almost every fuel combustion process, including diesel, gasoline, and jet engines, as well as external combustion processes such as wood burning. Consequently, there is growing concern that people living in close proximity to highly trafficked roadways and other sources of combustion-related pollutants (e.g. airports and rail yards) may be exposed to significant levels of UFPs and other air toxics.

Over the last decade, substantial efforts have been made to better characterize the physical and chemical properties of UFPs and their potential impact on people living in close proximity to roadways and other emissions sources. Two areas of research have received particular attention:

- On-roadways, near-roadways, and in-vehicle measurements: UFP emissions from motor vehicles are not static after leaving the tailpipe and undergo physical transformation and chemical reactions in the atmosphere as they are transported away from the source. In order to study the dynamic nature of UFP formation, evolution and transport, as well as their physical and chemical properties, and human exposure, UFP measurements have been taken at the tailpipe, at different distances from the edge of roadways, and inside vehicles.
- Effect of UFP reduction technologies: As modern engines and emissions controls continue to evolve, the mass of combustion-related PM has been dramatically reduced through sophisticated control of combustion conditions, introduction of ultra low sulfur diesel fuel, and the application of after-treatment control technologies such as diesel particulate filters (DPFs). In some cases, emission controls designed for PM mass have facilitated the formation of a greater number of UFPs. However, properly designed emission control technologies can limit the formation and emission of UFP as well as PM mass.

From a regulatory perspective, the U.S. focus has been on reducing the mass of PM emitted in the ambient air. However, UFPs contribute a very small portion of the overall atmospheric particle mass concentration. Thus, there has been growing interest over the last two decades to study, understand, and regulate the size and number of particles found in PM generated from diesel and other combustion engines. Partly because light-duty diesel vehicles are very common in European countries, the European Union has already adopted standards that phase in particle number limits for passenger car and light-duty vehicle emissions. However, there are still concerns related to the health impacts of non-solid organic UFP components that are not addressed by the European solid particle number standard.

Recently, CARB staff prepared a preliminary discussion paper on proposed amendments to California's Low-Emission Vehicle (LEV III) Regulations, to address UFP emissions from light-duty motor vehicles by promoting a solid particle number based PM compliance strategy (CARB, 2010)³. CARB staff ultimately decided that the complexity of the issues warranted further study and understanding before proceeding. Although the District has limited authority to regulate mobile source pollution in the near-roadway environment, District staff has implemented a variety of measures to assess and reduce the health impacts of near-roadway emissions on local communities. The District continues to demonstrate and incentivize the deployment of zero/near-zero emission technology, has implemented numerous installations of high-efficiency air filtration in schools, and conducts outreach and education on near-roadway health impacts. Furthermore, on July 1, 2012 the District began the next Multiple Air Toxics Exposure Study (MATES IV) to characterize the carcinogenic risk from exposure to air toxics in the Basin. A new focus of MATES IV will be the inclusion of measurements of UFP and BC concentrations across the Basin, and near specific combustion sources (e.g. airports, freeways, rail yards, busy intersections, and warehouse operations) to evaluate the long- and short-term exposures to these pollutants.

This chapter of the AQMP first presents background information on UFPs and other important air pollutants emitted from motor vehicles. Next, recent results from ambient measurement studies conducted near traffic sources, on roadways, and inside vehicles are reviewed, followed by an explanation of the current state of knowledge on the health effects caused by UFPs and near-roadway exposure to pollutants.

³ http://www.arb.ca.gov/msprog/levprog/leviii/meetings/051810/pm_disc_paper-v6.pdf

Finally, potential control, mitigation, and policy strategies for limiting such exposures are discussed with recommendations for future actions to address this emerging and important topic.

ULTRAFINE PARTICLES

Formation and Transport

UFPs are emitted from both natural and anthropogenic sources, although in most urban environments vehicular fossil fuel combustion constitutes the major contributing source. The terms UFPs and nanoparticles (NP; diameter $< 0.05 \mu\text{m}$) are often used interchangeably, and the definitions of each generally vary with the study or application. While PM_{2.5} dominates the mass distribution of atmospheric particles, UFPs account for about 90% of the total particle number (Stanier et al., 2004a and Zhang et al., 2004). For this reason, their concentration is usually expressed in terms of total particle count (i.e. # per cubic centimeter of sampled air, or $\#/ \text{cm}^3$), even though a small fraction of the particles being counted may be above 100 nm.

In the late 1990s, pioneering research by the University of Minnesota (Kittelson, 1998) made significant new progress by identifying three size categories for particles found in diesel engine emissions: 1) coarse mode ($1 \mu\text{m} < d < 10 \mu\text{m}$), 2) accumulation mode ($\sim 0.05 \mu\text{m} < d < 1 \mu\text{m}$), and 3) nuclei mode ($d < 0.05 \mu\text{m}$). As shown in Figure 9-1, UFPs ($d < 0.1 \mu\text{m}$) and NPs in particular dominate the total number concentration (blue line).

Today we know that, typically, three UFP size modes appear in the exhaust of motor vehicles:

- Narrow nucleation mode at around 10 nm that corresponds to nucleated particles that have grown by condensation of gaseous precursors. It is mostly comprised of sulfate particles and semi-volatile organic compounds (SVOCs).
- Larger nucleation mode at around 20 to 30 nm which also contains sulfate particles and SVOCs.
- Accumulation mode at around 60 nm that results from the combustion process and that mostly includes soot and non-volatile organic compounds, but also sulfate and SVOCs. This mode is primarily associated with diesel exhaust.

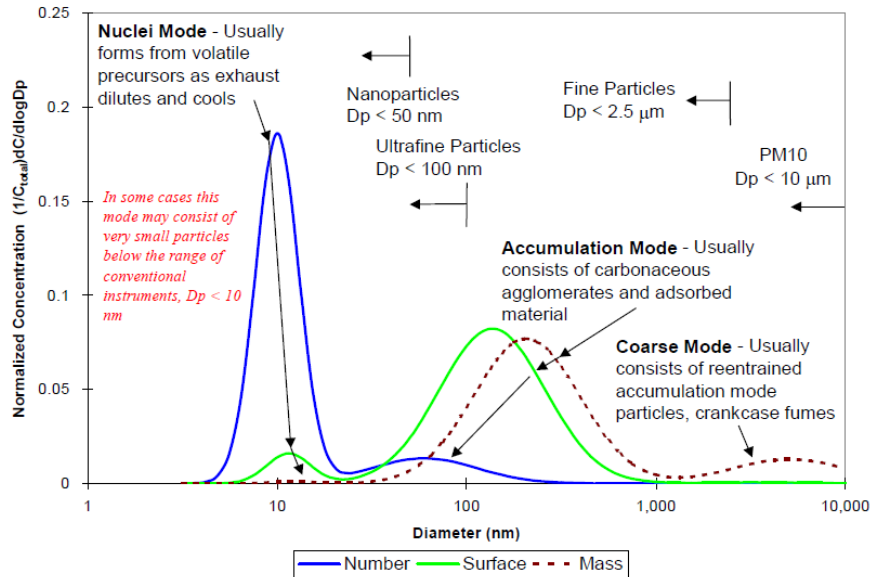


FIGURE 9-1

Typical Particle Size Distribution for Uncontrolled Diesel Emissions (Kittelson, 1998)

Particles from motor vehicle emissions can be divided into two broad categories, depending on the location of their formation:

- **Primary combustion particles:** formed in the engine or tailpipe, they are mostly sub-micrometer agglomerates of solid phase carbonaceous material ranging in size from 30 to 500 nm. These particles may also contain metallic ash (from lubricating oil additives and from engine wear), adsorbed or condensed hydrocarbons, and sulfur compounds (Morawska et al., 2008).
- **Near-tailpipe UFPs:** as the hot exhaust gases are expelled from the tailpipe, they quickly cool and condense on existing particles or nucleate to form large numbers of very small particles in the air. They consist mainly of hydrocarbons and hydrated sulfuric acid, are generally 30 nm or less in diameter and are most commonly observed near busy freeways, especially those where a large fraction of heavy-duty diesel vehicles is present (Westerdahl et al., 2005; Ntziachristos et al., 2007; eskinen and Ronkko, 2010). These particles are formed very quickly and are distinct from UFPs derived from photochemical nucleation processes occurring in the atmosphere further away from the source (Stanier et al., 2004b).

Once released into the atmosphere, UFPs undergo dilution with ambient air and are subject to chemical reactions and physical processes such as evaporation, condensation, and coagulation. Thus, particles measured away from roadways and other emission sources generally have different characteristics than those measured immediately after formation. Wind speed and direction, precipitation, relative humidity, and temperature are the main meteorological factors affecting UFP transport.

Ambient Diurnal and Seasonal Variations

In ambient urban environments, strong diurnal variations in UFP concentration have been reported in many studies and shown to closely follow the temporal variation in traffic density, with the highest levels observed on weekdays during rush hours (Hussein et al., 2004; Morawska et al., 2008; AQMD, 2012)⁴. Typically, weekdays are characterized by two peaks in UFPs, one early in the morning and another in the afternoon coinciding with traffic rush hours. A wider mid-day peak is usually observed on weekends. Photochemical particle formation also contributes to increasing the afternoon number concentration of UFPs, especially in the summer.

Several meteorological factors contribute to the seasonal variability in the concentration of atmospheric PM and UFPs; these include:

- Lower mixing layer height and greater atmospheric stability in winter, which tend to increase particle levels by not allowing for vertical mixing in the atmosphere.
- Lower winter temperature, which leads to increased nucleation of volatile combustion products, particularly during morning rush hours.
- Higher photochemical activity in the summer, which favors photochemical particle formation.

It should be noted that the effects of these meteorological factors on particle concentration are more pronounced in areas where there are significant meteorological differences between seasons. Pirjola et al. (2006) and Virtanen et al. (2006) showed that the average UFP concentrations in winter in Finland were 2–3 times higher than in the summer, with the highest values observed in February. The highest and lowest monthly average UFP concentrations in Pittsburgh (U.S.A.) reported by Zhang et al. (2004) were measured in December and July, respectively.

⁴ http://www.aqmd.gov/tao/AQ-Reports/I710Fwy_Study.pdf

In the wintertime most of the factors leading to an increase in particle concentration tend to occur early in the morning (i.e. rush hour traffic, low mixing height, low wind speed and temperature). Summer minima are usually associated with increased ambient temperature (which does not favor the nucleation process), although increased photochemical activity can lead to new UFP formation.

Concentration Levels in Different Environments

Morawska et al. (2008) compared particle concentration levels reported for different environments including: road tunnel, on-road, road-side, street canyon, urban, urban background, rural, and clean background (Figure 9-2). The mean and median values for each category were calculated using available literature data and are shown below to illustrate the typical atmospheric variability in UFP number concentration measurements.

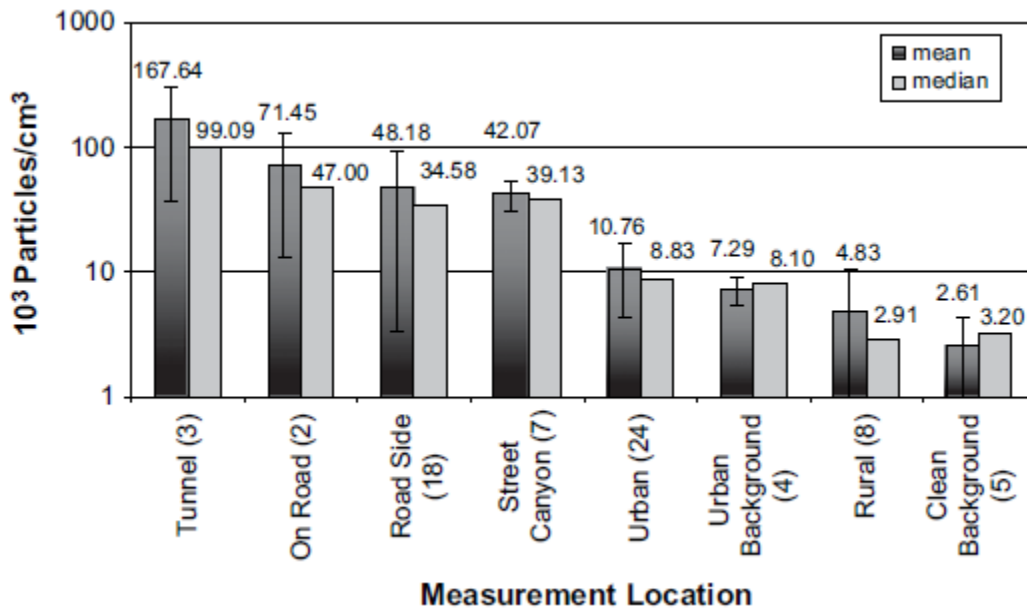


FIGURE 9-2

Mean and Median Particle Number Concentrations for Different Environments

In brackets are the numbers of sites for each environment used to calculate the mean and median UFP values. Vertical lines represent standard deviations (from Morawska et al., 2008)

Substantially higher peak particle number levels are expected in each environment over shorter time periods (e.g. seconds to minutes), and in close proximity to specific sources such as roadways and airports. For example, in a recent study conducted by the District near the Santa Monica Airport (SMO; a general aviation airport), 1-min average UFP levels as high as 2,600,000 #/cm³ were measured 35 m downwind of the runway during jet aircraft take-off (AQMD, 2011)⁵. One-minute maxima between 1,500,000 and 2,000,000 #/cm³ (also associated with jet aircraft departures) were observed 100 m downwind of the runway in the backyard of a local residence.

Chemical Composition

Comprehensive knowledge of the chemical composition of UFPs in ambient air is still not available, mostly because of the small amount of mass available for analysis, and because most studies have been conducted using different measurement protocols, sampled particles in different size ranges, and focused on different aspects of their chemical composition (Morawska et al., 2008). However, it is known that engine emissions include sulfur dioxide (SO₂) or sulfur trioxide (SO₃) and NO_x, and that nucleation of these gaseous species into sulfate and nitrate particles is an important mechanism for increasing particle formation near traffic sites.

A few studies have investigated the composition of UFPs in urban environments. Kuhn et al. (2005) showed that UFP samples collected in downtown Pittsburgh were mostly comprised of organic matter (45 to 55% by weight) and salts of ammonium and sulfate (35 to 40%). In a study conducted at two Los Angeles sites (urban and inland), Sardar et al. (2005) found that organic carbon (OC; the amount of carbon present in the collected organic material) ranged from 32 to 69% (by weight), elemental carbon (EC; an indicator of diesel PM and closely related to BC) from 1 to 34%, sulfate from 0 to 24% and nitrate from 0 to 4%. In these and other cases, organic material was found to comprise the larger fraction of UFP by mass especially in the summer, when photochemical formation of organic aerosol is higher. UFP chemistry, including elemental composition, was investigated by Pakkanen et al. (2001) at two sites (urban and rural) in Helsinki (Finland). The most important trace elements at both sites were Ca, Na, Fe, K and Zn (present in higher concentrations), and Ni, V, Cu, and Pb (“heavy metals”). These measured species accounted for less than 1% of the total UFP mass and their presence was probably related to local combustion sources, possibly traffic exhaust, and combustion of heavy fuel oil. Overall, the

⁵ http://www.aqmd.gov/tao/AQ-Reports/Supplement_GA_Report.pdf

chemical composition of UFPs differs significantly from place to place and depends on the types of local sources and their relative contributions.

Measurement Methods

A basic knowledge of the instruments used for monitoring UFPs is critical as the resulting measurements are dependent on the method and measurement principle used. Since there is no “standard” measurement technique or calibration standard by which different instruments can be evaluated and compared, UFP measurements are somewhat operationally defined. Below is a list of the most common instruments that have been used to monitor the mass and number concentration and size distribution of UFPs in the atmosphere and in exhaust streams. For a more comprehensive discussion on the issues associated with measuring UFPs see Maricq and Maldonado (2010) and Robinson et al. (2010).

- Condensation Particle Counter (CPC): it provides the total number concentration of particles above a lower size limit (~3 -20 nm, depending on make and model) in real-time. UFPs are grown through condensation in a controlled super-saturation environment to larger sizes and then measured (counted) using a photodetector. Alcohol or water are usually used as condensing liquids. Although CPCs are the most widely used instruments in most applications, they do not provide any information on the original size of the particles counted.
- Scanning Mobility Particle Sizer (SMPS): particle counters can also be used in conjunction with electrostatic classifiers (used to separate airborne particles according to their size) to characterize the particle size distribution of UFPs. Typically, SMPSs provide size distribution data in almost real-time for particles as small as 10 nm.
- Electrical Low-Pressure Impactors (ELPI): this instrument provides real-time number weighted size distributions in the particle diameter range of 30 to 10,000 nm. ELPIs are very sensitive instruments and measure ambient aerosol concentrations and size distributions. They can be used to measure particle charge distribution in real-time, and also allow for particle collection and direct mass measurements.
- Engine Exhaust Particle Sizer (EEPS): it measures particle size distributions in real time and covers a range from ~3 to 500 nm. It was designed specifically to measure particles emitted from internal combustion engines and motor vehicles,

but newer versions are designed for ambient applications. Its fast response (e.g. ~10 Hz data collection) allows for the measurement of transient signals, but also tracks well with the CPC concentrations and SMPS size distributions.

- Micro Orifice Uniform Deposition Impactor (MOUDI): it provides integrated mass-based size distribution measurements covering particle sizes from ~56 to 10000 nm. Nano MOUDIs are used for smaller particle size ranges (i.e. ~ 10 to 56 nm). Particle samples collected using a MOUDI can also be analyzed for chemical composition in the lab.

Most of the instruments outlined above have been used in engine/vehicle emission testing. Ambient air monitoring of UFPs is also performed using some of the same instrumentation, especially CPCs and SMPSs. It should be noted that different make/model CPCs are characterized by different particle size ranges, sampling flow rates, optical detection techniques, and other instrumental characteristics and, thus, they may provide significantly different results. Therefore, UFP number measurements from different studies should be compared with caution. The District has worked in collaboration with the University of California, Los Angeles (UCLA), CARB, and with various CPC manufacturers to study intra- and inter-model variations in total number concentration measurements taken with several CPC units (Lee et al., submitted).

OTHER NEAR-ROADWAY POLLUTANTS

The majority of air monitoring studies conducted near- and on-roadways in the past decade has focused not only on the measurements of UFPs, but also on the emissions of more traditional and well-studied pollutants. These include:

- Carbon monoxide (CO): ambient concentrations of this pollutant have declined through the adoption of emission control technologies and regulations. However, motor vehicles (especially light-duty, gasoline-powered vehicles) remain the primary source of CO at most locations.
- Oxides of nitrogen (NO_x): although all motor vehicles emit NO_x, the majority of current on-road NO_x emissions occur from diesel vehicles. In terms of primary emissions, the majority of NO_x exhaust is in the form of NO. NO₂ is the focus of concern in terms of health effects and quickly forms by a photochemical reaction from the oxidation of NO. Primary NO_x emissions from heavy-duty diesel engines

with after-treatment devices may contain a greater percentage of NO₂ relative to NO.

- Particulate matter (PM): suspended particles are generally divided in UFP (already discussed), PM_{2.5} and PM₁₀. Significant near-roadway sources of PM mass include direct emissions from motor vehicle combustion (mostly PM_{2.5}), brake and tire wear, and re-suspension of dust from the road surface (mostly PM₁₀ and larger). The atmospheric concentration of PM_{2.5} is mostly affected by contributions from regional sources, and the impact of direct emissions from motor vehicles is generally small in near-roadway environments.
- Volatile organic compounds (VOCs) and carbonyls: these gaseous air toxics are emitted from both natural and anthropogenic sources (including motor vehicles), are involved in the photochemical formation of atmospheric O₃, and some of them have been associated with both short- and long-term toxic health effects. Typical VOCs of concern for near-road monitoring include benzene, toluene, ethylbenzene, xylenes, styrene, formaldehyde, acetaldehyde, and acrolein, all of which are also toxic air contaminants.
- Black (or elemental) carbon (BC or EC): often referred to as “soot,” BC (or EC) is a common constituent emitted from motor vehicles. Both BC and EC are operationally defined and represent the black, graphitic-containing portion of PM. Although BC and EC are often associated with emissions from heavy-duty diesel engines, a portion of all motor vehicle combustion emissions contains these constituents. A recent study conducted by Liggió et al. (2012) has shown that BC emissions from light-duty-gasoline-vehicles may be at least a factor of 2 to 9 times higher than previously thought. Other sources of BC exist in urban areas, but emissions from motor vehicles, primarily diesel trucks, usually dominate these sources in near-roadway environments.

Most near-road studies showed good correlation among the pollutants listed above (with the exception of PM_{2.5}, whose atmospheric concentration is mostly influenced by regional sources), indicating a common traffic origin (Zhu et al., 2002a,b; Sardar et al., 2005; Hagler et al., 2010). In particular, BC is often very well correlated with UFP concentrations in urban air, given that both are emitted from motor vehicles and the larger relative BC content found in the ultrafine particle size range.

AMBIENT MEASUREMENTS

Near-Roadway Studies

The majority of all near-roadway studies conducted to date have focused on the influence of proximity to roadways on outdoor (residential) and indoor exposure to air pollutants. In virtually all of these works, it was found that the outdoor concentrations of primary pollutants emitted from motor-vehicle emissions (UFP and BC in particular) were more strongly correlated with distance from roadways than the outdoor concentrations of species dominated by atmospheric formation or other regional sources (e.g. PM_{2.5}). Measured concentrations of these primary pollutants were typically highest in close proximity to a roadway and decreased exponentially with increasing distance from (and downwind of) the source. In a study conducted in the Los Angeles area in the daytime, Zhu et al. (2002a) found that the concentrations of CO, BC, and UFPs were highest in the immediate vicinity (17 m) of the I-710 (a freeway highly influenced by heavy-duty diesel trucks), and decreased exponentially to upwind background levels after about 300 m (Figure 9-3a). A companion study was carried out next to the I-405 freeway (dominated by gasoline vehicle traffic) with similar results (Zhu et al. 2002b) (Figure 9-3b).⁶ As discussed earlier, the dynamic pollutant mix evolves during transport from the road: nucleation leads to formation of new particles very soon after emission, followed by their growth by condensation, diffusion to surfaces, evaporation and coagulation. Therefore, at the edge of a roadway, particle concentrations are dominated by the smallest particles (in the 6-10 nm range), with the peak in distribution shifting to the larger sizes at greater distances.

⁶ For each air pollutant, upwind and downwind concentrations were normalized to the highest level measured at the edge of the freeway and expressed as relative values (i.e. 0 to 1)

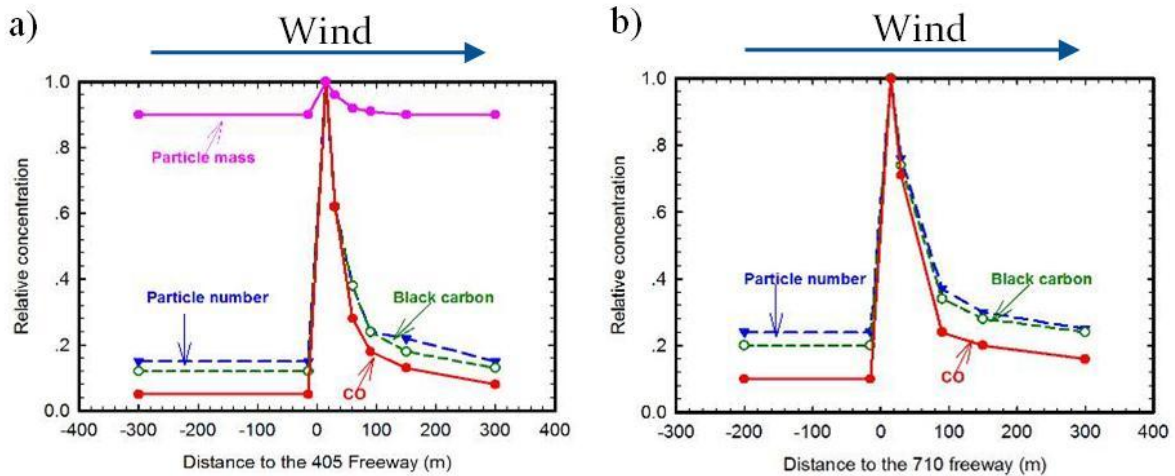


FIGURE 9-3

Relative Black Carbon (BC), Carbon Monoxide (CO), Particle Number (a surrogate for ultrafine particles or UFP), and Particle Mass (PM_{2.5}) Concentrations Upwind and Downwind of the I-405 (a) and I-710 (b) Freeways (from Zhu et al., 2002a; 2002b).

Note that PM_{2.5} was not measured at the I-710.

Measurements conducted in communities adjacent to the Ports of Los Angeles and Long Beach revealed that concentrations of UFP, BC, and NO₂ (mostly from heavy-duty diesel trucks) were frequently elevated two to five times within 150 m downwind of freeways (compared to more than 150 m) and up to two times within 150 m downwind of arterial roads with significant amounts of diesel traffic (Kozawa et al. 2009). In the winter and summer of 2009 the District conducted an intensive study in the vicinity of the I-710 to characterize the spatial and temporal variations of motor vehicle emissions, and their potential impact on the surrounding communities (AQMD, 2012)⁷. Emissions 15 m downwind of the freeway were found to be enriched in BC, UFP, and NO_x, combustion pollutants emitted directly from gasoline and, especially, diesel vehicles. The atmospheric concentration of PM_{2.5} mass and VOCs was not as heavily impacted by proximity to the I-710.

During a recent daytime study conducted in New York City before, during, and after vehicle traffic was excluded from a major street (Park. Ave.), Whitlow et al. (2011) showed that the curbside airborne PM_{2.5} level always peaked in the morning regardless of traffic conditions, while UFP number concentration was 58% lower

⁷ http://www.aqmd.gov/tao/AQ-Reports/I710Fwy_Study.pdf

during mornings without traffic. Furthermore, UFP count varied linearly with traffic flow, while PM_{2.5} spiked sharply in response to random traffic events that were weakly correlated with the traffic signal cycle. As expected, UFP concentrations decayed exponentially with distance from the street with unrestricted traffic flow, reaching background levels within 100 m of the source. It is likely that background concentrations of most motor vehicle related pollutants in large urban areas like New York City are more elevated than those found elsewhere.

Karner et al., (2010) summarized data reported in 41 roadside monitoring studies (all conducted during daytime) and found that almost all combustion-related pollutants decay to background by 115-570 m from the edge of road. Changes in pollutant concentrations with increasing distance from the road fell into one of three groups: 1) at least a 50% decrease in peak/edge-of-road concentration by 150 m, followed by consistent but gradual decay toward background (e.g. CO and UFP); 2) consistent decay or change over the entire distance range (e.g. benzene and NO₂); and 3) little or no trend with distance (e.g. PM_{2.5} mass concentrations).

It should be noted that nighttime conditions can lengthen the distance at which near-road pollutant concentrations decay to background. For instance, Hu et al. (2009) observed a wider area of air pollutant impact downwind of the I-10 freeway during pre-sunrise hours. In particular, UFP concentrations peaked immediately downwind of the I-10 and reached background levels only after a distance of about 2600 m (Figure 9-4).⁸ Other combustion related pollutants, such as NO and particle-bound polycyclic aromatic hydrocarbons (p-PAHs), exhibited similar long-distance downwind concentration gradients. The authors associated these elevated pre-sunrise concentrations over a wide area with a nocturnal surface temperature inversion, low wind speeds, and high relative humidity. It should be noted that, occasionally, nighttime near-road UFP number concentrations exceeded daytime conditions, despite reduced traffic volumes.

Further work is needed to integrate daytime and nighttime findings and to assess their relative importance given daytime and nighttime differences in traffic activity, near-road pollutant concentrations, and factors affecting human exposure.

⁸ Upwind and downwind UFP concentrations were normalized to the highest level measured at the edge of the freeway and expressed as relative values (i.e. 0 to 1)

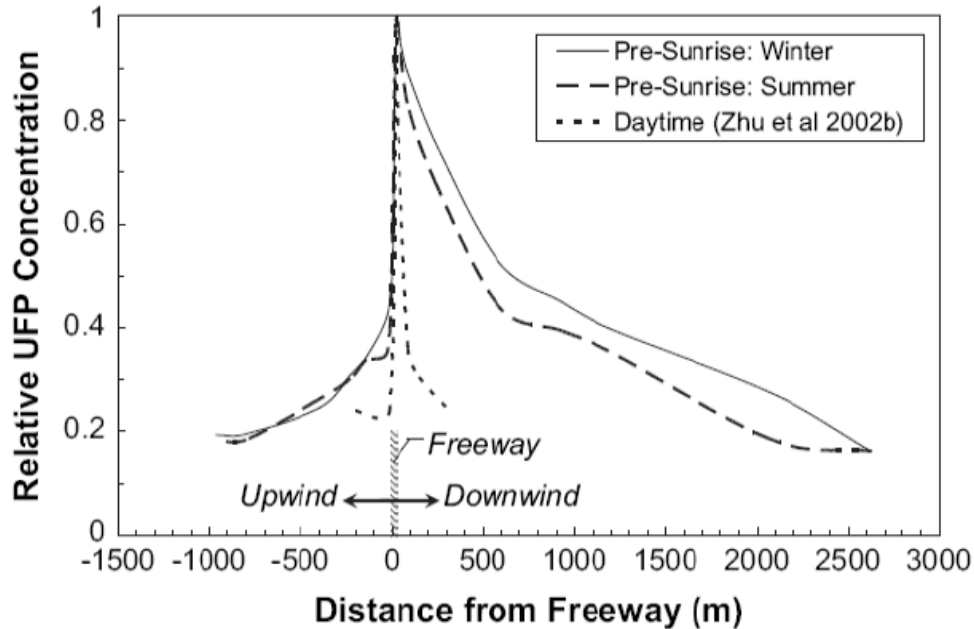


FIGURE 9-4

Relative Averaged UFP Concentrations and Gradients During Pre-sunrise Hours along the I-10 (Hu et al., 2009) and the I-710 Freeways (Zhu et al., 2002b)

In the last few years, new powerful instruments have been developed to characterize the physical and chemical characteristics of freshly emitted aerosols in real time. For example, Sun et al. (2012) used a High-Resolution Time-of-Flight Aerosol Mass Spectrometer to study the mass concentrations and chemical composition of sub-micron aerosol species (PM_{10}) in the vicinity (30 m) of a major highway in New York City. The mass spectrometer data (taken at 1-min time resolution) was complemented by rapid measurements (down to 1 Hz) of particle number concentrations and size distributions. Overall, hydrocarbon-like organic (HOA) species dominated the composition of traffic-related PM_{10} especially during periods of high traffic intensity. Significant enhancements in ultrafine organic aerosol mass and particle number concentrations were frequently observed in traffic plumes, suggesting that UFPs are dominated by HOA species from vehicle emissions near highways.

On-road Studies and In-Vehicle Exposure

Several studies have found that, while commuting, individuals are exposed to air toxic levels that are several times higher than the corresponding ambient concentrations measured at fixed near-roadway monitoring sites. Most of these on-road studies have been conducted using zero-emissions mobile platforms outfitted with real-time

instruments to spatially characterize particle and gaseous pollutant concentrations. Fujita et al. (2003) found that concentrations of BC and NO_x in Harbor communities of Wilmington, West Long Beach, and San Pedro (California) were about ten times higher on roadways than at regional air monitoring sites. Similarly, Westerdahl et al. (2005) showed that concentrations of UFP, NO, BC and CO on Los Angeles freeways were often ten times higher than those on residential streets.

Heavily impacted industrial communities are also characterized by increased on-road air pollutant concentrations. For example, elevated UFP, BC, and NO concentrations were observed across the residential neighborhood of Boyle Heights in Los Angeles (Hu et al. 2012). UFP concentrations were nearly uniform spatially, in contrast to other areas in the greater metropolitan area of Los Angeles where UFP concentrations exhibit strong gradients downwind of roadways. This was attributed to the presence of high heavy-duty traffic volumes on the freeways surrounding Boyle Heights, and substantial numbers of high-emitting vehicles on local surface streets. The high density of stop signs and lights, and short block lengths, requiring frequent acceleration of vehicles, may contribute to elevated UFP levels observed in this area.

Fruin et al. (2008) characterized air pollutant concentrations on Los Angeles freeways and arterial roads. On freeways, concentrations of UFPs, BC, NO_x, and p-PAH were generated primarily by diesel emissions, despite the relatively low fraction (~6%) of diesel-powered vehicles. However, UFP concentrations on arterial roads appeared to be driven mainly by proximity to gasoline-fueled cars undergoing hard accelerations. Concentrations were roughly one-third of those on freeways. They concluded that 33 to 45% of total UFP exposure for Los Angeles residents occurs due to time spent traveling in vehicles. A previous study conducted by the same research group showed that time spent in vehicles contributes between 30 and 55% of Californian's total exposure to diesel PM (Fruin et al., 2004). The applicability of these estimates to other regions of the United States is largely unknown.

Due to the high air exchange rates (AERs) of moving cars/trucks, in-vehicle concentrations are typically close to roadway concentrations. Inside-to-outside UFP concentration ratios are best measured under realistic conditions because AERs and other factors influencing these ratios are determined by vehicle speed and ventilation preference, in addition to vehicle characteristics such as age. Two independent studies conducted in Southern California showed that in-cabin concentration of UFPs can be reduced substantially (i.e. up to ~85%) by turning the recirculation fan on (Zhu et al. 2007; Hudda et al. 2011). Evidence suggests that increased ventilation is also a key

determinant of in-cabin UFP concentrations in buses, ferries, and rail modes (Knibbs et al., 2011). Where a vehicle is fitted with a cabin air filter, its particle removal efficiency is a key determinant of what proportion of on-road UFPs reach the cabin (Burtscher et al., 2008; Pui et al., 2008).

Important Factors Affecting Near-Roadway Measurements

The air quality monitoring studies described above measured elevated concentrations of UFPs and other combustion pollutants near roadways. However, most of these studies were conducted under different environmental conditions. In order to interpret results from these and future near-roadway activities and to better evaluate the risks associated with living in close proximity to highly trafficked freeways, it is important to consider all variables influencing the observed monitoring data. These may include:

- **Traffic activity:** parameters such as the total number of vehicles, the fleet mix (e.g., gasoline vs. diesel), and vehicle speeds affect the concentration of near-road pollutants. This information can usually be obtained from local transportation agencies or on the web.⁹
- **Meteorological parameters:** wind speed and direction, temperature, humidity, and atmospheric stability can be used to better evaluate the generation, transformation and transport of traffic-generated emissions and for interpreting near-road air quality data.
- **Roadway type:** proximity to busy freeways has generally been associated with an increase in atmospheric UFPs. However, most urban areas contain arterial roadways that experience regular increases in UFP levels, especially during morning and afternoon rush hours. Increased number of stop-and-go operations from traffic signals, longer idling times, and cold start conditions all contribute to increased UFP emissions.
- **Roadway design:** road grades create an increased load on vehicles ascending the grade, leading to increased exhaust emissions and potential tire wear, while vehicles descending the grade experience increased brake emissions. The presence of ramps, intersections, and lane merge locations can also lead to increased brake

⁹ For example, see Caltrans' Performance Measurement System (PeMS); <http://pems.dot.ca.gov>

wear emissions and idling vehicle conditions due to increased congestion (Baldouf et al., 2009).

- **Roadside structures:** the presence of roadside features such as noise barriers, trees, and buildings can change the dynamics of air pollutant dispersion downwind of a freeway. Results from two recent studies conducted in Raleigh, NC and in Los Angeles indicate that near-roadway concentrations of combustion particles (e.g. UFP and BC) and related gaseous co-pollutants (e.g. CO and NO₂) were lower where a noise barrier was present than in open terrain (Bowker et al., 2007 and Ning et al., 2010). However, a longer downwind distance was generally needed to reach background levels, indicating a larger impact zone of traffic emission sources. Noise barriers adjacent to a roadway may also inhibit air movements off the road, leading to elevated on-road pollutant concentrations (Bowker et al. 2007; Baldauf et al. 2008). The District has several ongoing research efforts to better evaluate the mitigation potential of various roadside features.

HEALTH EFFECTS

Ultrafine Particles

Short- and long-term exposure to particles produced from combustion processes have been associated with numerous adverse health effects in humans including various cardiovascular and respiratory diseases (Pope and Dockery, 2006). It has been hypothesized that the ultrafine portion of atmospheric PM may be responsible for the majority of the observed health effects (Brugge et al., 2007; Balmes et al., 2009; Jarrett et al., 2009; Hoek et al., 2010; Ljubimova et al., 2012). Thus, recent research studies have specifically focused on UFPs and their ability to be absorbed deeply into the lungs, move across cell membranes, and translocate into the bloodstream and other parts of the body. As noted in the preceding sections, the formation and subsequent evolution of UFPs is complex. They are formed and processed on the order of minutes, but their composition continues to change depending on intricate interactions in the exhaust stream and in ambient air. Thus, exposures will vary depending on location within the exhaust plume and with distance from the emission source.

The mechanisms linking UFP exposure to observed health impacts are still not completely understood, but one of the most plausible hypotheses is that many of the adverse health effects may derive from oxidative stress, initiated by the formation

of reactive oxygen species (ROS) within affected cells. Work conducted at the University of California Los Angeles (UCLA) Southern California Particle Center in the past decade has demonstrated that because of their high OC and polycyclic aromatic hydrocarbon (PAH) content, UFPs have the highest potential to generate ROS and to induce oxidative stress in macrophages and epithelial cells (Li et al., 2003). This, in turn, may promote allergic inflammation in the lungs, the progression of atherosclerosis, and precipitation of acute cardiovascular responses ranging from increased blood pressure to myocardial infarction (Delfino et al., 2005; Araujo et al., 2008). From the analysis of summertime ambient PM samples collected near downtown Los Angeles in the morning and in the afternoon, Verma et al. (2009) showed that both primary (traffic dominated) and photochemically formed quasi-ultrafine particles ($d < 250$ nm) possess high reduction-oxidation activity. However, the latter particle type appeared to be more potent in terms of generating oxidative stress and leading to subsequent damage in cells. The semi-volatile component of quasi-ultrafine urban aerosols (mostly OC and PAHs) seems to be responsible for most of the oxidative potential of PM (Verma et al., 2011).

Recent works have examined the health consequences due to UFP exposure on the most susceptible part of the population such as elderly individuals, children and subjects with asthma and diabetes. For example, between 2005 and 2007 the University of California Irvine (UCI) led a multi-disciplinary project (i.e. Cardiovascular Health and Air Pollution Study or CHAPS) to study the health effects of environmental exposure to different PM fractions (including UFPs) in elderly retirees affected by coronary artery disease (Delfino et al. 2008; 2009). Results suggested that traffic-related emissions of primary OC, PAHs, and UFPs were associated with adverse cardio-respiratory responses including elevated blood pressure (Delfino et al., 2010) and increased risk of myocardial ischemia (Delfino et al., 2011).

Other studies tried to elucidate the link between inhalation of UFPs and cardiovascular responses in children and young adults. In most studies, healthy young subjects were exposed to filtered “particle-free” air or UFPs at rest and during exercise (e.g. Shah, et al. 2008; Zareba, et al. 2009; Samet, et al. 2009). Short-term exposure to UFPs did not cause marked changes to the electrocardiography (ECG) parameters, although acute exposure had mild inflammatory and prothrombotic responses. In a recent experiment conducted by Pope et al. (2011), healthy, non-smoking young adults were exposed a) to known amounts of PM_{2.5} ($150-200 \mu\text{g}/\text{m}^3$) from wood and coal combustion, and b) to uncontrolled ambient air. The researchers

did not find any vascular response following the few hours of PM_{2.5} exposure, but noted declines in vascular response with elevated ambient particle exposures, possibly due to the deleterious contributions from mobile source emissions.

There are no long-term studies of human population exposure to ultrafine particles, as there is a lack of a monitoring network in the U.S. There have been several cross sectional epidemiological studies of ultrafine particles, mainly from Europe. Some of these studies found effects on hospital admissions, emergency department visits, for respiratory and cardiovascular effects. Other studies, however, have not found such effects (U.S. EPA, 2009). Concentrations of ultrafine particles can vary geographically, and it is not clear how well central site monitors may capture actual exposures.

The current U.S. EPA Integrated Science Assessment for Particulate Matter (U.S. EPA, 2009)¹⁰ summarized that evidence is inadequate to determine a causal relationship between short-term exposures of UFPs to mortality or central nervous system effects, but that the evidence is suggestive of short-term exposures causing cardiovascular and respiratory effects. The Assessment also concluded that there is inadequate evidence linking long-term exposure of UFPs to health effects, including respiratory, developmental, cancer, and mortality. Overall, epidemiological studies of atmospheric PM suggest that cardiovascular effects are associated with smaller particles, but there are few reports that make a clear link between UFP exposures and increased mortality.

Recently, Hesterberg et al. (2011) hypothesized that the health effects caused by exposure to controlled diesel exhaust will be much less than those from uncontrolled diesel emissions, mostly because particles generated from nucleation of unfiltered sulfur vapors are believed to be less toxic than UFPs emitted from uncontrolled diesel combustion, which are made primarily of organic compounds (Seigneur, 2008). Additional studies are needed to support this hypothesis. The current ongoing Advanced Collaborative Emissions Study (ACES) will provide more data on the health effects of newer diesel engines meeting the U.S. 2007 standards. Similar testing may be necessary for advanced gasoline and alternative fueled engine exhaust as well as for the newer heavy-duty diesel engines meeting the U.S. 2010 standards.

¹⁰ <http://www.epa.gov/ncea/isa/pm.htm>

Considerably more information and data are needed in order to understand the underlying mechanisms and emission properties that affect human health. In 2011, the Health Effects Institute (HEI) convened an expert panel to conduct a critical evaluation of knowledge regarding the potential for UFP and NP to harm human health. The panel's report will be published as part of the HEI Perspective series. The Advanced Collaborative Emissions Study (ACES), which is jointly managed by HEI and the Coordinating Research Council (CRC) has undertaken a major effort to document improvements in vehicle emissions associated with advanced emissions controls. HEI investigators are analyzing the associated health effects.

Near-Roadway Health Impacts

Recent studies have found a positive association between living near busy roadways and asthma exacerbation, decreased lung function, increased heart disease, and other respiratory and cardiovascular effects (Kan et al., 2008; Andersen et al., 2010; HEI, 2010). Exposure to traffic emissions has also been linked to a faster progression of atherosclerosis in subjects living within 100 m of highways in Los Angeles (Künzli et al., 2010), increased risk of low birth weight and premature delivery (Llop et al., 2010; Wilhelm et al., 2011), and lower immune function and increased risk of Type 2 diabetes in post-menopausal women (Krämer et al., 2010; Williams et al., 2011). These studies do not differentiate exactly which pollutant or pollutants may be responsible.

Children are among the most susceptible segment of the population affected by exposure to traffic related pollutants. Their immune, neurological, and respiratory systems are still under development, they typically spend a substantial amount of time playing outdoors, and they have higher breathing rates per body mass. Neighborhood exposure to traffic-related air pollution has been linked to increased medical visits and hospital admissions for childhood asthma, increased wheezing and bronchitis, and the development of new asthma cases (McConnell et al., 2006; 2010; Chang et al., 2010).

In 2005 the District sent an advisory to all school districts under its jurisdiction to bring attention to findings regarding the potential for adverse health effects resulting from exposures to traffic emissions, and to encourage school districts to consider exposure to vehicle emissions when selecting and evaluating sites for new facilities such as schools, playgrounds, and residences (http://www.aqmd.gov/prdas/aqguide/doc/School_Guidance.pdf). As mentioned early in this document, the concentration of vehicle related pollutants drops off to near-background levels after about 300 m from the edge of the roadway (Zhu et al., 2002a;

2002b). A survey of California schools revealed that approximately 2.3% of public schools were located within 150 meters of high-traffic roads (greater than 50,000 vehicles per day), and an additional 7.2 % were within 150 meters of medium traffic roads (25,000 – 50,000 vehicles per day) (Green et al., 2004).

FUTURE RESEARCH AND ASSESSMENT NEEDS

Chemical Composition

Large differences in UFP chemical composition depend on many factors, including vehicle technology, fuel used and after-treatment devices, but also on atmospheric chemical reactions after being emitted. Since particle composition may be a factor determining particle toxicity, there is a need for developing a better knowledge of UFP chemistry near roadways and in different environments.

Processes Leading to Formation

More work is needed to better characterize the mechanisms that lead to UFP formation right after emission and in the atmosphere. Developing a clearer picture of particle formation dynamics in different environments, including those which are influenced by traffic, would greatly assist control measures to regulate emissions of UFPs.

Standardized Measurement Methods and Procedures

Currently, there is no standard method for conducting size-classified or particle-number measurements. The terms UFP and NP are not clearly defined and often used improperly. In addition, the UFP characteristics measured in ambient and emission testing studies (e.g. volatile vs. solid components; mass vs. number concentration) are highly dependent on the measurement instrument/protocol used and its setting. Therefore, there is a need to develop and utilize standardized measurement methods and procedures to enhance meaningful comparison between results from different studies and to guarantee reproducible results.

Increased Measurements at “Hot Spot” Locations

The range of UFP number concentrations between clean and vehicle-affected environments spans over two orders of magnitude. UFPs and NPs are usually not uniformly dispersed in the atmosphere, but concentrated in areas where large numbers of vehicles are operated. Thus, future ambient UFP measurements should be

conducted in areas where concentrations are likely to be higher (“hot spots”). These may include busy roads and intersections, rail yards, airports, etc.

Emission Inventories

Currently vehicle emission factors for different particle size ranges and for particle numbers are highly uncertain, and there are no emission inventories for UFPs from motor vehicles. Also, long-term UFP concentration data in urban environments is scarce. This knowledge is critical for developing management and control strategies for UFP emissions. New estimations of UFP levels should not be derived solely based on vehicle emission factors (which mostly reflect emissions of primary combustion particles), but have to include predictions for UFP formation near the tailpipe and in the atmosphere.

Air Quality Modeling

Exposure assessment of UFPs will require the development of modeling tools to simulate formation and transport over a wide range of atmospheric conditions and emission scenarios. In particular, there is a need to better understand the atmospheric dispersion and transformation of UFP and UFP precursor emissions within the first few hundred meters of the roadway, a region often characterized by complex flow. This complex flow may also affect how pollutants enter multi-story buildings characteristic of higher density environments. Additional new near-roadway studies and laboratory measurements are also necessary to better validate these models.

Health Effects

New toxicological and epidemiological studies targeting exposure to controlled and uncontrolled emissions from gasoline and diesel vehicles are needed to better characterize the exposure-response relationships to UFPs and to help develop health guidelines and potential regulations. The health effects of inorganic (largely related to oil consumption ash constituents) UFP emissions from vehicles are only now starting to receive significant attention.

Other Types of Sources

UFPs are formed through many types of combustion processes. Motor vehicles powered by internal combustion engines are major sources, but stationary source combustion and other processes also contribute significantly to UFP emissions and formation. More work is needed to better understand the size, composition and health impact of these particles near airports, rail-yards, port areas, natural gas electric generators and other potential “hotspot” locations.

PLANNING AND REGULATORY ISSUES

Jurisdiction over Near-Roadway Exposures

The jurisdictional authority for controlling exposure to mobile source pollutants in the near-roadway environment is generally split between 1) federal and state authority over vehicle tailpipe emissions standards; and 2) local government (e.g. cities, counties) authority over land use planning and zoning decisions. In broad terms, tailpipe emission standards affect the source of mobile source emissions, while land use planning affects the exposure to those pollutants. In particular:

- On-road emission standards: U.S. EPA and CARB set standards for the level of pollutants that are allowed from new on-road engines and the fuels used to power them. Chapter 3 and Appendix III details how the emission standards for on-road vehicles are projected to affect total vehicle emissions in future years. While tighter emission standards in the future are expected to lower overall emissions, the near-roadway environment is still expected to have higher concentrations of mobile source pollutants relative to areas further away, especially for ultrafine particles.
- Local land use planning and zoning: local governments maintain the authority to determine the types of land use that are allowed within their jurisdiction. For example, in city General Plans, each parcel of land within that city is given a land use designation (e.g. residential, industrial, etc.). Land use types that do not fall within the General Plan designation are not allowed, with limited exceptions.¹¹ Because the majority of the area within the District jurisdiction has been built out in the past century, many of the current land use patterns are based on historical land use decisions. These legacy decisions have resulted in a large number of residents living in close proximity to freeways. As an example, approximately 691,000 people in Los Angeles County live within 500 feet of a freeway.¹²

¹¹ For example, school districts generally have the authority to supersede local land use authority when determining where to site new schools.

¹² 2012 Regional Transportation Plan, SCAG. Environmental Justice Appendix, Table 40.

Sustainable Communities Strategies

Pursuant to California Senate Bill 375 (SB 375) passed in 2008, CARB developed regional greenhouse gas reduction targets for passenger vehicle emissions in years 2020 and 2035. As required by SB 375, the Southern California Association of Governments (SCAG) used these regional targets¹³ to develop a Sustainable Communities Strategy (SCS) integrating land use, housing, and transportation planning, all as a part of the adopted 2012 Regional Transportation Plan (RTP).

One of the key features of the RTP/SCS is the encouragement of Transit-Oriented Development (TOD) that promotes higher residential and employment densities in High Quality Transit Areas (HQTA)¹⁴. Among the many benefits of well designed TODs, one of their primary purposes under SB 375 is to reduce the total vehicle miles travelled (VMT) in the region by placing homes and jobs closer to public transportation. However, because much of the original and planned transit network lies in close proximity to existing freeways, many of the HQTA areas overlap with freeway proximate areas. For example, with implementation of the RTP/SCS, approximately 282,000 households in the SCAG region will be located both within a HQTA and within 500 feet of a freeway in the year 2035. Some TODs can therefore present a challenge by potentially reducing regional emissions while increasing the exposure of residents in those project areas to elevated pollutant concentrations found in the near-roadway environment.

Enhanced Environmental Analysis

The California Environmental Quality Act (CEQA) requires that all projects requiring discretionary action by a public agency must evaluate and identify the potential environmental impacts of that project, and implement all feasible methods to reduce, avoid, or eliminate any significant adverse impacts.¹⁵ This analysis is reported in CEQA documents such as Negative Declarations or Environmental Impact Reports. Therefore, CEQA requires that a project proponent analyze how the project itself may impact its surrounding environment. For example, if a project includes a new apartment building located adjacent to a freeway, the project will result in new

¹³ 8% reduction below 2005 levels on a per capita basis by 2020, and 13% reduction by 2035

¹⁴ A HQTA is defined as the ½ mile corridor surrounding a fixed bus route with service intervals no longer than 15 minutes during peak commute hours, or the ½ mile area surrounding a rail transit station, ferry terminal served by bus or rail, or the intersection of two or more major bus routes with service intervals no longer than 15 minutes during peak commute periods. See Public Resources Code 21155(b) and 21064.3 for further details.

¹⁵ Public Resources Code §21000 *et seq.*

emissions from vehicles driven by future residents of the apartment building, and these emissions must be evaluated to determine the impact on air quality and the environment.

In a more rigorous CEQA analysis, the impacts from the surrounding environment on people living in the project itself could also be evaluated (Figure 9-5). Using the same example from above, emissions from all of the vehicles on the adjacent freeway would also be evaluated for their potential impact on the proposed apartment residents.

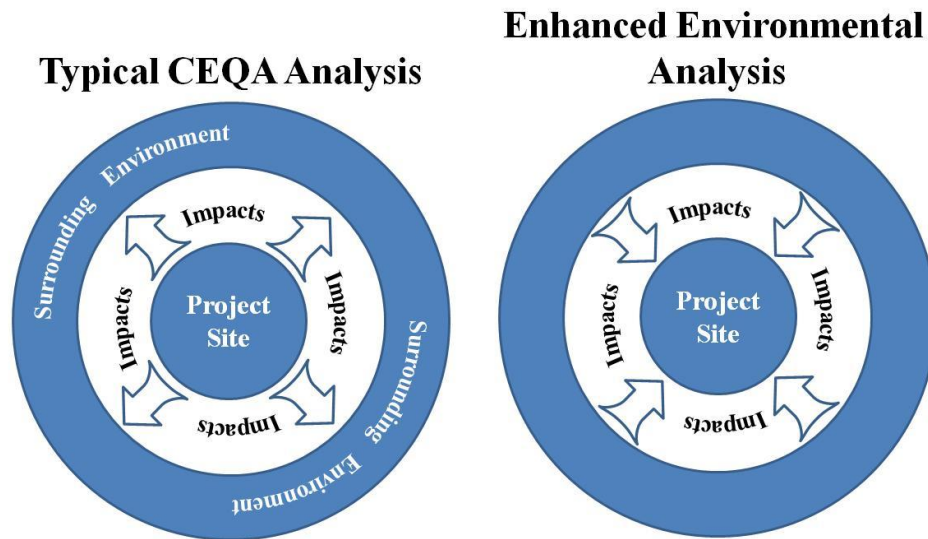


FIGURE 9-5

Example of Typical and Enhanced Environmental Analyses

Although section 15162.2 of the CEQA Guidelines provides that an environmental impact report “shall also analyze any significant environmental effects the project might cause by bringing development and people into the area affected,” recent court rulings have found that CEQA does not require an analysis of the impacts of the environment on a project.¹⁶

¹⁶ *Ballona Wetlands Land Trust v. City of Los Angeles* (2011) 201 Cal.App.4th 455, 473-474 (a revised environmental impact report for a coastal multi-family residential development was not *required* to address impacts on the project from sea-level rise caused by global warming); *see also South Orange County Wastewater Authority v. City of Dana Point* (2011) 196 Cal.App.4th 1604 (analysis of impacts from locating a residential development next to an existing source of noxious odors was not *required*)

However, notwithstanding these court rulings, lead agencies (such as a city or county or air district) that approve CEQA documents retain the authority to include any additional information they deem relevant to assessing and mitigating the environmental impacts of a project. Because of the District's concern about the potential public health impacts of siting sensitive populations within close proximity of freeways, District staff will continue to recommend that, prior to approving the project, lead agencies consider the impacts of air pollutants on people who will live in a new project and provide mitigation where necessary.

Guidance is available for conducting health risk assessments related to mobile sources from the District and from the California Air Pollution Controls Officers Association (CAPCOA).¹⁷

Mitigation Measures

A variety of mitigation measures have been proposed and are under study to reduce exposure to the high concentration of pollutants found in the near-roadway environment. Although some of these exposure controls may have some effectiveness, the solution that would have the greatest effect still lies in source control. Reducing vehicle emissions remains the only way to ensure that all pollutant concentrations in the near-roadway environment can be reduced for everyone, not just for certain pollutants, or for those that can implement mitigation. While emissions from vehicles are expected to continue to decline with existing regulations and fleet turnover, near-roadway environments are still expected to have elevated concentrations of some mobile source pollutants for the foreseeable future. In the interim, there are some measures that may reduce exposure that are briefly described in the table below. All of these conventional methods require further research to determine their effectiveness and feasibility for the variety of land uses found in the near-roadway environment. In addition, District staff will continue to support and monitor the outcome of research on newer technologies such as photocatalytic cement, roadway canopies, and sound barriers with active or passive filtration/ventilation.

Besides buffer zones, none of the measures listed in the table below (Table 9-1) has been found to be effective to reduce all mobile source pollutants to background levels in the near roadway-environment. Because of this limitation, the mitigation

¹⁷ http://www.aqmd.gov/ceqa/handbook/mobile_toxic/mobile_toxic.html
http://www.capcoa.org/wp-content/uploads/2012/03/CAPCOA_HRA_LU_Guidelines_8-6-09.pdf

considered for new land uses may be different than that considered for existing land uses. For example, new land uses could consider buffer zones or site configurations before considering other measures such as enhanced HVAC filtration.

For existing land uses that do not have the same ability to incorporate buffer zones as new land uses, other measures may be considered first, such as encouraging development of outdoor recreation spaces and playgrounds within walking distance but beyond 300 m from a freeway at the same time as considering enhanced filtration in HVAC systems.

Emission Control Technologies

The application of advanced emissions control technologies to both compression-ignition (diesel) and spark-ignition (gasoline, natural gas) engines has led to new concerns about the formation and health effects of UFPs. Since larger accumulation mode particles have effectively been removed from the exhaust of state-of-the-art vehicles, this has eliminated possible condensation surfaces for volatile gases and UFPs. The net result is that while larger-sized particles (accounting for most of the PM mass) are dramatically reduced by control technologies such as diesel particulate filters (DPFs), an increase in the number of UFPs and NP may potentially occur. Additional evaluation regarding a possible increase in UFP and NP number concentration should be addressed. Below is a brief description of the two main PM control technologies in use today:

- Particulate filters are devices capable of achieving over 90% reduction of the solid portion of the total exhaust particles, with some control of the soluble organic fraction (SOF). With most of the solid particles removed, nucleation, rather than condensation, of the remaining gas phase species can occur, potentially increasing particle number emissions (Morawska et al., 2008). However, particulate filters can also be effective in controlling UFPs if designed properly, for example when used in conjunction with an oxidation catalyst.

TABLE 9-1

MITIGATION MEASURE	POLLUTANT TARGETED	RANGE OF REDUCTION	COMMENTS	KEY REFERENCES
Buffer zones	All pollutants	0-100%	Varies with distance. Up to 100% reduction to background levels at 500 feet.	-CARB Air Quality and Land Use Handbook, (2005) (http://www.arb.ca.gov/ch/handbook.pdf)
Enhanced filtration in building Heating, Ventilation, and Air Conditioning (HVAC) systems	PM	30-90% for indoor environments	Effectiveness varies depending upon rating of filter (>MERV 13 recommended near roadways), HVAC design, maintenance of HVAC system, whether doors and windows stay closed, and amount of time people spend outdoors	-AQMD Pilot Study of High Performance Air Filtration for Classroom Applications (http://www.aqmd.gov/rfp/attachments/2010/AQMDPilotStudyFinalReport.pdf) -SCAG 2012 RTP/SCS PEIR Appendix G Measure AQ-19 (http://rtpscs.scag.ca.gov/Documents/peir/2012/final/2012fPEIR_AppendixG_ExampleMeasures.pdf)
Sound walls	All pollutants	15-50% close to barrier at ground level	Effectiveness varies with distance from freeway, with concentrations sometimes increasing >80m downwind of wall. Other site-specific characteristics may significantly alter effectiveness.	-Impact of noise barriers on near-road air quality, Baldauf et al., (2008) -Impact of noise barriers on particle size distributions and pollutant concentrations near freeways, Ning et al., (2010) -The effect of roadside structures on the transport and dispersion of ultrafine particles from highways, Bowker et al., (2007)
Vegetated barriers	PM	Varies	Effectiveness varies with barrier height, thickness, density, and species. Some configurations may increase concentrations.	-Local measures for PM10 hotspots in London, Air Quality Consultants (2009) -Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions, Hagler et al., (2012)

Common Mitigation Measures Adopted To Reduce Exposure to Motor Vehicle Emissions In Near-Road Environments

- Oxidation catalysts are effective in removing more than 90% of the SOF fraction of total emissions as well as UFPs formed later in the exhaust. Their effectiveness, however, depends on whether the catalyst is formulated to produce little or no sulfate emissions at high temperature. In fact, special catalyst formulations must be employed to hinder the catalytic generation of sulfate particles from SO₂ present in the exhaust gas. While oxidation catalysts are effective in reducing the SOF fraction and smaller particles, it has little effect on larger accumulation or coarse mode particles. An effective control technology should be based on a system addressing both particle mass and number emission reduction.

Testing Protocols

Under the U.S. gravimetric method for certifying heavy-duty engines, exhaust PM mass is collected on inert filters as each engine is operated over official engine dynamometer testing schedules (e.g. the Federal Test Procedure, or FTP). A constant volume sampler (CVS) system collects the exhaust at prescribed conditions (e.g. temperature, dilution ratio). The preconditioned particulate filters are then weighed to obtain the mass of PM emitted over the test cycle. The mass of emitted PM is then normalized according to the work performed over the test cycle in brake horsepower-hour (bhp-hr). The calculated mass emissions values are compared to the PM emissions standard in g/bhp-hr.

Procedures for characterizing emissions from light-duty (diesel) vehicles are similar from the perspective of collecting the PM on preconditioned filters and determining mass emissions. A key difference is that the light-duty vehicle emissions standards are in grams of pollutant per distance driven (g/mile in the U.S.), instead of work performed. Testing of light-duty vehicles is conducted on chassis dynamometers in contrast to heavy-duty engines, which are tested on engine dynamometers prior to vehicle integration.

In the U.S., the focus on measuring and controlling PM emissions has been almost exclusively on the heavy-duty vehicle sector, because overall emissions are dominated by diesel engines. The mass-focused testing methodology described above has worked well for heavy-duty engine technologies meeting PM standards of 0.1 g/bhp-hr (i.e. up to the 2006 engine model year). Such engines emit relatively large amounts of solid material (soot, metals, and ash) from combustion, engine wear, and lube oils. All of this is collected on the preconditioned filters, along with volatiles in the exhaust that condense on the filters including water vapor, sulfates, and other

organics. The net result is that the mass of PM collected during the test cycle over a known amount of work performed can be compared to the PM emissions standard.

However, as more advanced diesel PM control technology was developed and deployed to meet tighter emissions standards (DPFs to meet the U.S. 2007 heavy-duty engine PM standard) the PM mass collected over the FTP was significantly reduced. In some cases, PM mass levels were too low for detection by existing instrumentation in the test methodology. Also, at these low mass levels, testing anomalies can occur due to absorption of semi-volatile gas molecules on sampling filters or on PM already collected, which possibly leads to bias towards higher weight measurements. Similarly, tunnel wall or sampling line losses can also cause erroneous results. The need for better precision at low mass levels led U.S. EPA to revise the protocol to improve accuracy. At the same time, testing in the United States and in Europe shed new light on the characteristics of diesel PM in the exhaust, raising questions as to the relative importance of measuring particle mass versus particle number and/or size (Swanson et al., 2010).

In the late 1990s, the occupational health and safety authorities of Austria, Switzerland and Germany conducted a comprehensive program called Verminderung der Emissionen von Real-Dieselmotoren im Tunnelbau (VERT), which in English stands for Reduction of Diesel-emissions in tunneling to ensure functional and beneficial systems are utilized for the removal of harmful diesel emissions in underground environments. One of the main objectives of VERT was to look at the composition of diesel exhaust in terms of particle size, surface area, and concentration, and to establish whether mass is a good proxy for subsequent exposures and human health effects. PM, primarily BC and UFPs were found to be of major concern to the extent that in tunneling and other major construction sites, particle-traps for diesel equipment/vehicles became mandatory. This work laid the foundation for two additional important programs, the “Particulates Program” and the “Particle Measurement Programme” (PMP), both of which are further discussed below.

- Particulates Program: this program developed a sampling procedure to characterize both the volatile and non-volatile components of exhaust emissions from light- and heavy-duty vehicles. In particular, it developed sampling methodologies capable of assessing the formation of nucleation- and accumulation-mode particles from a minimum size of 7 nm. Figure 9-6 shows the sampling system used in the Particulates Program. The main results for light-duty

and for heavy-duty-vehicle applications are described in Ntziachristos et al. 2004, and in Thompson et al. 2004, respectively.

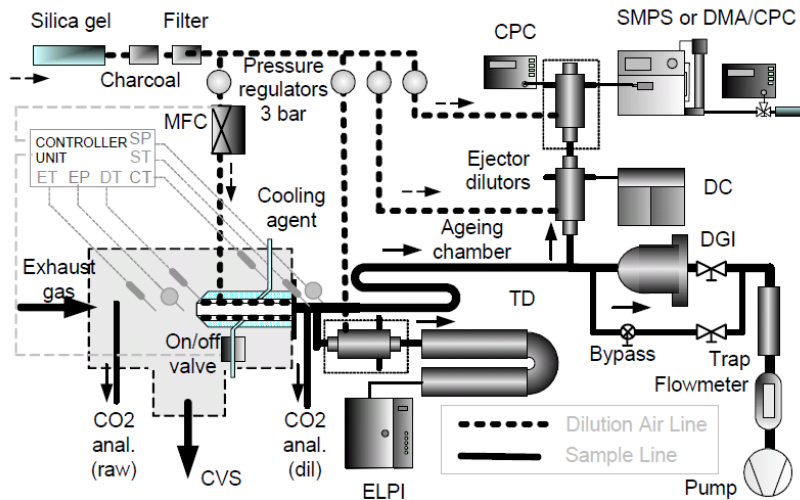


Figure 9-6

Sampling System used in the Particulates Program (from Samaras et al., 2006)

The basic premise behind the testing protocol was that each vehicle technology can and should be tested under consistent conditions. This enables comparison between the various technologies and fuels used. The procedure entails measuring particle mass, active surface (surrogate for surface area), solid particle number, total particle number, and particle size distribution. Both light-duty and heavy-duty programs investigated the effects of vehicle technology, fuel properties, and driving cycle.

- **Particle Measurement Programme (PMP):** this program is aimed at developing a test protocol to measure only the impact of solid particles in motor vehicle exhaust. The PMP is a collaboration of the United Nations Economic Commission for Europe and GRPE (Working Party on Pollution and Energy). The goal of this program is to find a new approach to measure particle emissions from vehicles that can either replace or coexist with the current mass-based particulate measurements. A result of this work has been the development of instrumentation and methodologies for counting solid (i.e. low-volatility particles that survived evaporation after a residence time of 0.2 seconds at 300 °C) particles down to a size of 23 nm. The PMP was implemented in a number of testing labs in Europe, Japan, and the U.S. The results of the lab emission testing for light- and heavy-duty vehicles is provided by Andersson et al. (2007; 2010). Figure 9-7 shows an example of a PMP setup for particle number count testing. New test requirements

are continuously being added to European light-duty vehicle emissions regulations, including those specific to particle number.

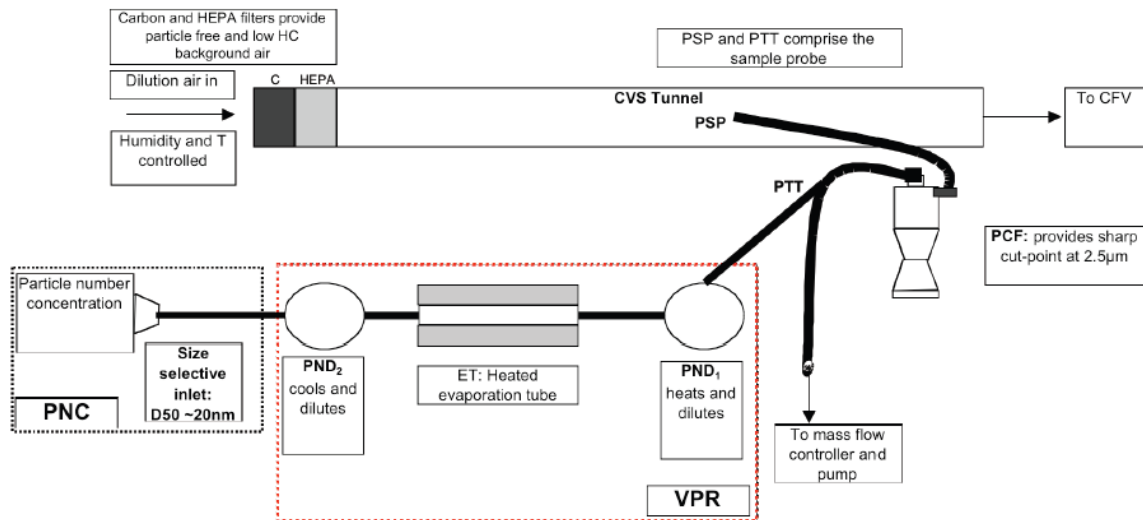


FIGURE 9-7

Schematic of PMP Testing Setup for Particle Number Count (from Kasper et al., 2006)

There have also been a number of related studies or research reports on the evaluation of various components of the PMP methodology. For example, CARB studied this method for light-duty vehicles using the “Golden Vehicle” (GV; a single vehicle that has been shipped to laboratories in Italy, Sweden, United Kingdom, Germany, Greece, Japan, Korea and France for testing) and the Golden Particle Measurement System (GPMS; a set of particle counting instruments that was sent along with the GV) to compare results with the other nine international laboratories that participated in the PMP (CARB, 2008).¹⁸ Additional testing was done on heavy-duty vehicles and results indicated that further study was needed to include a wider range of vehicles and after-treatment systems (Robertson et al., 2007).

The PMP protocol has gained acceptance in Europe and Japan. American regulators, industry and researchers continue to evaluate this methodology. Researchers in the U.S. (e.g., Swanson et al. 2010) favor alternative methods that focus on measuring surface area including solids and volatiles. Kittelson et al. (2011) noted that for engines equipped with particle filters setting the limit to 23 nm effectively regulates all sizes. However, vehicles without filters may emit large concentrations of solid

¹⁸ http://www.arb.ca.gov/research/veh-emissions/pmp-ld/CARB_Golden_Vehicle_PMP_Report_Final-05JAN09.pdf

particles below 23 nm that are not counted by the current method. The next generation of high-efficiency direct injection gasoline engines is also challenged by the current 23 nm limit. They proposed extending solid PM measurements to 10 nm although this may be problematic due to formation of particles as small as 3 nm downstream of the PMP Volatile Particle Remover (VPR) system.¹⁹

As noted, the European PMP protocol has been implemented to include numbers-based particle emission standards. While there is no consensus in the U.S. at present regarding how to standardize particle measurements, research work and regulatory discussions are ongoing among industry and regulatory agencies such as U.S. EPA, CARB, and the District. For now, U.S. EPA and CARB continue to regulate PM mass only.

Emissions Standards

European Standards

Europe's new emission levels for light-duty and medium-duty vehicles are Euro 5 and Euro 6. Euro 5's goal is to reduce the emissions of PM from diesel cars from 25 mg/km to 5 mg/km. Euro 6 will become effective in January 2014, and will reduce the NO_x emissions from diesel cars from 180 mg/km to 80 mg/km. A solid particle number emission limit of 6×10^{11} km⁻¹ became effective in September 2011 for all categories of diesel vehicles. Europe's reason for adopting the number standard is to promote the use of DPF technology. A particle number emissions limit for gasoline vehicles will be determined in 2014.

California Standards

In 2010, CARB considered adopting certain particle number standards as an alternative under the LEV III requirements, and proposed that for all vehicles subject to LEV III, beginning in 2014, manufacturers must select one of two standards to demonstrate compliance (CARB, 2010)²⁰:

1. Federal Test Procedure weighted PM mass emission limit to 0.006 g/mi (2014) and 0.003 g/mi (2017)
2. Federal Test Procedure weighted particle number emission limit to 6.0×10^{12} particles/mi (2014) and 3.0×10^{12} particles/mi (2017)

¹⁹ <http://www.unece.org/fileadmin/DAM/trans/doc/2011/wp29grpe/PMP-26-06e.pdf>

²⁰ http://www.arb.ca.gov/msprog/levprog/leviii/meetings/051810/pm_disc_paper-v6.pdf

CARB's reason for proposing the particle number limit is to take advantage of the latest methodology advances by PMP. The PMP method was considered because it is the only particle emission measurement method that went through extensive international scrutiny and laboratory testing. Excellent sources of information about CARB's LEV III proposals and objectives specific to fine particles can be found on CARB's 2011 publication "LEV III PM Technical Support Document: Development of Particulate Mass Standards for Future Light-Duty Vehicles".²¹

National Standards

The National Ambient Air Quality Standards (NAAQS) set by the U.S. EPA are designed to protect public health and the environment. The standards are developed based on a variety of scientific studies, including the results of epidemiologic studies that evaluate how human health has been affected by pollutant concentrations in the past. These standards are periodically reviewed and updated based on recent scientific developments. Most recently, the NO₂ and CO NAAQS were reviewed and updated, with a new provision that new permanent monitors must be established near roadways. The most recent AQMD monitoring plan provides details about how and where these new monitors may be located.²² The recent PM NAAQS revision proposed on June 14, 2012, by U.S. EPA for the first time includes near-roadway monitoring requirements for PM_{2.5}. Currently, U.S. EPA notes that, in their assessment, there is not sufficient health evidence to support a separate standard for UFPs.

DISTRICT FUTURE ACTIONS

Although the District has limited authority to regulate mobile source pollution in the near-roadway environment, there are a variety of measures that District staff will continue to take to reduce this public health impact.

- The District will continue to fund health effects, exposure, atmospheric chemistry, modeling, and other research activities aimed at investigating the impact of UFPs exposure in communities impacted by traffic emissions. An AQMD-funded study is currently underway to assess potential air quality impacts and the effectiveness of mitigation measures (e.g. sound walls and vegetated barriers) in the near roadway environment. The multi-pronged approach of this study includes a

²¹ <http://www.arb.ca.gov/regact/2012/leviiiighg2012/levappp.pdf>

²² <http://www.aqmd.gov/tao/AQ-Reports/AQMonitoringNetworkPlan/AQnetworkplan.htm>

review of different mitigation techniques implemented throughout the world, pollutant monitoring combined with dispersion modeling of local freeway emissions, development of alternative models, and laboratory-based simulations in flow tanks. The results of this study are expected by early 2013.

- Since the problem of near-roadway exposure can effectively be addressed by controlling tailpipe emissions, the District will continue to encourage U.S.EPA and CARB to set vehicle emission standards for UFP.
- District staff will continue to work with local and state agencies to address near-roadway exposures. This includes outreach and education to local governments and elected officials on the health risks associated with mobile source pollution and recommending measures that can be taken to reduce those risks. As an example, General Plans prepared for a city can include requirements to provide buffer zones, as feasible, between freeways and any new development with sensitive receptors.
- Through the CEQA Intergovernmental Review program, CEQA documents submitted to the District are reviewed during the public comment period. For those projects that may expose sensitive populations to elevated concentrations of mobile source pollution, District staff will recommend that the potential impacts be quantified and that all feasible mitigation measures be considered to reduce this impact below a significant level.
- As part of the Clean Communities Program (CCP), District staff will continue to work in the pilot study areas of Boyle Heights and San Bernardino to address exposure to mobile source pollution and will apply those lessons learned to other areas in the District. Further, as part of CCP Measures Outreach-1 and Agency-01, District staff will prepare a document titled “Proximity Matters” that will provide an additional resource for local agency planners to use when addressing near-roadway exposures.
- On July 1, 2012 the District began MATES IV, a year-long study designed to characterize the carcinogenic risk caused by exposure to air toxics in the Basin. MATES IV will enhance the spatial resolution of previous measurement efforts by characterizing the localized exposure to UFPs and Diesel Particulate Matter in residential, industrial, and commercial communities. Mobile monitoring platforms will be deployed for short-term monitoring at six to eight sites in areas close to mobile sources such as airports, rail yards, freeways and warehouse operations.

- District staff will continue to work with instrument manufacturers, CARB, and U.S. EPA on the evaluation of new technologies for monitoring UFPs, BC and other traffic-related pollutants, and on the development of methods for the standardization of UFP measurements.

REFERENCES

- Andersson, J., Barouch, G., Munoz-Bueno, R., Sandbach, E., and Dilara, P. (2007) “Particle Measurement Programme (PMP), “Light-duty Inter-laboratory Correlation Exercise (ILCE_LD) Final Report”, Institute for Environment and Sustainability, European Commission - Directorate General - Joint Research Center, EUR 22775 EN
- Andersen, Z.J., Hvidberg, M., Jensen, S.S., 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
- Andersson, J., Mamakos, A., Giechaskiel, B., Carriero, M., Martini, G. (2010) “Particle Measurement Programme (PMP) Heavy-duty Inter-laboratory Correlation Exercise (ILCE_HD) Final Report”, JRC Scientific and Technical Reports, EUR 24561 EN
- Araujo, J.A., Barajas, B., Kleinman, M., Wang, X.P. et al. (2008) “Ambient particulate pollutants in the ultrafine range promote early atherosclerosis and systemic oxidative stress”, *Circulation Research*, 102(5): 589-596
- Baldauf, R., Thoma, E., Khlystov, A., et al. (2008) “Impacts of noise barriers on near-road air quality”, *Atmospheric Environment*, 42(32): 7502-7507
- Baldauf, R., Watkins, N., Heist, D., Bailey, C., Rowley, R., Shores, R. (2009) “Near-road air quality monitoring: Factors affecting network design and interpretation of data”, *Air Quality Atmospheric Health*, 2:1-9
- Balmes, J.R., Earnest, G., Katz, P.P., Yelin, E.E., Eisner, M.D., Chen, H., Trupin, L., Lurmann, F. and Blanc, P.D. (2009) “Exposure to traffic: Lung function and health status in adults with asthma”, *The Journal of Allergy and Clinical Immunology*, 123(3):626-631
- Bowker, G.E., Baldauf, R., Isakov, V., et al. (2007) “The effects of roadside structures on the transport and dispersion of ultrafine particles from highways”, *Atmospheric Environment*, 41(37): 8128-8139

Brugge, D., Durant, J.L. and Rioux, C. (2007) “Near-highway pollutants in motor vehicle exhaust: A review of epidemiologic evidence of cardiac and pulmonary health risks”, *Environmental Health*, 6:23

Burtscher, H., Loretz, S., Keller, A., Mayer, A., Kasper, M., Artley, R.J., Strasser, R., Czerwinski, J. (2008) “Nanoparticle filtration for vehicle cabins” SAE Paper 2008-01-0827

Chang, J., Delfino, R.J., Gillen, D. et al. (2010) “Repeated Respiratory Hospital Encounters Among Children With Asthma and Residential Proximity to Traffic” *Occupational Environmental Medicine*, 66: 90-98

Delfino, R.J., Sioutas, C., Malik, S. (2005) “Potential role of ultrafine particles in associations between airborne particle mass and cardiovascular health”, *Environmental Health Perspectives*, 113(8): 934-946

Delfino, R.J., Staimer, N., Tjoa, T., Polidori, A., et al. (2008) “Circulating biomarkers of inflammation, antioxidant activity, and platelet activation are associated with primary combustion aerosols in subjects with coronary artery disease”, *Environmental Health Perspectives*, 116(7): 898-906

Delfino, R.J., Staimer, N., Tjoa, T., et al (2009) “Air Pollution Exposures and Circulating Biomarkers of Effect in a Susceptible Population: Clues to Potential Causal Component Mixtures and Mechanisms”, *Environmental Health Perspectives*, 117(8): 1232-1238

Delfino, R.J., Tjoa, T., Gillen, D.L. et al. (2010) “Traffic-related Air Pollution and Blood Pressure in Elderly Subjects With Coronary Artery Disease”, *Epidemiology*, 21(3): 396-404

Delfino, R.J., Gillen, D.L., Tjoa, T., et al. (2011) “Electrocardiographic ST-Segment Depression and Exposure to Traffic-Related Aerosols in Elderly Subjects with Coronary Artery Disease”, *Environmental Health Perspectives*, 119(2): 196-202

Fruin, S.A., Winer, A.M., Rodes, C.E. (2004) “Black carbon concentrations in California vehicles and estimation of in-vehicle diesel exhaust particulate matter exposures”, *Atmospheric Environment*, 38(25): 4123-4133

Fruin, S., Westerdahl, D., Sax, T., Sioutas, C., Fine, P.M. (2008) “Measurement and Predictors of On-Road Ultrafine Particle Concentrations and Associated Pollutants in Los Angeles”, *Atmospheric Environment*, 42(2), 207-219

Fujita E.M., Campbell, D.E., Zielinska, et al. (2003) “Diurnal and weekday variations in source contributions of ozone precursors in California’s south coast air basin”, *Journal of the Air & Waste Management Association*, 53:844-863

Green R, Smorodinsky S, Kim J, McLaughlin R, Ostro B. (2004) “Proximity of California Public Schools to Busy Roads”, *Environmental Health Perspectives* 112;1:61-66

Hagler, G.S., Thoma, E.D., Baldauf R, W. (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, G.S.W., Lin, M.Y., Khlystov, A., et al. (2102) “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

Health Effects Institute (2010) “Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects”, <http://pubs.healtheffects.org/>

Hesterberg, T.W., Long, C.M., Sax, S.N., et al. (2011) “Particulate Matter in New Technology Diesel Exhaust (NTDE) is Quantitatively and Qualitatively Very Different from that Found in Traditional Diesel Exhaust (TDE)”, *Journal of the Air & Waste Management Association*, 61(9): 894-913

Hoek, G., Boogaard, H., Knol, A., De Hartog, J. et al. (2010) “Concentration Response Functions for Ultrafine Particles and All-Cause Mortality and Hospital Admissions: Results of a European Expert Panel Elicitation”, *Environmental Science & Technology*, 44: 476-482

Hu, S.S., ; Fruin, S., Kozawa, K., et al. (2009) “A wide area of air pollutant impact downwind of a freeway during pre-sunrise hours”, *Atmospheric Environment*, 43(16): 2541-2549

Hu, S.S., Paulson, S.E., Fruin, S. et al. (2012) “Observation of elevated air pollutant concentrations in a residential neighborhood of Los Angeles California using a mobile platform”, *Atmospheric Environment*, 51: 311-319

Hudda, N., Kostenidou, E., Sioutas, C., Delfino, R.J., Fruin, S.A. (2011) “Vehicle and Driving Characteristics That Influence In-Cabin Particle Number Concentrations”, *Environmental Science & Technology*, 45(20): 8691-8697

Hussein, T., Puustinen, A., Aalto, P., Makela, J., Hameri, K., Kulmala, M. (2004) “Urban aerosol number size distributions”, *Atmospheric Chemistry and Physics Discussions* 4, 391–411

Jerrett, M., Finkelstein, M.M., Brook, J.R., Arain, M.A., Kanaroglou, P., Stieb, D.M. Gilbert, N.L. Verma, D., Finkelstein, N., Chapman, K.R. and Sears, M.R. (2009) “A Cohort A-33 Study of Traffic-Related Air Pollution and Mortality in Toronto, Ontario, Canada” *Environmental Health Perspectives*, 117:772-777

Kan, H., Heiss, G., Rose, K.M., Whitsel, E.A., Lurmann, F., London, S.J. (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, A., Eisinger, A. and Niemeier, D. (2010) “Near-Roadway Air Quality: Synthesizing the Findings from Real-World Data”, *Environmental Science and Technology*, 44:5334–5344

Keskinen, J. and Ronkko, T. (2010) “Can Real-World Diesel Exhaust Particle size Distribution be Reproduced in the Laboratory? A Critical Review”, *Journal of the Air & Waste Management Association*, 60: 1245-1255

Kim, J.J., 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 & Critical Care Medicine*, 170: 520-526

Kittelson, B.D. (1998) “Engines and nanoparticles: a review”, *Journal of Aerosol Science* 29 (5), 575–588

Knibbs, L.D., Cole-Hunter, T., Morawska, L. (2011) “A review of commuter exposure to ultrafine particles and its health effects”, 45(16): 2611-2622

Kozawa, K.H., Fruin, S.A., Winer, A.M. (2009) “Near-road air pollution impacts of goods movement in communities adjacent to the Ports of Los Angeles and Long Beach”, *Atmospheric Environment*, 43(18): 2960-2970

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., Krudysz, M., Zhu, Y., Fine, P., Hinds, W., Froines, J., Sioutas, C. (2005) “Volatility of indoor and outdoor ultrafine particulate matter near a freeway”, *Journal of Aerosol Science* 36, 291–302

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

Lamia Benbrahim-Tallaa, Robert A Baan, Yann Grosse, Béatrice Lauby-Secretan, Fatiha El Ghissassi, Véronique Bouvard, Neela Guha, Dana Loomis, Kurt Straif, on behalf of the International Agency for Research on Cancer Monograph Working Group, Carcinogenicity of diesel-engine and gasoline-engine exhausts and some nitroarenes, *The Lancet Oncology*, Early Online Publication, 18 June 2012, doi:10.1016/S1470-2045(12)70280-2 [http://www.thelancet.com/journals/lanonc/article/PIIS1470-2045\(12\)70280-2/fulltext](http://www.thelancet.com/journals/lanonc/article/PIIS1470-2045(12)70280-2/fulltext)

Lee, E.S., Polidori, A., Koch, M., Fine, P.M., et al. “Water-based Condensation Particle Counters Comparison Near a Major Freeway with Significant Heavy-Duty Diesel Traffic”, submitted for publication to *Atmospheric Environment*

Li, N., Sioutas, C., Cho, A., Schmitz, D., Misra, C. et al. (2003) “Ultrafine particulate pollutants induce oxidative stress and mitochondrial damage”, *Environmental Health Perspectives*, 111(4): 455-460

Liggio, J., Gordon, M., Smallwood, G., et al. (2012) “Are Emissions of Black Carbon from Gasoline Vehicles Underestimated? Insights from Near and On-Road Measurements”, *Environmental Science & Technology*, 46(9): 4819-4828

Ljubimova, J.Y., P.R. Gangalum, J. Portilla-Arias, R. Patil, B. Konda, M. Paff, J. Markman, S. Inoue, A. Espinoza, A. Chesnokova, M. Kleinman, R. Holler, K.L. Black. “Molecular Changes in Rat Brain Due to Air Nano Pollution,” Nanotechnology Conference and Expo, June, 2012, Santa Clara, CA

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

Maricq, M.M. and Maldonado, H. (2010) “Directions for Combustion Engine Aerosol Measurement in the 21st Century”, *Journal of the Air & Waste Management Association*, 60(10): 1165-1176

McConnell, R., Berhane, K., Yao, L., et al. (2006) “Traffic, susceptibility, and childhood asthma”, *Environmental Health Perspectives*, 114(5): 766-772

McConnell, R., Islam, T., Shankardass, K., et al. (2010) “Childhood Incident Asthma and Traffic-Related Air Pollution at Home and School”, *Environmental Health Perspectives*, 118(7): 1021-1026

Morawska, L., Ristovski, Z., Jayaratne, E.R., Keogh, D.U., Ling, X. (2008) “Ambient nano and ultrafine particles from motor vehicle emissions: Characteristics, ambient processing and implications on human exposure”, *Atmospheric Environment* 42 (2008) 8113–8138

Ning, Z., Hudda, N., Daher, N., et al. (2010) “Impact of roadside noise barriers on particle size distributions and pollutants concentrations near freeways”, *Atmospheric Environment*, 44(26): 3118-3127

Ntziachristos, L., Mamakos, A., Samaras, Z., Mathis, U., Mohr, M., Thompson, N., Stradling, R., Forti, L., de Serves, C. (2004) “Overview of the European “Particulates” Project on the Characterization of Exhaust Particulate Emissions From Road Vehicles: Results for Light-Duty Vehicles”, SAE 2004-01-1985

Ntziachristos, L., Ning, Z., Geller, M.D., Sioutas, C. (2007) “Particle concentration and characteristics near a major freeway with heavy duty diesel traffic”, *Environmental Science and Technology* 41, 2223–2230

- Pakkanen, T., Kerminen, V., Korhonen, C., Hillamo, R., Aarino, P., Koskentalo, T., Maenhaut, W. (2001) "Urban and rural ultrafine (PM_{0.1}) particles in the Helsinki area", *Atmospheric Environment* 35, 4593–4607
- Pirjola, I., Paasonen, P., Pfeiffer, D., Hussein, T., Hameri, K., Koskentalo, T., Virtanen, A., Ronkko, T., Keskinen, J., Pakkanen, T., Hillamo, R. (2006) "Dispersion of particles and trace gases nearby a city highway: mobile laboratory measurements in Finland", *Atmospheric Environment* 40, 867–879
- Pope, C.A., Hansen, J.C., Kuprov, R., et al. (2011) "Vascular Function and Short-Term Exposure to Fine Particulate Air Pollution", *Journal of the Air & Waste Management Association*, 61(8): 858-863
- Pui, D.Y.H., Qi, C., Stanley, N., Oberdörster, G. (2008) "Recirculating air filtration significantly reduces exposure to airborne nanoparticles", *Environmental Health Perspectives* 116: 863-866
- Robertson, W.H., Herner, J.D., Ayala, A., Durbin, T.D. (2007) "Investigation of the Application of the European PMP Method to Clean Heavy Duty Vehicles", Presented at the 2007 Diesel Engine-Efficiency and Emissions Research Conference, August 2007
- Robinson, A.L., Grieshop, A.P., Donahue, N.M., Hunt, S.W. (2010) "Updating the Conceptual Model for Fine Particle Mass Emissions from Combustion Systems", *Journal of the Air & Waste Management Association*, 60: 1204-1222
- Samet, J.M., Rappold, A., Graff, D., et al. (2009) "Concentrated Ambient Ultrafine Particle Exposure Induces Cardiac Changes in Young Healthy Volunteers", *American Journal of Respiratory and Critical Care Medicine*, 179(11): 1034-1042
- Sardar, S.B., Fine, P.M., Mayo, P.R., Sioutas, C. (2005) "Size-fractionated measurements of ambient ultrafine particle chemical composition in Los Angeles using the NanoMOUDI", *Environmental Science and Technology* 39, 932–944
- Seigneur, C. (2009) "Current Understanding of Ultrafine Particulate Matter Emitted from Mobile Sources", *Journal of the Air & Waste Management Association*, 59: 3-17

Shah, A.P., Pietropaoli, A.A., Frasier, L.M., et al. (2008) “Effect of inhaled carbon ultrafine particles on reactive hyperemia in healthy human subjects”, *Environmental Health Perspectives*, 116(3): 375-380

Stanier, C., Khlystov, A., Pandis, S. (2004a) “Ambient aerosol size distributions and number concentrations measured during the Pittsburgh Air Quality Study (PAQS)”, *Atmospheric Environment* 38, 3275–3284

Stanier, C., Khlystov, A., Pandis, S. (2004b) “Nucleation events during the Pittsburgh air quality study: description and relation to key meteorological, gas phase, and aerosol parameters”, *Aerosol Science and Technology* 38 (S1), 253–264

Sun, Y.L., Zhang, Q., Schwab, J.J. et al. (2012) “Characterization of near-highway submicron aerosols in New York City with a high-resolution aerosol mass spectrometer”, *Atmospheric Chemistry and Physics*, 12(4): 2215-2227

Swanson, J., Kittelson, D., Pui, D., Watts, W. (2010) “Alternatives to the Gravimetric Method for Quantification of Diesel Particulate Matter Near the Lower Level of Detection”, *Journal of the Air & Waste Management Association*, 60: 1177-1191

Thompson, N., Ntziachristos, L., Samaras, Z., Aakko, P., Wass, U., Hausberger, S., Sams, T. (2004) “Overview of the European Particulates Project on the Characterization of Exhaust Particulate Emissions From Road Vehicles: Results for Heavy Duty Vehicles”, SAE 2004-01-1986

Venn, A.J., Lewis, S.A., 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

Verma, V., Ning, Z., Cho, A.K., Schauer, J.J. et al. (2009) “Redox activity of urban quasi-ultrafine particles from primary and secondary sources”, *Atmospheric Environment*, 43(40): 6360-6368

Verma, V., Pakbin, P., Cheung, K.L., et al. (2011) “Physicochemical and oxidative characteristics of semi-volatile components of quasi-ultrafine particles in an urban atmosphere”, *Atmospheric Environment*, 45(4): 1025-1033

Virtanen, A., Ronkko, T., Kannosto, J., Ristimäki, J., Mäkelä, J., Keskinen, J., Pakkanen, T., Hillamo, R., Pirjola, L., Hameri, K. (2006) “Winter and summer time distributions and densities of traffic related aerosol particles at a busy highway in Helsinki”, *Atmospheric Chemistry and Physics* 6, 2411–2421

Westerdahl, D., Fruin, S., Sax, T., Fine, P., 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

Whitlow, T.H., Hall, A., Zhang, K.M., Anguita, J. (2011) “Impact of local traffic exclusion on near-road air quality: Findings from the New York City Summer Streets campaign”, *Environmental Pollution*, 159(8-9): 2016-2027

Wilhelm, M., Ghosh, J.K., 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”, *Environ Health* 10: 89

Williams, L.A., Ulrich, C.M., Larson, T., Wener, M.H., Wood, B., Campbell, P.T., Potter, J.D., McTiernan, A., De Roos, A.J. (2009) “Proximity to traffic, inflammation, and immune function among women in the Seattle, Washington, area”, *Environmental Health Perspectives*, 117(3): 373-8

Zareba, W., Couderc, J.P., Oberdorster, G., et al. (2009) “ECG Parameters and Exposure to Carbon Ultrafine Particles in Young Healthy Subjects”, *Inhalation Toxicology*, 21(3): 223-233

Zhang, Q., Stanier, C., Canagaratna, M., Jayne, J., Worsnop, D., Pandis, S., Jimenez, J. (2004) “Insights into the chemistry of new particle formation and growth events in Pittsburgh based on aerosol mass spectrometry”, *Environmental Science and Technology* 38, 4797–4809

Zhu, Y., Hinds, W., Kim, S., Shen, S., Sioutas, C. (2002a) “Study of ultrafine particles near a major highway with heavy duty diesel traffic”, *Atmospheric Environment* 36, 4323–4335

Zhu, Y., Hinds, W.C., Kim, S., Sioutas, C. (2002b) “Concentration and size distribution of ultrafine particles near a major highway”, *Journal of the Air and Waste Management Association* 52 (9), 1032–1042

Zhu, Y.F., Eiguren-Fernandez, A., Hinds, W.C. Miguel, A.H. (2007) “In-cabin commuter exposure to ultrafine particles on Los Angeles freeways”, *Environmental Science & Technology*, 41(7): 2138-2145