UNDERSTANDING PARTICULATE MATTER:

PROTECTING PUBLIC HEALTH IN THE SAN FRANCISCO BAY AREA

NOVEMBER 2012

BAY AREA AIR QUALITY MANAGEMENT DISTRICT

UNDERSTANDING PARTICULATE MATTER: PROTECTING PUBLIC HEALTH IN THE SAN FRANCISCO BAY AREA

The Air District has prepared this report for informational purposes only. This report builds upon the Bay Area 2010 Clean Air Plan, which defines the Air District's current particulate matter (PM) control strategy. This report will inform future PM planning in the Bay Area, but does not commit the Air District to any specific course of regulatory action.

BAY AREA AIR QUALITY MANAGEMENT DISTRICT

TABLE OF CONTENTS

EXECUTIVE SUMMARY VII

INTRODUCTION 1

- Reducing Population Exposure to PM 1
- What is PM? 2
- Public Health Impacts 2
- PM Planning in the Bay Area 3
- Progress in Reducing PM Levels in the Bay Area 5
- Why We Need to Reduce PM Further 5
- Challenges 5

SECTION 1 : PM IMPACTS 7

SECTION 1-A: THE PUBLIC HEALTH EFFECTS OF PM 7

- Challenges in Analyzing the Health Effects of PM 8
- Early Evidence of PM Health Effects 8
- Analyzing the Health Effects of PM 9
- Recent Research on Health Effects of PM 10
- PM Impact on Premature Mortality and Life Expectancy 11
- Reaction to Findings 13
- Summary of PM Health Effects 13
- No Safe Threshold Has Been Identified 17
- Recent Findings 17
- Biological Pathways: How PM Harms the Body 18
- Which sizes and types of particles are most dangerous? 20
- PM Damage to Cells 21
- Relationship Between Particle Composition and Health Effects 21
- Estimating PM Health Impacts in the Bay Area 25
- Areas that Require Additional Research 28

SECTION 1-B: POPULATION EXPOSURE TO PM 30

- Linking PM to Health Effects 30
- Sensitive Populations 33
- Which Environments Pose the Greatest Risk? 35

TABLE OF

CONTENTS

Exposure to PM from Busy Roadways 36
Indoor Exposure to PM 41
Summary 46

SECTION 1-C: PM AND CLIMATE CHANGE 47
How PM Affects Climate Change 47
Climate Forcing 48
Short-Term vs. Long-Term Impacts 52
Geographic Scale of Impacts 52
Net impact of PM on the Climate 53
Impacts of Climate Change on PM Levels 55
Trade-offs 58
Next Steps 58

SECTION 1-D: PM IMPACTS ON ECOSYSTEMS & VISIBILITY 59
Effects of PM on Vegetation and Soils 60
PM and Acid Rain 61
Effects of PM on Water, Aquatic Systems, and Wildlife 63
PM and Visibility (Haze) 64
Effects of PM on Materials and Property Values 66

SECTION 2: PM TECHNICAL INFORMATION 68
PM Characteristics 68
PM Formation & Dynamics in the Bay Area 75
Source Contributions to Ambient PM Concentrations 79
PM Emissions Inventory 81
Sources of Precursors Pollutants That Form Secondary PM 91
Predicting Future Emissions Trends 94
Projected Trends for Primary PM and Precursors To Secondary PM 96

SECTION 3: PM AIR QUALITY STANDARDS AND TRENDS 100

SECTION 3-A: PM MONITORING PROGRAM 100
Regional PM Monitoring Network 100
Measuring PM Concentrations at the Local Scale 102
Measuring Ultrafine PM 104

TABLE OF CONTENTS

SECTION 3-B: PM STANDARDS AND PM PLANNING REQUIREMENTS 106

PM Standards 106

SECTION 3-C: TRENDS IN AMBIENT PM CONCENTRATIONS 112

PM2.5 Trends 112

PM10 Trend 117

SECTION 4: SUMMARY OF PM CONTROL PROGRAM 118

CARB PM Reduction Program 118

EPA Actions to Reduce PM from "Federal Sources" 122

BAAQMD PM Reduction Program 122

Reducing Population Exposure to PM 137

SECTION 5: LOOKING FORWARD 144

Why It's Important to Continue Reducing PM 144

Challenges We Face 145

Policy Guidelines to Inform Future PM Planning 146

Areas for Further Evaluation 147

Technical Enhancements Needed to Support the Air District's Efforts 151

How Bay Area Residences Can Reduce Their Personal Exposure to PM 155

Conclusion 156

APPENDIX 157

Table 1: Bay Area Winter Emissions Inventory for Primary PM & PM Precursors 2010-2030 157

LIST OF SOURCES 161

LIST OF
TABLES

Table 1-1 US EPA Findings on Health Effects for Particulate Matter 14

Table 1-2 Estimated increase in hospital admissions rate for a 10 µg/m^3 increase for short-term and long-term exposure to PM2.5 by cause of admission 16

Table 1-3 Comparison of Ultrafine Particle Concentrations 39

Table 1-4 Climate-Forcing Properties of PM Components 49

Table 1-5 Summary of Negative Impacts of PM on Ecosystems, Visibility, and Materials 60

Table 2-1 Characteristics of Particulate Matter by Size Range 70

Table 2-2 Bay Area Annual Average Primary PM2.5 Emissions – Year 2010 On-Road and Off-Road Motor Vehicles 84

Table 3-1 Bay Area PM Monitoring Sites 102

Table 3-2 Basic Design Value Calculation Method for National PM2.5 Standards 107

Table 3-3 PM Standards, Bay Area Attainment Status, and Design Values 109

Table 3-4 Exceedances of 24-Hour PM2.5 (35 µg/m^3) 114

Table 4-1 CARB Diesel Air Toxic Control Measures for Heavy-Duty Vehicles, Equipment and Ships 119

Table 4-2 Estimated Reductions in Primary PM & PM Precursors from BAAQMD Regulations (tons per day) 125

Table 4-3 Stationary Source Measures to Reduce PM & PM Precursors in Bay Area 2010 Clean Air Plan 126

Table 4-4 Mobile Source Enforcement Summary for Port of Oakland: 1/1/2010-12/31/2011 129

Table 4-5 Air District Grant Programs: Projects Funded from 2007 through 2011 130

LIST OF
FIGURES

Figure 1-1	How Particulate Matter Enters Our Body	19
Figure 1-2	Cells Exposed to Fine PM (PM2.5) for 16 Hours	21
Figure 1-3	Cells Exposed to Ultrafine PM for 16 Hours	21
Figure 1-4	Bay Area Air Pollution Health Burden: Past & Present	27
Figure 1-5	Number of Particles Versus Distance from Roadway: Two Freeways in Southern California (Zhu, 2002)	37
Figure 1-6	Formation and Deposition of Acid Rain	62
Figure 2-1	Comparison of PM10, PM2.5, and Ultrafine PM	69
Figure 2-2	Ratio of surface area to volume	71
Figure 2-3	Spatial distribution of simulated 24-hr primary and secondary PM2.5 levels averaged across the 52 simulated days when measured Bay Area 24-hr PM2.5 level exceeded 35 µg/m^3	78
Figure 2-4	Estimated Source Contributions to Annual PM2.5 Concentrations	80
Figure 2-5	Estimated Source Contributions to Peak PM2.5 Concentrations	81
Figure 2-6	2010 Annual Primary Emissions of PM2.5, 47 tons/day	
	2010 Winter PM2.5 Emissions	88
Figure 2-7	2010 Winter Primary Emissions of PM2.5, 49 tons/day	89
Figure 2-8	2010 Annual Average Primary Emissions of PM10, 106 tons/day	90
Figure 2-9	2010 Winter Primary Emissions of PM10, 104 tons/day	90
Figure 2-10	2010 Winter Emissions Reactive Organic Gases (ROG) 294 tons/day	91
Figure 2-11	2010 Winter Emissions Oxides of Nitrogen (NOx), 347 tons/day	92
Figure 2-12	2010 Winter Emissions Sulfur Dioxides (SO_2), 29 tons/day	93
Figure 2-13	Bay Area Winter Primary PM2.5 Emissions Trends	96
Figure 2-14	Bay Area Winter PrimaryPM10 Emissions Trends	97
Figure 2-15	Bay Area Winter ROG Emissions Trends	98
Figure 2-16	Bay Area Winter NOx Emission Trends	99

LIST OF FIGURES

Figure 2-17	Bay Area Winter SO_2 Emissions Trends	90
Figure 3-1	Bay Area PM2.5 Annual Design Value 1999-2001 through 2009-2011	112
Figure 3-2	Bay Area Design Values for the 24-Hour Standard 1999-2001 through 2009-2011	113
Figure 3-3	Bay Area PM2.5 Exceedances by Winter Number of days exceeding the 24-hour NAAQS, November 15 – February 15	113
Figure 3-4	Bay Area PM2.5 Exceedances and Conducive Days by Winter	115
Figure 3-5	Design Values for Annual PM2.5 Standard for 3 Central California Air Basins	116
Figure 3-6	Design Values* for 24-Hour PM2.5 Standard for 3 Central California Air Basins	116
Figure 3-7	Bay Area Annual Mean PM10	117
Figure 4-1	Air District Grants Awarded by Project Type from 2007 through 2011 (Total value = $308 million)	131
Figure 4-2	Grant Funds Awarded to Projects in Impacted Communities in 2011 (Total value = $60 million)	131
Figure 4-3	BAAQMD Clean Air Communities Initiative	139

EXECUTIVE SUMMARY

The air we breathe is saturated with millions of microscopic particles. This particulate matter (PM), especially the finest particles, can evade the body's natural defenses and penetrate deep into the lungs, blood stream, brain and other vital organs, and individual cells. Health studies in recent decades have shown that exposure to PM, on both a short-term and a long-term basis, can have a wide range of negative health effects, including respiratory effects such as asthma, bronchitis, and impaired lung development in children, as well as serious cardiovascular effects such as hardening of the arteries, heart attacks and strokes. Health studies in cities throughout the world have found that mortality (death) rates increase with higher PM levels.

PM is a complex pollutant composed of a diverse assortment of extremely small airborne particles, including a mixture of solid particles and liquid droplets that vary greatly in terms of their size and mass, chemical composition, and toxicity. PM originates from a variety of man-made processes and sources such as fossil fuel combustion, residential wood burning, and cooking, as well as from natural sources such as wildfires, volcanoes, sea salt, and geological dust. PM is generated indoors as well as outdoors. Indoor sources include stoves, heaters, fireplaces, consumer products, and cigarettes. Although researchers have been making progress in analyzing PM, there are still major gaps in our understanding of PM and its effects on public health, climate change, and ecosystems.

The Bay Area Air Quality Management District (Air District) and the California Air Resources Board (ARB) have been working to reduce PM levels and human exposure. Thanks to these efforts, PM levels in the Bay Area have been significantly reduced in recent decades. The reduction in PM levels has provided significant public health benefits and has helped to increase average life expectancy in the region. But despite this progress, PM is still by far the air pollutant most harmful to public health in the Bay Area. Although monitoring data shows that the Bay Area currently meets all national (and most State) standards for PM, health studies show that there are negative health effects associated with exposure to PM even below the current air quality standards.

The purpose of this report is to synthesize the latest scientific information about PM and its impacts, describe the Air District's current efforts to analyze and reduce PM in the Bay Area, and lay the groundwork for the Air District's continuing efforts to further reduce PM and better protect public health. The report provides technical information about how PM is emitted and formed in the Bay Area; describes progress in reducing PM levels in the San Francisco Bay Area in recent years; summarizes current regulations and programs to reduce PM emissions and concentrations; identifies future technical work needed to improve the Air District's understanding of PM; and explains the importance of continuing and enhancing the Air District's efforts to reduce PM in order to protect public health, the climate, and the environment.

INTRODUCTION

The mission of the Bay Area Air Quality Management District (Air District or BAAQMD) is to protect and improve air quality, public health, and the global climate. Although we have made great progress in improving Bay Area air quality over the past 50 years, new challenges continue to emerge. Research in recent years indicates that particulate matter (PM) suspended in the air we breathe is the air pollutant that imposes the greatest health burden on Bay Area residents. The available evidence indicates that the most effective way that the Air District can fulfill its mission of protecting public health is to reduce the population exposure of Bay Area residents to PM.

Although PM has been regulated by U.S. EPA as one of the original "criteria air pollutants" since the early 1970's, early efforts to improve air quality primarily focused on other pollutants such as ground-level ozone (smog), carbon monoxide, and toxic air contaminants. PM moved to the forefront of the air quality agenda only in recent years, beginning in the mid-1990's, in response to a series of compelling health studies that linked population exposure to PM with a wide range of respiratory and cardiovascular health effects, including premature death. Indeed, the recognition that PM must be treated as an air pollutant of the highest priority represents perhaps the most important development in the air quality arena in recent years.

This report describes particulate matter and its impacts on public health, climate change, and ecosystems; summarizes technical information about PM, and how it is emitted and formed in the Bay Area; describes progress in recent years in reducing PM levels in the San Francisco Bay Area in relation to State and national PM standards; describes current regulations and programs to reduce PM emissions and concentrations; identifies future technical work needed to improve our understanding of PM; and provides a roadmap to focus Air District resources in the effort to reduce PM and protect public health in the Bay Area in the years to come.

Reducing Population Exposure to PM

Air quality planning to date, in the Bay Area and elsewhere, has generally focused on reducing emissions and ambient concentrations of air pollutants in order to attain State and national ambient air quality standards. This approach has enabled the Bay Area and other regions to make substantial progress in improving air quality, especially for pollutants that are regional in nature, such as ozone. However, in recent years there is a growing recognition that if we want to achieve the ultimate goal of protecting public health, then reducing emissions and concentrations of air pollutants at the regional scale may not suffice. We need to directly consider where, when, and how people are being exposed to air pollution. This is especially true in the case of PM, a complex pollutant whose concentrations in the air can vary substantially depending upon location and time. Therefore, the major objective of this report is to advance our understanding of how the Bay Area public is exposed to PM, which sources

and types of PM are most harmful, and where we should focus efforts to reduce PM in order to better protect public health.

What is PM?

The term **particulate matter** (PM) describes a complex pollutant composed of a diverse assortment of extremely small airborne particles, including a mixture of solid particles and liquid droplets known as aerosols. Most air pollutants (such as ozone, carbon monoxide, and sulfur dioxide) consist of a single molecule or compound. This means that the pollutant will have the same physical properties and the same impacts on public health and the environment, regardless of the source, or combination of sources, from which it is emitted. PM, by contrast, includes a wide range of disparate particles that vary greatly in terms of their size and mass (ultrafine, fine, and coarse), physical state (solid or liquid), chemical composition, toxicity, and how they behave and transform in the atmosphere.

PM includes a wide range of particles that vary in size, chemical composition, and toxicity.

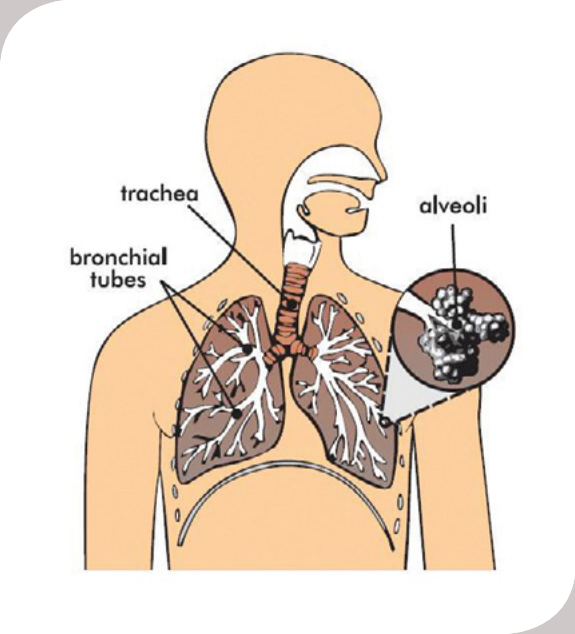
Particles originate from a variety of man-made processes and sources such as fossil fuel combustion, residential wood-burning, and cooking, as well as from natural sources such as wildfires, volcanoes, sea salt, and geological dust. PM is emitted directly from tailpipes, smokestacks, and fireplaces, and also formed indirectly by chemical reactions among precursor pollutants. Particulate matter is generated indoors as well as outdoors. Indoor sources include stoves, heaters, fireplaces, and consumer products, and cigarettes (if smoked inside). As described in Section 1-B, most people experience a significant percentage of their personal exposure to PM in the indoor environment where they are exposed to both ambient (outdoor) PM that penetrates inside as well as PM emissions produced by indoor sources.

Public Health Impacts

Every breath we take contains millions of tiny airborne particles.

PM is a stealthy pollutant - it is generally tasteless and odorless, and most particles are too small to be seen by the naked eye (though PM makes the air look hazy in the distance). But even on clear days when ambient PM concentrations are low and well within air quality standards, we inhale contains millions of tiny particles with each breath. Health studies show that these airborne particles cause and/or contribute to a wide range of respiratory and cardiovascular problems. In addition to effects such as asthma and bronchitis, exposure to PM can trigger major health impacts such as heart attacks or strokes. In fact, the evidence indicates that exposure to PM contributes to the death of more Bay Area residents each year than more visible causes such as auto accidents. Analysis shows that, even at the relatively moderate concentrations that prevail in the Bay Area, PM imposes economic and social costs to Bay Area residents and employers (in terms of sickness, lost productivity, and premature mortality) that run to billions of dollars per year, as discussed in Section 1-A.

How many particles do we breathe?



The number of airborne particles that we are exposed to on a daily basis is truly staggering. The air we breathe contains a very minute amount of PM in terms of its overall mass. However, even such a miniscule amount of mass contains enormous numbers of particles. For example, air with an ambient concentration of 10 micrograms of fine particulate matter (PM2.5, or particles less than 2.5 microns in diameter) per cubic meter - roughly the average concentration of Bay Area PM2.5 on an annual basis - may contain on the order of 100 million particles per cubic meter.

For this reason, we inhale huge numbers of particles. For purposes of illustration, consider the fact that urban air typically contains in the range of 5,000 to 30,000 particles per cubic centimeter, primarily in the ultrafine size range (particles less than 0.1 microns in diameter). The average adult inhales 450 cubic centimeters (roughly one pint) of air per breath. This means that in a typical urban environment we inhale from 1 million to 10 million minute particles with every breath we take. But that figure can spike to much higher levels in close proximity to high-volume roadways or other major outdoor emission sources, or indoor sources such as stoves and ovens. The bottom line is that, during the course of a single day, we inhale many trillions of fine and ultrafine particles, even when the air we are breathing meets air quality standards. Fortunately, our bodies have defenses in the nasal passages, throat, and lungs to filter out particles, so not all the pollutants that we inhale actually reach the air sacs (alveoli) where they can damage the lungs. But some of these tiny particles - which may be coated with acids, metals, and other toxic substances – are able to evade the body's defense mechanisms and penetrate deep into the lungs, bloodstream, cells, and vital organs where they can trigger various biological responses that harm the body.

PM Planning in the Bay Area

In response to concern about the health impacts of PM, in 2003 the State legislature enacted SB 656 (codified as Health & Safety Code Section 39614). This legislation required the Air Resources Board and local air districts to evaluate potential PM control measures and to develop a PM implementation schedule for appropriate PM-reduction measures. The Air District complied with this legislation; staff developed a Particulate Matter Implementation Schedule that was adopted by the Air District's Board of DIrectors in November 2005, and the Air District adopted the measures identified in the Implementation Schedule.

In fall 2010, the Air District adopted the Bay Area 2010 Clean Air Plan (2010 CAP) to update the region's plan to control ground-level ozone. In developing the 2010 CAP, the Air District was inspired by the recommendations issued by the National Research Council in 2004 which called for a new approach to air quality planning based on integrated multi-pollutant planning focused on achieving key outcomes such as protecting public health, the global climate, and ecosystems.

The Bay Area 2010 CAP identified two key goals: (1) protecting public health, and (2) protecting the climate. The 2010 CAP also pursued a multi-pollutant approach in developing an integrated control strategy to reduce four types of air pollutants: ground-level ozone; PM; toxic air contaminants (TACs); and greenhouse gases, such as carbon dioxide and methane, that contribute to climate change.

To inform the development of the 2010 CAP, Air District staff performed a "health burden" analysis, based upon the results of peer-reviewed health studies, in order to estimate:

- the public health effects of air pollution in the Bay Area, based upon key health endpoints such as chronic bronchitis, asthma emergency room visits, hospital admissions for respiratory or cardiovascular diseases, heart attacks, and premature mortality;
- the role of each air pollutant in causing or contributing to these health effects;
- the health benefits due to progress in improving Bay Area air quality in recent years; and
- the economic benefit of the improvement in public health.

Air quality issues are often presented in highly technical terms, using a specialized vocabulary and arcane units of measurement (such as parts per million or micro-grams per cubic meter) that mean little to the average person. The health burden analysis, by contrast, served to put a "human face" on the benefits of better air quality, by expressing its results in terms of tangible outcomes that make sense to policy-makers and the public.

From the policy perspective, the most important finding from the health burden analysis is that PM is the air pollutant that poses *by far* the greatest health risk to Bay Area residents, as shown in Figure 1-4. Although evidence of the public health risk related to PM has been mounting in recent years, it was only by performing this side-by-side health burden analysis for the 2010 CAP

that the predominant impact of PM on public health in comparison to other air pollutants was so starkly revealed.

Progress in Reducing PM Levels in the Bay Area

Although revelations about the health impacts of PM are cause for concern, the good news is that we have already achieved major progress in reducing PM levels in the Bay Area, as described in Section 3-C. Thanks to this progress, the Bay Area currently meets the national ambient air quality standards that apply to PM, and is making steady progress toward attaining more stringent, health-protective California PM standards. The reduction in PM levels in recent years translates into improved public health and vitality, and longer average life span. These benefits are worth billions of dollars in cost savings to Bay Area residents and employers.

Why We Need to Reduce PM Further

The fact that the Bay Area has made substantial progress in reducing PM levels does not mean that we can rest easy, however. There are several reasons why it is important to continue to enhance our efforts to reduce PM emissions, concentrations, and population exposure.

- Researchers have not been able to establish a safe threshold for population exposure to PM. Epidemiological studies have shown that there are health effects from PM2.5 exposure even at concentrations below current standards.
- The U.S. Environmental Protection Agency (EPA) reviews the national PM2.5 standards on a regular basis and may issue more stringent standards in the future.
- Even at the current, relatively low concentrations, PM is the most hazardous air pollutant in the Bay Area in terms of health impacts, including premature mortality, heart attacks, chronic bronchitis and other key health endpoints.
- PM concentrations – and population exposure to PM – can vary significantly at the local scale, as discussed in Section 1-B). Even though the Bay Area currently meets national PM standards based on the measurements from the regional PM monitoring network, some communities and individuals are exposed to higher concentrations of PM. People who live or work near major roadways, ports, distribution centers, or other major emission sources, or in proximity to wood-burning activities, may be disproportionately exposed to certain types of PM (e.g. ultrafine particles), so it is important to implement effective measures to reduce their exposure and health risks.

Challenges

Because PM is a complex pollutant and has become the focus of intense research only in recent years, there are still major gaps in our understanding of PM and its effects on public health, climate change, and ecosystems. These gaps are especially profound in regard to ultrafine PM, the smallest

particles. As discussed in Section 1-A, health researchers are working to better understand which sizes and types of PM are most damaging to public health, and to explain the precise biological mechanisms by which PM damages our health. Similarly, climate scientists are striving to better define the various mechanisms by which different types of particles act upon the climate, and the overall effect of ambient PM on the climate.

Although many health studies to date suggest that breathing PM of all types may have negative health effects, researchers suspect that certain types of particles may be especially harmful. And intuitively, it makes sense that the size and chemical composition of particles should make a difference in terms of their health effects. Because health studies have not yet clearly defined the specific particle types that are most harful, regulators currently treat all fine PM as equal in terms of its health impacts.[1] However, determining the types of particles which are the most harmful is vitally important in the quest to understand PM. The current across-the-board approach to reducing PM has clearly provided major benefits in terms of reducing PM concentrations and protecting public health. But if certain particle types can be identified as the key culprits, and if specific sources account for the bulk of their emissions, then we may be able to identify appropriate control measures with a higher degree of precision, rather than pursuing reductions in all types of PM across the board. The ability to target the particles with the most severe health impacts would enable us to better protect public health, and also to identify measures that would achieve the greatest benefit at the lowest cost.

Since it is clear that we need to enhance our efforts to reduce PM in order to protect public health, PM will continue to be a major focus of air quality planning, regulation, and public education in the Bay Area over the next decade. Despite the gaps in our understanding of PM, we must develop and implement policies to control PM in the near-term, while refining our policies and priorities to reflect new information as it becomes available. Because we still have a great deal to learn, this report cannot serve as the final word on how to address PM in the Bay Area. But it is meant to lay the groundwork to guide the Air District's efforts to reduce PM in the coming years.

1 Certain types of particles, such as metals, polyaromatic hydrocarbons (PAHs), and diesel PM, are classified as toxic air contaminants (TACs), and are thus subject to regulation as TACs.

SECTION 1 : PM IMPACTS

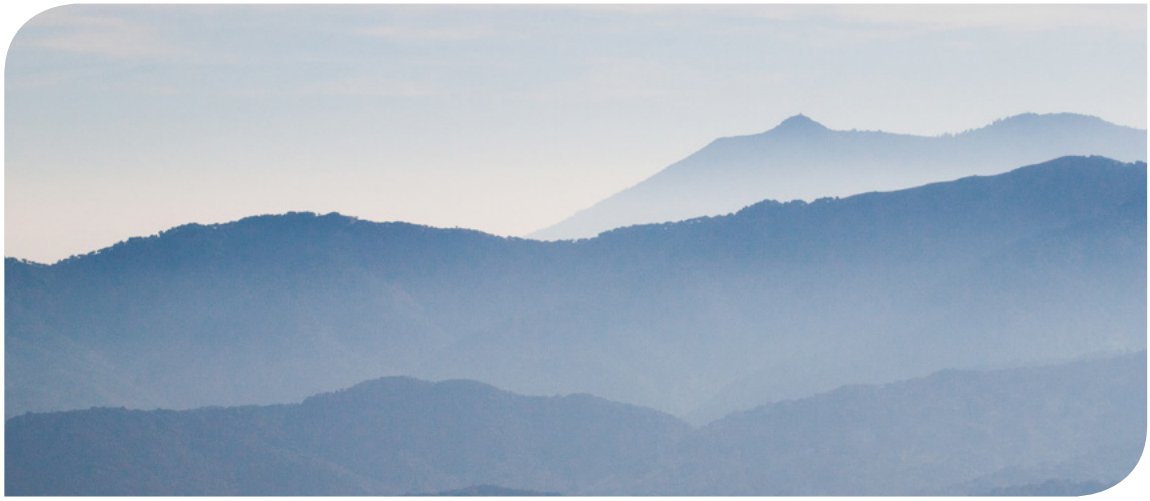
SECTION 1-A: THE PUBLIC HEALTH EFFECTS OF PM

This section summarizes methods used to study PM health effects, the current evidence regarding public health impacts related to exposure to PM; the biological pathways by which PM affects the body; which sizes and types of particles pose the greatest health risk; the estimated health burden from PM in the Bay Area; and why it is important to further reduce PM levels to protect the health of Bay Area residents.

This section will consider several key questions regarding the health effects of particulate matter:

- What types of negative health impacts are associated with exposure to PM?
- Does evidence show that exposure to PM is bad for public health?
- How does PM damage the body?
- Which types and sizes of particles are most harmful to health?
- Are there safe levels of PM?
- How does PM affect public health in the San Francisco Bay Area?

The discussion presented below attempts to synthesize information from the vast literature of studies that have analyzed the health effects of various particle sizes, including PM10 (particles less than 10 microns in diameter), PM2.5 (particles less than 2.5 microns in diameter), and ultrafine PM (particles less than 0.1 microns in diameter). An explanation of the various PM size categories is presented in Section 2 of this report.



A great deal of research has been performed in the past 25 years to identify and quantify the health risks of particulate matter. Health studies have linked exposure to PM with a wide range of negative health effects. The research provides evidence that exposure to PM, even at low and moderate levels, can cause or contribute to a wide range of respiratory and cardiovascular disease, including:

- irritation of the airways, coughing, or difficulty breathing
- decreased lung function
- aggravated asthma
- chronic bronchitis
- irregular heartbeat
- strokes
- heart attacks
- premature death in people with heart or lung disease

Challenges in Analyzing the Health Effects of PM

Determining the health effects of air pollutants is inherently difficult. But because PM is a heterogeneous pollutant comprised of particles that vary in size, mass, and chemical composition, this presents special challenges in determining its health effects. In the case of air pollutants composed of a single molecule, such as ozone (O3) or carbon monoxide (CO), the pollutant has exactly the same chemical composition – and thus the same potential health effects – regardless of the emissions source. However, in the case of PM, the composition of particles in a given air sample – and the corresponding health effects – will vary depending on the mix of emission sources.

Early Evidence of PM Health Effects

Several dramatic episodes in the first half of the 20th century demonstrated that very high levels of PM and other air pollutants can cause sickness and death. Early scientific research into the health effects of PM and air pollution was triggered by the December 1930 episode in the heavily populated and industrialized Meuse Valley of Belgium; this extreme air pollution episode killed more than 60 people over a three-day period. A similar tragedy occurred in Donora, Pennsylvania in October 1948 when an inversion layer trapped a lethal mix of PM, sulfuric acid, nitrogen dioxide, and other pollutants from local industrial plants for five days. Nearly half of the town's 14,000 residents became sick, twenty people perished, and 800 animals died.

Perhaps the most infamous air pollution episode occurred in London in December 1952, when a combination of coal combustion, cold weather and windless conditions trapped a thick layer of PM and

other pollutants over the city, killing thousands. By comparing death rates during this event with normal conditions, London's Ministry of Health estimated at the time that nearly 4,000 deaths occurred as a result of the extreme air pollution. However, more recent research (Bell et al. 2004) suggests that the number of fatalities was considerably greater, on the order of 12,000. Death certificates and autopsies show that the main causes of death were respiratory and cardiovascular disease. These extreme episodes showed the need to study the effects of air pollution on public health.

Analyzing the Health Effects of PM

Researchers have developed various methods to analyze the health effects of PM and other air pollutants in terms of both morbidity (disease or illness) and mortality (premature death). Two of the most important techniques used to analyze the health effects of PM are epidemiological studies and clinical studies. Epidemiological studies analyze health data for a defined population group; the objective is to tease out the health effects of air pollution by looking for correlations between the amount of exposure to a pollutant and the observed incidence rate for various health endpoints (e.g., cases of respiratory or cardiovascular disease, hospital admissions, or premature mortality). If a correlation is observed, researchers must then try to determine whether the relationship may be inferred to be causal, meaning that exposure to the pollutant actually causes the observed health effect.

Establishing a causal relationship between PM and a given health effect is difficult because exposure to PM is only one factor among many that may cause, contribute to, or exacerbate a specific health effect. Other factors that affect our health include genetic and biological factors, environmental conditions (air quality, water quality, climate), and lifestyle (diet, exercise, drinking, and smoking), to name but a few. Therefore, in designing studies to analyze the health effects of air pollutants, epidemiologists attempt to isolate the effect of the air pollutants by controlling for (masking) the effect of these other socioeconomic (e.g. income and education), demographic (age, gender, etc.), environmental, and lifestyle factors that impact public health. One of the difficulties in air pollution epidemiology is that the health risks associated with current ambient levels of air pollution, while significant, are nonetheless extremely small when compared to other known risk factors, such as cigarette smoking, lack of physical activity, obesity, etc. Because these other risk factors have a powerful impact on health, it is difficult to distinguish the more subtle effects of air pollution from the health effects attributable to these other factors.

One of the key challenges in epidemiology is estimating how much the people in a study group have been exposed to the pollutant in question. Exposure estimates are generally based upon PM monitoring data and/or results of computer modeling to simulate ambient PM concentrations. Many studies rely on ambient air quality data from monitoring networks, but these data may not capture exposures in micro-environments. And even if accurate estimates of population exposure to ambient (outdoor) PM are available, epidemiological studies generally do not include indoor exposure to PM, which accounts for a significant portion of total exposure for many people, as discussed in Section 1-B. Improved methods to estimate population exposure to PM across the full range of indoor and outdoor environments would be valuable to enable epidemiologists to better analyze the health effects related to exposure to PM.

Analyzing health effects related to PM is also complicated by the fact that the various species of PM, as well as a variety of other pollutants and toxic air contaminants, are all mixed together in the air that we breathe. Therefore, isolating the health effects of PM from other types of pollutants, or distinguishing the effects of a certain size fraction of PM, or a certain chemical species of PM, from the overall mass of PM is a difficult task.

Despite these caveats, epidemiological studies are of great value in helping to illuminate the relationship between air pollutants and health effects. For example, exposure to PM is rarely, if ever, cited as the cause of death in a coroner's report when someone dies of a heart attack or stroke or lung disease. However, epidemiological studies indicate that exposure to PM is an important contributing factor in hundreds, perhaps thousands, of deaths in the Bay Area each year. Epidemiological studies are used to analyze:

- Correlations between exposure to air pollutants and the incidence rate of both acute (short-term) and chronic (long-term) health effects among the general population or defined sub-groups;
- Concentration-response functions; i.e., how a change in the ambient concentration of a pollutant may affect the incidence rate of a specific health effect. Concentration-response functions can be used to estimate the reduction in health effects that can be expected from a given improvement in air quality, such as attaining an ambient air quality standard in the Bay Area or other metropolitan area.
- Safe thresholds, i.e., a "no-effects" threshold such as an ambient concentration below which no health effects can be observed. This is especially important for purposes of ensuring that ambient air quality standards are sufficiently health protective.

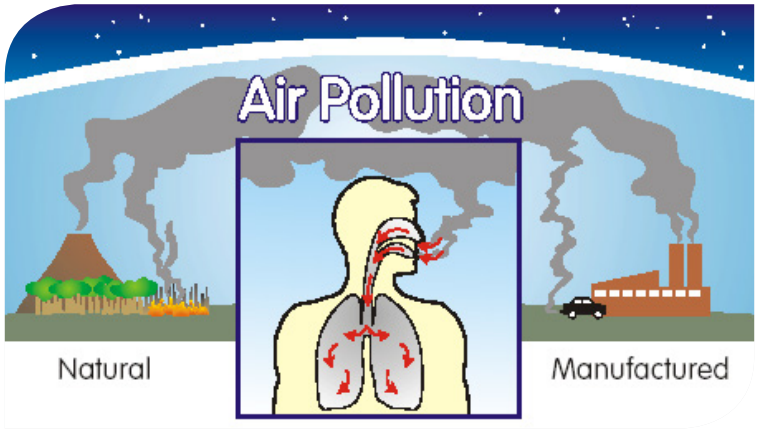
Epidemiological studies are an essential tool to discern correlations between exposures to air pollutants and health outcomes. However, these studies are based on statistical analysis of large population groups; they cannot definitively "prove" that air pollution causes a specific health effect either in an individual case or among a larger population group. Nor can they explain the precise biological mechanisms by which PM causes or contributes to the negative health effects observed. To investigate these issues, researchers perform clinical studies of small groups of people or animals in which they can carefully control the exposure and dosage and observe the impacts over a specific timeframe. These clinical studies are valuable in terms of confirming results of large-scale epidemiological studies at the individual level. Clinical studies also help to define biological mechanisms; that is, exactly how PM or other air pollutants act on and harm the body.

Recent Research on Health Effects of PM

By the 1970s, a link between exposure to PM and respiratory disease, such as triggering asthma episodes or other pulmonary disorders, had been well established, although there was uncertainty as to the level of PM exposure required to trigger significant public health impacts. Based on the

evidence regarding the **respiratory effects** of particulate matter, such as asthma, bronchitis, and diminished lung function, PM was included among the six original "criteria pollutants" identified in the ground-breaking federal Clean Air Act of 1970. However, in the ensuing two or three decades after the Clean Air Act was enacted, other air pollutants such as ozone, carbon monoxide, and lead, were thought to pose a greater health risk than PM. As a result, air pollution control efforts focused primarily on reducing these other pollutants.

PM began to move to the forefront of concern about the health impacts of air pollution beginning in the 1990s in response to a new series of studies on PM health effects. Research in recent years provides evidence that, even at moderate or low levels, PM has a wide range of negative health impacts and can contribute to premature mortality. Whereas earlier research focused primarily on respiratory effects of PM, recent years have seen a great deal of research into the effects of PM on the **cardiovascular system**, the heart and blood system which takes oxygen from the lungs and distributes it throughout the body. Negative impacts of PM on the cardiovascular system include atherosclerosis (hardening of the arteries), ischemic strokes (caused by obstruction of the blood supply), and heart attacks. These new findings about the cardiovascular effects of exposure to PM, especially the increase in premature mortality in adults, have given greater urgency to the need to reduce PM.



PM Impact on Premature Mortality and Life Expectancy

Concern about PM health impacts was crystalized in the early to mid-1990s by a series of epidemiological studies that analyzed the correlation between PM and premature mortality (death).

- Studies in various cities with different climates, pollution mixes, and demographics consistently found a correlation between daily changes in PM levels and daily mortality.
- The two most important studies were the Harvard "Six Cities Study" (Dockery et al. 1993) which followed the health of over 8,000 people for a period of 14 to 16 years, and the March 1995 American Cancer Society study (Pope et al. 1995) which analyzed a study group of over half a million people in 151 cities. Both studies found that long-term exposure to PM is associated with cardiopulmonary mortality in adults. The Six Cities Study found that an increase of 10 $\mu g/m^3$ in ambient PM2.5 concentrations increases the risk of death from all cardiovascular causes by 19%. The American Cancer Society

study found that an increase of 10 μg/m^3 in ambient PM2.5 levels increases the risk of death from all cardiovascular causes by 13%.

It was already known, based on the severe pollution episodes in years past described above, that exposure to extremely high concentrations of PM and other air pollutants can kill people. But these new studies found that people may experience serious health effects, including premature mortality, from exposure to ambient PM at concentrations that most people would not even notice, including clear days when PM levels are below the current national ambient PM standards. For example, a recent study (Wellenius et al. 2012) on the link between PM and ischemic strokes in the Boston area (a region which attains the national 24-hour PM2.5 standard) found that the risk of stroke was 34% higher on days with "moderate" PM2.5 levels compared with days with "good" PM2.5 levels, as defined by the EPA Air Quality Index. The study also found that exposure to PM2.5 levels considered safe by the EPA increases the risk of ischemic stroke onset within hours of exposure and that the increase in risk was greatest within 12 to 14 hours after exposure to PM2.5.

People may experience negative health effects from exposure to PM even on clear days when PM levels are below the current national standards.

In assessing the linkage between PM and premature mortality, it is instructive to consider the leading causes of death in America. According to Center for Disease Control data for 2009, heart disease (25%), chronic lower respiratory disease (5%), and strokes (5%) are three of the four leading causes of death in the U.S., and collectively they account for 35% of all mortality. So if exposure to PM exacerbates cardiovascular and respiratory conditions even to a modest extent, this can be expected to exert a tangible impact in terms of increasing the overall mortality rate.

Since exposure to PM has been found to increase the incidence of premature mortality, it stands to reason that reducing PM levels should prevent premature death and thus help to extend average life expectancy. One recent study (Pope et al., 2009) analyzed the change in life expectancy as PM levels declined over the 20-year period from 1980 through 2000, based on data from 211 U.S. counties in 51 metropolitan areas. This study found that a 10 μg/m^3 decrease in PM2.5 levels was associated with a 7.3 (± 2.4) month increase in life expectancy. Analysis by Air District staff estimated that the improvement in air quality from 1990 to 2008 increased average Bay Area life expectancy by approximately six months per person during this period.[2] Since PM is estimated to be responsible for roughly 90% of the premature mortality related to air pollution in the Bay Area, most of this improvement in life expectancy due to improved air quality can be attributed to reduced PM concentrations.

2 See Appendix A in Bay Area 2010 Clean Air Plan: www.baaqmd.gov/Divisions/Planning-and-Research/Plans/Clean-Air-Plans.aspx

Reaction to Findings

The findings of these studies in the 1990s linking PM to premature mortality provoked controversy and skepticism. Researchers were surprised by results showing a broad range of health impacts from exposure to low ambient concentrations of PM. Health experts were perplexed by these findings, because at that time there were no known biological mechanisms to explain how exposure to relatively low concentrations of PM would produce the health effects observed in the epidemiological studies, especially in terms of cardiovascular disease and death.

In response to the controversy generated by these studies, researchers reexamined the results of the studies, and also embarked on a search for biological mechanisms to explain the health effects observed in these studies. To address concerns about methodological issues with previous studies, the Health Effects Institute funded the *National Morbidity, Mortality, and Air Pollution Study* (NMMAPS) (Samet et al. 2000). Over a five-year period through 2005, NMMAPS performed a time-series study using a consistent method to analyze health impacts of PM10 in the 90 largest American cities, cities that cover a wide geographic area and have varying levels of air pollutants. The NMMAPS largely confirmed the the findings in the original studies that, on average, for every 10 μg/m^3 increase in PM10, there was a 0.5% increase in overall mortality on the following day, as well as a 2% increase in hospital admissions for pneumonia and chronic obstructive pulmonary disease.

Summary of PM Health Effects

To inform its period review (once every five years) of PM air quality standards, U.S. EPA prepared a detailed synthesis of the vast body of literature on PM health effects and issued its December 2009 *Integrated Science Assessment for Particulate Matter*. Based on the cumulative weight of the studies in the literature, EPA's conclusions regarding the strength of the evidence to support a finding of causality between exposure to PM2.5 and key health effects are summarized in Table 1-1. EPA also reviewed the evidence as to whether exposure to coarse PM and to ultra-fine PM has been proven to cause negative health effects; they found that the evidence currently available was either **suggestive** of causality or **inadequate to establish causality** in the case of coarse PM and ultra-fine PM.

Table 1-1 US EPA Findings on Health Effects for Particulate Matter

Health Outcome	Causality Determination	Examples of Health Effects
Size Fraction: $PM_{10-2.5}$ Coarse PM		
Short -Term Exposure		
Cardiovascular Effects	Suggestive	Increase in hospital admissions and emergency room visits for cardiovascular causes
		Reduction in heart rate variability
Respiratory Effects	Suggestive	Increase in hospital admissions and emergency room visits for respiratory causes, particularly in children
		Pulmonary inflammation
Mortality	Suggestive	
Central Nervous System	Inadequate	
Long -Term Exposure		
Cardiovascular Effects	Inadequate	Increase in hospital admissions for ischemic heart disease
		Arrhythmia
		Reduction in heart rate variability
Respiratory Effects	Inadequate	
Mortality	Inadequate	
Reproductive & Developmental	Inadequate	Low birth weight
Cancer, Mutagenicity, Genotoxicity	Inadequate	
Size Fraction: $PM_{2.5}$ Fine PM		
Short -Term Exposure		
Cardiovascular Effects	Causal	Myocardial ischemia (reduced blood flow to the heart)
		Congestive heart failure
		Altered vasomotor function (stiffening and reduced flexibility of blood vessels)
Respiratory Effects	Likely to be causal	Alterations in lung function & respiratory symptoms in asthmatic children
		Chronic obstructive pulmonary disease
		Respiratory infections

Health Outcome	Causality Determination	Examples of Health Effects
Mortality	Causal	Cardiovascular- and respiratory-related mortality
Central Nervous System	Inadequate	Pro-inflammatory responses in the brain that may lead to neurodegenerative diseases
Long -Term Exposure		
Cardiovascular Effects	Causal	Higher blood pressure
		Increased blood coagulation
		Enhanced development of atherosclerosis (hardening of the arteries)
		Reduction in heart rate variability
		Increased risk of heart disease and stroke
Respiratory Effects	Likely to be causal	Impaired lung development
		Increased respiratory symptoms
		Asthma
		Altered pulmonary function
		Chronic bronchitis
Cancer, Mutagenicity, Genotoxicity	Suggestive	Lung cancer
Reproductive & Developmental	Suggestive	Low birth weight
Mortality	Causal	Cardiovascular mortality, lung cancer mortality, and Infant mortality due to respiratory causes
Size Fraction: Ultrafine PM		
Short -Term Exposure		
Cardiovascular Effects	Suggestive	Increased markers of oxidative stress
		Changes in vasomotor function
		Alterations in heart rate variability parameters
Respiratory Effects	Suggestive	Oxidative, inflammatory and allergic responses
		Decreases in pulmonary function

Health Outcome	Causality Determination	Examples of Health Effects
Mortality	Inadequate	
Central Nervous System	Inadequate	
Long -Term Exposure		
Cardiovascular Effects	Inadequate	
Respiratory Effects	Inadequate	Pulmonary inflammation
		Oxidative and allergic responses
Mortality	Inadequate	
Reproductive & Developmental	Inadequate	
Cancer, Mutagenicity, Genotoxicity	Inadequate	

Source: EPA Integrated Science Assessment, December 2009, Table 2-6

Table 1-2 presents the findings of a recent Harvard School of Public Health study (Kloog et al. 2012) that analyzed hospital admission rates throughout New England in terms of the correlation between PM2.5 exposure and hospital admission rates for respiratory disease, cardiovascular disease, strokes and diabetes. The effects from long-term exposure to PM2.5 are significantly higher than for short-term exposure for all four causes of admission.

Table 1-2: Estimated increase in hospital admissions rate for a 10 μg/m³ increase for short-term and long-term exposure to PM2.5 by cause of admission

PM2.5 Exposure Type	All Respiratory	Cardiovascular Disease	Stroke	Diabetes
Short-term	0.70%	1.03%	0.24%	0.96%
Long-term	4.22%	3.12 %	3.49%	6.33%

Source: Kloog et al. Acute and Chronic Effects of Particles on Hospital Admissions in New England. Harvard School of Public Health, 2012. www.hsph.harvard.edu/clarc/sac2012/kloog-ne.pdf

No Safe Threshold Has Been Identified

The federal Clean Air Act requires US EPA to adopt ambient air quality standards for PM and other criteria pollutants at a level that provides an "adequate margin of safety ... requisite to protect the public health." EPA is charged with reviewing the standards every five years based on the latest scientific evidence on health effects. A key issue in setting standards is whether researchers can identify a safe threshold below which level no negative health effects are observed. To date, researchers have not been able to identify a "no-effects" threshold for PM. The evidence suggests that in terms of the effect of PM on premature mortality, the concentration-response function (i.e., how the incidence of a given health effect varies in response to a change in ambient concentration of the pollutant) is essentially linear (EPA Integrated Science Assessment for PM, 2009). These findings suggest that people exposed to PM at levels below the current EPA standards may still experience negative health effects. (PM air quality standards are discussed in Section 3.)

Recent Findings

Research on the health effects of PM is on-going. Our understanding of PM health impacts is gradually enhanced as new studies and journal articles appear at a steady rate. The new research reinforces earlier findings regarding negative impacts of PM on both respiratory and cardiovascular health, and increased rates of health impacts such as heart attacks, strokes, and premature death in response to PM exposure. However, in addition to confirming the results of earlier research, new research is also uncovering evidence of a wider range of potential health effects from exposure to PM, including, linkages to diabetes, reduced cognitive function in older adults, and oxidative damage to DNA.

New research is uncovering evidence of a wider range of potential health effects from exposure to PM, including linkages to diabetes, reduced cognitive function in older adults, and oxidative damage to DNA.

Diabetes: The incidence of Type 2 diabetes (sometimes referred to as "adult onset" diabetes) has increased rapidly in recent years in response to sedentary lifestyles, changes in diet, and higher rates of obesity. People are also contracting Type 2 diabetes at a younger age as well. Experts predict major impacts on public health and enormous costs to the health care system as a result of increasing diabetes rates. Although diet and lifestyle are key factors in diabetes incidence, a recent nationwide study (Pearson et al. 2010) found that air pollution may also be a risk factor for diabetes. The study concluded that diabetes prevalence increases with increasing PM2.5 concentrations, with a 1% increase in diabetes prevalence seen with a 10 $\mu g/m^3$ increase in PM2.5 exposure. These results suggest that PM2.5 may contribute to increased diabetes prevalence in the adult U.S. population and that air pollution is a risk factor for diabetes. There is also some evidence that people with diabetes may be more vulnerable to the negative health effects of PM. A recent study (O'Donnell et al. 2011) by the Harvard School of Public Health found that diabetics exposed to PM may be at higher risk for ischemic stroke compared to the background population.

Impacts on the Brain and Cognition: Although the lungs and the circulatory system are the primary path by which particles are transported throughout the body, studies (e.g., Oberdörster et al. 2010) have found that particles can also enter the central nervous system and then the brain via olfactory neurons in the nasal passages. When ultrafine particles travel via olfactory nerves to the brain, they are able to bypass the blood-brain barrier, the defensive shield that blocks unwanted chemicals from reaching sensitive brain cells. Studies which exposed mice to both fine and ultrafine particles showed inflammatory responses in the brain. Ultrafine particles can also damage brain cells in the basal ganglia, the region of the brain impacted by degenerative nerve diseases such as Parkinson's (Peters et al. 2006).

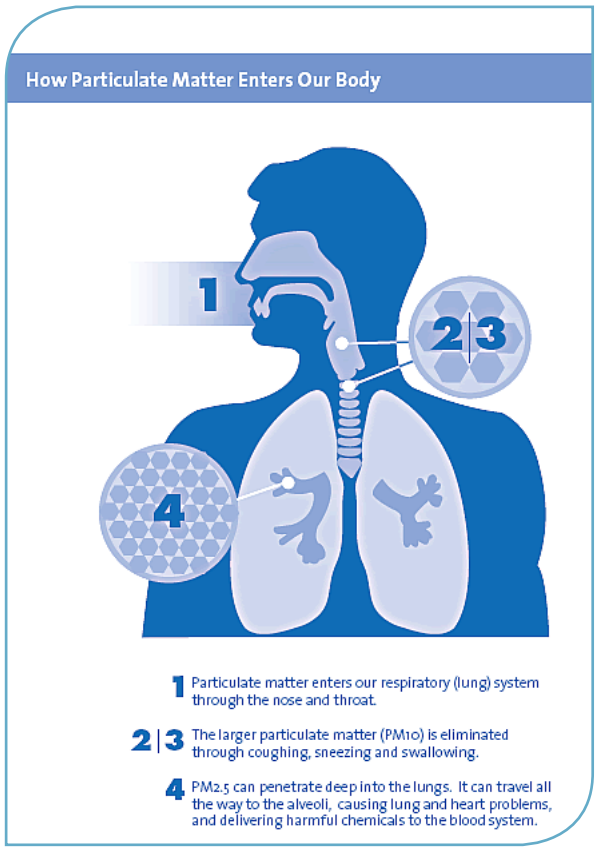
A recent study (Weuve et al. 2012) found an association between long-term exposure to both fine PM and coarse PM and cognitive capability in older women. This study, based on the longitudinal Nurses' Health Study Cognitive Cohort, examined the effects of PM exposure over 7-14 years for nearly 20,000 American women aged 70 to 81. The study found that women exposed to higher levels of PM experienced more rapid cognitive decline, and concluded that the effect of a 10 $\mu g/m^3$ increment increase in long-term PM exposure is equivalent to approximately two years of cognitive aging. The study noted that higher levels of exposure to ambient PM are associated with worse cognitive decline, and that the effects observed occurred at levels of exposure typical of many areas of the United States. The authors suggest that reducing particulate levels may help to reduce the future incidence of age-related cognitive decline and dementia. In a clinical postmortem study (Calderon-Garciduenas et al. 2004) that also points to a potential connection between PM and cognitive impairment, researchers found higher levels of amyloid-B42, a hallmark of Alzheimer's disease, in the brains of people who lived in cities with higher pollution levels. Clinical studies in animals have shown increased brain inflammation in response to PM exposures.

Biological Pathways: How PM Harms the Body

External exposure to PM can cause short-term impacts to external organs, such as irritation of the eyes. But the most damaging effects are caused when pollution enters the body via the respiratory system. The mechanisms by which PM and other air pollutants damage the lungs and the respiratory system are well understood. Our lungs serve as the entry point to the body for PM and other pollutants, so they are the organ most directly impacted by air pollution. In addition, the lungs are especially sensitive to air pollutants because they contain a large surface of exposed membrane to facilitate the delivery of oxygen to the blood system. Our respiratory system has defenses in the nasal passages, throat, and lungs that filter out particles, but the smallest particles are most likely to elude the body's filtration mechanisms. For example, as much as 50% of ultrafine particles with a diameter of 0.02 microns or smaller are estimated to be deposited in the alveolar region of the lung. Particles inhaled deep into the lungs can then be transported to cells and organs throughout the body. And once particles become deeply embedded in our body, they can remain there for weeks, months, or even years.

Figure 1-1 depicts how PM enters the body. The larger particles are typically filtered out; in contrast, particles less than 2.5 microns in diameter can penetrate deep into the lungs which are where most health problems begin.

Figure 1-1 How Particulate Matter Enters Our Body



Source: British Columbia Air Quality (www.bcairquality.ca/health/air-quality-and-health.html)

On the individual basis, the health impact of long-term exposure to PM is likely to be determined by the number of particles that are transported from the lungs into the body, the chemical composition of the particles, and how quickly the particles are cleared from the body.

Researchers have been making progress in recent years in explaining how PM damages the cardiovascular system and other organs and systems, but this is still an area of on-going research. Research to date indicates that inflammation and oxidative stress are two of the key ways that PM damages the body.

Inflammation: When foreign substances are deposited in the body, this irritates the impacted area and causes an inflammatory response. Studies (e.g., Araujo et al. 2010) have found that exposure to PM can lead to chronic, low-level inflammation. An inflammatory response to PM or other air pollutants can damage the body in many ways. In the vascular system, an inflammatory response to PM can stiffen blood vessels and reduce their flexibility, leading to higher blood pressure, increased blood coagulation, hardening of the arteries (atherosclerosis), altered cardiac autonomic function (the system that controls the heart), and reduction in heart rate variability (a risk factor for future cardiovascular problems). All these effects can increase long-term risk of heart disease or stroke. Based on high particle numbers, high lung deposition efficiency and surface chemistry, ultrafine PM may be especially dangerous in terms of its potential to induce inflammation.

Oxidative Damage to DNA: Studies (e.g., Risom et al. 2005) indicate that exposure to PM increases **oxidative stress**. This term describes the effect of oxidation in which an elevated level of reactive oxygen species, such as free radicals (e.g. hydroxyl, nitric acid, superoxides) or non-radicals (e.g. hydrogen peroxide, lipid peroxide) causes oxidative damage to specific molecules, thereby injuring cells or tissue. There is evidence that ultrafine PM may cause oxidative damage to DNA. For example, a Danish study (Vinzents et al. 2005) found that participants who rode bicycles in traffic in Copenhagen, and were thus subjected to increased exposure to ultra-fine PM, sustained oxidative damage to their DNA, thus demonstrating an association between DNA damage and ultrafine PM exposure in live subjects.

Cardiovascular effects: In terms of explaining how PM damages the cardiovascular system, more study is needed to determine how exposure to PM affects intermediate health outcomes such as heart rate variability and inflammation markers. In a paper (Pope & Dockery 2006) reviewing research on the health effects of PM, two of the leading researchers summarize their discussion

of biological mechanisms as follows: "Various plausible pathways have been identified. However, none has been definitively demonstrated to be the pathway that directly links exposure to PM with cardiopulmonary morbidity and mortality. In fact, it is unlikely that any single pathway is responsible. There are almost certainly multiple pathways with complex interactions and interdependencies."

Which sizes and types of particles are most dangerous?

Evidence suggests that PM health effects depend upon both particle size and particle composition.

Particle Size: Research indicates that the health effects of PM depend upon particle size. Smaller particles (in the fine and ultrafine size ranges) are generally more harmful than coarse particles. Smaller particles typically remain suspended in the air for longer periods; penetrate more readily and deeply into the lungs, bloodstream and organs; and present a large amount of reactive surface area relative to their mass.

Ultrafine PM: A growing body of evidence documents public health effects from ultrafine particles. Motor vehicles are a major source of ultrafine particle emissions, and these particles are highly reactive when emitted from internal combustion engines. Because ultrafine particles are so miniscule, they can travel deep into the lungs and organs and pass through cell membranes. These particles can also carry toxic compounds into the body. Based on high particle numbers, high lung deposition efficiency, and surface chemistry, ultrafine particles may have a greater potential than PM2.5 for inducing inflammation and oxidative stress, key mechanisms by which PM harms the body. In clinical studies, greater inflammatory and oxidative stress (cell, tissue or organ damage), resulting in damage to DNA, has been associated with exposure to ultrafine particles compared to the larger particles at comparable mass doses. In some cases, the substances absorbed on to the ultrafine particles may be responsible for some of the effects observed, including oxidative stress, rather than the particles themselves. A study (Oberdoster et al. 2010) that examined the effects of combustions fumes on laboratory rats found that, compared to larger particles, ultrafine particles cause a greater inflammatory response in the lungs of rats and increased antioxidant levels in their lung tissues.

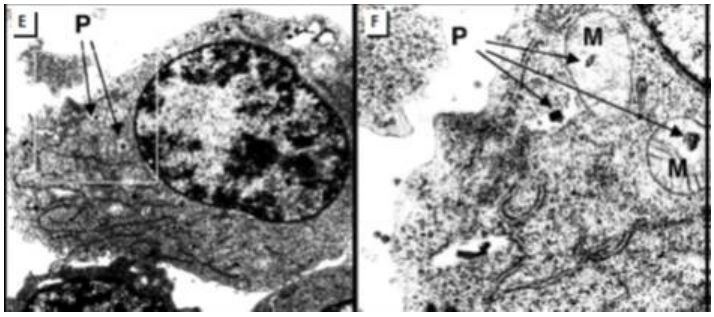
Numerous studies (e.g., Wichmann 2000) have found a correlation between exposure to ultrafine PM and increased incidence of health effects such as premature mortality, hospital admissions, lung cancer and other cancers, cardiovascular disease, adverse birth outcomes, effects on the immune system, and neurotoxicity. In cell cultures exposed to ambient particles, ultrafine particles were found in the mitochondria where they induced structural damage.

Research on health effects related to exposure to ultrafine PM is still very limited compared to the amount of research that has been performed into the health effects of PM2.5. For example, specific mechanisms of health effects from exposure to ultra-fine nitrate and sulfate particles are not well defined, nor are the health effects of semi-volatile organic compounds and trace metals found in ultrafine PM. However, existing studies suggest that ultrafine PM may have significant health effects, and that some of the health effects related to ultrafine particles may be independent of the effects from exposure to PM2.5 and/or PM10.

PM Damage to Cells

Figure 1-2 depicts an image of what happens when PM passes through the lungs and penetrates into cells. Photos E and F (magnified x 6,000 and 21,000, respectively) show a cell exposed for 16 hours to fine PM (PM2.5). The "P" indicates damage to **cristae**, the inner membrane of the mitochondria, which are studded with proteins and increase the surface area for chemical reactions, such as cellular respiration, to occur. The "M" points to the presence of particles inside the mitochondria as well as ultra-structural damage to the mitochondria. Mitochondria, sometimes described as "cellular power generators" supply cellular energy, and are involved in a number of processes such as signaling, cellular differentiation, cell death and the control of the cell cycle and cell growth. Mitochondria have a central place in cell metabolism and their damage plays an important role in a wide range of health effects.

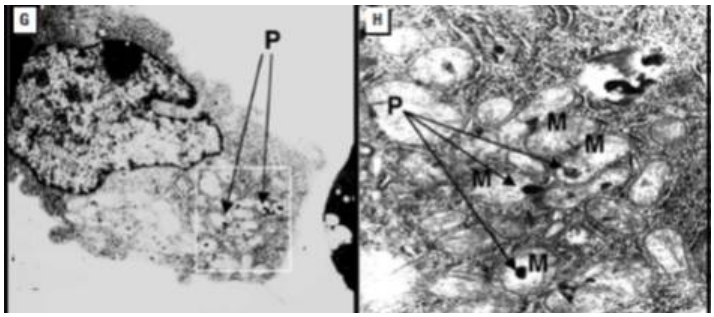
Figure 1-2 Cells Exposed to Fine PM (PM2.5) for 16 Hours



Source: Cho et al. *Ultrafine Particulate Pollutants Induce Oxidative Street and Mitochondrial Damage.* Environmental Health Perspectives. 2003 April; 111(4): 455–460.

Figure 1-3 shows images of a cell exposed to ultrafine PM for 16 hours. As in the figure above, the "P" points to damage to the cristae, and the "M "shows the presence of particles inside the mitochondria as well as structural damage. The degree of ultra-structural damage in this study was found to be greater in the cells exposed to ultrafine PM than the cells exposed to fine PM (and even more so than those exposed to coarse PM, which experienced little if any mitochondrial damage).

Figure 1-3 Cells Exposed to Ultrafine PM for 16 Hours



Source: Cho et al. 2003.

Relationship Between Particle Composition and Health Effects

The available evidence from epidemiological studies to date suggests that fine particles themselves are harmful, regardless of their emissions source or chemical composition. Isolating and pinpointing the health effects of a specific particle type through epidemiological studies is difficult, because many particle types and sizes are co-emitted by the same sources and processes, and the air we breathe always includes a diverse mix of particle sizes and types. Because risk estimates for any specific particle type are subject to confounding by co-pollutants, the evidence for differential health risk among PM2.5 components is not as robust as for PM2.5 as a whole. Therefore, when estimating the health impacts of PM, most researchers currently assume that all mixtures of PM2.5 are equally potent. And in the absence of information to clearly distinguish the relative risk of different particle

types, US EPA and ARB currently treat all particles alike, regardless of their chemical make-up, for purposes of PM air quality standards. (It should be noted, however, that ARB does call out diesel PM for special attention as a toxic air contaminant.)

But even though it is difficult to determine the relative harmfulness of different particle types, variation in particle composition and behavior suggests that their health effects are likely to differ as well. There is some evidence that specific particle types, such as black carbon and diesel PM2.5, may be especially harmful. For example, fine and ultrafine particles produced by fuel combustion may be more toxic, because they are highly reactive and because they include sulfates, nitrates, acids, trace metals and other toxic contaminants. Researchers have also hypothesized that insoluble ultrafine particles with a solid core may be more harmful than soluble particles. Whereas soluble particles will dissolve as they interact with blood and body liquids, the insoluble particles persist in solid form and can thus penetrate through protective barriers to irritate and inflame deep within the body (Ostiguy et al., IRSST, 2006).

As the science advances, at some future date it may be possible to link the various health effects associated with PM to specific particle types, or combinations thereof. From the standpoint of protecting public health, determining which sizes or types of particles are most harmful is vitally important in the quest to understand PM. If new information becomes available to identify and help target the most harmful particle types, then we should be able to develop more effective control measures to maximize public health benefits in the most cost-effective manner.

From the standpoint of protecting public health, determining which sizes or types of particles are most harmful is vitally important in the quest to understand PM.

Motor Vehicle Emissions

From the standpoint of population exposure, PM from both gasoline and diesel powered vehicles is of special concern, because of the large number of people exposed to motor vehicles emissions in urban areas, including pedestrians, bicyclists, motorists, and people who live, work or go to school in proximity to busy roadways. Vehicle tailpipe emissions include primary ultrafine and fine PM from fuel combustion and lubricating oil, as well as gaseous PM precursors such as ROG, NOx, and ammonia. Vehicles also produce particles from brake and tire wear that include toxic chemicals such as copper and cadmium; these toxic substances pollute soil and water as well as the air. In addition, motor vehicles re-suspend dust (primarily coarse particles) that has been deposited on roadways from a variety of emission sources, so that these particles once again become available to be inhaled.

ARB's *Air Quality and Land Use Handbook* (April 2005) cites several key findings regarding health impacts from near-roadway exposures.

- Reduced lung function in children was associated with traffic density, especially trucks, within 1,000 feet; this association was strongest within 300 feet. (Brunekreef, 1997)
- Increased asthma hospitalizations were associated with living within 650 feet of heavy traffic and heavy truck volume. (Lin, 2000)
- Asthma symptoms increased with proximity to roadways; the risk was greatest within 300 feet. (Venn, 2001)
- Asthma and bronchitis symptoms in children were associated with proximity to high traffic in a San Francisco Bay Area community with good overall regional air quality. (Kim, 2004)
- A San Diego study found increased medical visits in children living within 550 feet of heavy traffic. (English, 1999)

The ARB *Handbook* notes that truck traffic densities and distance from the roadway are key factors affecting the strength of the association with adverse health effects. In the health studies cited in the ARB *Handbook*, adverse health effects diminished with distance; adverse health effects were seen within 1,000 feet of high-volume roadways, with the strongest effects within 300 feet.

Exposure to vehicle emissions has been linked to increased blood pressure and thickening of the arteries. A recent clinical study (Brook et al. 2009) that exposed subjects to PM levels typically found near highways showed an immediate increase in blood pressure. This study also found that exposure to PM induced inflammation; this effect typically manifested within roughly 24 hours after exposure. Another recent study (Kunzli et al. 2010) found that thickening of artery walls progressed more than twice as quickly among people living within 100 meters of a Los Angeles freeway (where ultrafine PM levels are typically elevated) compared to those who lived farther away.

The Brugge (2007) review of health studies concludes that there is strong evidence that exposure to high volume roadways is linked to higher asthma rates and to reduction of lung function in children. In addition, recent studies (Schwartz et al. 2005, and Adar et al. 2007) have found that heart rate variability, a risk factor for future cardiovascular problems, is altered by traffic-related pollutants, particularly in older people and people with heart disease.

Lubricating Oil

Recent research indicates that engine lubricating oil may contribute to PM emissions from motor vehicles. To investigate how lubricating oil (and fuels) contributes to the formation of PM and semi-volatile organic compounds (SVOC) in vehicle exhaust, the National Renewal Energy Lab, ARB, South Coast AQMD and other partners worked together on the Collaborative Lubricating Oil Study on Emissions (CLOSE). The objective was to evaluate how much PM emissions come from lubricating oil and explore ways to reformulate oil so as to reduce PM emissions.

The CLOSE project found that in the vehicles tested unburned lubricating oil makes up more than 70% of organic carbon (OC), which constitutes a large portion of UFPM. The results of the CLOSE project indicate that lubricating oil and fuels may lead to the formation of PM. However, further study is needed to test a wider range of vehicles, and to investigate the effects of oil type on PM and SVOC formation.

Diesel PM

Diesel PM is a subset of PM2.5 that is emitted by diesel engines. Although diesel PM accounts for a small portion (less than 10%) of the overall PM2.5 emission inventory, it has been called out for special attention by ARB because of its toxicity. In 1998, in response to a comprehensive health assessment of diesel exhaust, ARB formally identified diesel PM as a toxic air contaminant (TAC), a special class of air pollutants that can impair public health even at very low exposures or dosages. TACs can cause both acute and chronic effects, including cancer. Diesel exhaust also contains more than 40 other TACs, including carcinogens such as benzene, arsenic, nickel, and formaldehyde. The Air District performed an analysis of TACs for its Community Risk Evaluation (CARE) program and found that diesel PM accounts for approximately 85% of the total cancer risk from TACs in the Bay Area. As discussed in Section 4, diesel PM has been the focus of control efforts by both ARB and the Air District.

Wood Smoke

Although wood fires may have an aesthetic appeal and some people may perceive wood smoke as natural or even healthy, findings from health studies to date indicates that wood smoke particles cause the same types of negative health effects as other types of fine PM. Wood smoke accounts for a major portion (38%) of the Bay Area PM2.5 inventory during the winter season.

Wood smoke is produced by incomplete combustion from residential fireplaces and wood stoves. Whereas combustion in diesel and gasoline engines is carefully controlled to regulate oxygen supply and the fuel-to-air ratio

in order to maximize the efficiency of the combustion process, the wood-burning combustion process in fireplaces is largely uncontrolled. This leads to inefficient combustion, resulting in a high rate of smoke and PM emissions compared to other types of combustion. In addition to PM, wood smoke contains thousands of chemicals, including criteria pollutants such as sulfur oxides (SOx), nitrogen oxides (NOx), and carbon monoxide (CO); as well as several dozen toxic air contaminants such as acrolein and acetaldehyde, and carcinogenic compounds such as polycyclic aromatic hydrocarbons (PAHs), benzene, formaldehyde and dioxins. More research is needed to evaluate how the various pollutants in wood smoke may interact in terms of health impacts.

In addition to PM, wood smoke contains various toxic and carcinogenic compounds.

A review of research on the health effects of residential wood smoke (Zelikoff et al. 2002) found that prolonged inhalation of wood smoke contributes to chronic bronchitis, chronic interstitial lung disease, pulmonary arterial hypertension, and altered pulmonary immune defense mechanisms in adults. Studies (e.g., Larsen & Koenig, 1994) found that young children living in homes heated by a wood-burning stove had a greater occurrence of moderate and severe chronic respiratory symptoms than children who did not live in homes heated with a wood-burning stove. Effects on preschool children living in homes heated with wood burning stoves or in houses with open fireplaces include decreased lung function in young asthmatics, increased incidence of acute bronchitis, and increased incidence and duration of acute respiratory infections. One study (Danielsen et al. 2011) found that wood smoke PM has small particle size and a high level of polycyclic aromatic hydrocarbons (PAH). This study found that, in terms of health effects, exposure to wood smoke produces high levels of free radicals, may trigger inflammatory and oxidative stress in cultured human cells, and may damage DNA.

Studies of wood smoke health effects to date have focused primarily on respiratory impacts. Additional research is needed to evaluate potential cardiovascular effects from exposure to wood smoke.

Estimating PM Health Impacts in the Bay Area

The Air District has performed two recent analyses to estimate the public health impacts (morbidity and premature mortality) of PM and other air pollutants in the Bay Area.

- *Bay Area Air Pollution Burden: Past and Present* (see Appendix A in the Bay Area 2010 Clean Air Plan, issued September 2010).
- *Health Impact Analysis of Fine Particulate Matter in the San Francisco Bay Area,* September 2011.

These analyses were based on methodologies employed by US EPA and ARB to estimate the health impacts and the monetary costs of air pollution. They rely on the results of peer-reviewed

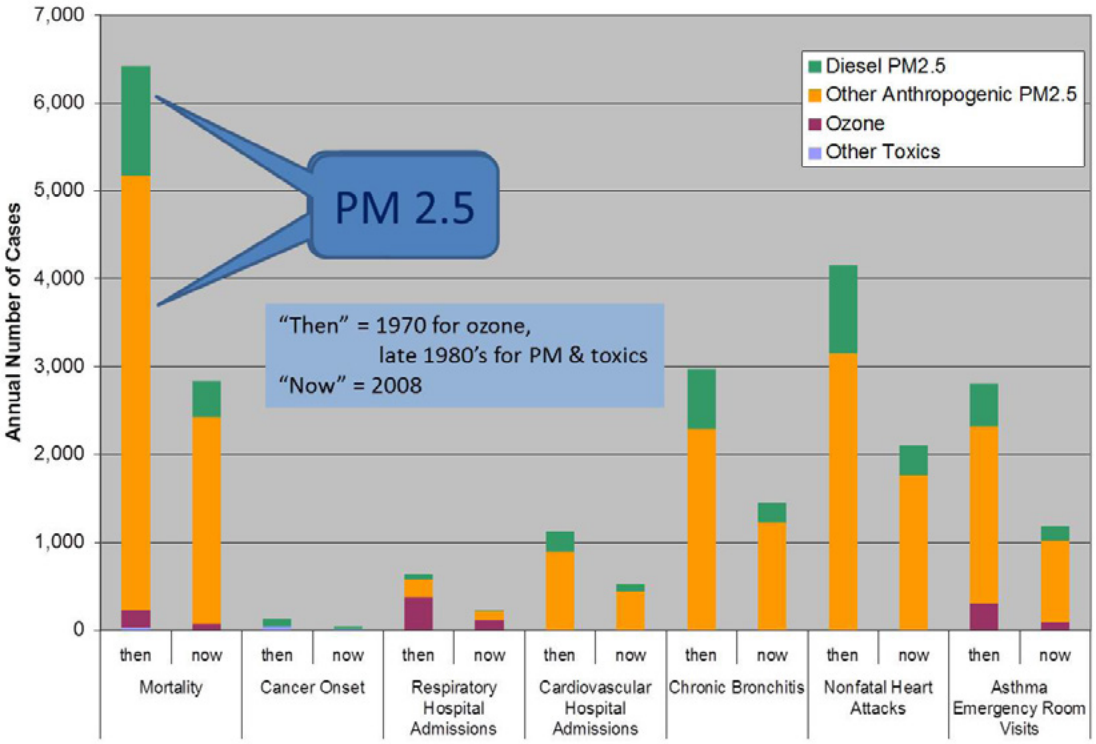
epidemiological studies and US EPA's BenMAP program, in combination with air quality modeling results performed in-house by Air District staff. Key findings from these studies include the following:

- Improvements in Bay Area air quality in recent decades have greatly reduced the health burden from air pollution. Most of the public health benefit is due to the substantial reduction in PM levels in recent years, as discussed in Section 3-C.
- The reduction in health impacts has provided cost savings (in terms of reduced treatment costs, increased productivity, and longer life span) to the region valued at multiple billions of dollars per year. Most of this economic benefit is due to progress in reducing PM levels.
- Average life expectancy in the Bay Area increased from 75.7 years in 1990 to 80.5 years in 2006. Improved air quality – primarily the reduction in PM levels – in the Bay Area during this period accounts for roughly 6 months of the overall increase in average Bay Area life expectancy.
- Despite progress in reducing PM levels and related health impacts, exposure to fine PM (PM2.5) remains the leading public health risk, and contributor to premature death, from air pollution in the Bay Area. The vast majority of premature deaths associated with air pollution - more than 90% - are related to exposure to fine particulate matter (PM2.5). Most of the deaths associated with PM2.5 are related to cardiovascular problems. Based on current PM levels, exposure to PM is estimated to contribute to approximately 1,700 premature deaths per year in the Bay Area; this represents roughly 3-5% of total annual deaths in the region. The economic cost of these negative health impacts is estimated at multiple billions of dollars per year.
- PM emitted by diesel engines is believed to be the leading toxic air contaminant (TAC) in the Bay Area. However, the current evidence suggests that only 10-20% of PM-related deaths in the Bay Area are linked to diesel exhaust. PM from other (non-diesel) sources (such as wood smoke, cooking, combustion of other (non-diesel) fossil fuels, and secondary PM formed by precursors such as NOx, SO2, and ammonia) appears to be responsible for most of the PM and the PM-related deaths in the Bay Area.
- The Air Resources Board has identified diesel PM as a carcinogenic pollutant that may cause lung cancer. Although lung cancer is clearly a major public health issue, it should be noted that exposure to diesel PM may cause a wide range of respiratory and cardiovascular effects in addition to lung cancer. In fact, to the extent that diesel PM contributes to premature mortality, analysis suggests that this is primarily due to its role as a component of PM2.5, in which it contributes to mortality related to heart attacks, emphysema, strokes, etc.

PM is the air pollutant that causes by far the greatest harm to public health in the Bay Area.

Figure 1-4 depicts findings from the health burden analysis performed for the Bay Area 2010 Clean Air Plan. The graph shows the number of cases of seven key health efects that are related to population exposure to current Bay Area air pollution levels (2008, labeled "now) compared to the estimated number of cases that would have occurred if the quantifiable air quality improvements had not been made (labeled "then"). The "then" data is based on the earliest data available - 1970 for ozone, and the late 1980's for toxics and PM. Figure 1-4 shows that the annual cases of health effects associated with exposure to air pollutants in the Bay Area has dropped dramatically, by more than half. Of particular interest, premature mortality related to air pollution has decreased from an estimated 6,400 per year to an estimated 2,800 per year. Despite this substantial progress, the health impacts from air pollution are still significant. And as the graph shows, PM2.5 accounts for the vast majority of the health effects in comparison to ozone or other (non-diesel) toxic air contaminants.

Figure 1-4 Bay Area Air Pollution Health Burden: Past & Present



Estimated contribution of PM, ozone, and key air toxics to health endpoints among Bay Area residents, based on Bay Area air pollution data for year 2008.

Summary of Key Points on the Health Effects of PM

- A robust body of epidemiological studies has established that there are a wide range of negative health impacts from both short-term and long-term exposure to PM2.5. These impacts include both respiratory and cardiovascular effects, including key health endpoints such as heart attacks and strokes.
- Although researchers are still working to define which specific particle types are more harmful to human health, the available evidence indicates that smaller particles are most dangerous because they can most easily penetrate into the lungs, bloodstream, organs, and cells of the body.
- There are documented health effects from exposure to PM2.5 even below current PM air quality standards, and researchers have not been able to establish a safe threshold below which there are no health risks.
- Even although the Bay Area either attains or is close to attaining State and national air quality standards for PM, analysis by Air District staff indicates that PM is the air pollutant that imposes by far the greatest harm to public health in the Bay Area.
- Even in regions with relatively low PM concentrations, such as the Bay Area, efforts to further reduce PM levels will results in public health improvements and longer average life expectancy, thus providing significant social and economic benefits.

Areas that Require Additional Research

This chapter has attempted to summarize current information regarding the health effects related to PM.

Although there is robust evidence that exposure to PM can cause a wide range of respiratory and cardiovascular effects, many fundamental questions have not yet been fully answered. Researchers are actively working to provide better answers to key questions, including the following:

- Which particle types are most dangerous?
- What biological mechanisms cause the observed health effects?

- Is there a safe level (no-effects threshold) for short-term or long-term exposure to PM, below which no health effects occur?
- Do ultrafine particles cause health effects independent of the health effects caused by exposure to PM2.5?
- If ultrafine particles do cause health effects independent of the effects caused by exposure to larger particles, are these effects related to short-term peak exposure, chronic exposure to lower levels of UFPM, or a combination of both acute and chronic exposure?
- How does exposure to PM affect intermediate health outcomes such as heart rate variability and inflammation markers?
- What is the relationship between exposure to PM emissions from roadways and health effects such as cardiovascular disease, lung cancer, and premature mortality?

SECTION 1-B: POPULATION EXPOSURE TO PM

This section summarizes key information regarding population exposure to PM.

In order to protect Bay Area residents from the negative health effects related to PM described above, we need to better understand population exposure to PM. The key questions are: Who is exposed to PM? And when, where, and how much PM are people exposed to?

Reducing personal (individual) exposure and population exposure (the aggregate exposure experienced by all Bay Area residents combined) to PM can provide important public health benefits. Key questions considered in this section include:

- Who is at greatest risk from exposure to PM?
- How do PM concentrations vary at the local scale?
- Which types of environments pose the greatest risk?
- How much exposure to PM occurs in the indoor environment compared to outdoors?
- How do PM concentrations and population exposure to PM change based upon distance from emission sources?

Linking PM to Health Effects

The connection between PM and negative health effects can be explained by a pathway that includes the following links:

1. **Emissions:** A wide range of sources release primary PM and PM precursors into the air.
2. **Ambient PM concentrations:** The combination of emissions and meteorological conditions determines the ambient concentration of PM, that is, the level of PM in the air.
3. **Exposure:** Exposure occurs when people actually inhale PM into their lungs. The level of exposure to PM is closely linked to the ambient PM concentration.
4. **Health effects:** Health effects may occur as a result of exposure to PM, depending upon the intensity, duration and frequency of population exposure, as well as the size and physical condition of the receptor population.

The Air District has detailed information about PM emissions and ambient concentrations of PM[3] at the regional scale, and there is a wealth of epidemiological studies analyzing the relationship

3 The emissions inventory described in Section 2 provides information on emissions by source. Information regarding ambient concentrations of PM is available from monitoring data and photochemical modeling.

between population exposure and health effects. However, as discussed below, estimating population exposure to PM at the regional scale is difficult. In analyzing how PM effects public health via the steps described above, the greatest uncertainty relates to estimating population exposure.

Measuring population exposure to PM, and the related health risks, is challenging for several reasons:

- PM concentrations vary both temporally and spatially
- The composition of PM varies depending upon the mix of emission sources and meteorology
- Personal activity patterns are complex
- Indoor exposure may account for a significant share of total exposure

Emissions: Many different sources, both stationary (factories, refineries, etc.) and mobile (cars, trucks, locomotives, marine vessels, and farm and construction equipment) emit direct emissions of PM and/or PM precursors such as NOx and SOx. Identifying the key emission sources and developing strategies to reduce emissions from these sources is the first and most fundamental step to improve air quality.

Ambient Concentrations: This term refers to the level of pollutants that are measured in the air. PM air quality standards are expressed in terms of ambient concentrations, as discussed in Section 3. The relationship between emissions and ambient concentrations is complex and depends upon many factors, including meteorological conditions (temperature, humidity, wind speed and direction, vertical mixing, etc.) the ratio of precursor pollutants, and regional topography. Ambient concentrations of PM can vary greatly at the local scale.

Population Exposure:

From the standpoint of protecting public health, the key objective is to reduce population exposure to PM and other air pollutants. The issue is not simply how much pollution may be degrading the quality of the air that we breathe, but rather how much people are exposed to the pollution and how much each individual actually inhales and absorbs (dosage). Key factors in determining population exposure include how much pollution is in the air at the time and location that exposure occurs, the number of people exposed, the duration

of exposure, and the frequency of exposure. People are exposed to air pollutants in both the outdoor and indoor environments. In the case of PM, the evidence suggests that most people experience a major portion of their total PM exposure when they are indoors, as discussed later in this Section.

Population exposure to PM can also be analyzed in terms of **intake fraction**, i.e., the fraction of an emitted pollutant that is actually inhaled by the population. High PM emissions in a sparsely-populated area may cause little damage to public health, because the intake fraction and population exposure are low. Conversely, moderate levels of emissions in proximity to a densely populated environment may result in a higher intake fraction, more population exposure, and greater public health impacts.

Factors that determine individual exposure to PM and other air pollutants include:

- The pollution profile: the level of pollution, mix of co-pollutants, the specific mix of particle sizes and their chemical composition, all of which vary depending on geographical location and emissions sources, season of the year, and weather conditions.
- Where people live, work, and play.
- Activity patterns and lifestyle choices such as how much time people spend outside, or how much time they spend driving on busy roadways.

Personal exposure to PM for a given individual on a specific day can be calculated by multiplying the time spent in each activity by the PM concentration in each location, and then summing the exposure for each activity. The degree of exposure may vary greatly depending on the type and location of the activity. Therefore, an activity that involves high exposure for a relatively short period of time, such as driving on a freeway for 30 minutes, may account for a major portion of total daily exposure.

Estimating total population exposure to PM is challenging because people are mobile and PM levels may vary substantially from place to place. Estimating population exposure to PM requires three steps:

1. Documenting activity patterns for a specific individual: i.e., where, when, and for how long he or she performs various activities.
2. Estimating the ambient concentration of PM that the individual is exposed to at each time and location. These estimates are derived from air quality monitoring data and/or computer modeling results.
3. Aggregating each individual's personal exposure across an entire defined population.

Dosage: The amount of an air pollutant that an individual actually inhales is called **dosage**. And the amount that is absorbed by the body and becomes available for interaction with biologically significant organs and tissues is called the **internal dose**. Once absorbed, the chemical can undergo

metabolism, storage, excretion, or transport within the body. The amount transported to a specific organ or system is termed the **delivered dose**.

The air we breathe serves as the carrier medium by which harmful pollutants can enter the body. The average adult takes about 25,000 breaths and inhales a total volume of approximately 14,000 liters of air every day. So even though we may only be exposed to a tiny amount of pollution per breath, on a cumulative basis this can result in a substantial amount of pollution inhaled over time.

The pollutant dosage depends upon the amount of pollution in the air and an individual's inhalation rate relative to their body weight. Inhalation rate varies depending upon age, metabolic rate, body weight, and type of activity. When people are exercising, they inhale more frequently and more deeply, resulting in a higher dosage. So walkers, runners, and bicyclists experience greater dosage from a given exposure; this may be a concern if people engage in these activities in close proximity to busy roadways or other major emission sources.

Children may experience higher dosage than adults, because they are more physically active, have a higher metabolic rate and inhale more air on a per-pound basis than adults. Children also tend to breathe more through their mouths more than adults; as a result, more PM may reach their lungs because the mouth is less effective than the nose at filtering out PM. For these reasons, children typically experience a greater dosage into their bodies from a given exposure to pollution.

Sensitive Populations

Just as individual exposure differs, so does the ability of our bodies to tolerate exposure to pollutants. People vary in their susceptibility to health effects from air pollution depending upon factors such as genetic features, gender, age, lifestyle (e.g., smoking status and nutrition), and their health status. To protect public health, we need to focus on reducing exposure among the most sensitive populations and the most heavily impacted communities.

The key aspect to protecting public health is to reduce personal exposure for the people who are most susceptible to air pollution; these "sensitive populations" include children, pregnant women, seniors, and people burdened with existing cardiovascular or respiratory conditions. Children are especially vulnerable to air pollution due to their higher inhalation rates, narrower airways, less mature immune systems, and the fact that their lungs and other key organs are still developing. In addition, children with allergies may have an enhanced allergic response when exposed to pollutants such as diesel exhaust. Children also tend to spend more time outside than adults, so they may be more exposed to pollutants in the ambient air. Seniors and people with existing cardiovascular or respiratory conditions are more vulnerable to the effects of air pollution than healthy adults because their lungs, hearts, and immune systems may already be weakened or compromised.

Some epidemiological studies suggest that PM health effects may be influenced by gender. For example, a 2007 study by the Women's Health Initiative (Miller et al. 2007), which examined the impacts of PM exposure on post-menopausal women, found that a relatively modest increase in PM2.5 levels (an increase of 10 $\mu g/m^3$ or micrograms per cubic meter) was associated with a 76% increase in the risk of death from cardiovascular disease. This is much higher than the increase in risk associated with an increase of 10 $\mu g/m^3$ that was observed for the general population in the Harvard Six Cities study (19%) and the American Cancer Society study (13%).

Although members of sensitive populations live in communities throughout the Bay Area, we know that certain communities experience higher-than-average levels of air pollution. And in many cases, people who live in communities that are disproportionately impacted by air pollution may be especially vulnerable to the negative effects of air pollution because of their demographic and socioeconomic status. Studies have shown that socioeconomic factors such as income, race, access to health care, and level of educational attainment, can profoundly affect health status and life expectancy.

But although a correlation between socioeconomic factors and health outcomes has been well documented, determining the precise correlation between a particular socioeconomic factor and a specific health outcome is complicated because the various factors are closely intertwined in most communities. Identifying the specific mechanism(s) by which socioeconomic factors affect health outcomes is also difficult. But researchers have found that factors such as poverty and race contribute to stress, thus increasing susceptibility to the health effects of air pollution, since stress weakens the immune system and may be a factor in initiating some types of disease.

Recognizing that certain neighborhoods and communities in the Bay Area are disproportionately impacted by local air pollutants, the Air District launched the Community Air Risk Evaluation (CARE) program in 2004. Air District staff performed technical analysis which identified six impacted communities most affected by toxic air contaminants. The Air District has been making a concerted effort to reduce emissions and population exposure to PM and toxic air contaminants in these communities, as described in Section 4.

To sum up, many factors go into determining population exposure to air pollutants and the degree to which an individual's health may be affected by that exposure. The amount of pollution in the air and the frequency and duration of the exposure are key factors. But individual attributes such as age and gender; personal activity patterns; lifestyle (active or sedentary); socioeconomic status; and health status all play a role as well in determining how much pollution people are exposed to and how their bodies respond to that exposure.

Which Environments Pose the Greatest Risk?

In the course of their daily activities and routines, Bay Area residents are exposed to PM and other air pollutants in a variety of locations and environments. Several of these environments may expose people to elevated levels of PM and account for a significant portion of total exposure to PM.

Population Exposure to Motor Vehicle Emissions

Most Bay Area residents are exposed to motor vehicle emissions on a daily basis. Motor vehicles emit the entire spectrum of ultrafine, fine, and coarse PM by means of several mechanisms. Gasoline and diesel vehicles produce tailpipe emissions of both primary PM in the fine and ultrafine size ranges, as well precursor pollutants that form secondary PM, such as ROG, NOx, and ammonia. Lubricating oil has also been identified as a potential important source of ultrafine PM. In addition to these combustion-related emissions, motor vehicles generate PM from brake wear and tire wear, and they cause dust that has settled on roads to become re-suspended in the air. Studies have found a wide range of negative health effects among people who are exposed to PM emissions from motor vehicles, as discussed in Section 1-A.

The amount of primary PM and PM precursors emitted by vehicles on a given roadway, and the chemical composition of those emissions, depend upon many factors, including:

- the volume of traffic and the level of traffic congestion;
- the composition of the vehicle fleet, and whether there are any restrictions for certain types of vehicles, such as trucks;
- the age mix of the vehicles, the effectiveness of their emissions control devices, and the fraction of vehicles that are high-emitters;
- the mix of fuel types: gasoline, diesel, or alternative fuel vehicles;
- season of the year and weather conditions; and
- vehicle speed and operating mode; vehicles emit more particles when accelerating and when traveling at high speed (Hall & Dickens, 1999).

Near-Roadway Concentrations and Population Exposure

Although the emissions inventory (see Section 2) indicates that on-road vehicles account for a relatively modest share of overall primary PM2.5 emissions in the Bay Area, anyone who drives in traffic, walks or cycles on urban streets, or lives in close proximity to a busy roadway incurs significant exposure to PM. Exposure to roadway emissions has emerged as an important social equity issue because major roadways, especially those that carry a high volume of heavy-duty diesel-powered trucks, often run through or in close proximity to low-income and minority communities.

Studies show that ambient concentrations of ultrafine and fine PM are generally much higher than average near major roadways, especially in the downwind direction. Numerous studies have found increased incidence of respiratory and cardiovascular disease among people who live in close proximity to heavily-traveled roadways. The good news is that PM concentrations, exposure, and health effects all tend to decrease rapidly with greater distance from the roadway.

Population exposure to roadway emissions depends upon the amount and the chemical composition of emissions generated by the vehicles on a given roadway; meteorological conditions, such as wind speed and prevailing wind direction; the number of people in proximity to the roadway, their distance from the roadway, and their demographic characteristics; the type of land uses and buildings near the roadway; and the presence of buildings, trees, sound walls or other barriers that affect air pollution dispersion patterns.

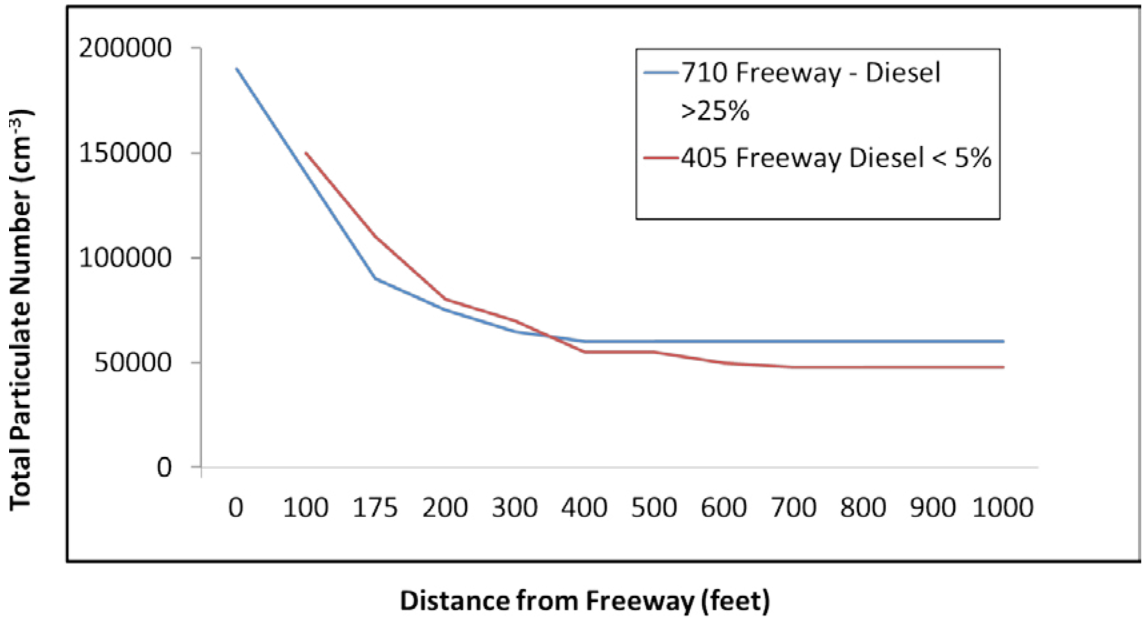
Exposure to PM from Busy Roadways

Key findings from studies on population exposure to PM emissions from roadways are summarized here:

- Numerous studies have found increased rates of respiratory and cardiovascular disease among people who live in close proximity to busy roadways.
- In close proximity to high-volume roadways, ambient concentrations of PM may be greatly elevated compared to background levels, especially in the downwind direction.
- When vehicle emissions are trapped in enclosed areas, such as urban street canyons and tunnels, this can lead to much higher pollution concentrations and population exposure on a local basis.
- In-vehicle exposure may be a leading source of exposure to PM and other air pollutants for people who drive on freeways or major arterials on a regular basis. Exposure rates may be 5 to 10 times higher than average when driving on busy roadways. Driving on a freeway or busy arterial road for even a modest time or distance can account for a significant portion of total daily exposure to ultrafine particles.
- Both PM2.5 mass and ultrafine particle number decrease as distance from the roadway increases. The concentration of ultrafine particles drops off rapidly within the first 50 to 100 meters from the source, and generally reverts to background levels 100-300 meters of the roadway.
- How quickly the particle concentration declines as a function of distance from the roadway depends upon the specific mix of particles emitted by the vehicles, as well as the atmospheric conditions and wind speed and direction in the area of the roadway.

A number of studies have analyzed how PM concentrations change in relation to distance from roadways. For example, a study in Southern California (Zhu et al., 2002) found that the concentration of ultrafine particles decreased rapidly within approximately 300 feet (~ 100 meters) of the I-710 and I-405 freeways, as shown in Figure 1-5. Although the 710 freeway had much more diesel traffic (more than 25% of the vehicles) than the 405 freeway (less than 5% of the vehicles), the results were similar for both freeways.

Figure 1-5 Number of Particles Versus Distance from Roadway: Two Freeways in Southern California (Zhu, 2002)



The chemical composition and size distribution of freshly-emitted ultrafine and fine PM are transformed during transport to downwind locations by the processes of condensation, evaporation, and dilution. Although PM2.5 mass and ultrafine particle number both decrease with distance from a roadway, the number of ultrafine particles generally drops off much more rapidly than PM2.5 mass. This is due to the fact that ultrafine particles coagulate very rapidly to form larger particles upon exposure to ambient air; coagulation reduces particle number, but does not significantly affect overall PM2.5 particle mass.

Another way to analyze how roadway emissions affect population exposure to PM is to consider **intake fraction**; i.e., the percentage of emitted PM that is actually inhaled by a human receptor. A study by the EPA-funded Harvard Center for Ambient Particle Health Effects performed dispersion modeling of primary PM2.5 emissions for 23,000 road segments in the Boston area. For each segment modeled, the study estimated how much of the intake fraction occurs among people in close proximity to the roadway. The study found that although the intake fraction varied considerably among the different segments, on average 46% of the total population exposure occurs within 200 meters of the road segment. These findings support the notion that in a dense urban environment, such as Boston or many parts of the San Francisco Bay Area, a considerable portion of the overall population exposure to roadway emissions occurs in close proximity to the roadway. However, the findings also suggest that even though emissions from a roadway become diluted and disperse rapidly within a few hundred meters of the road, a significant share of the total population exposure to primary PM2.5 emissions from a roadway still occurs at a distance greater than 200 meters from the roadway.

The spatial distribution and extent of roadway emissions may vary based upon temporal factors, such as time of day and season of the year. A study (Zhu et al. 2006) which compared ultrafine particle numbers for daytime and nighttime conditions near a major freeway (I-405) in Los Angeles found that the rate of decrease in ultrafine particles downwind of the freeway was much less at night than during the day. Although traffic volume on I-405 at night was only 25% of the daytime volume, the particle count 30 meters downwind of the freeway was about 80% of the daytime value. The authors attribute the higher ratio of particles to traffic volume at night to a combination of lower wind speed and weaker atmospheric dilution, as well as cooler temperatures which cause increased particle formation in the vehicle exhaust. The study also found that particle counts near the freeway were higher in winter than in summer, for similar reasons to the factors that lead to higher particle counts at night.

Dispersion is key to reducing ambient concentrations and exposure to PM. However, it is important to note that some urban environments, such as tunnels and "urban street canyons", are not conducive to dispersion of air pollutants. When emissions are trapped in enclosed areas, this can lead to much higher local concentrations, and thus much higher population exposure. One study (Morwaska et al. 2008) found that ultrafine particle numbers in the near-roadway environment were roughly 18 times higher than in a non-urban background environment, while measured concentrations in street canyons and tunnels were 27 and 64 times higher, respectively, than background. Another study (Zhou et al. 2008) found that, due to high population density, combined with the lack of dispersion, the intake fraction of emissions in urban street canyons is very high, similar in magnitude to the intake fraction associated with indoor tobacco smoke.

In-Vehicle Exposure

Concerns about elevated exposure to PM near major roadways also apply to drivers and passengers traveling in vehicles on high-volume roads. In fact, the evidence suggests that in-vehicle exposure may be a leading source of exposure to PM and other air pollutants for people who drive on freeways or major arterials on a regular basis. In-vehicle exposure depends on the volume and mix of vehicles on a given road, as well as the type of ventilation system used in the vehicle. Moving vehicles typically have high air exchange rates, allowing emissions from the stream of traffic to penetrate into vehicles. One study (Fruin et al. 2008) found that 36% of total daily exposure to ultrafine particles occurred during a daily commute of 1.5 hours round trip (6% of the day) in Los Angeles, and that 22% of total exposure occurred during 0.5 hours (just 2% of the day) that was spend on freeways. This indicates that exposure rates may be 5 to 10 times higher than average when driving on busy roadways. Thus, even limited time on a freeway can account for a significant portion of total daily exposure to ultrafine particles.

Freeways are also where people are most likely to experience higher exposure to diesel PM, which has been classified by the Air Resources Board as a toxic air contaminant. The 2008 Fruin study found that on freeways in Los Angeles, concentrations of ultrafine PM, black carbon, nitric oxide, and polycyclic aromatic hydrocarbons (PAH) bound to small particles are generated primarily by diesel-powered vehicles, even though diesel vehicles account for only a small fraction (6%) of the traffic on LA freeways. This study also found, however, that on arterial roads concentrations of ultrafine

particles appear to be emitted primarily by gasoline-powered vehicle undergoing hard accelerations. Concentrations of ultrafine particles on arterials were roughly one-third those of freeways.

"Self-pollution", which occurs when the exhaust from a vehicle infiltrates its own passenger cabin, may also contribute to in-vehicle exposure. This has raised concern about risks to children who ride to school on diesel-powered buses. One study (Adar et al. 2008) found that PM2.5 on school buses was double the on-road levels, and that 35% of PM2.5 measured in school buses came from self-pollution. (See description of the Lower-Emission School Bus Program in Section 4 regarding actions to address this issue.)

Aircraft and Airports

Studies conducted by the South Coast AQMD suggest that jet aircraft may be major emitters of ultrafine particles. Typical ultrafine particle concentrations are on the order of 50,000-200,000 particles per cm^3 near freeways; by contrast, ultrafine particle concentrations near jet exhaust can reach 6,000,000 particles per cm^3. As shown in Table 1-3.

Table 1-3 Comparison of Ultrafine Particle Concentrations[4]

Environment	Ultrafine Particle Concentration
Clean background	500 – 2,000 particles per cubic centimeter
Typical urban air	5,000 – 30,000 particles per cc
Freeway	50,000 – 200,000 particles per cc
Jet exhaust	Up to 6,000,000 particles per cc

A study (Hu et al. 2009) that measured ultrafine particles near the Santa Monica Airport, at the residence closest to the airport, and at a nearby school showed correlations of ultrafine particle concentrations from jet exhaust at all three locations. Aircraft operations resulted in average ultrafine particle concentrations elevated by a factor of 10 at 100 meters downwind and by a factor of 2.5 at 660 meters downwind. In fact, the area impacted by elevated UFPM concentrations was found to extend beyond 660m downwind and 250m perpendicular to the wind on the downwind side of the

4 Presentation by Dr. Philip Fine of South Coast AQMD to BAAQMD Advisory Council Meeting: Ultrafine Particles 2012 Atmospheric Monitoring of Ultrafine Particles, February 2012.

Santa Monica Airport. This study demonstrated that there may be health implications for residences living in proximity to jetports, especially in the downwind direction.

A study by Carnegie Mellon University researchers (Miracolo et al. 2011) evaluated the effects of photo-oxidation on ultrafine PM emissions from a gas turbine engine designed to mimic a jet aircraft engine. The study found that photo-oxidation created substantial secondary PM, suggesting that it is also important to consider potential secondary PM formation when assessing the influence of jet aircraft emissions.

Back-up Generators

Back-up generators (BUGs), also known as stationary engines and emergency generators, are used frequently by hospitals, office buildings, schools, grocery stories, and government facilities to supply power to a building during a power failure. While power failures are generally rare, BUGs are operated several times a year for testing. Diesel BUGs emit diesel particulate matter and other toxic air contaminants and may contribute significantly to people's exposure to toxics and health risks. In addition, BUGs tend to be concentrated in populated areas, where high numbers of people may be already exposed to high levels of pollution.

A new BUG installed today in the Bay Area poses little health risk during its operating testing hours due to the Air District's and ARB's regulations. However, old BUGs that were installed prior to regulations and continue to be in use today generate high levels of toxics and pose a serious health risk challenge. Even though these BUGs may be used as little as 100-50 hours a year, they can emit enormous amounts of diesel PM since their engines do not comply with any emission standards or contain retrofit technologies. In the Air District's general screening of health risks for BUGs in the Bay Area, the cancer risk for grandfathered BUGs ranges from 20 to 200 in a million in some cases. There are close to 3,000 BUGs in the Bay Area, approximately 1,500 of which may have cancer risks over 10 in a million. The majority of these BUGs are located in Bay Area urban centers. These BUGs contribute heavily to health risks already experienced by people living near roadways and other mobile emissions of diesel PM. The Air District's general health risk screening for stationary sources indicates that addressing emissions from grandfathered back-up generators could significantly reduce exposure to diesel PM, especially in urban areas with already high exposure rates.

Indoor Exposure to PM

Studies have found that most people experience a major portion of their total PM exposure when they are indoors. This is not surprising, since people spend the majority of their time indoors, in the home, office, school, stores, restaurants, etc. According to one study (Qing Yu Meng et al. 2005), adults typically spent 87% of their time indoors, 7% in vehicles, and just 6% outside. The PM that we breathe indoors is a combination of ambient (outdoor) PM that penetrates to the indoor environment, as well as PM emissions produced by indoor sources.

Most people experience a major portion of their exposure to PM when they are indoors.

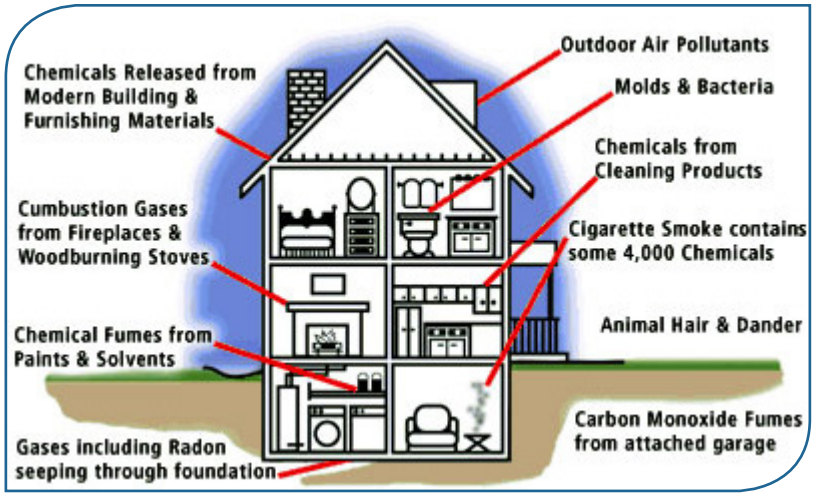
Studies to date to measure indoor PM levels and population exposure have generally been limited to small numbers of sites, because gaining access to suitable sites (private homes, schools, etc.), installing monitors, and analyzing data requires substantial time and resources. Analyzing indoor concentrations and exposures in multi-unit buildings, such as apartment buildings, is complicated by the fact that PM created indoors can move between units, as well as the fact that heating and ventilation systems, if not properly designed and maintained, can transfer pollutants between units. Nonetheless, the findings of existing studies suggest that indoor exposure to PM is a serious issue that merits more attention.

Factors that determine indoor exposure to PM include (1) the ambient (outdoor) PM concentration in the vicinity of the building, 2) the **infiltration rate**: i.e., how much of the ambient outdoor PM penetrates indoors, 3) the **air exchange rate**: how quickly indoor air is replaced by outdoor air, and (4) the amount of primary PM emissions and PM precursors produced in the indoor environment from sources such as cooking, wood-burning, and cigarette smoking. These factors can vary considerably depending upon building type and location, the type of heating and ventilation system, and meteorological conditions.

The infiltration rate of ambient (outdoor) PM to the indoor environment depends upon building materials, characteristics, and design, such as the type of ventilation system, the location of air intake units, whether windows are open or closed, and whether a building has air conditioning or an air filtration system. The PM infiltration rate also varies upon the size and composition of the particles present in the ambient PM. Because different sizes and types of particles have different infiltration rates, the composition of PM in the indoor environment generally differs from the ambient outdoor PM. Ammonium nitrate levels, for example, are generally higher outside than indoors. Ammonium nitrate can exist in either particle or gaseous form in the atmosphere, depending upon temperature. In colder weather, ammonium nitrate particles account for a sizable portion of total ambient PM2.5 in the Bay Area. However, when they encounter warmer air in the indoor environment, ammonium nitrate particles generally volatize (convert to the gaseous form), such that they no longer exist in particle form.

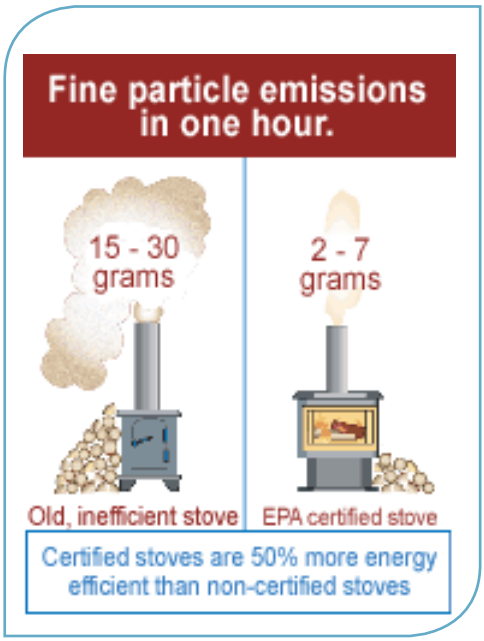
Ultrafine particles are less likely to penetrate through a building envelope because they deposit more rapidly on building surfaces due to Brownian motion at the molecular level. Whereas typical infiltration factors for PM10 and PM2.5 are in the range of 50%, (Ott et al. 2000), infiltration factors for ultrafine particles are on the order of 30% (Wallace & Howard-Reed, 2002). Since ultrafine particles do not easily penetrate to the indoors, this suggests that indoor sources of ultrafine particles play an important role in determining total personal exposure to UFPM.

Sources of PM in the Home Environment



Although PM in outdoor air does penetrate to the indoor environment, particles generated within the home often account for a substantial share of indoor PM levels and exposure. Indoor sources of PM include fireplaces and wood stoves, cooking, gas stoves, cleaning products, cigarette smoking, candles, and incense, laser printers, as well as human activities that may re-suspend PM2.5. Indoor PM may also include a mixture of dander from pets, other types of allergens, chemical substances, mineral particulate, mold spores, viruses and bacteria. The RIOPA study (Polidari, A. et al. 2006) found that fine organic particles dominates indoor-generated PM2.5 in the homes that were studied. Indoor sources of PM can cause PM levels to spike, especially because the emissions are often retained within a confined area. Several of the key sources of PM generated in the home environment are briefly described below.

Cooking: Studies have found that cooking is a leading source of ultrafine particles in many homes. Indoor monitors show that ultrafine particle counts spike whenever cooking occurs. Studies suggest that emissions of UFPM are higher from natural gas stoves than from electric stoves, but the particle emission rates are high in both cases. Ultrafine particle levels tend to be significantly higher in homes with gas stoves that use a pilot light (compared to pilot-less stoves). Emission rates when the oven is in use may be greater than for stove-top cooking. One study found that the indoor concentration of ultrafine particles jumped from 5,000 particles per cubic centimeter to 1 million particles – a 200-fold increase – within a few minutes after the oven in a residential kitchen was turned on. [5]



Wood-burning devices: People are exposed to wood smoke in both indoor and outdoor environments. In addition to its negative impact on outdoor air quality, residential wood-burning can be a major source of indoor PM, especially if the chimney or stovepipe does not vent smoke to the outdoors effectively. This problem occurs most commonly when a fire is first ignited and the fireplace flue is not warmed up, thus failing to draw smoke efficiently. One

5 Presentation by Susanne Hering, Ph. D., of Aerosol Dynamics to BAAQMD Advisory Council on March 9, 2011.

study (Pierson et al. 1989) found that 70% of smoke from chimneys can reenter the home where it originated and/or neighboring dwellings.

Appliances: Common household appliances, such as clothes dryers, toaster ovens, irons, and laser printers can also produce ultrafine particles, especially appliances that operate by heating metal surfaces.

Cleaning products: Household cleaning products can also produce ultrafine and fine particles in the indoor environment. Scented cleaning products contain terpenes such as pinene (pine scent) and limonene (citrus scent); these terpenes can react with ozone to form ultrafine particles.

Contribution of Indoor Exposure to Total PM Exposure

Lance Wallace and Wayne Ott have done pioneering work using portable particle counters to measure personal exposure to ultrafine particles. In one of their recent studies (Wallace & Ott, 2010) using personal monitors to measure exposures in environments such as homes, cars, and restaurants, they estimated that, on average, 47% of daily personal exposure to ultrafine particles for the participants in the study can be attributed to indoor sources, 36% to outdoor sources, and 17% to in-vehicle exposure. Consistent with the SHEDS-PM estimates for PM2.5 described below, cooking and cigarette smoking were the dominant sources of indoor emission of UFPM. In households with one or more smokers, the cigarette smoke more than doubled the exposure from all other sources. By measuring the particle count per cubic centimeter (cm^3) and multiplying this by the size of the impacted indoor area, this study estimates that smoking a single cigarette emits approximately 2 trillion (2×10^{12}) ultra-fine particles.

Lynn Hildebrand at Stanford University and William Nazaroff at UC Berkeley have also done important research to advance our understanding of exposure to PM in various micro-environments. A recent study directed by Professor Nazaroff (Bhangar at al. 2011) monitored ultrafine particle concentrations and exposures in seven residences (with non-smoking inhabitants) in urban and suburban Alameda County. This study provides several findings of interest:

- Ultrafine particle concentrations in the home environment are heavily impacted by episodic **indoor source events** that cause sharp spikes in particle counts. These events are triggered by activities such as cooking on the stove; uses of appliances such as toaster ovens, steam irons, or clothes dryers; burning candles; and use of the furnace.
- Frequency of use of the cooking range (either gas or electric) is the single most important determinant of exposure from episodic indoor sources.
- Gas stoves with pilot lights are a key source of indoor emissions and exposures to ultrafine particles.
- Indoor particle counts are much higher when occupants are at home and active (thus generating particles via indoor source events), compared to when they are away from home, or at home but asleep.

- Emissions from indoor sources of ultrafine particles accounted for roughly 60% of the indoor particles; the remaining 40% represent particles that infiltrated from outdoor air.
- Active particle removal systems can reduce indoor particle levels (of both particles generated indoors, as well as particles that infiltrate from outdoors) by a factor of 2 to 4.

The papers cited above analyzed personal exposure to PM at the individual level. Efforts have also been made to estimate the major sources of aggregate population exposure to PM in various urban areas. Many of these studies have employed the *Stochastic Human Exposure & Dosage Simulation for PM* (SHEDS-PM) model developed by the US EPA National Exposure Research Laboratory. Synthesizing data from many sources, including personal activity logs, ambient PM2.5 concentrations for outdoor air, and results from studies of indoor PM, the SHEDS-PM model has been used to estimate the contribution of outdoor exposure and indoor exposure to total population exposure, and to examine the role of key indoor sources of PM2.5 such as cigarette smoking and cooking.

An analysis (Burke et al. 2001) using SHEDS-PM for Philadelphia found that, on average, ambient (outdoor) PM2.5 accounted for only 37.5% of total exposure; however, this percentage varied greatly within the population. The study found relatively low variation in personal exposure to ambient (outdoor) PM2.5; however, exposure to PM in the indoor environment varied greatly, with high levels of indoor exposure caused primarily by emissions from cigarette smoking and/or cooking. Another study (Cao & Frey, 2011) had similar findings, using SHEDS-PM to analyze and compare PM exposures in three different areas and climate zones (New York City; Harris County, Texas; and six counties along the I-40 corridor in North Carolina). This study found that ambient exposure accounted for approximately 40% of the estimated total daily average PM2.5 exposure in each of the three areas. As in the case of the Burke study of Philadelphia, the Cao study also found that some individuals have extremely high PM exposures, primarily due to indoor emissions from cigarette smoking and/or cooking.

The *Relationship of Indoor, Outdoor and Personal Air* (RIOPA) study (Polidari et al. 2006) investigated residential indoor, outdoor and personal exposures to PM2.5 in three cities with different climates: Houston, TX; Los Angeles, CA; and Elizabeth, NJ. The study found that the median contribution of ambient (outdoor) sources to indoor PM2.5 concentrations was 56% for all study homes (63%, 52% and 33% for California, New Jersey and Texas study homes, respectively).

Exposure to PM in Schools

Another recent study directed by Professor Nazaroff (Mullen et al. 2011) measured PM concentrations in six elementary school classrooms in Alameda County; measurements were performed for a total of 18 days (from 2-4 days in each classroom). None of the schools was in close proximity to a major freeway; distance from the nearest freeway was 0.5 km or greater in all cases. Two of the classrooms were equipped with mechanical ventilation systems; the other four used natural ventilation (windows and doors that open). The study found that (1) indoor particle counts were typically about half of the outdoor concentrations, and (2) roughly 90% of the ultrafine particles measured in the classrooms originated outdoors. The authors compared exposure in the classrooms to exposure in the homes (per Bhangar 2011), noting that the results suggest that elementary school students are subject to much greater overall exposure to ultrafine particles in the home environment, because in-home particle counts are higher and because the students spend more time at home than at school. The authors attribute the difference in concentrations to the fact that fewer ultrafine particles are emitted in classrooms than in homes. In particular, indoor source events, such as cooking, that lead to sharp spikes in UF particle levels, are common in the home, but much less prevalent in the school setting.

Summary of Indoor Population Exposure to PM

Key findings regarding indoor exposure to PM can be summarized as follows:

- Ambient contribution to indoor PM exposure depends on outdoor concentrations in combination with the infiltration rate.
- When indoor sources are present, indoor PM concentrations can be substantially higher than outdoor PM concentrations.
- Indoor PM emissions are generated primarily by specific activities and sources: cooking, cleaning, ironing clothes, burning candles, use of forced-air furnaces, fireplaces, etc.
- PM levels in the home are characterized by sharp spikes triggered by the types of activities mentioned above.
- Ventilation to control PM spikes can greatly reduce indoor concentrations and population exposure.
- PM concentrations in the home are generally much lower at night (when people are sleeping, and PM-generating activities are not occurring) than when people are at home and active.

Occupational Exposure

Exposure to PM and other pollutants on the job is regulated by the Occupational Safety & Health Administration (OSHA). Occupational exposure to PM may differ from ambient exposure in terms of particle type and composition, as well as the intensity, frequency, and duration of exposure. Certain job types may expose workers to significant occupational exposures. For example, truck drivers and other people who drive a lot on the job may be exposed to higher levels of PM from both diesel and gasoline vehicles. Restaurant workers may be exposed to PM from cooking and wood smoke from charbroilers. Construction workers and quarry workers may be exposed to diesel PM, as well as to geologic dust particles from mechanical processes. Firefighters, especially those who combat wildfires, may be subject to extremely high acute exposures to PM. Janitorial workers may be exposed to high levels of PM in the indoor environment when they use cleaning products that contain chemicals which react with ambient ozone to form PM. Researchers (Morawska et al. 2007) have founds that people who work in office buildings may be exposed to PM (as well as VOCs) from printers.

Brigham and Woman's Health Hospital conducted a study (Laden et al. 2007) of mortality patterns associated with job-specific exposure to fine particulate and especially particulate matter from vehicle exhaust. They examined rates of cause-specific mortality and compared this to the general population. This study concluded that in the U.S. trucking industry there was an excess of mortality due to lung cancer and heart disease particularly among drivers.

Summary

Population exposure to PM is heavily dependent on individual activity patterns and the types of PM emissions sources that people are exposed to in the course of their day-to-day activities. PM levels, and population exposure to PM, may be greatly elevated in certain micro-environments, such as in-vehicle, near-roadway, and in the home.

The key to avoiding negative health impacts from PM is to reduce population exposure to PM among Bay Area residents. Recognizing the importance of reducing population exposure to air pollutants, the Air District has been working to identify areas that are disproportionately impacted and implementing policies and programs to protect these communities, as described in Section 4.

But to better protect public health, we need to improve our understanding of population exposure to PM in the Bay Area. Future steps to enhance our understanding of population exposure to PM are discussed in Section 5.

Simple steps that Bay Area residents can take to reduce their exposure to PM in the course of their day-to-day activities are also described in Section 5.

SECTION 1-C: PM AND CLIMATE CHANGE

This section describes the complex interplay between particulate matter and climate change, including how PM affects climate, as well as how higher temperatures due to climate change may impact local PM levels.

Although more work is needed to fully discern the connections, research reveals a two-way relationship in which air pollutants impact the climate at both the local and global scale, while changes in climate impact air quality. Most discussion has focused on the need to reduce emissions of carbon dioxide and other greenhouse gases, but researchers have found that particulate matter also affects the climate, especially the type of PM known as black carbon.

How PM Affects Climate Change

The thin atmosphere that surrounds the Earth enables our planet to support life and the complex ecosystems that sustain us. There is irrefutable scientific evidence that the Earth's atmosphere is getting hotter, and that a wide range of human activities, such as combustion of fossil fuels, emit carbon dioxide (CO2) and other **greenhouse gases** (GHG) that are building up in the atmosphere and changing the climate at the global scale. The effects of this man-made global heating are already being experienced in California and on a global basis in terms of temperature trends, extreme weather events (e.g., drought, frequency and intensity of hurricanes and cyclones), sea-level rise, changes in precipitation patterns, the frequency and intensity of wildfires, changes in habitat for flora and fauna, etc.

Certain types of PM, especially black carbon, can have a potent effect in heating the climate.

Efforts to date to protect the climate have focused primarily on reducing man-made emissions of GHGs that trap solar radiation (heat) that would normally escape back into space. Reducing emissions of CO2 has been the main focus of climate protection efforts to date, because on a mass basis emissions of CO2 dwarf the other GHGs, and because CO2 remains in the atmosphere for a very long time.

However, in recent years researchers have discovered that other short-lived air pollutants, including particulate matter and tropospheric ozone, also affect the climate. Although the effects are complex, there is evidence that certain types of particulate matter, especially **black carbon**, can have a potent effect in heating the climate at both the local scale (in the area where PM is emitted) and the global scale. In response to this research, there is a growing recognition that we need to incorporate strategies to reduce emissions of black carbon into climate protections efforts. Reducing black carbon can help to slow the rate of atmospheric heating in the near-term, while also protecting air quality and public health. Emission control opportunities that provide co-benefits in terms of protecting both air quality and the climate are highly desirable from the policy perspective.

Climate Forcing

Climate change is primarily caused by man-made activities that impact the Earth's energy balance (Denman et al. IPCC, 2007). Energy constantly flows to the Earth in the form of sunlight and other forms of solar radiation. Some of this solar energy is reflected back into space, and the rest is absorbed by the planet and stored in the atmosphere, as well as in oceans, forests, etc. Factors external to the natural energy system – so-called **external forcings** - can disturb the Earth's energy balance. These external forcings can be positive or negative. Positive forcers, such as carbon dioxide, methane, and other greenhouse gases, cause more of the sun's energy to be retained by the planet. In contrast, negative forcers, such as volcanic dust that reflects sunlight back into space, cause less of the sun's energy to be retained by the planet. The overall impact of human activities on the climate depends upon the net sum of positive and negative forcings caused by a wide spectrum of man-made activities, including emissions of GHGs and other air pollutants, agriculture and forestry practices, land development and road-paving that affect the reflectivity (albedo) of the Earth's surface.

Climate Forcing Effects of Particulate Matter (PM)

Particulate matter is composed of solid or liquid particles that are suspended in the air; these particles are sometimes referred to as **atmospheric aerosols.** Fine particles affect the climate by means of several direct and indirect processes, some of which heat, and others of which cool, the climate. All PM in the atmosphere can affect the Earth's climate either by absorbing light or by scattering light. Particles that absorb sunlight add energy to the earth's system; they act as positive forcers that lead to climate heating. Particles that scatter light increase the reflection of incoming sunlight back to space; they serve as negative forcers that cool the climate. In addition to the direct effect caused by absorbing or scattering incoming sunlight, fine particles may also have indirect effects on the climate by altering the properties of clouds in various ways. [6] More analysis is needed to fully define the impacts of particles on clouds, but researchers have noted various different processes by which aerosols can affect the reflectivity and lifespan of clouds, in ways that can have both heating and cooling effects, as further describe below. (The 2007 IPCC report discusses five processes; Jacobson 2002 lists 12 processes.)

For purposes of analyzing the impacts of PM on climate, scientists have identified several types of carbon: black carbon, brown carbon, and organic carbon. The effect of primary (directly-emitted) PM on sunlight spans a continuum from light-absorbing to light-scattering, with **black carbon** at the light-absorbing end of the spectrum, most **organic carbon** at the opposite, light-scattering end of the spectrum, and **brown carbon** (a subset of organic carbon) somewhere in the middle. The ratio of black carbon, brown carbon and organic carbon produced by fuel combustion depends upon the specific fuel being burned and the type of combustion conditions. PM emitted by diesel engines is primarily black carbon, whereas the PM emitted by gasoline engines is mostly organic carbon.

Table 1-4 lists the most significant types of anthropogenic (man-made) aerosol particles in terms of impact on the climate, and their most common sources. At the global scale, the dominant negative

6 "Atmospheric Aerosol Properties and Climate Impacts" U.S. Climate Change Science Program Synthesis and Assessment Product 2.3; January 2009.

forcing agent is sulfate,[7] whereas the dominant particle as a positive forcing agent is black carbon. But organic carbon, brown carbon, and ammonium nitrate also affect the climate in various ways that can have both heating and cooling effects. In the Bay Area, ammonium nitrate levels are greater than sulfates.

Table 1-4 Climate-Forcing Properties of PM Components

Negative Forcer (Cooling Agent)	Positive Forcer (Heating Agent)	Direct Effect	Indirect Effect	Source
Sulfates				
X		Reflects sunlight	Increases reflectivity of clouds	Secondary PM formed by SO2 emissions from fossil fuel-burning
Ammonium nitrate				
X		Reflects sunlight	Increase reflectivity of clouds	Secondary PM formed by combination of NOx and ammonia emissions.
Black carbon				
	X	Absorbs sunlight	1) Reduces reflectivity of clouds; impacts cloud formation. 2) Heats snow & ice by reducing their reflectivity in polar regions.	Incomplete combustion of fossil fuels, biofuels, and biomass (wood-burning)
Brown carbon				
	X	Absorbs some wavelengths of sunlight		Incomplete combustion of fossil fuels, biofuels, and biomass (wood-burning)
Organic carbon				
?		Mildly absorbs sunlight		Incomplete combustion of fossil fuels, biofuels, and biomass (wood-burning)

The various particle types are never emitted into the atmosphere in isolation. The emissions produced by a given combustion process or event contain a mixture of black carbon, brown carbon,

7 Text from NASA Fact Sheet: "While a large fraction of human-made aerosols come in the form of smoke from burning tropical forests, the major component comes in the form of sulfate aerosols created by the burning of coal and oil. The concentration of human-made sulfate aerosols in the atmosphere has grown rapidly since the start of the industrial revolution. At current production levels, human-made sulfate aerosols are thought to outweigh the naturally produced sulfate aerosols." http://www.nasa.gov/centers/langley/news/factsheets/Aerosols.html

and organic carbon, as well as other co-pollutants including nitrates and sulfates, and various air toxics. The climate effects from a given emissions source will depend on the mix and ratio of the PM components and other co-pollutants, and the way these pollutants interact in the atmosphere. Therefore, unlike greenhouse gases, the climate effects from aerosol particles can vary regionally.

PM as Negative Forcer (Cooling Agent): Sulfates & Ammonium Nitrate

As discussed in Section 2, sulfates and ammonium nitrate are the two leading forms of secondary PM, formed by interaction of precursor chemicals such as SOx, NOx, and ammonia (NH3). Sulfate particles reflect sunlight, thereby acting as a negative forcer (cooling agent) on the climate. Sulfate aerosols also have an indirect cooling effect on the climate by increasing the reflectivity of clouds.

Sulfate particles serve as nuclei for the condensation of water vapor; higher rates of condensation increase the brightness of clouds and thus their reflectivity. Sulfates and other aerosols may also lengthen cloud lifetimes. The overall impact of sulfate and ammonium nitrate particles is to increase the Earth's atmospheric **albedo**, or reflectivity. This causes less sunlight to reach the Earth and thus has a cooling effect on the climate. The cooling effects of sulfates are somewhat regional in nature, that is, the cooling effects seem to be concentrated near areas where the emissions occur, such as areas of industrial activity.

Due to the atmospheric presence of sulfate and nitrate particles which function as cooling agents, the evidence suggests that the climate has experienced less heating in recent decades than would have otherwise occurred. However, since these particles are harmful to human health, we need to further reduce sulfate and nitrate levels. As we reduce sulfate and nitrate levels to protect public health, this will lend increasing urgency to the need to reduce emissions of the greenhouse gases, as well as particles such as black carbon that contribute to climate heating.

PM as Positive Forcer (Heating Agent): Black Carbon & Brown Carbon

Several types of particles act as heating agents. Black carbon, often referred to as "soot", is a solid particle formed of mostly pure carbon that absorbs solar radiation (light) at all wavelengths. Black carbon has been identified as a potent climate heating agent. In fact, black carbon can absorb a million times more energy than carbon dioxide per unit of mass. Black carbon is black in color because it is highly efficient in absorbing all the wavelengths of light in the visible spectrum. The vast majority of black carbon is man-made. Black carbon is produced by incomplete combustion of fossil fuels, biofuels and biomass (wood-burning).

Combustion of fossil fuels (gasoline, diesel, coal, and natural gas) and biomass (wood and vegetation) are the major sources of black carbon on a global basis. In general, fossil fuel combustion from diesel engines, energy production and industrial processes accounts for most black carbon in developed countries, with the major contribution coming from diesel engines. Approximately 75% of the PM in diesel exhaust is black carbon. By contrast, biomass burning produces most of the

black carbon in developing countries. In developing countries, burning of biomass occurs both to clear land and for domestic uses such as cooking and home-heating.

A recent analysis by Air District staff, based on the Bay Area emissions inventory and chemical mass balance (CMB) analysis of PM captured on filters, indicates that fossil fuel combustion accounts for approximately 65% of black carbon emissions (diesel engines accounts for 50%; other fossil fuels 15%) in the Bay Area. Wood smoke from all sources accounts for 35% of black carbon emissions in the Bay Area, most of which (25%) is produced by residential wood-burning.

CO2 and other GHGs heat the atmosphere primarily by retaining heat from the outgoing infrared radiation (produced when sunlight is reflected off the Earth's surface) that would otherwise escape the atmosphere. By contrast, the impact of black carbon on the climate is more complex. It acts on the climate through multiple mechanisms while suspended as a particle in the atmosphere, and also when deposited on snow and ice. The impact of the black carbon heating mechanisms described below can be greater if other pollutants in the air adhere to the black carbon, thus making the particles bigger and their heat absorption greater.

Direct effect: Black carbon absorbs both incoming and outgoing radiation of all wavelengths (whereas GHGs only absorb outgoing radiation in the infrared range). When sunlight hits black carbon in the atmosphere, the carbon particle absorbs that solar radiation and heats the atmosphere. Black carbon also has a heating impact when it absorbs solar radiation reflected by the Earth and clouds, thus reducing the amount of heat that would otherwise radiate back into space.

Snow/ice albedo effect: When black carbon falls on to snow or ice, it darkens their surface. This decreases the reflectivity (albedo) of the snow or ice, so that more sunlight is absorbed, thus accelerating the melting of ice caps and glaciers. On a global basis, the albedo effect of black carbon on ice and snow accounts for about 25% of the total heating effect of black carbon (Hansen & Nazarenko, 2004). Nonetheless, the melting of ice caps and glaciers, which reduces and alters habitat for key arctic species such as polar bears, is one of the most dramatic manifestations of climate change. In addition, the impact of black carbon in polar regions is of special concern, because it may lead to abrupt transitions or "tipping points".

Two examples of potential tipping point phenomena include the melting of ice in the Arctic Sea, as well as the release from thawing permafrost of vast quantities of CO2 and methane which could further accelerate the process of global heating. While the most dramatic manifestations of the snow/ice albedo effects may occur in polar regions, it has implications for California and the western U.S. as well. For example, one study (Hadley et al. 2010) has found deposition of black carbon on snowpack in the Sierra Nevada and Rocky mountains contributes to faster melting of the snowpack earlier in the spring, thus reducing the amount of snowmelt that would normally occur later in the spring and summer. This may have impacts on water supply in the western U.S. by reducing the supply that can be captured for human use. Given the importance of the Sierra snowpack to water supplies in California, this could be one of the most important effects of black carbon emissions within the state.

Indirect and semi-direct effects: Black carbon also alters the properties of clouds, affecting cloud reflectivity, precipitation, and the surface dimming caused by cloud cover. Clouds permeated with black carbon reflect less sunlight back into space, thus causing more heat to be absorbed in the atmosphere. Because these effects are so complex, estimating the indirect heating effects of black carbon and other particles in terms of cloud formation and albedo and precipitation patterns is one of the greatest challenges for modelers who study climate change.

Grinnell Glacier 2005.jpg courtesy of the U.S. Geological Survey

Net effect of black carbon: Although black carbon has a complex mix of both cooling and heating effects, the evidence suggests that its net climate impact is positive forcing with significant climate heating potential. In fact, recent studies indicate that black carbon may be the second biggest contributor to global heating, after carbon dioxide (Jacobson 2010). However, because of the complexities related to analyzing the climate impacts of black carbon, most of the global-scale climate change models currently in use only consider black carbon in a simplified way by addressing a subset of its various forcing mechanisms.

Short-Term vs. Long-Term Impacts

Black carbon typically remains suspended in the atmosphere for a relatively short time, on the order of 10-12 days. This is a very brief timespan compared with greenhouse gases such as methane, which typically remains in the atmosphere for approximately 10-15 years, or carbon dioxide (CO2), which stays in the atmosphere for decades or even up to hundreds of years. Because its atmospheric timespan is brief, this means that reducing emissions of black carbon in the near-term will provide immediate climate cooling benefits. This could mitigate, in the short-term, the heating that continues to occur in the absence of effective national and international policies to reduce the on-going increase in emissions of longer-lived GHG emissions such as CO2 and methane. In other words, efforts to reduce black carbon can yield immediate cooling benefits, thus buying us time to address the longer-term solutions needed to reduce longer-lived GHG emissions.

Geographic Scale of Impacts

Whereas the climate impacts of the traditional greenhouse gases are global in scale, the evidence suggests that the climate impact of black carbon is more localized in nature. Certain regions of the world are more likely to be impacted by black carbon heating effects, either due to transport and deposition, such as polar regions, or to high levels of PM emissions in the region, such as Asia. This has several implications:

- Efforts to reduce black carbon can be targeted on the sources and locations where the heating effect of black carbon is most damaging. One of the great unknowns in terms of global heating is where and when climate change may

go beyond irreversible tipping points that could trigger disastrous impacts, such as greatly accelerated melting of the Greenland ice sheet or thawing permafrost. Well-targeted efforts to reduce black carbon emissions in the most sensitive regions may provide a means to avert or delay such tipping point scenarios.

Reductions in black carbon at the local level will provide direct local benefits, both in terms of reducing heating in the specific region where the black carbon reductions occur, as well as reducing the serious health impacts related to exposure to PM and black carbon.

Brown Carbon

The term "brown carbon" refers to organic carbon compounds that absorb visible and/or ultraviolet light, and thus heat the atmosphere. Like black carbon, it is a product of incomplete combustion. Brown carbon compounds are chemically diverse, so that the wavelengths of light they absorb, and thus their color, vary. The mixture of colors of brown carbon compounds appears brown to the human eye. The total quantity of solar energy absorbed by a brown carbon mixture depends upon the molecular structure of the compounds and the total mass of material. The net contribution of brown carbon to climate change is presently uncertain; this represents a key gap in our understanding of the net impact of PM on climate.

Net impact of PM on the Climate

Assessing the net impact of PM on the climate system is challenging. It requires analyzing the mix of the various particle types in the atmosphere in a given region, and then evaluating the different heating and/or cooling properties (both direct effects and the diverse indirect effects) for each particle type. And because fine particles are generally short-lived in the atmosphere, it is difficult to measure them on a global scale.

Despite the uncertainties, the available evidence suggests that, even though black carbon and brown carbon have a heating effect, fine particles as a whole currently have a net cooling effect on the climate.[8] In fact, a recent study (Sriver 2011) led by the National Oceanic and Atmospheric Administration found that a rapid build-up of aerosols (fine particles) in the stratosphere over the past decade has offset about one-third of the climate heating influence of CO2 during this period. The NOAA study concludes that the amount of aerosols in the stratosphere will play an important part in determining the overall change in climate in coming decades. As noted above, it is important to reduce emissions of fine particles to protect public health, but doing so may exacerbate the challenge we face in attempting to control the climate heating impacts of greenhouse gases and black carbon.

8 Stratospheric Pollution Helps Slow Global Warming," David Biello, Scientific American, July 22, 2011; www.scientificamerican.com/article.cfm?id=stratospheric-pollution-helps-slow-global-warming.
Quote from this article: "By analyzing satellite data and other measures, Daniel and his colleagues found that such aerosols have been on the rise in Earth's atmosphere in the past decade, nearly doubling in concentration. That concentration has reflected roughly 0.1 watts per meter squared of sunlight away from the planet, enough to offset roughly one-third of the 0.28 watts per meter squared of extra heat trapped by rising atmospheric concentrations of greenhouse gases such as carbon dioxide. The researchers calculate that the aerosols prevented 0.07 degrees Celsius of warming in average temperatures since 2000."

Air District staff has performed a preliminary analysis to examine how decreasing PM levels in the Bay Area may be affecting the local climate. Staff looked at pyranometer[9] readings for three sites with data stretching back to 1990: Bethel Island, Santa Rosa and San Martin. The data suggest that insolation (the amount of solar radiation hitting the earth's surface) for these sites has increased on the order of 2 Watts/m^2 per decade, or about 1% per decade. This finding, though preliminary, is consistent with the results from one paper (Wild et al. 2008) which found that surface net radiation over land rapidly increased by about 2 W/m2 per decade on a global basis for the 15-year period 1986–2000.

An April 2012 study (Leibensperger et al.) by the Harvard School of Engineering & Applied Sciences also sheds light on the cooling effect of sulfate particles and other aerosols. The Harvard study found that in the later part of the 20th century particulate pollution created a "cold patch" over the eastern United States where the effects of global warming were temporarily obscured. In addition to directly scattering incoming sunlight, the particles also helped form clouds that further reflected sunlight, thus indirectly leading to greater cooling at the earth's surface. The study found that as a result of efforts to reduce sulfates and other particles in recent years to protect public health, this "cold patch" effect has now been largely removed. In the words of the authors, "What we've shown is that particulate pollution over the eastern United States has delayed the warming that we would expect to see from increasing greenhouse gases. For the sake of protecting human health and reducing acid rain, we've now cut the emissions that lead to particulate pollution, but these cuts have caused the greenhouse warming in this region to ramp up to match the global trend. No one is suggesting that we should stop improving air quality, but it's important to understand the consequences. Clearing the air could lead to regional warming."

In analyzing the effects of PM on climate, one of the key technical issues is how to compare the climate forcing effects of fine particles with the effects of carbon dioxide and other greenhouse gases. A metric called **Global Warming Potential** (GWP) is generally used to compare the heating potential of various greenhouse gases in comparison to carbon dioxide. Although a range of values has been published in the literature, there is as yet no consensus as to the appropriate GWP value for black carbon or for fine PM as a whole; this is due to the complex combination of heating and cooling effects described above, as well as the fact that the impacts of PM on climate may vary from region to region depending upon the specific sources and composition of PM in a given area.

In comparing the impact of different climate forcing agents, it is important to consider the different atmospheric lifetimes of the various pollutants that impact the climate. For example, CO2 and methane remain in the atmosphere for many years; therefore, the benefit of reducing these gases in cooling the atmosphere will be spread over many years. By contrast, black carbon and other

9 A pyranometer measures solar irradiance, that is, the amount of solar energy hitting a flat horizontal surface. It works by using a black-coated flat disk called a thermopile: The black surface absorbs the solar energy and converts it to heat. The thermopile converts this thermal energy to electrical energy.

fine particles remain in the atmosphere for just a few days or weeks; therefore, the cooling effect from reducing black carbon is experienced immediately. So for purposes of policy decisions with a short-term time horizon, it may be appropriate to give greater weight to black carbon, since reducing black carbon (1) provides immediate climate protection benefits by helping to offset the rise in temperatures caused by the continued build-up of greenhouse gases in the atmosphere, and (2) provides localized health benefits by reducing PM concentrations and population exposure to PM.

Impacts of PM on Precipitation Patterns and Storms

In addition to the impacts of fine particles on climate summarized above, recent studies also describe potential impacts of PM on cloud formation and precipitation patterns. A study (Zhanqing Li et al. 2011) that analyzed rainfall patterns and aerosol level over a 10-year period in the southern Great Plains of the U.S. found that aerosol pollution will suppress cloud formation and reduce precipitation in relatively dry environments. Conversely, aerosols are likely to increase cloud formation and rainfall in the summertime in areas with an existing moist environment, thus worsen flooding. The authors conclude that "These findings have important implications for the redistribution, availability, and usability of water resources in different regions of the world."

Impacts of Climate Change on PM Levels

Meteorology plays a critical role in determining air pollution levels. Climate change may impact future PM levels by affecting key meteorological variables such as surface temperature, relative humidity, precipitation rate and patterns, wind speed, and mixing height (vertical mixing). Atmospheric mixing is important to disperse PM and prevent it from building up in the air, so any climate effects that would reduce horizontal or vertical mixing could lead to higher ambient concentrations of PM. In considering potential impacts of climate change on future PM levels, one of the main concerns is to determine whether there will be a "climate penalty" – i.e., whether climate change will increase ambient PM levels. Any such climate penalty would either lead to higher PM levels, or require additional controls, beyond those already enacted or anticipated, in order to achieve PM standards.

Researchers are still attempting to evaluate the potential impacts of climate change on future PM levels. There are many factors that introduce uncertainty into this exercise, including uncertainty about the degree of future change in the climate and future emissions of PM and its precursors. Key findings from a June 2010 report to ARB prepared by University of California scientists entitled *Climate Change Impact on Air Quality in California* include the following:

- The impact of climate heating on PM levels is difficult to pin down because some of the likely effects act in opposite directions. For example, higher temperatures discourage the formation of ammonium nitrate, a component of secondary PM that constitutes a sizable fraction of Bay Area PM2.5. However, as an offsetting effect, higher temperatures will also lead to

increased background concentrations of ozone, which encourages the formation of ammonium nitrate.

- Impacts of climate change on PM levels may vary by region, but, overall, climate change is expected to have only a small effect on PM levels and population exposure to PM in California's major air basins on an annual average basis.
- Climate change is likely to increase average wind speeds in coastal regions of California; this may lead to lower concentrations of primary PM, especially in coastal regions, such as the Bay Area.
- However, climate change may cause PM levels to be higher during extreme pollution events in the future, because future stagnation events which trap pollutants close to the emissions source will increase in strength.

Increased Wildfires

Climate change may cause an increase in the frequency and severity of wildfires by altering snowmelt and precipitation patterns. At least one study (Westerling, et al. 2006) has found an association between climate change and increased wildfires in forests in the western US. Wildfires can emit huge quantities of fine particles such as black carbon, as well as other air pollutants, such as carbon monoxide, NOx, and air toxics. Most of the particles from wildfires are in the very fine size range, the types of particles that can most effectively penetrate deep into the lungs. Wildfires can cause dramatic short-term spikes in pollution levels, and greatly increase population exposure to PM and other harmful pollutants. The outbreak of wildfires that swept across California in late June 2008 caused ambient concentrations of ozone and PM to soar to unprecedented levels.[10] A recent study (Wegesser et al. 2009) found that the PM concentrations not only reached high levels, but that the PM released by these June 2008 fires was much more toxic than the PM more typically present in the California atmosphere. Smoke from wildfires can cause a variety of acute health effects, including irritation of the eyes and the respiratory tract, reduced lung function, bronchitis, exacerbation of asthma, and premature death.

10 During the final week of June 2008, PM2.5 levels increased five or ten-fold compared to normal readings at several Bay Area monitoring stations.

In addition to these health effects, wildfires also release immense quantities of carbon dioxide stored in trees and vegetation into the atmosphere. Therefore, to the extent that climate change increases wildfires, this will increase emissions and atmospheric concentrations of black carbon and GHGs that contribute to climate change, in an unwelcome feedback loop.

Policy Considerations

The evidence suggests that there is a compelling rationale to reduce black carbon emissions for several reasons.

- Reducing black carbon will provide immediate climate protection benefits by (1) helping to offset temperature increases related to greenhouse gases, and (2) potentially averting or delaying the onset of "tipping point" scenarios, such as collapse of arctic ice cap or the sudden release of carbon stored in permafrost, which could have profound and irreversible impacts at the global level. Since emissions of greenhouse gases, especially CO2, continue to increase at the national and global scale, and efforts to reverse this trend have made little headway to date, reducing black carbon may buy society time to implement the more fundamental changes required to stem the rise of greenhouse gas emissions.
- In addition to protecting the climate, reducing black carbon will provide important public health benefits by reducing population exposure to PM2.5 and diesel PM, both of which have been shown to cause a range of negative health effects.
- Reducing black carbon will provide these health and climate benefits at the local scale; i.e. in the region where the emissions reductions occur.

The good news is that, thanks to efforts over the past 10-15 years to reduce emissions of fine PM and diesel PM in California and the Bay Area (described in Section 4) in order to protect public health, we have already made major progress in reducing ambient levels of fine PM and black carbon. Analysis of elemental carbon, which is closely associated with black carbon, indicate that Bay Area levels decreased 73% from 1989-91 through 2008-10. [11] Reductions in ambient concentrations of black carbon in California and the Bay Area have presumably helped to reduce the amount of climate heating caused by man-made emissions of GHGs and other climate forcers at both the local and global scale. Looking forward, black carbon emissions will be further reduced in response to adopted regulations, such as ARB's heavy-duty diesel engine regulations, that will be implemented over the next 10-15 years. The other side of the coin, however, is that because we have a "head start" on reducing diesel PM and black carbon in California, much of the "low-hanging fruit" has already been picked. Therefore, measures to reduce the remaining increment of fine PM and black carbon may entail higher cost or effort per unit of emissions reduced. However, because reducing black carbon provides benefits in protecting both public health and the climate,

11 See pages 36-37 in *Trends in Bay Area Ambient Particulates*, BAAQMD, November 2011. www.baaqmd.gov/Divisions/Planning-and-Research/Research-and-Modeling/Publications/Reports.aspx

it should still be possible to craft additional black carbon control measures or incentive programs that reduce black carbon at a favorable benefit/cost ratio.

Trade-offs

Because PM includes a variety of particle types with differing effects on climate, it is important to identify and mitigate potential trade-offs in developing control measures to reduce PM. As noted above, reducing emissions of particles that act as cooling agents (e.g., sulfates and ammonium nitrate) should protect public health, but may entail a trade-off in terms of protecting the climate. In another example of trade-offs, a recent study (Anenberg et al. 2011) that analyzed the global-scale health benefits of reducing black carbon noted that reducing black carbon could lead to a modest increase in sulfate (SO4) concentrations. Because sulfate particles scatter incoming sunlight, an increase in sulfates could provide additional benefit in terms of cooling the atmosphere. However, an increase in sulfates could have a negative impact on public health, depending on how this would affect PM2.5 levels and local population exposure to PM. As this example suggests, identifying and evaluating potential trade-offs, and determining the net benefit of potential control strategies, can be a complex exercise. The Air District will closely track ongoing research on these issues to inform policy decisions.

Next Steps

Although the impact of PM and aerosols on the global climate is complex, some type of particles such as black carbon contribute to climate heating. This suggests that efforts to reduce PM should place high priority on reducing emissions of those particles, such as black carbon, that both damage public health and contribute to climate heating. Potential policies and actions to address the climate impacts of PM are discussed in Section 5.

SECTION 1-D: PM IMPACTS ON ECOSYSTEMS & VISIBILITY

This section describes impacts of PM on ecosystems, visibility, and the built environment.

In addition to directly impacting public health and the climate, particulate matter also can have negative effects on water quality and on the ecosystems and environment that sustain us. These effects, as summarized in Table 1-5, include acid rain which leads to acidification of lakes and streams, changes in the nutrient balance of coastal waters and river basins, leaching of nutrients from soil and reduced nutrient uptake in plants, damage to forests and crops, reduced diversity and productivity of ecosystems, damage to stone and man-made materials, and reduced visibility and aesthetic values. According to the US EPA, the scientific evidence is sufficient to conclude that a causal relationship is likely to exist between deposition of PM and a variety of effects on individual ecosystems.

It is important to note that the varying chemical compositions found in PM concentrations affect different aspects of the ecosystem. As discussed in Section 2, PM is a complex pollutant made up of a number of compounds and originates from a variety of sources and processes. As such, specific chemicals and components of PM are linked to specific ecosystem affects. For example, elemental carbon and some crustal minerals are the most commonly occurring airborne particle components that absorb light. Reduced visibility is caused by light absorption (as well as light scattering). In another example, toxic responses in plants and foliage have been documented when exposed to PM concentrations containing acids, trace metal content, or saline compounds. Also, different chemical compounds can negatively affect segments of the environment to varying degrees. One significant trace metal component of PM is mercury, which is toxic and can move readily through ecosystems and food chains. Mercury emitted from a smoke stack of a factory, for instance, may settle into soil, then be transported from soils into a nearby water body, accumulate in the bodies of plankton and other smaller fish who are then consumed by larger predators such as animals and humans, thereby transferring the mercury content all the way up the food chain.

In summary, the overall impact of PM on the environment depends upon many factors, including the chemical composition of the particles, meteorology, season of the year, and the characteristics and viability of the impacted ecosystem.

Table 1-5: Summary of Negative Impacts of PM on Ecosystems, Visibility, and Materials

Effects of PM on:	Effects:	Economic/Social Ramifications:
Vegetation	Damaged leaf tissue; stunted growth; reduced starch storage capacity.	Reduced crop yields; less robust growth of vegetation that humans, animals, and insects depend upon.
Soils	Altered soil chemistry.	Plants absorb metals and other toxic elements, which are then transferred to animals & people that eat the plants. Can lead to an increase in invasive plant species. Polluted soil can run off into stream/water bodies.
Water & Aquatic Systems	Altered chemistry; increased acidity; increased mortality in fish, decreased stamina in fish.	Decline in fish populations; bio-accumulation effect which impacts plants, fish, and mammals from the bottom of the food chain to the top
Wildlife	Lung damage; neurological damage; chromosome damage.	Stress on wildlife populations. Bio-accumulation of pollutants up the entire food chain.
Visibility	Reduced visibility; aesthetic degradation.	Reduction in tourism & economic benefits from tourism. Reduced ability to enjoy scenic and/or historical vistas.
Materials	Damage and degradation of building materials and finishes.	Increased maintenance costs; degradation of historic structures.
Property Values	Reduction in property values.	Economic disbenefit to homeowners & landlords. Reduction in local government tax revenue.

Effects of PM on Vegetation and Soils

Airborne particles are deposited to a variety of surfaces, including soil and open ground; forests, crops, and other vegetation; water bodies such as lakes, streams, and oceans; and man-made surfaces such as buildings, roads, and parking lots. Particles are deposited via two processes: **wet deposition** (rain or snow) and **dry deposition**. Coarse particles typically are deposited by means of dry deposition, and generally settle close to the location where they were emitted. Conversely, fine particles are typically deposited via wet deposition and may travel farther from the point of origin.

PM can affect plant life through direct deposition on surfaces, or indirectly through altered soil chemistry. When directly deposited onto vegetation, PM can affect the metabolism and photosynthesis of plants by blocking light, obstructing stomata apertures, increasing their temperature, and altering pigment and mineral content. In general, the toxic responses documented in plants after exposure to high levels of PM are typically associated with acidity, trace metal content, or salinity of the deposited particles. Fine PM has been shown to enter the leaf through the stomata, penetrate the structure of the

leaf, and alter its chemistry. Coarse PM can form a "crust" on the leaf, which reduces photosynthesis, damages the leaf tissues, inhibits new growth of the tissue, and reduces starch storage.

The soil environment is one of the most dynamic sites of biological interaction in nature. Deposition of PM on soil can have a negative effect not just on the chemical composition of the soil itself, but also upon the plants which grow in it, the animals and people who eat those plants, and even nearby groundwater systems which run through the impacted soils. This phenomenon, whereby a substance (such as trace metal) moves up the food chain and becomes more concentrated during ascension, is also known as biomagnification. In general, plant growth is negatively impacted by the presence of trace elements and heavy metals in soils which can then enter the plant tissue. As the plants absorb heavy metals and other pollutants via PM deposition into the soil, this can have a biomagnification effect and negatively impact the health of the people or animals that eat them.

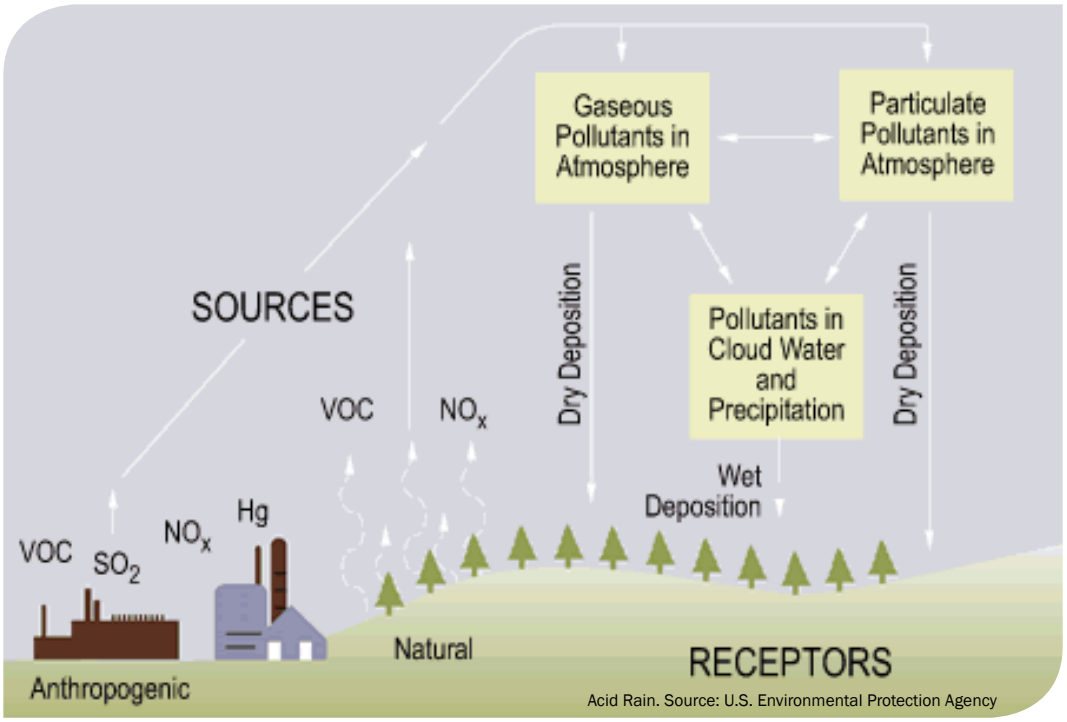
PM may have another potential impact on soil, flora, and fauna, to the extent that the ammonium nitrate component of PM acts as a source of reactive nitrogen. Deposition of reactive nitrogen on land acts as an unintended fertilizer which can have impacts on terrestrial flora and fauna. A growing body of literature documents the impacts of nitrogen deposition on ecosystems in western states. Studies demonstrate that increased nitrogen deposition is negatively affecting native plant communities which are adapted to live in low-nitrogen environments. These changes have enhanced invasion of exotic plant species such as annual grasses. Of the 225 plant species in California listed as threatened or endangered by the state or federal government, 101 are exposed to levels of nitrogen suspected of causing ecological disruption (Weiss, CEC 2006). In areas where reactive nitrogen is deposited on nutrient-poor soil, this can facilitate the expansion of invasive, non-native species that choke out native plants. As the flora changes, animal species that depend on the native vegetation may be adversely impacted.

The case of the Bay Checkerspot Butterfly, which has been on the federal endangered species list since 1987, provides an example of the impact of reactive nitrogen on diversity of native flora and fauna. The Checkerspot depends on native grasses that grow on nutrient-poor serpentine soils. The serpentine ecosystem provides food for both the larval and adult stages of the butterfly. Edgewood Natural Preserve in San Mateo County historically supported a healthy population of Checkerspots. However, nitrogen deposition from vehicles on Interstate 280, which is adjacent to the Preserve, has allowed aggressive, non-native grasses, such as Italian rye grass, to crowd out native grass species in recent years (Weiss 2002). As a result of habitat reduction, the Checkerspot population at Edgewood is in jeopardy.

PM and Acid Rain

Acid deposition, more commonly known as acid rain, is a widespread problem which effects water quality and ecosystems, and its effects have been well studied. Acid rain is a broad term which refers to a mix of wet and dry deposited particles from the atmosphere which contain high proportions of nitric and sulfuric acids. The precursors of such acids result from both natural and manmade sources. Natural sources include volcanoes and decaying vegetation, and manmade sources include emissions of SO2 and NOx from fossil fuel combustion. Figure 1-6 shows the process whereby natural and man-made emissions combine in the atmosphere to produce acid rain.

Figure 1-6 Formation and Deposition of Acid Rain



Acid Rain. Source: U.S. Environmental Protection Agency

Acid rain has negative effects on soil, water (freshwater and saltwater), aquatic ecosystems, and building materials. Regions where a high percent of ambient PM2.5 is composed of secondary particles such ammonium sulfate and ammonium nitrate (e.g., the eastern US) are more likely to experience greater negative impacts of acid rain. While a majority of the PM2.5 in the Bay Area is attributable to primary PM from wood smoke and fossil fuel combustion, during winter months a large portion of PM2.5, on the order of 35%, is composed of ammonium nitrate. Accordingly, while acid rain is not a serious problem in the western United States, due to the levels of ammonium nitrate in overall PM concentrations in the Bay Area, it is worthwhile to take precautions.

On land, acid rain can damage trees, especially at higher elevations, where exposure to acid-heavy clouds and mist is greater. The ability of a forest to cope with acid rain depends on the buffering capacity of its soil. Acid dissolves and removes the nutrients in forest soils before trees and other plants can use them to grow. At the same time, acid rain causes the release of substances that are toxic to trees and plants, such as aluminum, into the soil.

While acid rain is not a serious problem for water bodies in the Bay Area, because primary PM and PM precursors can travel a considerable distance in the atmosphere before depositing elsewhere, pollution emitted in the Bay Area may impact ecosystems in downwind areas including the Sierra Nevada. According to a National Parks Service report,[12] acid rain and snow is not as serious a problem in the Sierra Nevada as in the eastern U.S. or the Colorado Rockies. However, many high-elevation Sierra lakes have low buffering capacity (ability to cope with acid), so it is important to minimize any future acid deposition.

12 See http://www.nature.nps.gov/air/Pubs/pdf/techInfoEpaDeposition.pdf

According to the National Acid Precipitation Assessment Program Report to Congress (2011) and the U.S. Environmental Protection Agency, numerous negative ecosystem effects are attributed to increased acid deposition, including:

- Impaired visibility;
- Acidification of lakes and streams, which has a cascading effect onto fish in terms of reductions in total population, hardiness of the fish, age distribution, and size;
- Reduction in plankton biodiversity (specific to the western US);
- Reduction in acid neutralizing capacity;
- Decrease in pH (increase in acidity level) which can affect the ability of certain plant, insect and aquatic species to survive;
- High levels of nitrates in water which are toxic to aquatic life; and
- Depletion in oxygen levels of the water from accelerated plant life/death.
- Slower growth, injury or death of forests and plant species from altered soil chemistry, and/or damage to leaves or plant organs;
- Increases in atmospheric nitrogen deposition which tends to decrease species diversity (particularly in alpine plant communities); and
- Degrading effect on built structures and monuments, particularly those made of limestone, marble, lime mortars and carbonate-cemented sandstone.

Studies to date have found that the rise in CO2 concentrations in oceans via absorption, which causes decreases in ocean pH and alkalinity, is the major issue regarding ocean acidification. However, acid rain also contributes to ocean acidification. Approximately one-third of all nitrogen oxide emissions end up in the oceans. The contribution of acid rain to ocean acidification is likely greater in coastal regions such as the Bay Area, where the acidifying effect of nitrogen oxides can be as high as 10 to 50 percent of the impact of carbon dioxide (Doney, 2007). Studies have shown that increased acidity interferes with the formation of the shells and skeletons in coral, crabs, marine snails, and clams (World Wildlife Fund 2011).

Effects of PM on Water, Aquatic Systems, and Wildlife

As previously discussed, some components of anthropogenic (manmade) PM such as trace metals have a particularly damaging effect on ecosystems, including mercury, a significant trace metal component of PM that moves readily through ecosystems; as well as pesticides and polyaromatic hydrocarbons (PAHs). Once deposited, these pollutants may travel through the snow pack and feed into the water system. Deposition of PM containing these compounds has been found in the Sierra Nevada mountains in California, the major source of the state's water supply.

Some environments produce PM concentrations more toxic than others. In urban areas, motor vehicles emit toxic metals and other particles which are deposited on roads and parking lots, from where they are washed into the streams and bays, thus degrading nearby water quality. For example, particles from tire wear are a significant source of zinc, and brake pad wear is a significant

source of copper (Stolzenbach 2006). Copper from brake pads is toxic to aquatic organisms such as phytoplankton that serve as the foundation of the food chain, thus affecting the health of entire ecosystems. Elevated copper levels may also be one of the factors contributing to the decline of salmon populations.[13]

Physiological responses of fish to higher pollutant levels include increased mortality rates, chromosomal damage, retarded growth and development, and disruption of normal biological functions, including reduced stamina for swimming and maintaining positions in streams. An increase in concentrations of certain heavy metals such as aluminum, nickel, cadmium, copper, and mercury can poison fish and shellfish, and those who prey upon fish/shellfish.

Deposition of PM on land and water can have a range of negative impacts on ecosystems and wildlife from the bottom of the food chain to the top, due to the process of bio-magnification or bioaccumulation. For example, in addition to impairing the health of fish populations, air pollutants deposited in the aquatic environment can damage the broader ecosystem. To the extent that PM and related air pollutants are deposited in water and then absorbed by fish, frogs, snails and other marine life, these then travel up the food chain, increasing in concentration with each step up the ladder, to fish-eating predators including bald eagles, osprey, otters, pelicans, and grizzly bears.

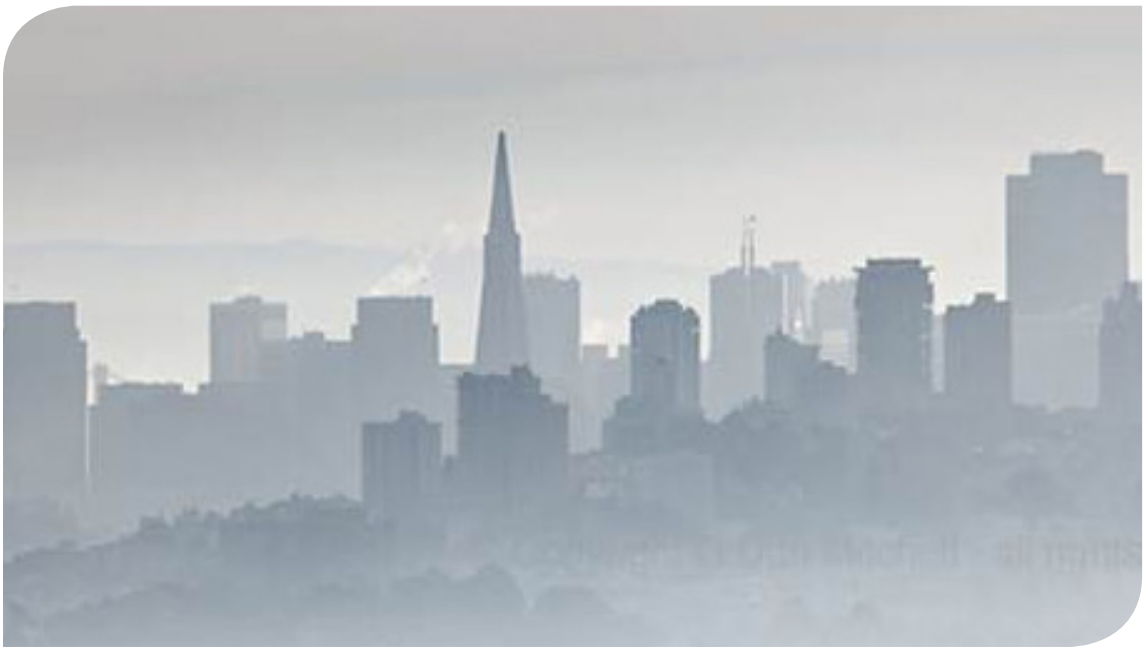
PM and Visibility (Haze)

Particulate matter is a major cause of reduced visibility, or haze, in both urban and rural areas. Haze is one of the most visible manifestations of air pollution. Reduced visibility is of special concern in areas of great natural beauty such as national and state parks and wilderness areas. In addition to detracting from the aesthetic enjoyment of vistas and landscapes, haze can have negative economic impacts in areas that depend on tourism. The emissions that create haze in parks and wilderness areas often originate elsewhere, sometimes from distant urban areas. For example, 33% of the haze found in the Grand Canyon is attributed to sources of particulate pollution in California.

To address regional haze problems, the US EPA created a Regional Haze Program and issued regulations to improve visibility, particularly in national parks and recreation areas. The original regulations, adopted in 1999, required states to develop plans to address the emissions that contribute to regional haze. In addition, all 50 states were required to submit a regional haze state

13 For discussion regarding the impact of copper from brake pads on water bodies, see http://www.suscon.org/bpp/#

implementation plan by December 2007 to demonstrate each state's long-term strategy for making reasonable progress towards achieving natural visibility conditions. In June 2012, US EPA proposed to issue a new urban visibility standard to provide increased protection from particle-induced haze in urban areas. As discussed in Section 3-B, the proposed standard would measure visibility on the basis of light extinction as expressed in units called **deciviews**.



Haze is caused when fine particulates in the air scatter and absorb sunlight. Some light is absorbed by particles, while other light is scattered away before it reaches the observer. More particles lead to greater absorption and scattering of light, reducing visual clarity and color. Some types of particles, such as sulfates, scatter more light. Haze-causing particles come from a variety of both manmade and natural sources, including windblown dust, wildfires, motor vehicles, electric utility and industrial fuel burning, and so on. Some particles which cause haze are produced primarily, while others are produced secondarily.

Visibility is closely tied to wind and weather conditions. Wind affects how pollutants are mixed and dispersed. On very windy days, the air is normally clear because particles are well dispersed. On days when surface winds are present but weaker, particles usually form a plume which causes reduced visibility. When no surface wind is present, haze typically forms near the ground and continues to build as long as the stagnant condition persists. These conditions are most conducive to reduced visibility.

Key sources contributing to the formation of haze include combustion of fossil fuels or biomass burning in electric utilities, manufacturing processes, and transportation. Natural sources of haze include wildfires, volcanoes and wind-blown dust. As a result of regulations to reduce emissions of PM2.5 and PM10, visibility has improved in many US cities and national scenic areas in recent years.

Reduced visibility may also impose monetary costs in terms of reduced property values, and negative impacts on tourism. An analysis performed by the South Coast AQMD for its 2007 Air Quality Management Plan (AQMP) found that visibility improvements related to achieving compliance with federal PM2.5 standards would provide an estimated $3.6 billion benefit per year in terms of increase property values in the South Coast air basin. South Coast staff analyzed the sales price of owner-occupied single family homes between 1980 and 1995 and found that visibility has an impact on property values. Their analysis demonstrated a willingness on the part of home-buyers to pay a premium for visibility. (Final Socioeconomic Report for the 2007 AQMP, June 2007, SCAQMD)

Effects of PM on Materials and Property Values

In addition to negative impacts on soil and water quality and ecosystems, PM and other air pollutants also damage the man-made built environment. Based on the available evidence, US EPA has determined that a causal relationship exists between PM and damage to building materials and other surfaces. Exposure to air pollutants can accelerate the natural wear and tear on buildings from wind, rain, moisture, and temperature changes, further damaging these surfaces. For example, PM deposition on buildings affects the durability of paint finishes and promotes discoloration, chalking, loss of gloss, erosion, and causes blistering and peeling of surface material. This requires costly cleaning or washing, and potentially re-painting, depending upon the soiled surface. The effect of PM deposition on national monuments and other cultural treasures and historical structures is of particular concern. Other effects on PM deposition on buildings and surfaces include:

- Enhanced weathering process on stone in combination with exposure to PM. Black crusts commonly develop from airborne particles deposited on stone surfaces;
- Corrosion of metals and masonry;
- Soiling of motor vehicles and damage to their finish;
- Increased building maintenance and repair costs; and
- Reduced property values.

Additionally, PM contributes to the formation of acid rain, which has a serious effect on structures and monuments, particularly those made of limestone, marble, lime mortars and carbonate-cemented sandstone.

The 2007 AQMP prepared by the South Coast AQMD also quantified the damage to wood and stucco surfaces of residential properties, as well as the cost of household cleaning, from PM2.5 emissions at eight locations in southern California. The total benefit of the decrease in costs for repainting stucco and wood surfaces, cleaning, and replacing damaged materials is projected to be $204 million, on average, every year between 2007 and 2025. Further, this figure is likely to be understated, because it takes into account only residential buildings. As previously discussed,

damage to historic buildings or monuments, such as statues, cemetery gravestones, and the like, as well as non-residential buildings, occurs from exposure to PM2.5. Taking into account other building types, especially special and historic ones, is likely to greatly increase the benefit from reduced PM2.5 emissions. (Final Socioeconomic Report for the 2007 AQMP, June 2007, SCAQMD)

SECTION 2: PM TECHNICAL INFORMATION

This chapter provides technical information about particulate matter, including PM size ranges, PM formation and dynamics, the results of PM air quality modeling, PM speciation data as to the contribution of key emission sources to ambient concentrations of PM, and the Bay Area PM emission inventory.

PM Characteristics

The term **particulate matter** (PM) encompasses a diverse assortment of microscopic airborne particles. Many air pollutants, such as ozone or carbon monoxide, consist of a single molecule or compound. PM, by contrast, includes a potpourri of disparate particles that vary greatly in terms of their size and mass, physical state, chemical composition, toxicity, and how they behave and transform in the atmosphere.

A variety of chemical & physical processes are involved in PM formation and transformation. Because PM is so heterogeneous and dynamic, this presents technical challenges in terms of measuring emissions and ambient concentrations, estimating population exposure, determining PM health impacts, assessing PM impacts on ecosystems and climate change, and devising appropriate control strategies.

PM typically consists of a mixture of solid particles as well as liquid droplets known as aerosols. The components of PM include elemental carbon, organic carbon, and trace metals; compounds such as nitrates, organics, and sulfates; and complex mixtures such as diesel exhaust, wood smoke, and geologic dust. Types of particles include:

- **Dusts and fibers** generated by handling, grinding, abrasion or cutting of bulk materials.
- **Mists** composed of liquid droplets generated by condensation from a gaseous state or breaking up of bulk liquid.
- **Smoke** produced by incomplete combustion of carbonaceous materials.
- **Fumes** composed of solid particle generated by condensation of vapors or gases from high temperature processes.
- **Bio-aerosols** composed of solid or liquid particles from biological sources.

Particles emanate from a variety of man-made processes and sources, such as fuel combustion, as well as from natural sources, such as wildfires, volcanos, and sea salt. Particulate matter is generated both indoors and outdoors. Emission sources that affect ambient (outdoor) air are described in the

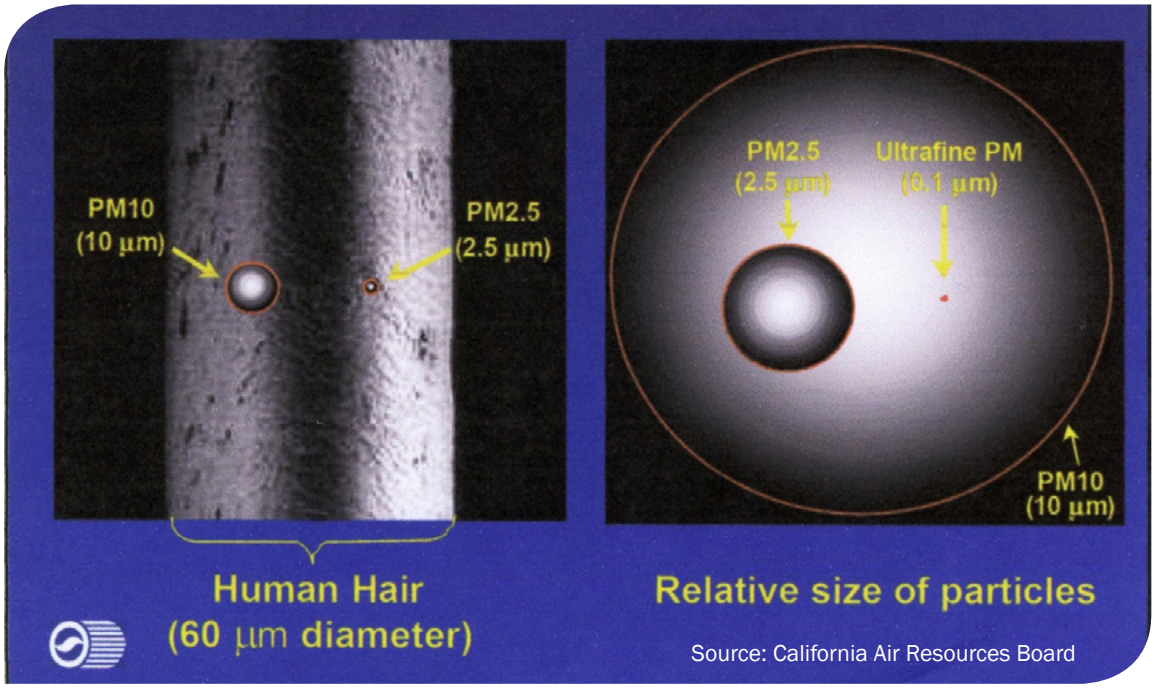
Emissions Inventory section below. Indoor sources of PM emissions, which include cooking, heating, fireplaces, appliances, smoking, and consumer products, are discussed in Section 1-B.

Particle Size

PM is commonly characterized on the basis of particle size. Figure 2-1 shows the various particle sizes in comparison to the diameter of a human hair.

- **Ultrafine PM** (PM0.1) includes the very smallest particles. The term generally refers to particles less than 0.1 micron in diameter (one micron equals one-millionth of a meter, or m x 10-6). Because ultrafine particles are so small, their size is often described in nanometers, or billionths of a meter (m x 10-9). By definition, the largest ultrafine particles measure 0.1 microns or 100 nanometers in diameter, but many ultrafine particles are as small as 3 nanometers to 20 nanometers at the time they are emitted.
- **Fine PM** or PM2.5 consists of particles 2.5 microns or less in diameter (including ultrafine PM).
- **Coarse PM** refers to particles between 2.5 microns and 10 microns in diameter. The term "coarse" particles may be misleading; it should be emphasized that even "coarse" particles are still very tiny, many times smaller than the diameter of a human hair.
- **PM10** consists of particles 10 microns or less in diameter (including ultrafine, fine and coarse PM).
- **Total suspended particles** (TSP) includes particles of all sizes, including particles larger than 10 micron in diameter.

Figure 2-1 Comparison of PM10, PM2.5, and Ultrafine PM



Source: California Air Resources Board

These distinctions based on particle size are important, because the different size ranges vary in terms of how the particles within each size range are formed and emitted; how long they remain suspended in the atmosphere and how far they travel; how easily they can evade the body's defenses and how deeply they can penetrate into the lungs and key organs; and the mechanisms by which the particles are removed from the air. However, although particle size is a useful way to categorize PM, it should be emphasized that the particles within each size range are by no means homogeneous. The diameter and mass of the particles within each of these ranges varies considerably, and there is great variation in terms of the chemical composition of the particles.

In terms of composition, coarse PM is generally dominated by geologic particles of dust and soil (from farms, quarries, mines, volcanos) and other particles of natural origin (sea salts, pollen, mold, spores, etc.). By contrast, fine and ultrafine PM are primarily the product of combustion and therefore contain compounds such as black carbon, sulfates, nitrates, acids, and metals which are more harmful to health.

Table 2-1 provides a summary of PM characteristics by particle size range.

Table 2-1 Characteristics of Particulate Matter by Size Range

Particle Size	Characteristics		
	Key Attributes	How Measured?	Key Emission Sources
Ultrafine PM: Particles less than 0.1 micron in diameter	Mostly primary PM. Short-lived in atmosphere. Local impacts. Produced by fossil fuel combustion. Particles can be inhaled deep into the body.	Particle count	Motor vehicles, diesel engines.
Fine PM: Particles less than 2.5 microns in diameter	Combination of primary & secondary formation. Produced by fossil fuel combustion & wood-burning. Particles can be inhaled deep into the body.	Mass; expressed in $\mu g/m^3$ (micro-grams per cubic meter)	Wood-burning, motor vehicles, off-road engines & equipment, industrial processes & combustion.
Coarse PM: Particles between 2.5 and 10 microns in diameter	Mostly primary PM. Relatively few particles on a number basis, but they account for about half of PM10 on a mass basis.	Mass; expressed in $\mu g/m^3$ (micro-grams per cubic meter)	Geologic dust, brake and tire wear, residential wood-burning, motor vehicles.

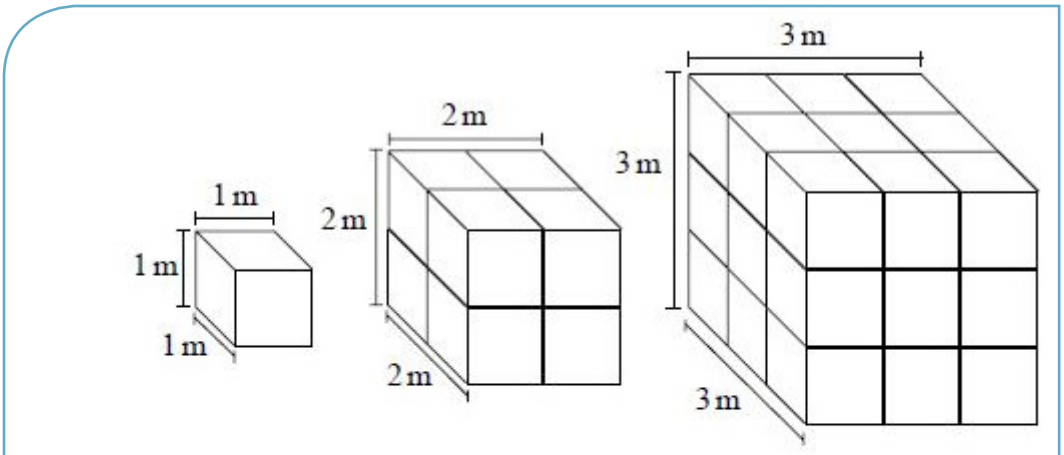
Relationship between Particle Count, Particle Mass, and Surface Area

The particles that comprise PM vary in both size (diameter) and mass (weight). Larger particles are much heavier than small ones; a single coarse particle may weigh more than thousands of ultrafine particles. Although larger particles account for most of PM on a mass basis, they represent only a

small percentage of the total number of particles. Conversely, smaller particles contribute less PM mass, but dominate in terms of the number of particles. Ultrafine particles account for the greatest **number** of particles in PM, but only a small proportion of the total **mass** of PM. Ultrafine particles account for roughly 90% of the total number of particles (Wu et al. 2008). There tends to be little correlation between the number of particles (most of which are in the ultrafine and fine size range) in a given air sample and the mass of PM2.5 or PM10 in that sample. So measuring the mass of PM inthe air generally reveals little as to the number of particles that make up that mass.

As shown in Figure 2-2, as particle size increases, particle mass (volume) increases much faster than the surface area. So a given mass of ultrafine PM will have a much greater particle number and total surface compared to an equal mass of fine PM or coarse PM. The huge number of fine and ultrafine particles suspended in the air collectively presents a great deal of surface area relative to their small mass. Surface area is a concern for two reasons. First, greater surface area means more surface to which microscopic airborne toxics can adhere. Fine and ultrafine particles coated with toxics can penetrate deep into the lungs when they are inhaled. Second, because of their relatively large surface area, once these fine and ultrafine particles enter the respiratory system, they interact with a large area of lung tissue; this means that they can do greater damage to the lungs (or other organs with which they come into contact).

Figure 2-2 Ratio of surface area to volume



surface area	$6m^2$	$24m^2$	$54m^2$
volume	$1m^3$	$8m^3$	$27m^3$
surface area: volume	6:1	3:1	2:1

Source: http://cikgurozaini.blogspot.com/2010/09/gas-exchange-in-animals.html

Primary PM versus Secondary PM

In addition to size ranges, PM is also categorized on the basis of how the particles are formed and emitted. **Primary PM** refers to particles that are directly emitted in solid or aerosol form. **Secondary PM** refers to particles that are formed in the atmosphere through chemical reactions among different pollutants.

Primary PM includes black carbon (soot) and fugitive dust from a wide variety of sources, including cars, trucks, buses, industrial facilities, cooking, power plants, construction sites, tilled fields, paved and unpaved roads, rock quarries, and burning wood. Some primary particles are emitted directly from a tailpipe or smokestack in particle form. However, primary PM also includes condensable PM (discussed below) which is formed when organic compounds that are emitted as hot gases condense into particles upon exposure to cooler ambient air. Organic carbon is the largest directly-emitted constituent of Bay Area PM2.5; its main sources are wood-burning, fossil fuel combustion, and cooking.

Secondary PM describes particles formed indirectly via chemical processes when precursor pollutants, such as sulfur oxides (SOx), nitrogen oxides (NOx), volatile organic compounds (VOC), and ammonia (NH_3), react in the presence of sunlight and water vapor. These precursor pollutants are emitted from fuel combustion, industrial processes, household activities, agriculture, natural vegetation, and other sources. Combustion of fossil fuels produces NOx, which converts to nitric acid (NO_3) and combines with ammonia (NH_3) in the atmosphere to form ammonium nitrate, as well as sulfur dioxide (SO_2), which converts to sulfuric acid (H_2SO_4) and combines with ammonia to form ammonium sulfate. In determining whether ammonia is a significant contributor to PM formation, the key question is which pollutant – ammonia, or NOx (in the form of nitric acid) - is the limiting factor in ammonium nitrate formation.

These secondary compounds account for roughly one-third of Bay Area PM2.5 on an annual-average basis and approximately 40-45% during winter peak periods. Ammonium nitrate, which is stable in solid form only during the cooler winter months, contributes an average of about 40% of total PM2.5 under peak PM conditions. The contribution of ammonium sulfate to Bay Area PM2.5 is relatively low, accounting for approximately 10% of total PM2.5 on an annual-average basis.

The distinction between primary PM and secondary PM is important for understanding and analyzing how the various emissions sources contribute to ambient PM concentrations. However, in ambient air where particles are constantly interacting and transforming, most individual particles are actually composed of a mix of primary and secondary PM. An individual primary particle typically has a core of carbonaceous material, often containing trace metals and other toxic materials. Layers of organic and inorganic compounds are then deposited onto the core particle. Depending on the composition of the material deposited on the core particle, the particle may become more toxic as it grows in size.

Physical Processes that Affect PM Formation

In addition to chemical processes in which precursor compounds react to form secondary PM, several physical processes also play an important role in determining how particles interact and transform while suspended in the air. The processes that affect PM vary depending on particle size.

Key physical processes that affect the formation of fine and ultrafine particles at the micro scale include **condensation, nucleation, and coagulation.** These processes occur very rapidly, especially in the initial seconds after a plume of emissions is released by a combustion process. During "plume processing", the hot particles and gases produced by combustion interact vigorously upon exposure to cooler ambient air. As a result of these processes, particle count and particle size distribution can change very rapidly. These physical processes are especially potent among ultrafine particles; because ultrafine particles are so numerous and have a great deal of surface area, they interact and agglomerate more rapidly than other types of PM. Therefore, ultrafine PM is very dynamic and short-lived in the atmosphere.

Condensation and nucleation are related processes. Combustion processes emit a great variety of organic compounds in gaseous form. Upon exposure to cooler ambient air, these hot gases seek to condense. When the hot gases condense by adhering to existing particles, this is called condensation. When the hot gases condense by forming new particles, this is called nucleation. There is competition between condensation and nucleation.[14] If the ambient air already contains an abundance of fine particles, then the hot gases will generally condense on to the existing particles. However, if the supply of existing particles is limited, then in the absence of existing particles on which to condense, the gaseous emissions will nucleate to form new particles, primarily in the ultrafine size range. The number of particles produced as hot gases condense thus depends in large part upon the supply of pre-existing particles in the air.

Because the presence of existing particles promotes condensation (instead of nucleation which forms new particles), this means that not only is PM2.5 mass concentration a poor surrogate for ultrafine particle count, but that PM2.5 mass and ultrafine particle count may actually be negatively correlated. The number of new ultrafine particles produced as a by-product of combustion will generally be low when the existing PM2.5 mass concentration is high, and vice versa. This helps to explain measurements showing that when particulate filters are installed on diesel engines, the mass of PM2.5 emitted by diesel combustion is greatly reduced, but the number of ultrafine particles in the diesel exhaust may actually increase (Van Setten et al. 2001).

Coagulation occurs when two or more existing particles join to form a larger particle. Coagulation is very prevalent among ultrafine particles, but tends to decrease as particles grow to a larger, more stable size. Ultrafine particles produced by combustion coagulate very rapidly to form larger particles upon exposure to ambient air. Coagulation reduces particle number and increases particle size, but does not affect overall PM2.5 particle mass. Due to the processes of coagulation and condensation, the number of ultrafine particles tends to drop off rapidly as distance from the emission source increases, whereas PM2.5 mass is more stable.

PM is removed from the air through processes such as diffusion, coagulation, and deposition. Because ultrafine particles are so small that they are only weakly affected by the force of gravity, they are removed mainly by diffusion, in which their random thermal motion (known as "Brownian motion") causes the particles either to adhere to man-made or natural surfaces or to adhere to other

14 For purposes of developing PM emissions inventories, the particles formed by both the condensation and the nucleation processes are referred to as "condensable" emissions.

particles (coagulation). As particles grow larger and heavier via coagulation, they are eventually deposited to the earth's surface by means of gravity through the processes of dry deposition or wet deposition (rain and snow). Fine and ultrafine particles often provide a nucleus that facilitates the condensation of water vapor in the atmosphere, thus forming water droplets; so these particles can also be removed from the air via wet deposition. Although beneficial for purposes of clearing the air, PM deposition may have negative impacts on soil, water, flora and fauna, as discussed in Section 1-D.

Spatial Variation in PM Concentrations (Concentration Relative to Distance from Emission Source)

The ambient concentration of a directly-emitted air pollutant, such as primary PM, generally decreases rapidly via dispersion as distance from the emission source increases. This means that concentrations of primary pollutants will vary considerably on a spatial basis. By contrast, ambient concentrations of pollutants that are formed by means of chemical processes in the atmosphere, such as ozone and secondary PM, are not so directly related to distance from the emission source; these secondary pollutants tend to be more broadly and evenly distributed on a spatial basis.

Since ultrafine PM is composed mainly of primary PM, the number of ultrafine particles typically decreases rapidly as distance from the emission source increases. Fine PM (PM2.5) and coarse PM, on the other hand, include a mix of both primary and secondary particles. So concentrations of primary PM from emission sources such as engine combustion and wood-burning can vary greatly at the local scale, whereas the distribution of secondary PM such as ammonium nitrate and ammonium sulfate tends to be more uniform across a region.

Relationship between PM and Toxic Air Contaminants

Air pollutants are generally regulated either as **criteria air pollutants** or as **toxic air contaminants** (TACs). Criteria pollutants are generally controlled on a regional scale in an effort to attain air quality standards which are based on ambient concentrations in the atmosphere. TACs are generally present in the atmosphere only in very low concentrations. But because of their high toxicity, TACs are regulated at the emissions source so as to limit individual exposure on the basis of risk-based standards; for example, a maximum cancer risk no greater than 10 in one million. Although PM is categorized and regulated as a criteria air pollutant, PM displays some characteristics of a TAC to the extent that it acts as a local air pollutant. Areas of overlap between fine PM and toxic air contaminants (TACs) include the following:

- In the case of both fine PM and TACs, exposure to even small amounts of the pollutant can cause negative health effects;
- PM and TACs share common emissions sources, such as combustion of fossil fuels and biomass;
- Diesel PM has been identified as a TAC by the California Air Resources Board;

- Some air toxics may be emitted in particle form, such as cadmium emitted from combustion of fossil fuels;
- TACs and PM are fellow travelers; air toxics frequently adhere to fine particles and then enter the lungs when these particles are inhaled.

PM Formation & Dynamics in the Bay Area

The basic chemical and physical processes described above that govern PM formation and transformation at the micro level hold true for the Bay Area. However, local meteorology and climate, the specific mix of PM sources and their geographical distribution within the region, and air exchange with neighboring air basins all influence PM formation and dynamics in the Bay Area.

Temporal & Seasonal Variation in Bay Area PM Levels

Ambient PM in the Bay Area varies considerably both in composition and spatial distribution on a day-to-day basis and on a seasonal basis, due to changes in emissions and weather. Changes in meteorological conditions are the most important factor in explaining the day-to-day and seasonal variation in PM concentrations. The Bay Area experiences its highest PM concentrations in the winter; exceedances of the 24-hour national PM2.5 standard almost always occur from November through February. High PM2.5 episodes are typically regional in scale, impacting multiple Bay Area locations. During other seasons, by contrast, Bay Area PM2.5 levels tend to be relatively low, due largely to the region's natural ventilation system. Thus, on an annual-average basis, PM2.5 levels in the Bay Area are among the lowest measured in major U.S. metropolitan areas.

Meteorological factors are the main reason that the Bay Area experiences its highest PM levels in winter months. However, it is important to note that winter is also the season when the most residential wood-burning occurs; in some parts of the Bay Area, wood smoke accounts for the majority of airborne PM2.5 during high PM episodes. In addition to higher wood smoke emissions, secondary PM2.5 levels are also elevated during the winter months. Cool weather is conducive to the formation of ammonium nitrate which contributes an average of about 40% of total PM2.5 under peak PM conditions.

Studies in Southern California have found that seasonal variation in meteorological conditions also affect emissions and concentrations of ultrafine particle. Similar to PM2.5, ultrafine particle numbers are higher in winter compared to spring and summer. This is likely due to fact that lower temperatures promote particulate formation; condensable organics emitted as hot vapors from tailpipes and other combustion sources quickly cool and condense to form particles. One study (Zhang et al. 2005) found that the ultrafine particle formation rate from vehicle exhaust is higher in winter than in summer because average particle size is smaller in winter (~ 10 nanometers) than in summer (~ 60 nanometers).

While PM emissions and concentrations tend to be highest in winter for the reasons described above, meteorological conditions primarily determine whether the concentrations will build up to levels that exceed the national 24-hour PM2.5 standard. Horizontal mixing (i.e., surface winds) and vertical mixing

(which occurs when air temperatures increase with height) are the key to dispersing particulates in the atmosphere, and thus keeping ambient concentrations below the PM standards. Winter is associated with decreased atmospheric mixing height and more stagnant, less windy weather.

Weather & Wind Patterns Conducive to High PM Concentrations

The Central Valley (comprised of the Sacramento and San Joaquin valleys) borders the Bay Area to the east, and there is considerable air exchange between them. In summer, the typical pattern is westerly winds blowing from the Bay Area into the Central Valley. In the winter, during periods of stagnation when PM concentrations are high, the pattern tends to reverse with easterly flow draining from the Central Valley through the Bay Area and into the Pacific Ocean.

Using a technique called **cluster analysis** to identify correlations between weather conditions and PM concentrations in historical data, Air District staff collaborated with UC Davis staff to analyze how meteorological conditions impact Bay Area PM levels during winter months. Weather systems conducive to high PM2.5 levels have shallow flows through the complex terrain that form stagnating cold pools in valleys that trap pollutants. Consecutive stagnant and rainless winter days are typically prerequisites for development of elevated PM2.5 episodes.

A single weather pattern was found to account for approximately 80% of all Bay Area PM2.5 exceedances. This pattern is characterized by a ridge of high pressure moving over the Bay Area during a period of multiple days. This system leads to calm conditions within the Central Valley, coupled with persistent easterly winds from the Central Valley into the Bay Area. The lower levels of solar radiation (sunlight) in the winter lead to stronger temperature inversions; these inversions prevent vertical mixing and are therefore conducive to the buildup of PM in ambient air near ground level.

During this weather pattern, PM levels in the Central Valley can be about 2-3 times higher than in the Bay Area. This is largely because meteorological conditions are more conducive to the transformation of NOx to nitric acid (needed for the formation of ammonium nitrate) in the Central Valley than for coastal locations. Conditions that enhance daytime and nighttime conversion of NOx to nitric acid include low wind speeds combined with abundant sunlight during the day and high humidity at night. Nitric acid then rapidly reacts with ammonia emissions, mostly from dairy activities, which are especially concentrated in the northern San Joaquin Valley, to form ammonium nitrate. The easterly winds that prevail during this pattern transport both primary and secondary PM from the Central Valley into the Bay Area, as further discussed in the modeling section below.

Although the weather pattern described above accounted for over 80 percent of all Bay Area exceedances, it should be noted that only around one in three days belonging to this pattern resulted in an exceedance. Therefore, this weather pattern constitutes a necessary, but not sufficient, condition for an exceedance to occur. Days with this pattern were further analyzed to distinguish the characteristics of days that result in exceedances of the 24-hour PM2.5 standard. Exceedance days could be defined in terms of a number of simultaneous meteorological characteristics: a ridge of high

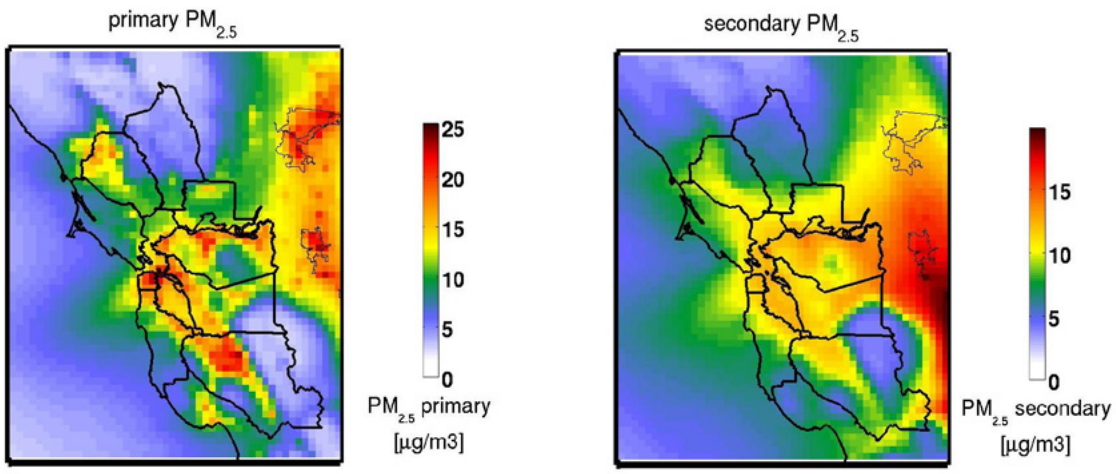
pressure over the Bay Area from strongly stable conditions aloft providing a weak surface pressure gradient over Central California; persistent shallow flows from the east through the Bay Area; winds channeled by terrain; enhanced nocturnal cooling under clear-sky conditions leading to enhanced overnight drainage flows off the Central California slopes; and at least two consecutive days of these listed conditions.

PM Photochemical Modeling Results

The Air District performs photochemical modeling to better understand the complex relationship between emissions, ambient concentrations, and population exposure to air pollutants. Air District staff has employed EPA's Community Multiscale Air Quality (CMAQ) model to simulate PM2.5 formation and dynamics in the Bay Area. PM2.5 simulations were performed with the CMAQ model for four months (December-January, 2000-01 and 2006-07). The modeling domain included the Bay Area and the entire Central Valley to account for the impact of inter-basin transport. The model was applied on 4-km horizontal grids. The results of the PM modeling have been summarized in the October 2009 report entitled *Fine Particulate Matter Data Analysis and Modeling in the Bay Area.*

Figure 2-3 shows the spatial distribution of simulated primary and secondary PM2.5 concentrations around the Bay Area. These results were averaged across the 52 simulated days for which measured Bay Area 24-hour PM2.5 levels exceeded 35 $\mu g/m^3$. For most of these episodic days, light winds flowed through the Bay Area from the east, and Central Valley conditions were near calm. Primary PM2.5 levels were elevated mainly in and around major Bay Area cities, including Oakland, San Francisco and San Jose; near industrial facilities and highways along the Carquinez Strait; at Travis AFB; and Santa Rosa. Secondary PM2.5, present mostly as ammonium nitrate, was not localized near the sources of its precursor emissions, NO_x and ammonia. Rather, secondary PM2.5 was regionally elevated. A sharp gradient existed, with very high secondary PM2.5 levels in the Central Valley decreasing westward through the Bay Area. Around San Francisco and San Jose, PM2.5 levels were dominated by primary (directly-emitted) PM. For other areas affected by PM episodes, such as the eastern, northern, and southern Bay Area and also the Delta, primary and secondary PM2.5 levels were comparable. Both primary and secondary build-up were required for exceedances to occur in these locations.

Figure 2-3 Spatial distribution of simulated 24-hr primary and secondary PM2.5 levels averaged across the 52 simulated days when measured Bay Area 24-hr PM2.5 level exceeded 35 μg/m³



(Bay Area counties and the California coastline are drawn using thick black lines.
City limits for Sacramento and Stockton are drawn using thin black lines.)

As noted above, analysis of meteorological patterns found that more than 80% of Bay Area PM exceedances occur when easterly winds blow into the Bay Area from the Central Valley. Therefore, Air District staff also performed photochemical modeling to estimate the contribution of PM transport from the Central Valley during elevated PM episodes in the Bay Area. Transport impacts were evaluated for 55 days (from 2000-01 and 2006-07) having simulated base-case PM2.5 concentrations of 35 μg/m³ or higher. Anthropogenic Bay Area emissions were eliminated to estimate the cumulative transport impacts from all sources outside of the Bay Area. These simulations found that significant amounts of both primary and secondary PM2.5 in the form of ammonium nitrate were transported into the Bay Area. On days when the Bay Area exceeded the 24-hour PM2.5 standard, modeling indicated that transported primary PM2.5 levels averaged as high as 8 μg/m³ and transported secondary PM2.5 levels averaged as high as 13 μg/m³. The largest transport impacts for both primary and secondary PM2.5 occurred along the eastern boundary of the Bay Area.

The modeling also examined the sensitivity of ambient PM concentrations in response to hypothetical reductions in Bay Area emissions of primary PM2.5, as well as reductions in precursor pollutants (ROG, NOx, SOx, and NH3) individually and in combination. Reducing Bay Area primary (directly-emitted) PM2.5 emissions provided far greater reductions in ambient Bay Area PM2.5 levels than reducing Bay Area secondary PM2.5 precursor emissions. Of the precursor emissions reductions simulated, Bay Area ammonia reductions were most effective. Reducing ammonia emissions by 20% was found to decrease PM2.5 concentrations by approximately 0.5 to 1.0 μg/m³. The ammonia emissions reductions lowered the ammonium nitrate component of PM2.5 only for relatively cold winter days favoring ammonium nitrate buildup. (Ammonium nitrate PM2.5 tends to evaporate faster than it forms at temperatures above around 60 degrees Fahrenheit.) Combined

NOx and ROG emissions reductions for the Bay Area were relatively ineffective. NOx emissions reductions were relatively ineffective because ammonium nitrate PM2.5 formation involves the relatively slow and incomplete conversion of NOx to nitric acid. Reducing Bay Area sulfur-containing PM precursor emissions typically had a small impact on Bay Area ambient PM2.5 levels. Under certain conditions, however, reducing Bay Area sulfur-containing emissions did decrease ambient Bay Area PM2.5 levels by approximately 1 $\mu g/m^3$.

The Air District also modeled wood smoke to estimate the impact of efforts to reduce residential wood-burning during the winter season. The modeling period included 8 of the 11 Spare the Air periods during the winter of 2008-09. Bay Area wood-smoke levels were simulated with and without wood-burning restrictions during these periods. Without burning restrictions during these Spare the Air periods, the simulations indicated that peak wood-smoke levels of up to 10-20 $\mu g/m^3$ would have occurred over the areas that generally have high wood-burning emissions. For many of the remaining populated locations within the Bay Area, wood-smoke levels would have been approximately 5 $\mu g/m^3$. Peak benefits of the wood-smoke rule were about 10 mg/m3 of reduced wood smoke. Maximum simulated benefits of the wood-smoke rule occurred for areas that generally have the highest wood-smoke levels. Often, the areas most heavily impacted by wood smoke are away from the Air District's PM monitoring locations. Therefore, reductions of population exposure to wood smoke resulting from the rule may be significantly greater than indicated by the monitoring data.

Source Contributions to Ambient PM Concentrations

Determining the relative contributions of various sources of direct PM2.5 emissions and PM2.5 precursors to total PM concentrations is complex. The Air District collects PM on filters at four monitoring sites (Livermore, West Oakland, San Jose, and Vallejo) for PM speciation purposes. The filters are then analyzed to estimate the contribution of various emission sources to the total ambient concentration of PM2.5 using a technique known as **chemical mass balance** (CMB).[15] To estimate the overall contribution of various sources, the results of the source apportionment analysis are combined with emissions data from the 2010 Emissions Inventory. The CMB analysis presented here updates a previous CMB analysis prepared in 2008[16] and includes data from July 2009 through December 2011. The goal was to represent the mix of PM2.5 sources as of 2010, including the reduced contributions from ships following the effective date of the ARB rule to require ocean-going ships to use low-sulfur fuel within 24 miles of the coast.

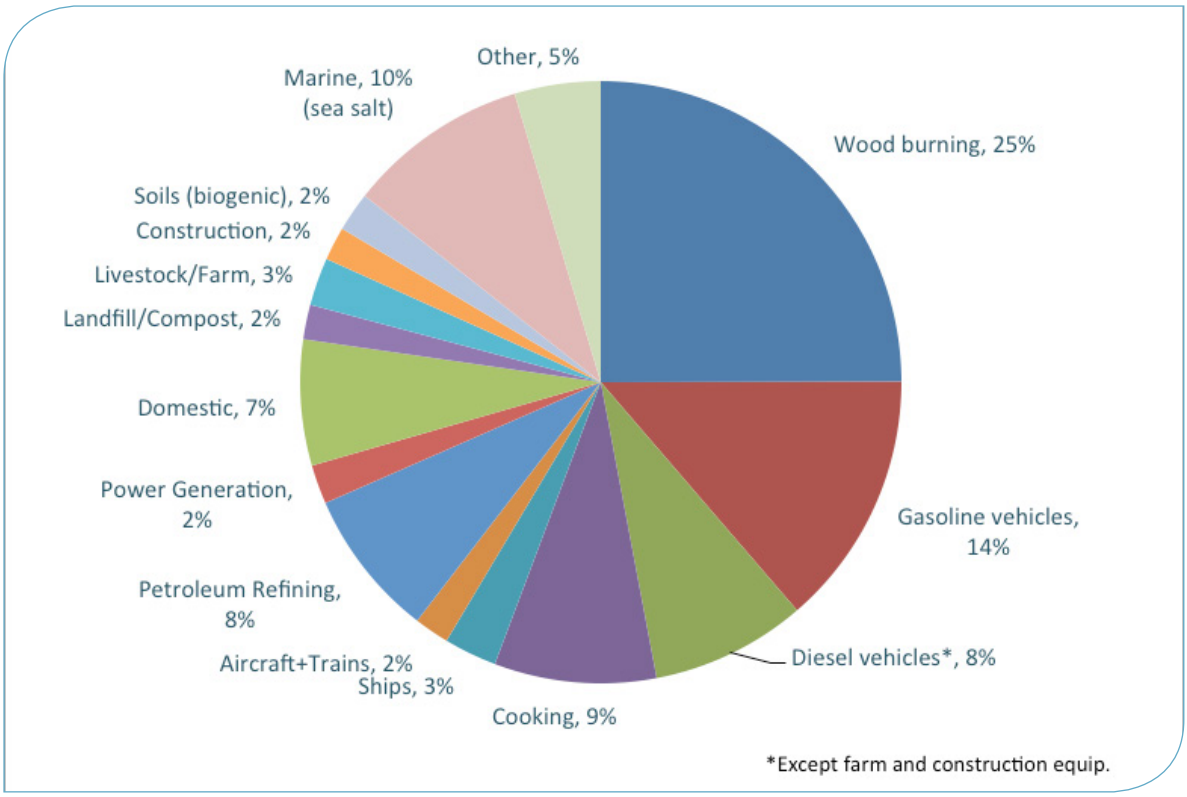
Figure 2-4 shows the estimated contributions to Bay Area annual PM2.5 concentrations using the average of the results from the four sites. Note that this includes contributions to secondary PM2.5; i.e., ammonium nitrate formed from NOx and ammonia, and ammonium sulfate formed from SO2 and ammonia. The source apportionment analysis shows that combustion of both fossil fuels and biomass are major PM2.5 contributors for all seasons. The largest contributor to annual PM2.5 is wood-burning,

15 Chemical mass balance (CMB) analysis is a methodology in which a computer model is used to apportion ambient PM2.5 collected on filters over 24-hour periods at monitoring sites around the Bay Area to a set of source categories. Each filter was analyzed for a range of chemical species. The same species were measured in special studies of emissions from various sources, such as motor vehicles and wood burning. The CMB model finds the mix of these source measurements that best matches the ambient sample, chemical species by chemical species.

16 See report entitled Sources of Bay Area Fine Particles, April 2008 at: www.baaqmd.gov/Divisions/Planning-and-Research/Research-and-Modeling/Publications/Reports.aspx

contributing about a quarter of the total. This is mainly from residential wood burning, but also includes wood smoke from controlled burns and wildfires. Nearly another quarter comes from on-road motor vehicles, 14% from gasoline and 8% from diesel.

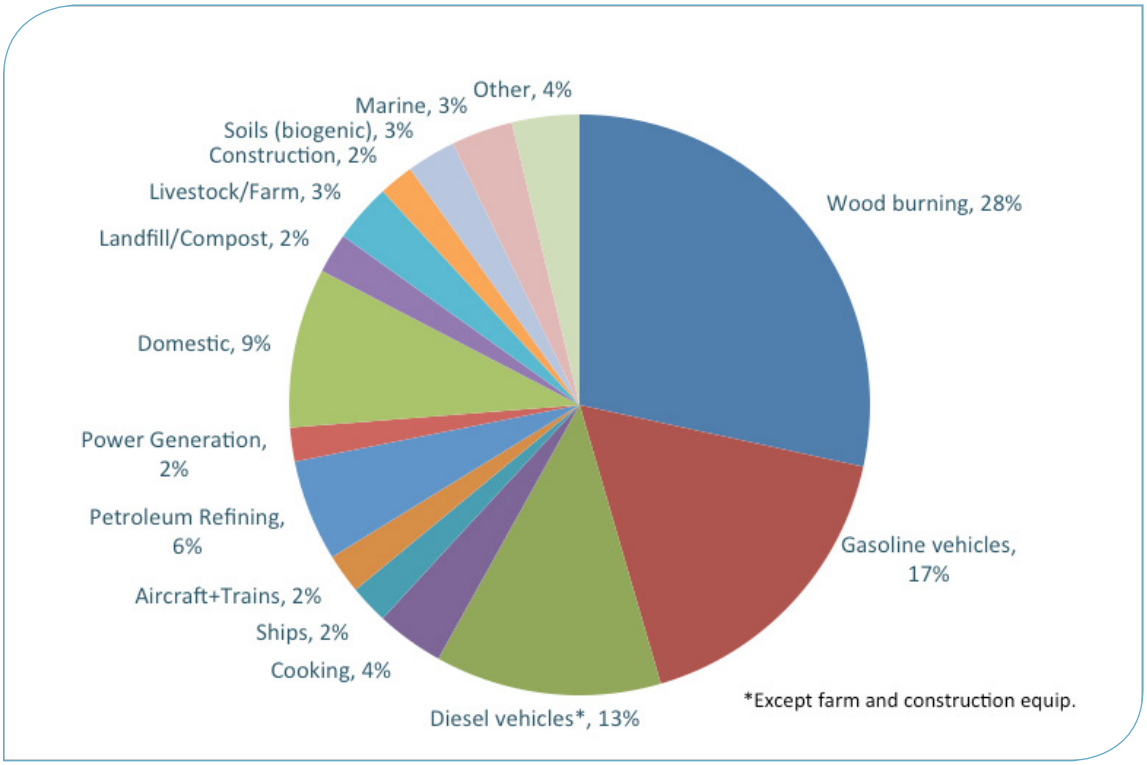
Figure 2-4 Estimated Source Contributions to Annual PM2.5 Concentrations



Cooking, petroleum refining, and domestic sources are also sizeable contributors, along with the naturally occurring sea salt from marine air. Domestic sources, for purposes of Figures 2-4 and 2-5, include emissions from use of natural gas for residential heating and cooking, as well as the contribution to formation of secondary PM2.5 as a result of ammonia emissions from pet waste and human perspiration and respiration Contributions from ships have been cut by two-thirds or more, thanks to the ARB rule mandating low sulfur fuel near ports. The estimate for construction equipment has also dropped substantially because of a revision in ARB's estimation method. Note that several sources – soils, livestock, and landfill – appear because of their ammonia emissions, which contribute to formation of ammonium nitrate and ammonium sulfate.

Figure 2.5 shows the sources contributing to peak PM2.5 concentrations, specifically, the 10 samples at each monitoring site with the highest PM2.5 concentrations. Almost all the highest Bay Area PM2.5 concentrations occur in winter, so the wood-burning contribution is higher than the annual, representing almost 30% of the peak total. The biomass combustion contribution to peak PM2.5 levels is about 3-4 times higher in winter than the other seasons, as confirmed by isotopic carbon (^{14}C) analysis, due to increased levels of wood burning during the winter season. Motor vehicles are also a larger contributor during winter months because their NOx emissions contribute most to the formation of secondary PM in the form of ammonium nitrate. Similarly, domestic sources are another large source of secondary PM because of their ammonia emissions. Marine air is a smaller contributor in the winter than on an annual-average basis, because winter winds are frequently offshore, unlike the typical on-shore pattern the rest of the year.

Figure 2-5 Estimated Source Contributions to Peak PM2.5 Concentrations



PM Emissions Inventory

An emissions inventory is an essential tool for air quality planning. The inventory contains a detailed breakdown of the estimated emissions from each source category, thus providing information as to the source, magnitude, and location of emissions. Emissions inventories are used to perform air quality modeling, to identify source categories where there may be opportunities for additional emission reductions, and to predict trends in terms of future air quality.

This section presents the Air District's latest Bay Area inventory for primary emissions (directly-emitted particles) of both PM2.5 and PM10, as well as precursors that combine via chemical reactions to form secondary PM. These precursors include reactive organic gases (ROG), oxides

of nitrogen (NOx), sulfur oxides (SOx), and ammonia (NH3). The Air District released it's first-ever emissions inventory for ultrafine PM in August 2012[17].

The inventory includes annual-average emissions, as well as emissions during the winter season when the Bay Area normally experiences its highest PM concentrations. In addition to the inventory for base year 2010, projected emissions for future years out to 2030 are also provided. Tables in Appendix A provide the detailed inventory showing estimated emissions by source category.

This inventory does not include "condensable" emissions that also form PM. Condensables are emissions which are emitted in a gaseous phase, but then condense to form particles upon exposure to cooler ambient air, as discussed in the section above entitled **Physical Processes that Affect PM Formation**. Depending on the emission source and combustion conditions, this condensable component may account for a significant share of overall PM emissions for certain emission sources. Recent US EPA guidelines call on air quality agencies to consider the condensable component of PM in developing PM emission inventories and control strategies. EPA has published a source test method to be used for source testing stationary sources (with a few minor exceptions). However, test methods and methodologies to estimate condensable emissions are not available at the current time for certain emission source categories. Therefore, in the interest of methodological consistency, the Air District has chosen to exclude condensable emissions in the current inventory. The Air District will work with ARB and other partners to develop estimates of condensable emissions for future PM inventories.

Methodologies Used to Estimate Emissions

The estimated emissions provided in the inventory are based upon data from source tests, published emission factors, and engineering calculations. Emission inventories are revised and improved on a regular basis. The PM inventory provided in this report differs significantly from the inventory provided in the Bay Area 2010 Clean Air Plan (2010 CAP). This is due to the fact that, since the release of the 2010 CAP, ARB and Air District staff reviewed and improved the methodologies used to estimate emissions from several of the most important PM source categories, as explained below.

Stationary (Point) Sources

Actual 2010 reported emissions from permitted facilities are included in this inventory. Examples of stationary sources that emit primary PM and/or PM precursors including oil refineries, metal smelters, charbroilers, and back-up generators used to supply emergency power at many facilities.

Residential Fuel Combustion

This category includes residential combustion of both wood and natural gas for space-heating, water-heating, and cooking. Most homes rely primarily (or completely) on natural gas (or electricity) for these purposes. Nonetheless, although only a minority of Bay Area households burn wood, PM from wood smoke is the largest single source of winter-time PM emissions in the Bay Area, and greatly exceeds the PM emissions from (the much more common) residential natural gas

17 See the report entitled, *Ultrafine Emissions Inventory for the San Francisco Bay Area*, BAAQMD August 2012

combustion. Previous estimates of the amount and location of residential wood burning were developed based on a Bay Area 2005-2006 telephone survey on wood burning. In 2008 the Air District adopted Regulation 6, Rule 3 to limit emissions of particulate matter (PM) and visible emissions from wood-burning devices, as described in Section 4. The District also implemented a robust outreach effort to inform Bay Area residents about "no-burn days" and the detrimental health effects of wood smoke through its winter Spare the Air program. Annual surveys of Bay Area households, as well as chemical mass balance analysis of PM captured on filters, both indicate that wood-burning has decreased approximately 40% since 2008 when the Air District's wood burning rule went into effect. Emissions from residential fuel combustion in this inventory have been revised to reflect this decrease in wood-burning.

Commercial Cooking

Previous estimates for this source category included condensable PM. The reason for this was that source testing conducted as part of the regulatory process to control emissions from this source category (via Regulation 6, Rule 2) included condensable PM. However, because methods to estimate condensable emissions for other source categories are not yet available, as discussed above, the condensable emissions for the Commercial Cooking source category have been omitted here for purposes of methodological consistency.

On-Road Motor Vehicles

Estimates for on-road motor vehicle emissions are based on ARB's latest emissions factor model, EMFAC2011. In preparing EMFAC2011, ARB staff conducted major research to determine the population and compositions (e.g. construction trucks, port trucks, in-state trucks, etc.) of medium and heavy duty diesel truck fleets (>14,000 pounds Gross Vehicle Weight), as well as age distribution and vehicle miles traveled for these vehicles. Also, emission factors for these vehicles have been updated to reflect the major benefits of recent ARB regulations to reduce emissions from diesel trucks and buses. The EMFAC2011 model also includes the impact of the recent economic recession on both diesel and gasoline vehicle activity.

The on-road category includes PM emissions from both diesel and gasoline engines. PM emissions from late-model light-duty gasoline vehicles are extremely low on a grams-per-mile basis. However, emissions from gasoline vehicles are significant on an aggregate basis because gasoline vehicles account for approximately 95% of the 175 million miles driven on an average day in the Bay Area.

Motor vehicle emissions that contribute to PM include tailpipe emissions of both primary PM and PM precursors from fuel combustion, lubricating oil, and particles generated by brake and tire wear. PM from tire wear and brake wear are included for on-road motor vehicles. There is insufficient information to produce estimates for tire-wear and brake-wear for off-road equipment; however, these emissions are expected to be very low as they are related to vehicle miles traveled (VMT) and most of the off-road equipment with tires have very low VMT.

A breakdown of annual average motor vehicle emissions in the current inventory is shown in Table 2-2.

Table 2-2 Bay Area Annual Average Primary PM2.5 Emissions – Year 2010: On-Road and Off-Road Motor Vehicles

On-Road Motor Vehicle	tons/day	%
Gasoline Exhaust	0.8	10%
Diesel Exhaust	2.7	37%
Tire/Brake-Wear (Gasoline Vehicles)	3.2	44%
Tire/Brake-Wear (Diesel Vehicles)	0.6	8%
Total On-Road Motor Vehicles	**7.3**	**100%**
Off-Road Motor Vehicles	**tons/day**	**%**
Gasoline Exhaust	1.7	37%
Diesel Exhaust	2.9	63%
Total Off-Road Motor Vehicles	**4.6**	**100%**
On-Road and Off-Road Motor Vehicles Combined		
All Motor Vehicles	**tons/day**	**%**
Total Gasoline Exhaust	2.5	21%
Total Diesel Exhaust	5.6	47%
Tire/Brake Wear	3.8	32%
Grand Total	**12.0**	**100%**

The new emission factors show a reduction in tailpipe emissions from both gasoline and diesel engines. However, the decrease in tailpipe exhaust has been offset to a considerable extent by a major increase in estimated PM emissions from brake wear. Brake-wear emissions of PM2.5 in

EMFAC2011 are three times the estimates produced by EMFAC2007. (It should be noted, however, that chemical mass balance analysis performed by Air District staff shows better agreement with the EMFAC2007 factors for brake and tire wear. Therefore, Air District staff will work with ARB staff to continue to investigate and improve PM emission factors for brake wear.)

Whereas brake wear and tire wear made up a relatively small portion of PM2.5 from on-road vehicles using the previous EMFAC2007 emission factors, they now account for half of total PM2.5 emissions from on-road vehicles, according to the EMFAC2011 model. Although PM2.5 exhaust (tailpipe) emissions from diesel vehicles are much greater than from gasoline vehicles, when the new brake wear factors are included, gasoline vehicles account for 54% of total PM2.5 from on-road vehicles, compared to 45% for diesel vehicles.

It is important to note that, in addition to their direct emissions of primary PM, motor vehicles are the major source of precursor pollutants that combine to form secondary PM. For example, on-road vehicles account for 37% of ROG, 57% of NOx, and 18% of ammonia emissions in the Bay Area inventory for year 2010, as shown in Figures 2-10, 2-11, and 2-12, respectively.

Although the Air District does not yet have an ultrafine PM inventory, emissions testing indicates that both gasoline and diesel engines are a major source of ultrafine particles. Tests indicate that gasoline vehicles emit especially large amounts of ultrafine particles when in a hard acceleration mode. Research also suggests that engine lubricating oil may be an important source of ultrafine particles. It is likely that when an ultrafine PM inventory for the Bay Area becomes available, it will show that combustion from both diesel and gasoline vehicles account for significant shares of UFPM emissions in the region.

Construction, Industrial and Airport Ground Support Equipment

Emissions estimates for off-road mobile sources (such as construction, cargo handling at ports, and airport ground support equipment) are taken from ARB's latest emissions factor model, OFFROAD2011. Emissions for this category have decreased significantly compared to the estimates in the previous inventory derived from ARB's OFFROAD2007 model. Research on fuel sales for off-road equipment showed that fuel usage, and hence emissions from these vehicles, had been substantially over-estimated in the OFFROAD2007 model.

In response, ARB staff improved the inventory for this category by revising equipment population estimates based on historical equipment sales data, and incorporating data from industry regarding

hours of equipment operation and load factor, a measure of how intensively the equipment is being used. When coupled with the impact of the 2007 recession, the new OFFROAD2011 model estimated PM2.5 emissions from this category to be just one-fifth of the estimate produced by EMFAC2007 that was used in the 2010 CAP.

Ships and Commercial Boats

ARB recently revised the methodology to calculate emissions from ships and commercial boats. For ships, the new inventory increases the specificity of the earlier inventory by including vessel-specific characteristics and activity for each port. Emissions were calculated by estimating ship emissions on a ship-by-ship and a port-by-port basis, using actual ship engine power, speeds, and berthing times where possible. Projected emissions for future years were estimated using a set of growth factors specific to each port and each ship type. For commercial boats, emissions were calculated based on data collected from ARB's 2004 Statewide Commercial Harbor Craft Survey. This survey collected information from boat owners as to vessel type, home port, engine characteristics, hours of operation, annual fuel usage, etc. This information along with other studies, such as emission inventories developed for the Ports of Los Angeles and Long Beach, were used to estimate emissions for boats. Cruise ship berthing emissions were taken from the 2005 Bay Area Seaports Air Emissions Inventory Report.

Another major difference in the current estimate of ship emissions, compared to the estimate provided in the 2010 CAP, is that ship emissions reported in this inventory are based on ship activity within three nautical miles of the coastline, whereas the 2010 CAP reported emissions for ship activity up to 100 nautical miles. Based on direction from ARB, using a limit of three nautical miles is consistent with the limit being used by other air districts that are in the process of preparing PM2.5 SIP submittals.

Aircraft

Aircraft emissions are based on actual 2010 activity data (landing and take-off data, taxi times between the runway and the terminal, etc.) at Bay Area airports, based on the current aircraft fleet mix and the latest emissions factors for PM, ROG, NOx, and SO2. Aircraft emissions are decreasing on a per-passenger mile basis, due to the shift toward larger planes and the development of

more fuel efficient engines. As a result of new aircraft engine technological changes that rely on higher combustion temperatures to improve fuel economy, ROG emissions are decreasing, but NOx emissions are increasing per landing and take-off.

Paved and Unpaved Road Dust (Re-entrained Dust)

Previous paved road dust emissions, including those reported in the 2010 CAP, were believed to be over-estimated when compared to observed ambient concentrations and source apportionment (chemical mass balance) analysis. A new methodology from US EPA was used to estimate PM emissions from vehicular travel on paved roads.[18] This methodology results in significantly lower estimates of PM10 and PM2.5 emissions compared with previous estimates. The revised estimates of road dust emissions from paved roads for PM10 and PM2.5 are only about one-third of the estimated emissions reported in the 2010 CAP.

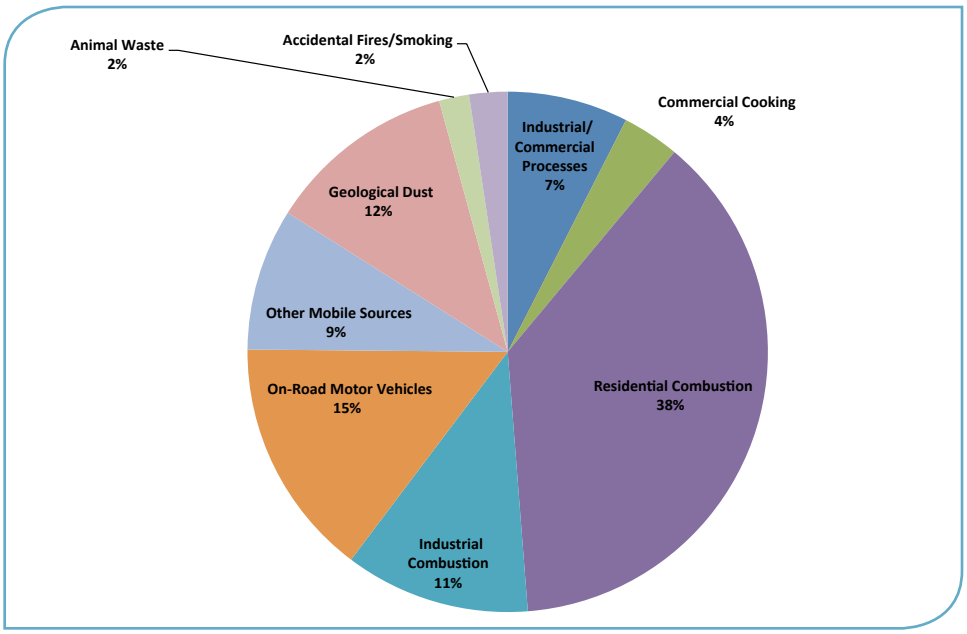
Unpaved road dust emissions were also updated to reflect the latest information from Caltrans on Bay Area unpaved road miles and vehicle miles traveled on these roads. As with the paved road dust estimates, the revised estimates of road dust emissions from unpaved roads for PM10 and PM2.5 are only about one-third of the estimated emissions reported in the 2010 CAP.

2010 Annual Average Primary PM2.5 Emissions

Estimated annual average emissions of primary PM2.5 have decreased significantly in the current inventory compared to the estimates provided in the 2010 CAP. Whereas the 2010 CAP reported 47 tons per day of primary PM2.5 for year 2009, the current inventory shows an estimated 87 tons per day of primary PM2.5 for year 2010, a decline of 46%. The revised inventory includes significant reductions in several major source categories, such as residential wood-burning, commercial cooking, off-road vehicles ("Other Mobile Sources"), and road dust (included in "Geological dust"). This decrease in the inventory is based in part on real emission reductions due to factors such as turnover in the vehicle fleet and the impact of new regulations that had not been accounted for in previous emission factors. However, changes in methodologies used to estimate emissions, as discussed above, also account for a significant portion of the decrease in the inventory. Figure 2-6 shows the annual average emissions of PM2.5 for year 2010 broken down by major source categories.

18 The new methodology for road dust emissions is set forth in two documents:
1) US EPA guidance, January 2011: www.epa.gov/ttn/chief/ap42/ch13/final/c13s0201.pdf and
2) Air Resources Board guidance re: Draft Entrained Paved Road Travel Paved Road Dust, (Section 7.9) 6/15/11

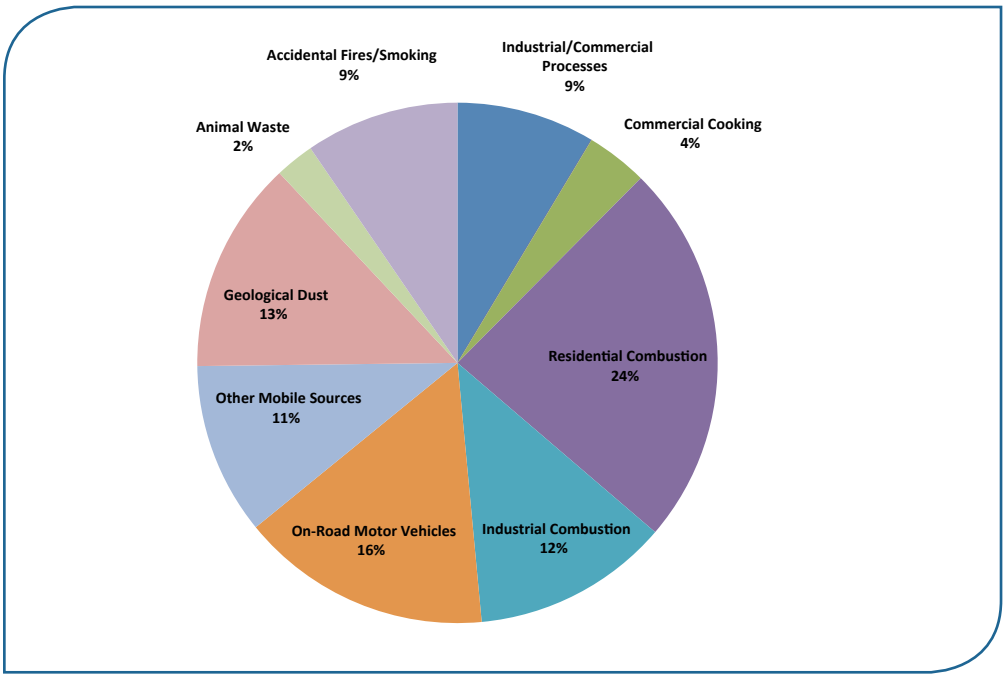
Figure 2-6 2010 Annual Primary Emissions of PM2.5, 47 tons/day



2010 Winter PM2.5 Emissions

The breakdown of primary PM2.5 emissions by source category differs for the winter PM2.5 inventory compared to the annual inventory. The key difference is that PM2.5 emissions from residential fuel combustion account for 38% of the winter inventory versus 24% in the case of the annual inventory. PM2.5 emissions from residential fuel combustion, which is dominated by wood-burning in fireplaces and wood stoves, are 65% higher (an additional 7 tons per day) in the winter months than the annual average emissions for this category. However, emissions from several source categories are lower in winter. For example, winter emissions from off-road equipment, as well as from the industrial sector, are lower than annual average emissions due to reduced activity during the winter months. Accidental fires and geological dust emissions are also lower in the winter than the annual average. Overall, however, winter-time PM2.5 emissions are 4% higher (an additional 2 tons per day) than annual-average emissions. Figure 2-7 shows the winter emissions of PM2.5 for year 2010 broken down by major source categories.

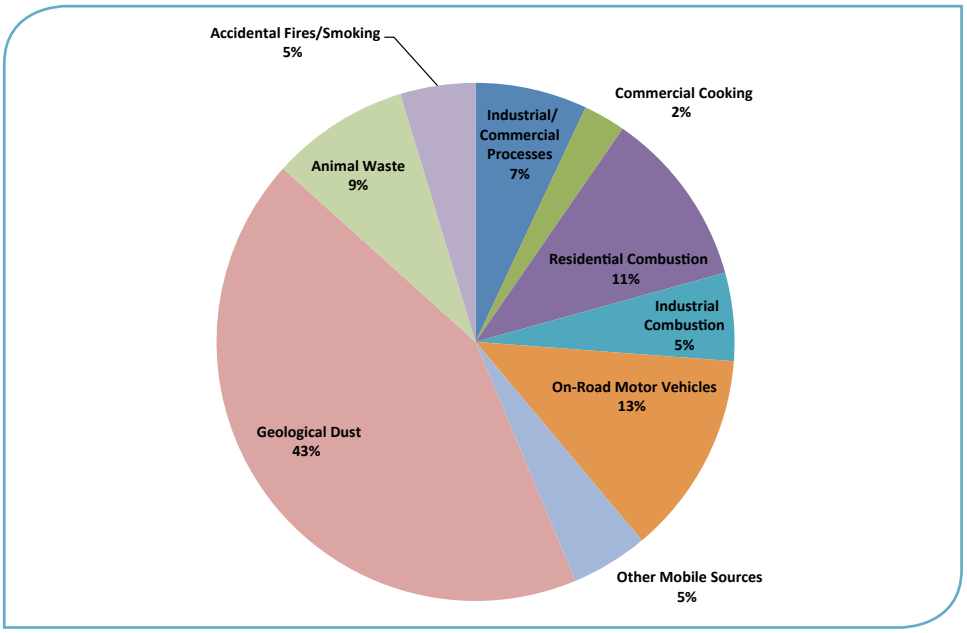
Figure 2-7 2010 Winter Primary Emissions of PM2.5, 49 tons/day



2010 Annual Average Primary PM10 Emissions

PM2.5 emissions are a sub-set of PM10 emissions. For some sources, such as the various types of engine combustion, virtually all PM10 actually consists of fine particles less than 2.5 microns in diameter. For example, 97% of diesel PM10 is PM2.5, meaning that diesel particulate is essentially all PM2.5. But for other sources, only a fraction of PM10 is made up of particles less than 2.5 microns in diameter, and the rest consists of coarse particles between 2.5 and 10 microns in diameter. For example, only 15% of PM10 from road dust is PM2.5; the remaining 85% is coarse particles. For the emissions inventory as a whole, on a mass basis, roughly half of PM10 is composed of fine particles less than 2.5 microns in diameter and half is composed of coarse particles between 2.5 and 10 microns in diameter. In Figures 2-8 and 2-9 showing annual and winter emissions of PM10, source categories that emit coarse particles become more prominent, thus contributing more to PM10 emissions compared to Figures 2-6 and 2-7 for PM2.5. In particular, geological dust, which includes dust from construction and farming operations, re-entrained road dust from paved and unpaved roads, and wind-blown dust, accounts for a much greater percentage of PM10 (43% on an annual average basis) than PM2.5 (13% on an annual average basis).

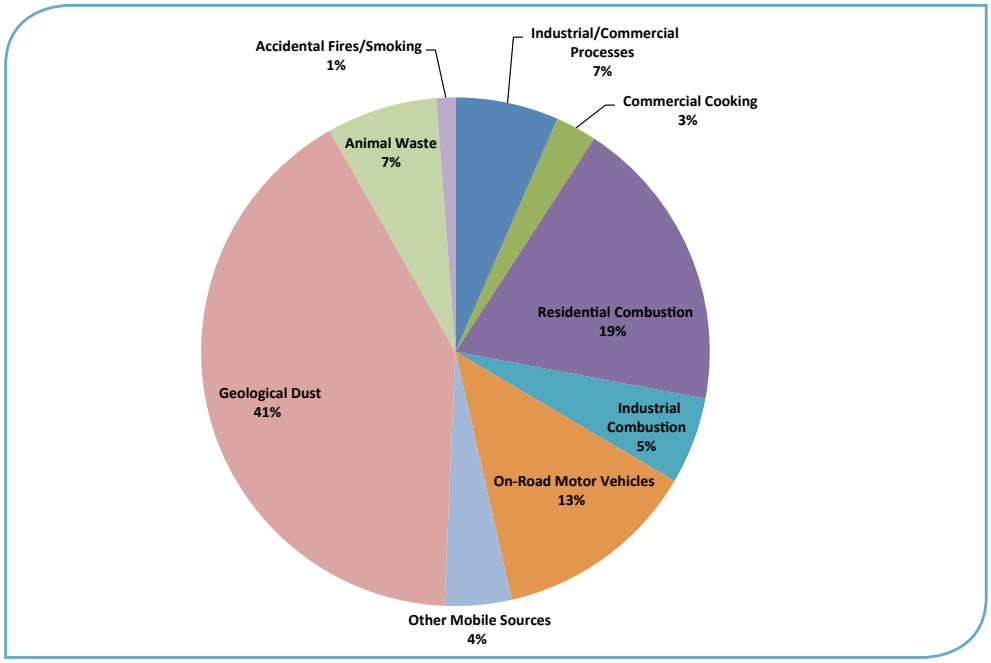
Figure 2-8 2010 Annual Average Primary Emissions of PM10, 106 tons/day



2010 Winter Primary PM10 Emissions

The relationship between annual average PM10 and winter PM10 (i.e., the relative contributions from various source categories) is similar to that for PM2.5. The main difference is that emissions for residential fuel combustion (primarily wood-burning) increase from 11% of the annual PM10 inventory to 18% of the winter PM10 inventory, while emissions from accidental fires (primarily wildfires) decrease from 5% of the annual PM10 inventory to 1% of the winter PM10 inventory. Figure 2-9 shows the winter emissions of PM10 for year 2010 broken down by major source categories.

Figure 2-9 2010 Winter Primary Emissions of PM10, 104 tons/day



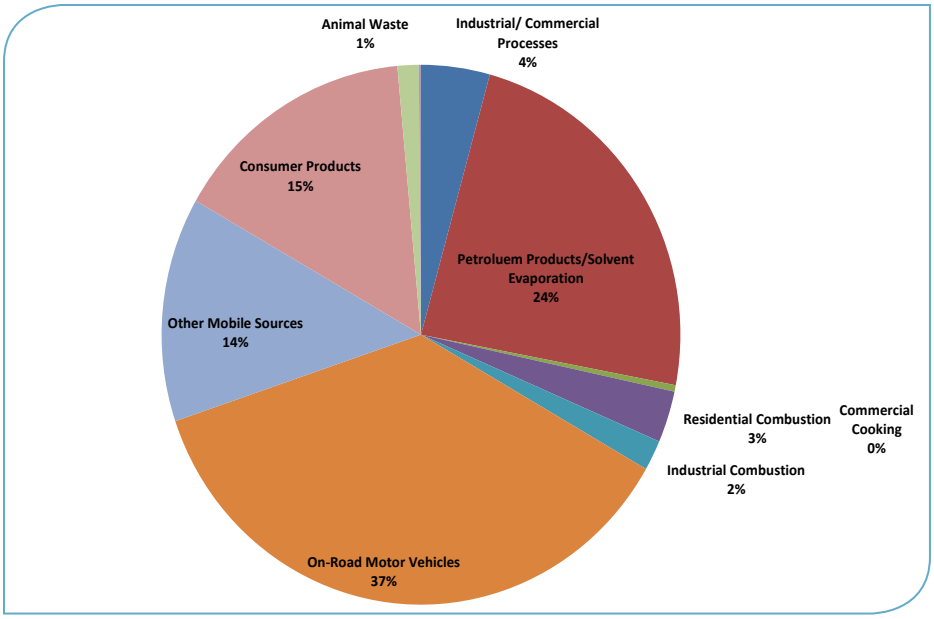
Sources of Precursors Pollutants That Form Secondary PM

Precursor pollutants that combine via chemical processes to form secondary PM include reactive organic gases (ROG), oxides of nitrogen (NOx), sulfur dioxide (SO2), and ammonia (NH3). The sources that produce these pollutants are described below, with pie charts depicting emissions during the winter season when secondary PM formation is greatest.

Reactive Organic Gases (ROG)

As shown in Figure 2-10, on-road motor vehicles (37%) and off-road vehicles (14%) together produce approximately 50% of the winter-time ROG emissions. Evaporation from petroleum products (including those from refineries and fuels distribution) and solvents (such as those from structures coating, adhesives, and sealants) are the second largest contributors to ROG emissions, accounting for approximately 24% of winter emissions. Emissions from consumer products contribute another 15% of the winter-time ROG emissions.

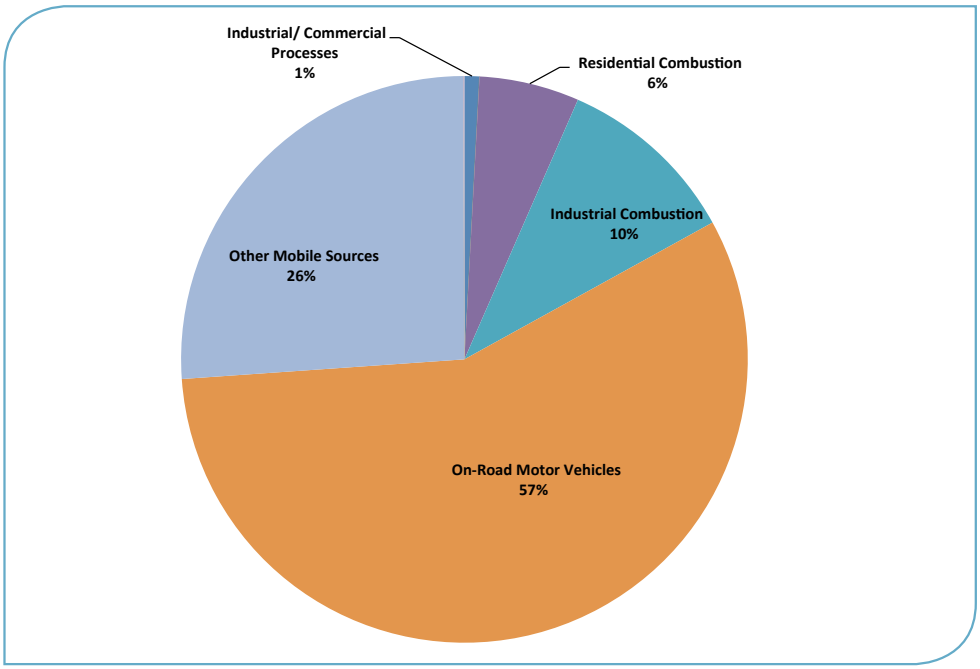
Figure 2-10 2010 Winter Emissions Reactive Organic Gases (ROG) 294 tons/day



Oxides of Nitrogen (NOx)

As shown in Figure 2-11, on-road motor vehicles are the single largest source of NOx emissions in the Bay Area. Together with off-road mobile sources, they produce over 80% of the winter-time NOx emissions. Industrial combustion and residential fuel combustion (including wood-burning) produce 10% and 6% of the winter-time NOx inventory, respectively.

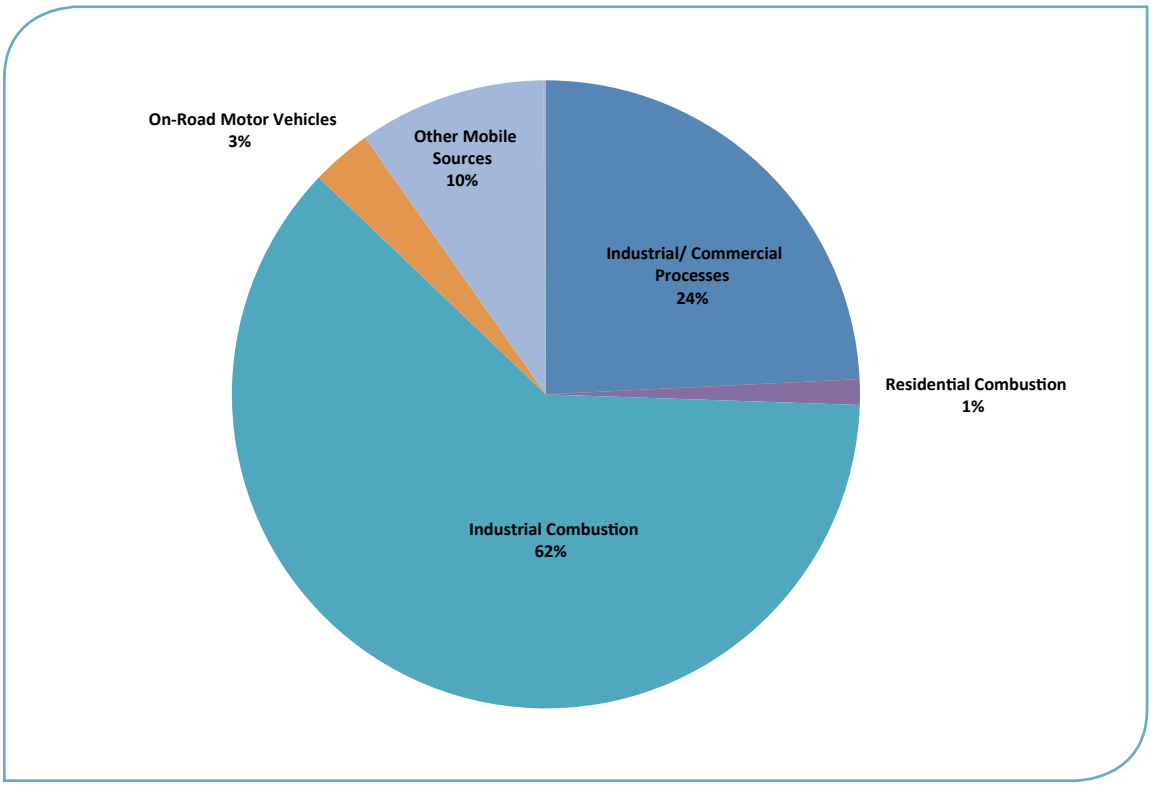
Figure 2-11 2010 Winter Emissions Oxides of Nitrogen (NOx), 347 tons/day



Sulfur Dioxide (SO2)

Figure 2-12 provides a breakdown of winter SO2 emissions for year 2010. The majority of SO2 emissions in the Bay Area are from combustion at industrial facilities; the Industrial Combustion wedge (62%) in Figure 2-12 includes SO2 emissions from refineries (50%) and other industrial facilities (12%). Industrial and commercial processes employed in the production of pharmaceuticals, cosmetics, inks, and resins, as well as those used at refineries, create another 24% of SO2 emissions in winter. Off-road and on-road motor vehicles produce 13% of the Bay Area winter emissions. Although most of the SO2 in the Bay Area (over 50%) is emitted during refinery operations, it is worth noting that the refinery products are used to fuel motor vehicles in the Bay Area and throughout California. This suggests that SO2 levels can be reduced both by further controlling emissions at the refineries, as well as by reducing motor vehicle use.

Figure 2-12 2010 Winter Emissions Sulfur Dioxides (SO_2), 29 tons/day



Predicting Future Emissions Trends

Predicting future trends in emissions is challenging, since many factors come into play, such as changes in control technologies; emission standards and fuel formulations for mobile sources; population growth and household formation; economic growth rates; land use decisions; and changes in transportation infrastructure and travel mode choice which affect motor vehicle travel. The inventory projections presented here include anticipated changes in population and economic activity, and well as emission reductions from ARB and Air District regulations that have already been adopted and turnover in the motor vehicle fleet (whereby older, dirtier vehicles are replaced by newer, cleaner vehicles)ARB. Implementation of ARB regulations on mobile sources is typically phased in, so the entire benefit of these adopted regulations will not be realized until they have been fully implemented over the next 10-15 years. At that point, emissions are projected to slowly increase in response to population and economic growth, if no additional regulations are adopted.

The projected emissions are based on a conservative "business as usual" assumption that no additional regulation or polices will be adopted to reduce emissions in the future. However, past experience suggests that it is likely that future measures will in fact be adopted and implemented to provide additional emission reductions. Past experience also suggests that the projected inventory may underestimate the future reduction in emissions. For example, whereas previous PM emissions inventories for the Bay Area predicted that overall emissions would increase over the past 10-15 years, monitoring data and CMB analysis shows that PM emissions and ambient concentrations actually declined substantially during that period. Given the fact that previous inventories under-predicted the emission reductions that were actually achieved, it is possible that this could occur again over the coming years.

Assumptions and methods used to estimate future emissions for key source categories are briefly discussed below.

Industrial and Commercial Processes and Combustions

PM emissions from industrial and commercial sources are projected to increase at a rate of around 1% per year based on previous observed growth and regulations adopted to date.

Commercial Cooking

PM emissions from commercial cooking are also projected to increase at a rate of around 1% per year based on previous observed growth and regulations adopted to date.

Residential Fuel Combustion

As noted above, estimated PM emissions from residential wood-burning were reduced for the 2010 inventory to reflect recent progress in response to the Air District's wood-burning regulation and its winter Spare the Air program. The projected inventory assumes that residential wood-burning rates will hold steady for the foreseeable future, with a slight increase based upon growth in population and households. Although it is possible that future emissions may decrease if the District is successful in increasing compliance with the wood-burning regulation and further educating Bay Area residents as to the health risks from wood smoke, Air District staff has opted to hold the wood-burning emissions steady, pending

development of better data to use in estimating future wood-burning trends, so as to provide a conservative estimate. Modest increases of emissions are expected in other residential combustion categories, mainly for space heating. This is assumed to grow in-line with population growth resulting in modest increases in overall residential combustion emissions.

On-Road and Off-Road Motor Vehicles

Emissions from on-road and off-road motor vehicles are expected to decline until 2020 due to aggressive regulations on diesel engines; retirement of older, dirtier vehicles; and penetration of cleaner gasoline vehicles into the fleet. After 2020, vehicle emissions are expected to increase by less than 1% per year until 2030. The projected increase in vehicle emissions rests upon two assumptions:

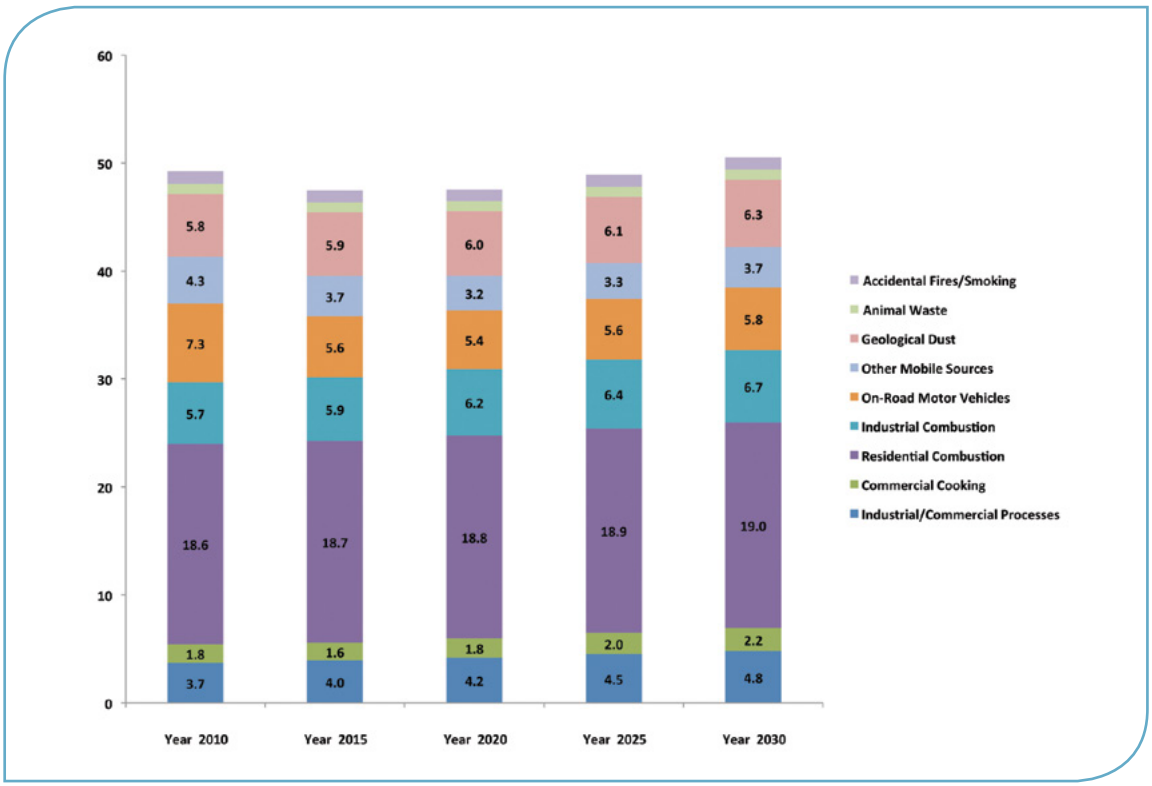
1. An increase in vehicular activity following recovery from the economic recession. ARB staff examined various economic recovery scenarios; the projected rate of growth in vehicle activity is based on an average between a slow-recovery scenario and a fast-recovery scenario.
2. No additional regulation apart from those already adopted by ARB. (The assumption that no future regulations will be adopted is unlikely, however. Although it will be technically challenging to further reduce motor vehicle emissions rates below the stringent standards already adopted in California, experience to date suggests motor vehicle emission standards will be further tightened in coming years as needed to continue progress toward attainment of air quality standards in the major urban areas of the state.)

It is important to note that the projected trends for diesel and gasoline vehicles differ. Whereas diesel PM emissions are projected to sharply decrease over the next decade in response ARB regulations, PM emissions from gasoline engines are expected to hold steady. For year 2010, diesel vehicles account for about half of the primary PM emissions from on-road vehicles, including both tailpipe exhaust and brake and tire wear. However, by 2030, this figure is projected to decrease to about 27%. It should be noted, however, that the EMFAC2011 model does not include the potential reduction in PM from light- and medium-duty vehicles that may occur in response to ARB's LEV III program, as described in Section 4. Efforts to reduce PM from mobile sources in recent years have focused on heavy-duty, diesel-powered vehicles. However, the fact that gasoline vehicles are projected to account for an increasing share of the PM from motor vehicles in coming years suggests that future efforts to reduce PM emissions from on-road vehicles will need to focus on reducing tailpipe emissions and emissions due to brake and tire wear from light-duty vehicles.

Projected Trends for Primary PM and Precursors To Secondary PM

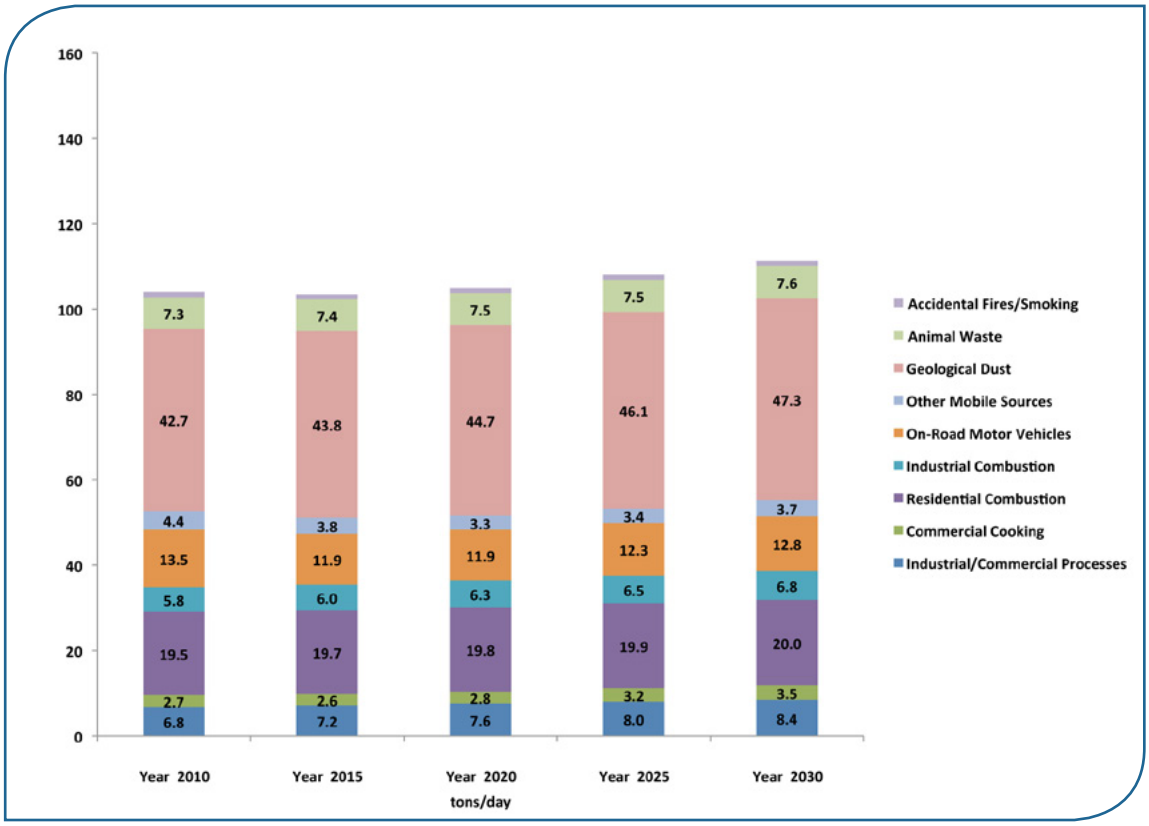
Projected trends for emissions of primary PM and PM precursors are presented in summary form in the bar charts below. A more detailed breakdown of projected future emissions by source category is provided in the tables in Appendix A. As shown in Figures 2-13 and 2-14, the overall inventory for emissions of primary PM2.5 and PM10 is projected to decrease thru 2020, then to begin to rise slowly through 2030 in tandem with population and economic growth. The same trend is projected for emissions from on-road motor vehicles, as well as other mobile sources.

Figure 2-13 Bay Area Winter Primary PM2.5 Emissions Trends



The trend for winter emissions of primary PM10 is similar to that for PM2.5, as shown in Figure 2-14.

Figure 2-14 Bay Area Winter Primary PM10 Emissions Trends



Emissions projections for key precursors to formation of secondary PM are mixed. Similar to primary PM, ROG emissions are projected to decrease through 2020 in response to already-adopted control measures, then to begin to increase slowly through 2030, as shown in Figure 2-15. NOx emissions are projected to decrease steadily and substantially through 2030 in response to already-adopted control measures, as shown in Figure 2-16. SO2 emissions, by contrast, are projected to increase slowly but steadily through 2030 in the absence of additional regulations or controls, as shown in Figure 2-17.

Reactive Organic Gases (ROG)

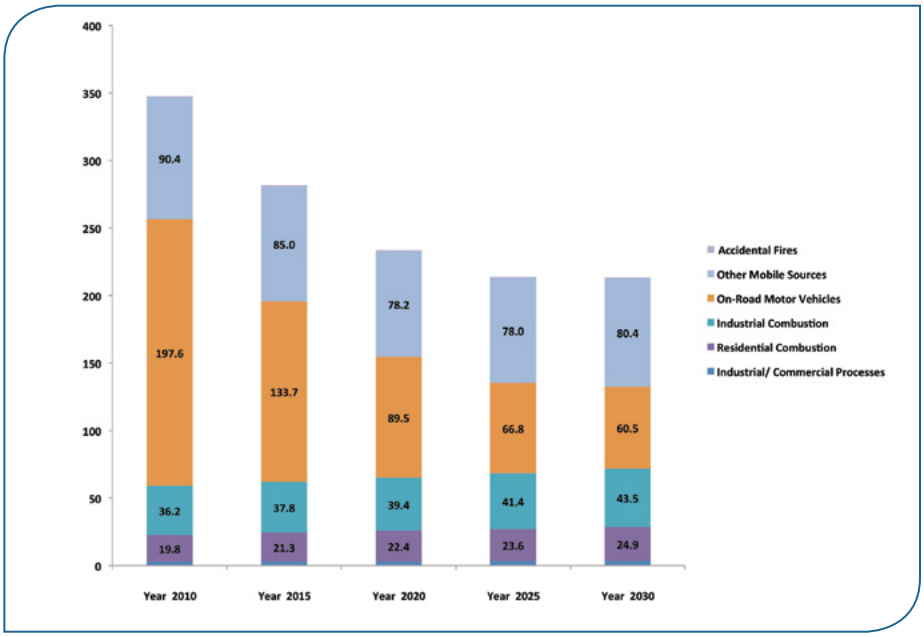
As shown in Figure 2-15, overall ROG emissions are expected to decline until 2025. ROG emissions from on-road motor vehicles are expected to decline due to fleet turnover, despite increases in vehicle population and VMT. Emissions from off-road mobile sources will continue to decline until 2020 due to implementation of already-adopted regulations. After 2020, a projected increase in off-road vehicular activity is expected to lead to increases in ROG emissions from off-road mobile sources. For the inventory as a whole, ROG emissions are projected to increase slightly after 2025 due to increased population and economic activity, in the absence of future regulatory measures.

Figure 2-15 Bay Area Winter ROG Emissions Trends

Oxides of Nitrogen (NOx)

NOx emissions from on-road motor vehicles are expected to decline due to fleet turnover despite increases in vehicle population and VMT, as shown in Figure 2-16. Emissions from other mobile sources will continue to decline until 2025 due to aggressive regulations on diesel vehicles. After 2025, projected increase in off-road vehicular activity is expected to lead to increases in NOx emissions from off-road mobile sources. Other major contributors to NOx emissions are expected to increase due to population increase unless new regulations are introduced. Overall NOx emissions are expected to decline until 2025 and then increase slightly. However, it is expected that with introduction of new rules on major sources of NOx emissions in the future, further reduction in NOx emissions is likely to occur.

Figure 2-16 Bay Area Winter NOx Emission Trends



Sulfur Dioxide (SO2)

After decreasing substantially in the past few years in response to regulations on sulfur content used in ships and commercial boats, SO2 emissions are projected to increase slowly in future years, as shown in Figure 2-17, primarily due to projected expansion in industrial activity. Overall SO2 emissions are expected to increase in line with SO2 emissions increases mentioned above. The rate of increase is less than 1% per year until 2030.

Figure 2-17 Bay Area Winter SO2 Emission Trends

SECTION 3: PM AIR QUALITY STANDARDS AND TRENDS

SECTION 3-A: PM MONITORING PROGRAM

Regional PM Monitoring Network

The Air District operates a network of monitoring stations to measure ambient concentrations of particulate matter in the Bay Area. The Air District's PM monitoring network has evolved in tandem with the evolution of the PM air quality standards. Because the original PM standards issued in response to the Clean Air Act of 1970 were based on total suspended particles (TSP), the initial PM monitoring stations measured TSP. When US EPA adopted standards for PM10 in 1987, the District established monitoring sites to measure ambient PM10 concentrations. Likewise, when US EPA issued standards for PM2.5 in 1997, the District established a network of monitoring sites to measure ambient PM2.5 concentrations. Therefore, we can track progress in reducing TSP in the Bay Area back to the 1970's, PM10 to the late 1980's, and PM2.5 to the late 1990's.

Until recently, all PM measurements were performed by collecting particles on filters, and PM concentrations were estimated by weighing the filters before and after collecting the particles. A filter is pre-weighed, and then placed in a sampler that draws air through the filter, typically for 24 hours. The PM concentration is estimated by comparing the before and after weight difference of the filter, divided by the total air flow, yielding a measurement of ambient PM expressed in micrograms per cubic meter ($\mu g/m^3$). Filter-based methods that meet specific operational requirements are called Federal Reference Method (FRM) and have been used for determining compliance with the national air quality standards. Because this process is labor-intensive, measurements have not been made every day at every station. At most stations, they were made either on a 1-in-3 or 1-in-6 day schedule. More recently, instruments have been developed to measure PM continuously; the Air District employs a continuous method known as a Beta-Attenuation Monitor (BAM).

The Air District began measuring PM10 concentrations at a number of sites in 1989 on a 1-in-6 day schedule. In addition to total PM10 concentrations, a set of ions has been measured: nitrate, sulfate, ammonium, and chloride. Potassium was added in 1995, and elemental and organic carbon were added in 2004. The District began measuring PM2.5 in 1999. In recent years, the number of sites measuring PM10 has been reduced, as US EPA guidelines have placed greater emphasis on the need to monitor PM2.5.The Bay Area PM monitoring network meets and exceeds both state and US EPA requirements. The network provides data to measure regional PM levels relative to state and national standards. The network includes 8 sites which measure PM10 and 13 sites which measure PM2.5. There are three categories of PM monitors:

- Filter-based Federal Reference Method (FRM);
- Real-time Beta-Attenuation Monitor (BAM) monitors designated as Federal Equivalent Method (hereafter referred to as FEM/BAM); and
- Ordinary Beta-Attenuation Monitors that are not designated FEM (hereafter referred to as BAM).

Ten PM2.5 monitoring sites provide data to determine whether the Bay Area meets national PM2.5 standards. This includes eight FEM/BAM sites that monitor PM2.5 on a continuous basis, as well as two FRM (Federal Reference Method) sites that use filters to measure PM2.5 on a schedule based on the location's PM2.5 level relative to the national standard.[1] The PM2.5 network includes four additional sites with BAM monitors that are used (in conjunction with the FEM and FRM sites) in determining whether the Bay Area attains State PM2.5 standards. (These four BAM sites are not included for purposes of determining compliance with federal PM2.5 standards.)

In addition to the sites used to determine compliance with State and federal PM2.5 standards, the Air District also operates SASS (Speciation Air Sampler System) instruments at four sites (San Jose, Vallejo, Livermore, and West Oakland) that provide PM2.5 speciation data; these speciation data are used to analyze PM by chemical type and emissions source category in order to refine the Air District's PM emissions inventory and to help identify emission source categories that may warrant additional control measures. The speciation data provided by these four monitors are the source for the information provided in Figures 2-4 and 2-5 in Section 2. The Air District also operates one mobile sampling van, as well as one re-locatable trailer-mounted unit that can be deployed to monitor local concentrations for special purpose monitoring studies lasting a minimum of one year. For example, the mobile van provided measurements used in the 2010 *West Oakland Monitoring Study* described below.

The Air District's current PM monitoring sites are shown in Table 3-1.

1 The schedule can be every day, once every three days, or once every six days depending on the site and season.

Table 3-1 Bay Area PM Monitoring Sites

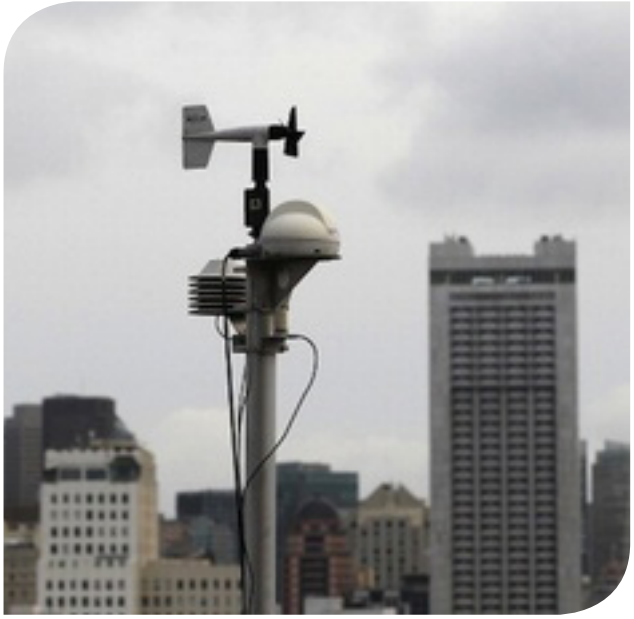
Location	PM10	PM2.5	Type of Monitor
Livermore		√	FEM/BAM & Speciation Sampler
Oakland		√	FEM/BAM
Concord	√	√	FRM
Bethel Island	√		
San Rafael	√	√	FEM/BAM
San Francisco	√	√	FEM/BAM
Redwood City		√	FEM/BAM
Gilroy		√	FEM/BAM
San Jose	√	√	FRM, BAM & Speciation Sampler
San Pablo	√		
Vallejo		√	FEM/BAM & Speciation Sampler
Santa Rosa		√	FEM/BAM
Cupertino	√	√	BAM
Napa	√	√	BAM
West Oakland		√	BAM & Speciation Sampler

Measuring PM Concentrations at the Local Scale

The primary objective of the Bay Area air quality monitoring network for PM is to measure ambient PM levels at the regional scale in comparison to State and federal PM standards. The network is not intended to measure ambient concentrations of PM and other air pollutants at a fine-grain local scale. Also, while the network can measure PM impacts from larger-scale incidents such as wildfires, it is not designed to measure localized PM impacts from short-term incidents and episodes at a specific facility or source. However, concentrations of pollutants such as PM, carbon monoxide, and air toxics can vary greatly at the local scale. Among its limitations, for example, the existing regional monitoring network cannot accurately measure the local impacts of residential wood-burning on ambient PM concentrations due to the highly localized and variable nature of this activity.

The Air District recognizes that information about local PM levels is needed in order to identify impacted areas and develop strategies to reduce PM concentrations in such areas. Since it is neither technically nor financially feasible to install and operate PM monitors in every neighborhood, the Air District has been working to estimate PM concentrations and population exposure at the local scale by means of computerized photochemical modeling. This approach has been used to develop local estimates of PM concentrations and population exposure in support of the District's Community Air Risk Evaluation (CARE) program, as well as two pilot Community Risk Reductions Plans (CRRPs) that are under development in partnership with the cities of San Francisco and San Jose.

The Air District has also performed special monitoring to develop better measurements of PM and other pollutants in various locations with specific air quality issues or concerns. Monitoring was performed in Berkeley from December 2007 through December 2009 in proximity to Pacific Steel Casting; in Benicia from April 2007 through December 2008 in proximity to the Valero oil refinery; and in Cupertino beginning in September 2010 (scheduled to run through December 2012) in proximity to the Lehigh cement plant, and in areas, such as West Oakland, using its mobile van. Several examples of localized studies of PM that were extremely helpful in quantifying PM levelsin communities believed to be significantly impacted by PM are briefly described below.



The Air District sponsored Desert Research Institute to assist with the West Oakland Monitoring Study (WOMS) [1] developing and analyzing air quality monitoring data for the West Oakland area during two seasonal periods of four weeks in summer 2009 and winter 2009/10. The WOMS data were used by the District to evaluate local-scale dispersion modeling of diesel emissions and other toxic air contaminants for the area within and around the Port of Oakland. The monitoring data showed spatial patterns of higher pollutant concentrations that were generally consistent with proximity to vehicle traffic. Concentrations of directly-emitted pollutants were highest on heavily traveled roads with consistently lower concentrations away from the roadways.

The Air District also measured PM2.5 and PM10 and analyzed concentrations of certain metals and other chemical species in the ambient air of West Oakland from August 2009 through July 2010. The goals were to look for how these concentrations vary spatially within West Oakland and specifically in the neighborhood of Custom Alloy Scrap Sales (CASS), and to look for evidence of elevated metals concentrations in the West Oakland area. PM2.5 filters were collected at 7 sites as part of the West Oakland Monitoring Study for a month in the summer of 2009 and the winter of 2009-10. PM10 filters were collected at four sites near CASS from August 2009 through July 2010. The monitoring did not reveal a clear signature from CASS. The estimated cancer risk from measured metals concentrations

1 West Oakland Monitoring Study, Desert Research Institute, 2010.
See: www.baaqmd.gov/Divisions/Planning-and-Research/CARE-Program/CARE-Documents.aspx

was less than 10 in a million, considerably less than from diesel exhaust. The concentrations are all within the corresponding reference exposure levels (RELs) for morbidity effects.

Air District staff is currently working to identify several sites to monitor near-roadway levels of nitrogen dioxide (NO2), as required by EPA regulations. NO2 monitors are expected to be installed in near-roadway environments in San Francisco, San Jose, and the I-80 or I-880 corridor in Alameda County. The Air District may install PM2.5 and/or ultrafine PM monitors at one or more of these sites.

To expand the Bay Area monitoring network, one possibility may be to deploy smaller and less expensive monitoring units to supplement the PM monitors that comprise the Air District's official PM2.5 monitors, provided that equipment and personnel funds can be secured to purchase and operate such units.

Measuring Ultrafine PM

As noted in Section 1-A, evidence suggests that ultrafine particles may be especially harmful to public health. However, measuring ultrafine particles (UFPM) presents unique challenges. Due to their extremely small size, conventional technologies are not well-suited to measuring ultrafine particles. PM2.5 and PM10 monitors measure the mass of particles in a given volume of air; however, UFPM is negligible on a mass basis. Therefore, UFPM measurements usually count the **number** of particles rather than the particle **mass**. Measuring UFPM is especially difficult because many of the particles are actually smaller than the wave length of light. Only in recent years has measurement technology progressed such that the size distribution of nanometer-size particles can be measured in the atmosphere. Current methods to measure UFPM typically expose the particles to water vapor to make them grow large enough that they can be counted. Although several UFPM monitoring devices are currently available, technologies are still evolving, equipment and maintenance costs are relatively high, and accuracy and dependability of the devices can be an issue.

There are currently no State or national requirements for monitoring ambient concentrations of ultrafine PM. Most of the ultrafine particle UFPM monitoring performed to date has occurred in the Los Angeles area; UFPM monitoring in the LA area has focused on measuring ultrafine particles in close proximity to major roadways. (See discussion of near-roadway measurements in Section 1-B.)

In spring 2012 the Air District purchased and installed UFPM particle counters (TSI EPC 3783) at three sites in Santa Rosa, Redwood City and Livermore. An additional UFPM counter on loan to the District has been in operation in San Pablo; the District is in the process of purchasing this monitor, so that it will continue to provide monitoring data for the San Pablo area. The Air District also plans to install an ultrafine particle counter in conjunction with the near-roadway NO2 monitor described above, once the location for that monitor has been finalized. These UFPM monitors will provide data on ambient concentrations of UFPM at the regional scale and on a near-roadway basis. The data from these monitors will be used to track progress in reducing ultrafine particle concentrations in the Bay Area and to inform the District's future UFPM computer modeling efforts.

In addition, measurements of ambient levels of UFPM levels for the Bay Area (and many other urban areas) is needed to provide data that epidemiologists can use to study the health effects of exposure to UFPM.

Although the monitors described above should be useful for purposes of determining baseline concentrations of ambient UFPM in the Bay Area, using traditional air quality monitoring networks to measure UFPM may be of limited value, given the great spatial and temporal variability exhibited by UFPM. To adequately measure the great variability in UFPM levels, air quality agencies may need to explore the use of smaller, cheaper devices (perhaps including personal monitors) that can be deployed more densely on a neighborhood scale.

Challenges with PM Monitoring: Air quality monitoring stations are expensive to build and maintain. Due to budgetary constraints in recent years, the Air District is currently hard-pressed to operate its existing air quality monitoring network. Expanding the monitoring network would entail securing funds for the initial capital cost to purchase monitoring equipment, finding good locations that meet applicable criteria, and deploying human resources to operate and maintain the sites on an on-going basis. As the Air District continues its technical work to develop a better understanding of the dynamics and distribution of PM in the atmosphere by means of computer modeling and special studies, this should enable the Air District to deploy its limited monitoring resources so as to measure ambient concentrations and population exposure to PM in the most cost-effective manner.

As mentioned above, the PM monitoring network is not designed to measure localized PM impacts from short-term incidents and episodes at a specific facility or source. Therefore, the Air District is investigating the possibility of augmenting the current network with incident response capabilities that would allow for accurate, real-time, mobile measurement of localized PM impacts from short-term episodes.

See Section 5 for additional discussion regarding future directions in monitoring ambient PM concentrations.

SECTION 3-B: PM STANDARDS AND PM PLANNING REQUIREMENTS

To protect public health and welfare, US EPA and the California Air Resources Board have both adopted **ambient air quality standards** for particulate matter. The federal Clean Air Act requires the US EPA Administrator to adopt standards for six "criteria pollutants", including PM, with an "adequate margin of safety to protect public health." EPA is charged with reviewing the standards every five years based on the latest scientific research on health and welfare effects, and considering recommendations provided by an expert panel called the Clean Air Scientific Advisory Committee (CASAC). PM standards have evolved and become more stringent over the past several decades in response to better understanding of the negative effects of PM on public health. In addition to **primary standards** which are designed to protect public health, U.S. EPA also issues **secondary standards** for PM to protect "public welfare", including visibility (clarity of the air), flora, fauna, and the built environment. The national secondary standards for PM are currently set at the same level as the primary standards.

PM Standards

Ambient air quality standards are based on three key elements: the averaging time period (e.g., 24-hour or annual); the form of the standard; and the level of the standard.

Annual average standards are intended to protect public health from chronic (long-term) health impacts related to PM. EPA adopted an annual average PM2.5 standard of 15 $\mu g/m^3$ in 1997. In 2002, the State of California adopted a (more protective) annual average standard of 12 $\mu g/m^3$ in 2002. In June 2102, EPA proposed to lower the national annual standard to a value in the range of 12 to 13 $\mu g/m^3$, as discussed below.

24-hour standards are intended to protect public health from acute (short-term) health impacts related to PM. In 2006, EPA significantly tightened the 24-hour PM2.5 NAAQS from 65 $\mu g/m^3$ to 35 $\mu g/m^3$. The State of California has not yet adopted a short-term 24-hour PM standard.

For criteria pollutants, the level of the standard is generally defined in terms of the **ambient concentration** of a pollutant in outdoor air, as expressed in terms of either a **parts per million** ratio (e.g., the state 8-hour ozone standard is 0.070 parts per million) or a **mass per volume** basis. For example, the national 24-hour PM2.5 standard is 35 mg/m^3, or micrograms per cubic meter (one microgram equals one-millionth of a gram). State and national PM standards for PM2.5 and PM10 are based on the mass (i.e., the total weight), rather than the number, of particles suspended in the air.

Design Value: Determining whether an air basin attains a given air quality standard requires comparing ambient pollutant levels with the standard to calculate the region's **design value**.[2] (For purposes of State standards, the term **designation value** is used.) The design value is calculated for each station in the official monitoring network (See Section 3-A for a description of the Bay Area PM monitoring network). A region meets the standard only if the design value for each and every official monitoring site does not exceed the standard. The stringency of an air quality standard depends upon (1) the numerical threshold and (2) the **form of the standard** which specifies the method and statistical protocol used to calculate the design value. The form of a standard may allow each region to exceed the standard on a limited number of occasions over a given time period. For example, the design value for the national 24-hour PM2.5 standard for any site is defined as the site's annual 98th percentile PM measurements averaged over a three-year period; thus, a site may exceed the standard on a limited number of days and still attain the standard. The basic steps to calculate the design value for the national PM2.5 standards are shown in Table 3-2.

The PM standards established by the State of California are more difficult to attain than the national standards; not only are the State standards set at lower numerical thresholds, but also they have a more stringent form of the standard. The State 24-hour PM10 standard allows fewer exceedances in order to remain in attainment. The State annual standard for PM2.5 is more stringent because it is based on the **maximum** of three annual averages, rather than the **average** of three annual averages). The design values that determine whether the Bay Area attains the various PM standards are calculated using measurements of ambient PM concentrations from the regional monitoring network described in Section 3-A.

Table 3-2 Basic Design Value Calculation Method for National PM2.5 Standards

Averaging Period	Ambient Concentration	Calculation Method – performed for each official monitoring station
24-hour	35 µg/m^3	**Step 1:** Determine the 98th percentile value for each year over a consecutive three year period. (In practice this means that the seven highest values per year are excluded.) **Step 2:** Average the three 98th percentile values. **Step 3:** Round the resulting value to the nearest 1.0 µg/m^3. **Step 4:** Compare the result to the standard.
Annual	15.0 µg/m^3	**Step 1:** Calculate the average of each quarter of each year over a three year period. **Step 2:** Average the four quarters in a calendar year to determine the average for each year. **Step 3:** Average the three annual values. **Step 4:** Round the resulting value to the nearest 0.1 µg/m^3. **Step 5:** Compare the result to the standard.

2 Details on how design values are calculated are provided in 40 Code of Federal Regulations (CFR) Part 50 Appendix N, and the April 1999 EPA document Guideline on Data Handling Conventions for the PM NAAQS. See http://epa.gov/ttncaaa1/t1/memoranda/pmfinal.pdf.

Bay Area Attainment Status for Current PM Standards

The current State and national standards for PM2.5 and PM10, the Bay Area's attainment status relative to those standards, and the region's design value for each standard, are summarized in Table 3-3. PM standards recommended by the World Health Organization (WHO) in 2005 are also shown for purposes of comparison; the national PM standards issued by US EPA are less stringent than the recommended WHO guidelines. Despite increasing concern about the health impacts of ultra-fine particles, as yet there are no State or national ambient air quality standards for ultra-fine PM.

The Bay Area attainment status shown in Table 3-3 is based on the current formal designation by US EPA or ARB. However, although the Bay Area is formally designated as non-attainment for these standards, monitoring data shows that the region currently meets the national 24-hour PM2.5 standard, the State annual PM2.5 standard, and the State annual PM10 standard, as indicated by the fact that the design value is less than or equal to the standard in each case. For purposes of attainment status, although monitoring data for an air basin may show that it meets a standard, once a region has been designated as non-attainment, it is still formally designated as non-attainment until such time as the region submits a redesignation request and maintenance plan which is approved by EPA.

National standards: The Bay Area attains the national 24-hour PM10 standard and the national annual PM2.5 standard. The region's design value for both these standards is well below the threshold. The national 24hour PM2.5 standard was tightened to 35 mg/m^3 in 2006. The Bay Area's attainment status for this standard is explained below in Federal PM Planning Requirements for the Bay Area.

State standards: The California Air Resources Board has adopted PM standards that are more stringent (health-protective) that the national standards. The most recent monitoring data (through 2011) demonstrates that the Bay Area continues to meet the State annual average PM2.5 standard. Recent data also shows that the Bay Area has attained the State annual PM10 standard for the first time ever, based on data for the 2009-2011 period. The Bay Area does not attain the State 24-hour PM10 standard; however, the region's design value for this standard has been decreasing in recent years, a sign that we are making progress toward attaining this standard.

Table 3-3 PM Standards, Bay Area Attainment Status, and Design Values

Averaging Time	National / California	Standard	Bay Area Design Value *	Attainment Status	World Health Organization PM Guidelines
Pollutant: PM2.5					
24-hour	National	35 μg/m³	30 μg/m³	Non-attainment	25 μg/m³
Annual	National	15 μg/m³	10.3 μg/m³	Attainment	10 μg/m³
	California	12 μg/m³	10.4 μg/m³	Non-attainment	
Pollutant: PM10					
24-hour	National	150 μg/m³	72 μg/m³	Unclassified	50 μg/m³
	California	50 μg/m³	70 μg/m³	Non-attainment	
Annual	California	20 μg/m³	20 μg/m³	Non-attainment	20 μg/m³

* Design values are calculated based on PM monitoring data thru year 2011.

Federal PM Planning Requirements for the Bay Area

Any state or region that fails to attain the national standard for any criteria pollutant is required to submit a State Implementation Plan (SIP) to U.S EPA to demonstrate how it will reduce ambient concentrations in order to attain the national standard. U.S. EPA designated the Bay Area as "non-attainment" for the revised 24-hour PM2.5 national standard in December 2009, based on air quality monitoring data for the three-year period 2006-2008. Areas designated as non-attainment for the revised standard, including the Bay Area, are required to submit a PM2.5 SIP to U.S. EPA by December 2012 to show how they will attain the standard by December 2014.

Although the Bay Area was designated as non-attainment for the national 24-hour PM2.5 standard based on monitoring data for the 2006-2008 period, the region exceeded the standard by only a slight margin. Since then, Bay Area PM2.5 levels have continued to decline. Air quality data from the regional monitoring network shows that the Bay Area met the national 24-hour PM2.5 standard during the three-year period from 2008 through 2010, as well as the three-year period from 2009 through 2011.

Under US EPA guidelines, a region with monitoring data showing that it currently attains an air quality standard can submit a "redesignation request" and a "maintenance plan" in lieu of a SIP attainment plan. However, the Air District believes that it would be premature to submit a PM2.5 redesignation request for the Bay Area at this time. Instead, the Air District is pursuing another option provided by US EPA guidelines for areas with monitoring data showing that they currently meet the PM2.5 standard. In December 2011, the Air Resources Board submitted a "clean data finding" request on behalf of the Bay Area. This request is currently under review by EPA. If EPA verifies that monitoring

data shows that the Bay Area currently meets the standard (i.e., has "clean data"), then EPA will suspend the SIP provisions that apply to preparing an attainment plan to demonstrate how the region will attain the standard by the specified target date. These SIP provisions will remain suspended as long as Bay Area monitoring data continues to show compliance with the standard. Although the SIP requirements related to demonstrating attainment would be suspended, the region will still be required to submit a "clean data" SIP consisting of the following elements:

- Amendments to the Air District's New Source Review (NSR) regulations to address PM2.5; and
- An emissions inventory for PM2.5 for the attainment year: i.e. the year in which monitoring data shows that the Bay Area first achieved attainment. For the Bay Area, the attainment year is 2010. The inventory must include both primary PM2.5 emissions by source category, as well as precursors to secondary PM formation.

The Air District is preparing these required SIP elements for submittal to US EPA in fall 2012.

State PM Planning Requirements

The California Clean Air Act of 1988, the primary legislation that defines State air quality planning requirements, is focused primarily on reducing ground-level ozone. The California Clean Air Act does not require that local air districts prepare plans to reduce PM. In response to concern about the health impacts of PM, in 2003 the State legislature enacted SB 656 (codified as Health & Safety Code Section 39614); this legislation required ARB and local air districts to evaluate potential PM control measures and to develop a PM implementation schedule for appropriate PM-reduction measures. The Air District complied with this legislation; staff developed a Particulate Matter Implementation Schedule that was adopted by the Air District's Board of Directors in November 2005. The three measures identified in the PM Implementation Schedule have been adopted and implemented: stationary internal combustion engines (Regulation 9-8); commercial charbroiling operations (Regulation 6-2); and the residential wood-burning rule (Regulation 6-3) which is further described in Section 4.

The SB 656 legislation sunset on January 1, 2011 and is therefore no longer in effect. Thus, despite the fact that State PM standards are more stringent than the national standards, formal PM planning efforts in California are governed primarily by the national standards and the SIP process describe above.

Proposed Revisions to National PM Standards

As noted above, EPA is required to review the national standards for PM and other criteria pollutants every five years based on the latest scientific research on health and welfare effects. After reviewing the evidence, EPA issued a draft proposal on the national PM standards for public comment on June 14, 2012. EPA proposes to:

- Strengthen the annual health standard for fine particles (PM2.5) by setting the standard at a level within the range of 12 μg/m^3 to 13 μg/m^3.
- Retain the existing 24–hour PM2.5 standard of 35 μg/m^3.
- Set a separate PM standard to improve visibility in urban areas, as discussed below.
- Retain existing secondary standards for PM2.5 and PM10 identical to primary standards to provide protection against other effects, such as ecological effects, effects on materials, and climate impacts.
- Retain the existing 24-hour standard for PM10 of 150 μg/m^3; this standard has been in place since 1987.

The proposed urban visibility standard would provide increased protection from particle-induced haze. The standard would measure visibility on the basis of light extinction as expressed in units called **deciviews**. Each deciview represents a constant change in visual air quality, with zero deciviews representing the most pristine conditions. EPA is proposing a 24-hour averaging time, a 90th percentile form averaged over 3 years, and a visibility level set at either 28 or 30 deciviews. Because monitors to directly measure visibility are not currently available, EPA proposes to use data on speciated PM2.5 mass concentrations as well as relative humidity, in conjunction with an algorithm, to calculate PM2.5 light extinction.

The Air District provided comments at a public hearing on the proposed standards in Sacramento on July 19, 2012, as well as written comments, urging EPA to adopt the most health-protective PM standards.

After reviewing public comments on the proposed revisions to the PM standards summarized above, EPA will issue final standards by December 14, 2012. Revisions to the current standards will trigger a process to evaluate monitoring data and issue new attainment designations for air basins throughout the nation. EPA expects to make attainment designations based on the revised standards by December 2014. A preliminary, unofficial review of Bay Area monitoring data for years 2008 through 2011 indicates that the region is likely to attain a more stringent annual standard set at either the 12 μg/m^3 or the 13 μg/m^3 level, provided that recent ambient PM2.5 concentrations prevail in future years.

SECTION 3-C: TRENDS IN AMBIENT PM CONCENTRATIONS

Trends in ambient PM concentrations can be analyzed in terms of **design value** (as explained in Section 3-B), as well as the number of days the region exceeds the PM standard. The Bay Area has been making progress in reducing PM levels as measured by both of these metrics. The graphs in Figures 3-1, 3-2, and 3-3 below show trends for ambient concentrations of PM2.5 and PM10. Trends in ambient PM10 concentrations are shown since the late 1980's, and trends in PM2.5 are shown since 1999, because these are the years for which monitoring data are available. The information presented here is derived from a more detailed report entitled *Trends in Bay Area Ambient Particulates* (BAAQMD, November 2011). The November 2011 *Trends* report also provides analysis showing trends in reducing several specific PM components, including nitrate, sulfate, potassium, elemental carbon, and organic carbon.

PM2.5 Trends

Figure 3-1 shows the trend in the District's design value relative to the national annual PM2.5 standard of 15 μg/m^3. The annual design value is the maximum of design values from individual PM2.5 sites. The annual design value for a particular site is the 3-year average of its quarterly averaged annual mean PM2.5 concentrations. The design values are marked at the third year of three year averages. The District's annual design value decreased from 14 μg/m^3 for 1999-2001 to 10 μg/m^3 for 2009-2011, a 28% reduction. As can be seen, the Bay Area met the national annual PM2.5 standard during the entire period.

Figure 3-1 Bay Area PM2.5 Annual Design Value 1999-2001 through 2009-2011

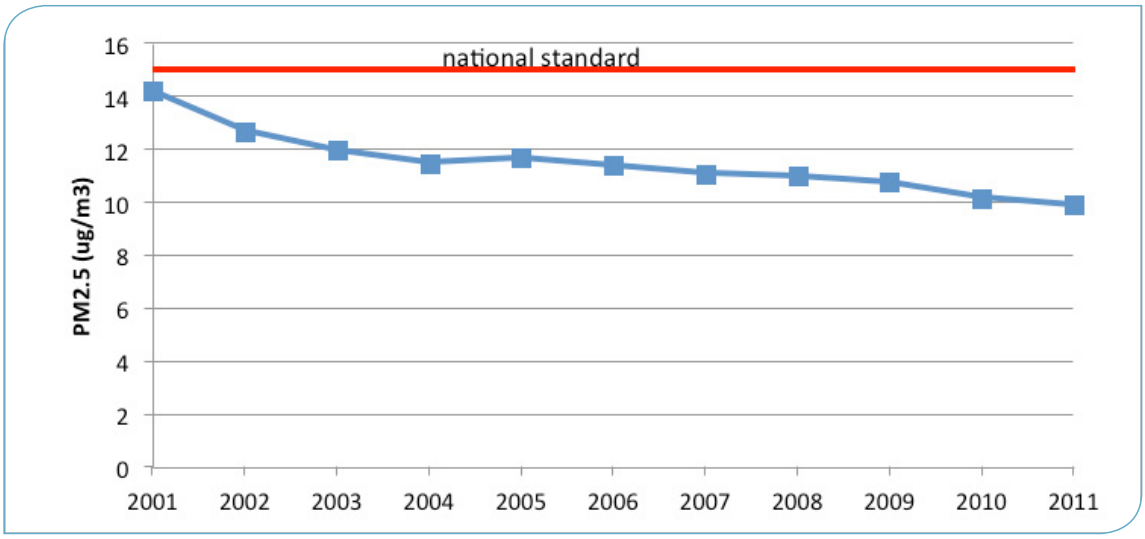


Figure 3-2 shows the District's design values relative to the national 24-hour PM2.5 standard. For the earliest period available, 1999-2001, the design value was 57 μg/m^3. By 2009-2011, it had

declined to 30 µg/m^3, well below the 35 µg/m^3 standard. The reduction from 1999-2001 to 2009-2011 was approximately 46%.

Figure 3-2 Bay Area Design Values for the 24-Hour Standard 1999-2001 through 2009-2011

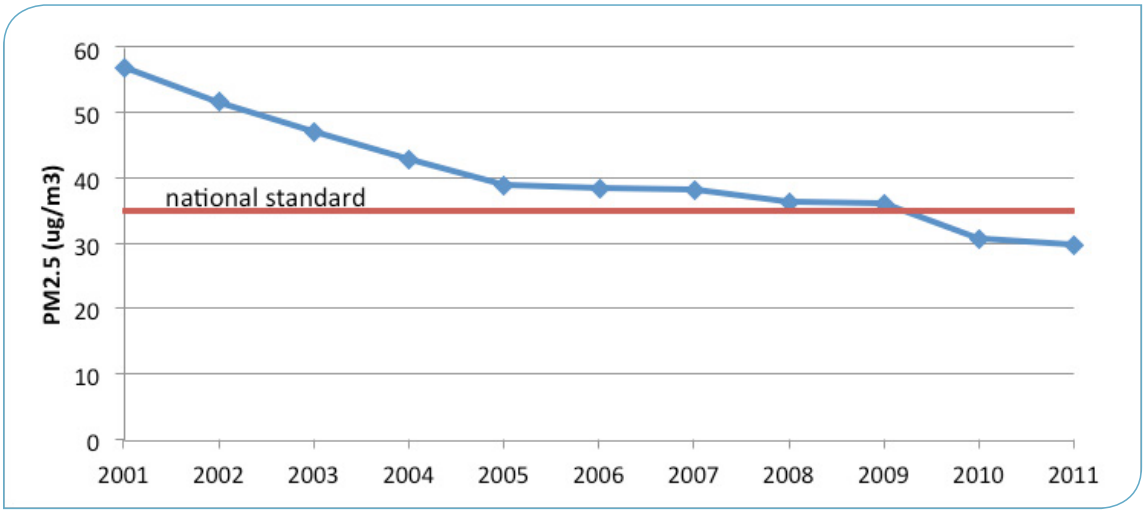
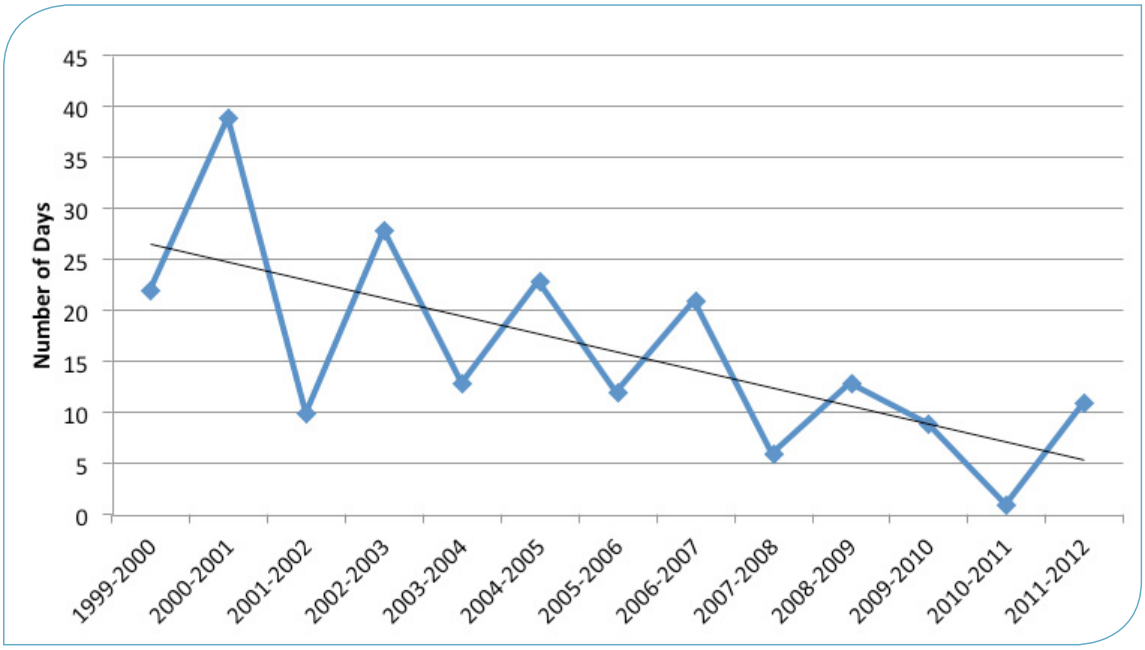


Figure 3-3 shows an overall downward trend in the number of days that Bay Area PM2.5 levels exceeded the 35 µg/m^3 standard for each winter from 1999-2000 through 2011-2012. (Although the 35 µg/m^3 standard did not take effect until 2006, the number of exceedance days per year is shown as if the 35 µg/m^3 standard had been in effect for the entire period shown.) The overall downward trend reflects the reduction in PM emissions in response to ARB and Air District control measures, whereas the sawtooth pattern in the number of exceedances is primarily due to year-to-year variation in meteorology, rather than short-term changes in emissions.

Figure 3-3 Bay Area PM2.5 Exceedances by Winter Number of days exceeding the 24-hour NAAQS, November 15 – February 15



Not only is the Bay Area experiencing fewer exceedance days per year, but when exceedances do occur, they are generally less severe. Table 3-4 shows the number of exceedances per year relative to the national 24-hour PM2.5 standard adopted in 2006. Both the number of exceedance days per year has declined, as well as the average value of the exceedances that occur in a given year. The average PM2.5 exceedance value has decreased from over 50 µg/m^3 in the 1999-2002 period to approximately 40 µg/m^3 in the 2009-2011 period. The combination of fewer exceedance days and lower peak values on the days when an exceedance of the standard does occur translates into reduced population exposure to unhealthy PM2.5 levels for Bay Area residents.

Table 3-4 Exceedances of 24-Hour PM2.5 (35 µg/m^3) [3]

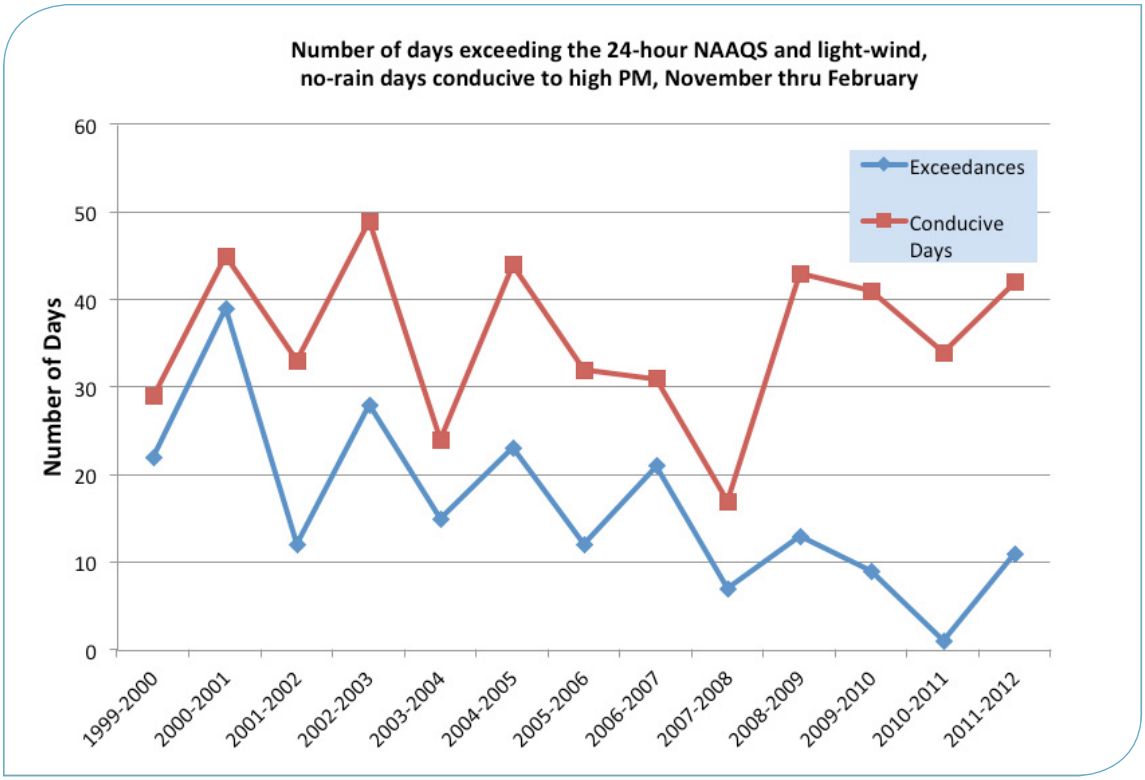
Year	Number of Exceedances	Mean Exceedance Value (µg/m3)
1999	29	52.2
2000	28	50.8
2001	17	61.1
2002	28	51.5
2003	16	42.0
2004	20	43.0
2005	21	41.9
2006	10	46.8
2007	14	44.1
2008	12	42.4
2009	11	38.2
2010	6	40.3
2011	8	40.5

3 Please note that the data shown in Table 3-4 is reported on a calendar year basis, whereas the data presented in Figures 3-3 and 3-4 is based on the winter season.

Relationship Between Meteorology and Exceedances of the 24-Hour PM2.5 Standard

Many factors affect PM ambient concentrations. Although emissions of primary PM and the precursor pollutants that contribute to secondary PM formation appear to be declining, meteorological factors (temperature, humidity, wind speed and direction) that affect PM build-up and transport have a strong impact on PM levels on a day-to-day basis. For example, analysis shows that winter periods of three or more days with light winds and no rain are conducive to build-up of PM, as discussed more fully in Section 2. Figure 3-4 shows that there is a clear correlation between the number of "PM-conducive" days (defined here as winter days with light wind and no rain) and the number of days that the Bay Area exceeds the national 24-hour PM2.5 standard in a given year.

Figure 3-4 Bay Area PM2.5 Exceedances and Conducive Days by Winter



Comparison with PM2.5 Trends in the Central Valley

Since there is considerable air flow between the Bay Area and the Central Valley – and vice versa – it is instructive to compare the current PM levels and design value trends among the three major central California districts: that is, Bay Area, Sacramento, and San Joaquin Valley. Figure 3-5 shows the trend in Bay Area design values for the national annual PM2.5 standard of 15 $\mu g/m^3$ compared with trends in the Central Valley. The trends in the Bay Area and Sacramento are similar, with an average reduction of 2.8% per year for the Bay Area and 1.9% per year for Sacramento. There is no clear trend for the San Joaquin Valley.

Figure 3-5 Design Values for Annual PM2.5 Standard for 3 Central California Air Basins

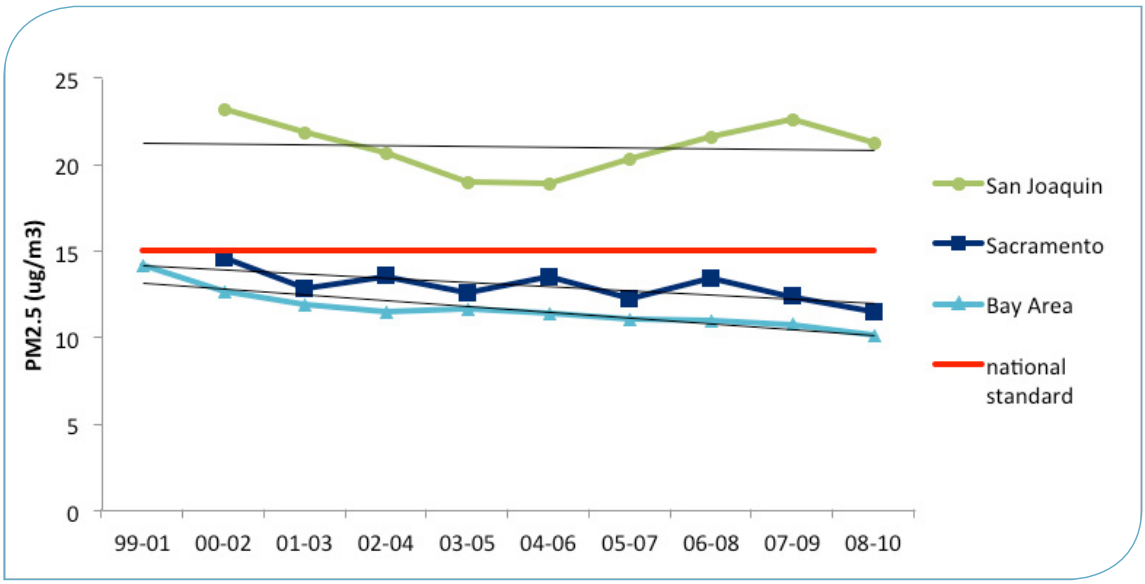
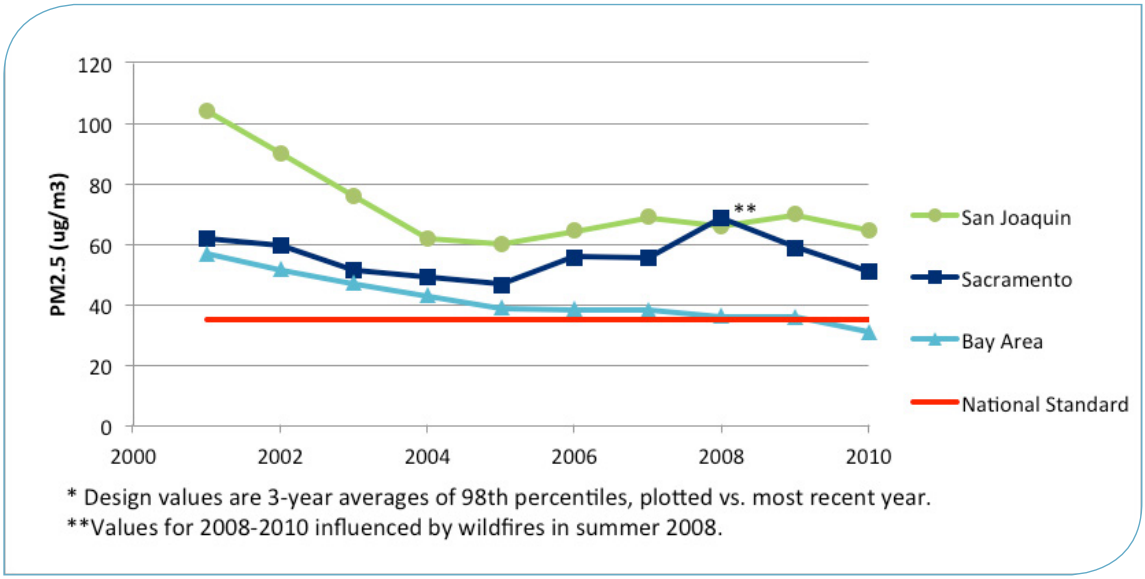


Figure 3-6 shows the design values for the national 24-hour PM2.5 standard of 35 µg/m^3 for the three air basins. The Bay Area's design value has decreased 5.8% per year from 2000 to 2010, and met the standard for 2008-2010. The design value in the San Joaquin Valley shows a decrease of 3.8% per year. Sacramento's design value shows no decrease, partly because of the 2008 wildfires. Excluding the wildfire months of June and July 2008, the decrease is 3.3% per year.

Figure 3-6 Design Values* for 24-Hour PM2.5 Standard for 3 Central California Air Basins

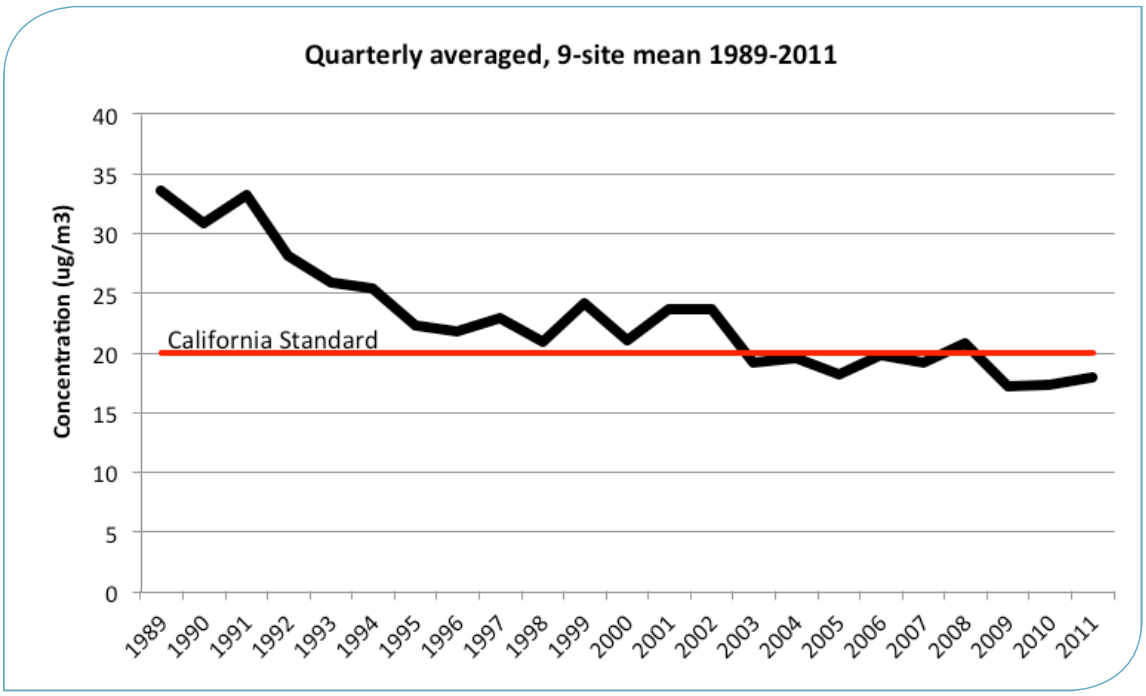


PM10 Trend

Bay Area PM10 levels have decreased significantly since 1990; peak concentrations have declined by approximately half and annual average values have declined by about one-third. Figure 3-7 shows quarterly-averaged annual PM10 concentrations from 1989 through 2011 relative to the State annual standard. (There is no national annual PM10 standard.) The solid line shows the average, based upon data from nine PM10 monitoring sites. The reductions were approximately 3%

per year in the 1990s and 2% per year from 2000 through 2011. The average decreased from 33 µg/m3 in 1989-1991 to 17 µg/m3 in 2009-2011, a reduction of 46%.

Figure 3-7 Bay Area Annual Mean PM10



In summary, we have made substantial progress in reducing PM levels in the Bay Area, but further reductions in PM would provide additional benefit by reducing the negative health impacts of PM described in Section 1-A.

SECTION 4: SUMMARY OF PM CONTROL PROGRAM

This chapter summarizes the existing regulations, policies, and programs that the Air District, the California Air Resources Board, and the US Environmental Protection Agency are implementing to reduce emissions of primary PM and PM precursors, and to reduce population exposure to PM.

Because primary PM and PM precursors are emitted by a wide range of stationary and mobile sources, a comprehensive and multi-faceted effort is needed to reduce ambient PM levels. As described in Chapter Section 1-A, there are negative health effects caused by both acute (short-term) and chronic (long-term) exposure to PM. Therefore, PM control programs aim to reduce both short-term (peak) and long-term (annual average) PM concentrations in order to protect public health.

As discussed in Sections 2 and 3, emissions inventory data and air quality monitoring data demonstrate that PM emissions and ambient PM concentrations have been greatly reduced in the Bay Area in recent years. So even though the Air District has never been required to prepare a formal PM SIP attainment plan to date, this data offers tangible evidence that the PM control efforts implemented by the Air District and other agencies summarized in this chapter have been effective in reducing PM and related public health effects in the Bay Area.

Although the Bay Area has made substantial progress toward meeting State and national PM standards, the Air District recognizes that some communities are exposed to above average levels of PM and that some individuals are especially vulnerable to the negative health effects of PM. Therefore, in addition to reducing emissions of PM and its precursors at the regional scale, the PM control effort also focuses on the need to reduce population exposure to PM, especially in the most heavily impacted communities and among the most sensitive populations.

ARB PM Reduction Program

The California Air Resources Board (ARB) has played a vital role in reducing PM by regulating emissions of primary PM and PM precursors from most mobile sources, such as on-road cars and trucks as well as off-road equipment. ARB has pursued an aggressive program to reduce PM emissions from mobile sources throughout California over the past 15 years. ARB classified diesel PM as a toxic air contaminant (TAC) in 1998. In September 2000, ARB adopted a Diesel Risk Reduction Plan with a goal of 75 percent PM reduction by 2010 and 85 percent by 2020. ARB has adopted a comprehensive set of regulations to implement the Diesel Risk Reduction Plan (DRRP)

and reduce population exposure to diesel PM. The ARB program to reduce emissions of diesel PM includes four key components:

- Regulations to reduce tailpipe emissions of primary PM and PM precursors from on-road and off-road mobile sources;
- Cleaner fuel, especially the requirement for ultra-low sulfur diesel;
- Restrictions on vehicle use, such as idling restrictions on diesel engines, and;
- Grants and incentives to encourage emission reductions over and above the regulatory requirements.

As summarized in Table 4-1, the heart of the DRRP is a set of regulations called **Air Toxics Control Measures** (ATCMs) to reduce diesel PM emissions from on-road trucks and buses; off-road equipment, including construction, farm and port equipment; harbor craft, and ocean-going ships. ARB has phased in the effective dates of these regulations in order to provide time for fleet owners to prepare and comply. These regulations will provide increasing benefit as they come into full effectiveness over the next 5-10 years. In addition to reducing emissions of primary PM, ARB regulations will reduce emissions of precursors that contribute to formation of secondary PM, such as ROG and NOx.

Table 4-1 ARB Diesel Air Toxic Control Measures for Heavy-Duty Vehicles, Equipment and Ships

Trucks and Buses	Since **2008**, idling limited to 5 minutes
	By **2016**, all trucks meet equivalent of 2007/2010 PM standard
	By **2023**, all trucks meet equivalent of 2010 NOx standard
Drayage Trucks	By **2010**, pre-MY 1994 trucks banned
	By **2010**, MY 1994-2003 trucks meet 2007/2010 PM standard
	By **2014**, all trucks meet 2007/2010 PM and 2007 NOx standards
	By **2023**, all trucks meet 2010 NOx standard
Public Fleet Vehicles	By **2012**, all vehicles meet equivalent of 2007/2010 PM standard
Garbage Trucks	By **2011**, all vehicles have installed Best Available Control Technology (BACT)
Transit Buses	By **2003**, met a NOx fleet average of 4.8 g/bhp-hr
	By **2007**, PM emissions reduced by 85% from 2002 baseline
	For fleets in the Bay Area with 200+ buses, 15% of new buses purchased from **2011-2026** must be zero emissions. (May be amended in 2012.)
Truck Refrigeration Units	By **2020**, engines must meet Ultra-Low Emission standard

Locomotives	In **2007**, begin using 15 ppm Sulfur fuel in California-based locomotives
	By **2008**, conduct health risk assessments for major rail yards
	By **2009**, install idling reduction devices on California based locomotives
Construction Equipment	Since June **2008**, idling limited to 5 minutes
	Between **2014 and 2023**, fleets with more than 5,000 total hp must meet fleet average NOx targets or turnover/replace 4.6-10% of fleet hp
	Between **2017 and 2023**, fleets with 2,501 to 5,000 total hp must meet fleet average NOx targets or turnover/replace 4.6-10% of fleet hp
	Between **2019 and 2029**, fleets with less than 2,501 total hp must meet fleet average NOx targets or turnover/replace 4.6-10% of fleet hp
Cargo Handling Equipment	By **2007**, new equipment meets equivalent of Tier 4 off-road engine standards or 2007 PM/NOx on-road engine standards
	By **2015**, pre-2007 yard trucks meet equivalent of Tier 4 off-road or 2007 PM/NOx on-road standards
	By **2017**, all other pre-2007 equipment must meet equivalent of Tier 4 off-road or 2007 PM/NOx on-road standards
Harbor Craft	Beginning **2009**, engines for new vessels or repowers meet Tier 2 or Tier 3 off-road standards; new ferries must be 85% below Tier 2 standards
	By **2016**, pre-2000 engines meet Tier 2,3 or 4 off-road standards
	By **2022**, all marine engines must meet Tier 2,3 or 4 off-road standards
Ships	In **2009**, ships began using Marine Diesel Oil (MDO) with 0.5% sulfur or Marine Gas Oil (MGO) with 1.5% sulfur. By August 2014, ships begin using MDO or MGO with 0.1% sulfur.
	By **2014**, 50% reduction in auxiliary engine use during 50% of visits by cruise and container ships (shore power)
	By **2017**, 70% reduction in auxiliary engine use during 70% of visits by cruise and container ships (shore power)
	By **2020**, 80% reduction in auxiliary engine use during 80% of visits by cruise and container ships (shore power)
Back-Up Generators (BUGs)	By **2008**, PM emissions for BUG's reduced by 85% in new engines

Light-Duty Vehicle Emission & Fuel Economy Standards

Although ARB's program to reduce PM emissions from diesel engines may have stolen the spotlight, its efforts to control emission from light-duty vehicles (LDVs) and medium-duty vehicles (e.g. vans and pick-up trucks) have also provided important PM reduction benefits. These vehicles account for the vast majority of the 175 million miles that Bay Area residents drive every day. So even though PM emissions from gasoline-powered LDVs are very low on a per-mile basis, the combined emissions of primary PM from light-duty vehicles are significant. In addition, LDVs account for a major portion of ROG and NOx emissions, which are important precursors to the formation of secondary PM.

ARB's Low Emission Vehicle (LEV) program is the backbone of its effort to reduce emissions from light-duty vehicles. The LEV program has greatly reduced emissions of ROG, NOx, and PM from LDVs throughout the state. In its initial phase, LEV I regulations reduced emissions in model year 1994-2003 vehicles. The more stringent LEV II program, which took effect in model year 2004, continues to provide major air quality benefits. As discussed in Section 5, ARB is in the process of adopting a new iteration of the LEV program – LEV III – to further reduce pollution from LDVs.

ARB is in the process of finalizing proposed amendments to California's Low Emissions Vehicle (LEV) regulations to strengthen the LEV program. One element of the LEV III proposal is more stringent PM standards for passenger cars and light-duty trucks. Although PM emissions from new light-duty vehicles are already very low, ARB staff is aware that California and federal emission requirements to reduce greenhouse gas emissions have fostered development of advanced internal combustion technology such as gasoline direct injection engines (GDI). To encourage the continued development of GDI engines that emit PM at the same low levels as port fuel injection engines, the LEV III standards would reduce the PM standard from 0.010 grams per mile for passenger cars and light-duty trucks. These standards would be phased in from 2017 through 2021. The LEV III amendments propose to further reduce the PM standard to 0.001 grams per mile (one milligram per mile) to be phased in during the 2025 and 2028 period. At this 1 mg/mile emission rate, a car would emit a total of 150g or 1/3 of a pound of particulate matter over a typical lifetime of 150,000 miles. The LEV III provisions should help offset the potential increase in PM emissions from light-duty vehicles that would occur if vehicle miles of travel (VMT) in the Bay Area rise in response to population growth or other factors.

In addition to the LEV tailpipe emission standards which reduce emissions on a per-mile basis, ARB has also adopted fuel economy standards to implement the Pavley legislation[4]. Although the impetus for improved fuel economy is primarily to reduce carbon dioxide emissions that contribute to climate change, by reducing fossil fuel combustion these standards also provide important benefits in reducing criteria air pollutants and air toxics.

The ARB regulations summarized above are primarily responsible for the statewide reductions in PM emissions from mobile sources to date. These regulations are expected to provide continued reductions in emissions of primary PM and PM precursors from mobile sources over the next two decades.

4 State legislation enacted in 2002 (Assembly Bill 1493, Pavley) directed the ARB to adopt regulations to reduce greenhouse gases from passenger vehicles. For additional information, see www.arb.ca.gov/cc/ccms/ccms.htm

EPA Actions to Reduce PM from "Federal Sources"

In addition to establishing ambient air quality standards for PM, US EPA is responsible for establishing emission standards for aircraft engines, new locomotive engines and new non-road engines less than 175 horsepower used in construction or farm equipment. US EPA regulations help to reduce PM emissions from trucks, locomotives, and marine engines that operate across state boundaries when these vehicles or engines operate within California. These EPA actions complement the ARB mobile source regulations described above. A summary of US EPA programs and actions to control PM and PM precursors is available at US EPA at www.epa.gov/pm/links.html.

In 1998, US EPA adopted more stringent "Tier 2" and "Tier 3" emission standards for ROG, NOx, and PM from new non-road diesel engines. This program established the first emission standards for non-road diesel engines less than 50 horse-power (hp), including marine engines in this size range. The Tier 2 standards were phased in for all engine sizes from 2001 to 2006. More stringent Tier 3 standards for engines between 50 and 750 hp were phased in from 2006 to 2008. The Clean Air Non-Road Diesel: Tier 4 rule was adopted to provide a comprehensive program to reduce emissions from future non-road diesel engines. The Tier 4 standards require engine manufacturers to produce new engines with advanced emission control technologies similar to those already mandated for on-road trucks and buses. Emissions from these engines are expected to decrease by more than 90 percent as a result of this rule. In addition to requiring new locomotives to meet stringent standards, US EPA regulations also mandate that old locomotives must be rebuilt to comply with cleaner standards.

Pursuant to Annex VI to the International Convention on the Prevention of Pollution from Ships (MARPOL), the US and Canada have collaborated to establish a North American Emissions Control Area (ECA) effective August 1, 2012. The ECA will require the use of low-sulfur fuel in ships operating within 200 miles of the coast, effective in 2015. The reduction in sulfur will reduce emissions of SO2 which combine with ammonia to form ammonium sulfate, a type of secondary PM.

BAAQMD PM Reduction Program

The Air District has developed a comprehensive program to reduce PM in the Bay Area. This includes measures to reduce emissions and ambient concentrations of PM, as well as population exposure to PM. The Air District implements a number of regulations and programs to reduce PM emissions. These include rules limiting primary PM emissions from open burning of agricultural and non-agricultural waste; limiting emissions from combustion sources such as boilers, cement kilns and furnaces; controlling dust from earth-moving and construction/demolition operations; regulating residential wood-burning during the winter season; and reducing PM from activities that generate dust or smoke.

The Air District's Community Air Risk Evaluation (CARE) program has identified communities in the Bay Area that are disproportionately impacted by local emission sources. The CARE program, which is further discussed later in this chapter, serves as the foundation for the District's efforts to reduce population exposure to toxic air contaminants (TACs), including diesel PM.

PM Reductions from Control Strategy in the Bay Area 2010 Clean Air Plan

In fall 2010, the Air District adopted the Bay Area 2010 Clean Air Plan (2010 CAP). The legal impetus for the 2010 CAP was to update the region's plan to control ground-level ozone as required by the State Health & Safety Code. However, the Air District took the initiative to expand the scope of this plan by developing a multi-pollutant air quality plan. The 2010 CAP laid out an integrated control strategy to reduce four types of air pollutants: ground-level ozone; primary PM as well as PM precursors; toxic air contaminants (TACs); and greenhouse gases, such as carbon dioxide and methane, that contribute to climate change. The 2010 CAP control strategy included a total of 55 control measures in five categories, including:

- **Stationary Source Measures (SSMs):** The control strategy includes 18 measures to reduce emissions from stationary and area sources, as further described below.
- **Mobile Source Measures (MSMs):** The control strategy includes 10 measures reduce emissions by promoting the use of advanced-technology vehicles and cleaner fuels that reduce emissions of criteria pollutants and/or greenhouse gases, as well as accelerating the replacement or repair of older vehicles with high emission rates.
- **Transportation Control Measures (TCMs):** The control strategy includes 17 measures to reduce motor vehicle emissions by decreasing vehicle use, vehicle idling, or traffic congestion by improving transit service; encouraging walking, bicycling, and transit use; improving the efficiency of the regional transit and roadway systems; supporting focused growth; and developing and implementing transportation pricing strategies.
- **Land Use and Local Impact Measures (LUMs):** The control strategy includes six measures to promote mixed-use, compact development to reduce motor vehicle travel and emissions, and to ensure that we plan for focused growth in a way that protects people from exposure to air pollution from stationary and mobile sources of emissions.
- **Energy and Climate Measures (ECMs):** The control strategy includes four measures designed to protect air quality and the climate by promoting energy conservation and energy efficiency; promoting renewable forms of energy production; reducing "urban heat island" effects; and promoting the planting of shade trees in order to lower air temperatures, provide shading to reduce energy use, and absorb CO2 and other air pollutants.

The control strategy defined in the 2010 Clean Air Plan is the backbone of the Air District's current PM control program.

In developing the 2010 CAP control strategy, the Air District sought to maximize reductions of primary PM as well as PM precursors, and to prioritize measures to reduce PM in the implementation

schedule for the control strategy. The control strategy defined in the 2010 CAP is the backbone of the Air District's current PM control program. Emissions of primary PM and PM precursors will be reduced as the Air District adopts and implements the measures in the 2010 CAP.

Reducing PM from Stationary Sources

Controlling emissions from stationary sources (factories, refineries, gas stations, etc.) is the Air District's core regulatory function. The Air District has a long history of controlling PM emissions by means of (1) regulations that apply to certain categories of facilities or sources, and (2) permit conditions imposed on individual facilities. Permit conditions vary depending upon the size of the facility and/or magnitude of emissions that it generates and the type of permit required.

In addition to controlling emissions of primary PM from stationary sources, the Air Districts also adopts and enforces regulations to reduce emissions of PM precursors such as NOx and SO2 from power plants, industrial facilities, and other combustion sources, as well as reactive organic gases (ROG) from oil refineries, coatings and solvents, fuel storage, transfer and dispensing activities, and many other industrial and commercial facilities and processes.

The Air District already controls PM10 emissions from facilities subject to its New Source Review (NSR) program, and is in the process of amending the NSR requirements to include PM2.5 as well. Major PM emission sources are required to implement Best Available Control Technology (BACT) for PM in permit conditions when new sources are constructed or existing sources are modified. Three types of control equipment are commonly used to abate particulate emissions from industrial facilities:

- Wet mechanical scrubbers and/or cyclones
- Baghouses
- Electrostatic precipitators

The Air District has adopted five regulations that directly address primary PM:

- **Regulation 5:** Open Burning: Generally prohibits open burning, but also allows for exemptions such as agricultural burning, disposal of hazardous materials, fire training, and range, forest, and wildlife management.
- **Regulation 6:** Particulate Matter, Rule 1: General Requirements: Limits PM emissions from stationary sources by controlling emission rates, concentration, visible emissions and opacity.
- **Regulation 6:** Particulate Matter, Rule 2: Commercial Cooking Equipment: Regulates emissions from commercial charbroilers in restaurants.
- **Regulation 6:** Particulate Matter, Rule 3: Wood Burning Devices: Regulates emissions from residential wood-burning devices (fireplaces and woodstoves)
- **Regulation 12:** Miscellaneous Standards of Performance, Rule 4: Sand Blasting

The estimated reductions in emissions of primary PM and PM precursors (NOx and SO2) from Air District regulations are shown in Table 4-2.

Table 4-2 Estimated Reductions in Primary PM & PM Precursors from BAAQMD Regulations (tons per day)

Category	Rule(s)	Description	Dates of Rule-Making	Primary PM Reduced tons/day	NOx Reduced tons/day
Wood-Burning & Cooking	6-2	Commercial Cooking (Charbroiling)	2007	0.6	0
	6-3	Wood-burning Devices (annual)	2008	0.7	0
	6-3	Wood-burning Devices (during peak season)	2008	6.0	0
Refinery & Chemical Plant Processing	12-11, 12-12	Flare Monitoring and Minimization (SO2 reduction)	2003 2005 2006		(SO2) 6.3
Combustion of Fuels (Nitrogen Oxides controls)	9-7, 10	Boilers, Steam Generators & Process Heaters	1992, 1994, 2008, 2010	0	41.3
	9-8, 11-17	Internal Combustion Engines	1993, 2007, 2011	0	27.6
	9-11	Electric Power Generating Boilers	1994, 2000	0	17.5
	9-9	Stationary Gas Turbines	1993, 2006	0	7.4
	9-6	Gas-Fired Water Heaters	2007	0	2.5
	--	All Others	n/a	0	5.7
			Total	**7.3**	**NOx: 102.0 SO2: 6.3**

In developing the control strategy for the Bay Area 2010 Clean Air Plan, the Air District performed a thorough review of its stationary source regulations, as well as regulations from other regions throughout the United States, and identified several new or amended rules to further reduce

emissions of primary PM as well as precursors to secondary PM. Stationary Source Measures in the 2010 CAP to reduce emissions of primary PM and PM precursors are shown in Table 4-3.

Table 4-3 Stationary Source Measures to Reduce PM & PM Precursors in Bay Area 2010 Clean Air Plan

Stationary Source Measure (SSM)	Description	Status	Completion Date
SSM #1 - Metal Melting Facilities	Limit emissions of organic compounds, fine particulates, toxic compounds, and odors from foundry operations and metal melting facilities.	Initial workshops, July 2011. Second workshops July 2012.	Fall 2012
SSM #2 Digital Printing	Establish VOC limits or control requirements for inkjet, electro-photographic and other digital printing technologies.	Not yet initiated.	TBD*
SSM #3 - Livestock Waste	Establish management practices to reduce ROG, ammonia, PM, GHG.	Not yet initiated.	TBD
SSM #4 - Natural Gas Production and Processing	Reduce emissions of VOCs and methane from natural gas production facilities.	Not yet initiated.	TBD
SSM #5 - Vacuum Trucks	Require carbon or other control technology on vacuum trucks to reduce emissions of VOCs.	Adopted April 18, 2012.	April 2012
SSM #6 - General Particulate Matter Emission Limitation	Reduce particulate weight limitation as a function of exhaust gas volume and/or as a function of process weight rate.	Rulemaking initiated May, 2011.	TBD
SSM #7 - Opening Burning	Further limit agricultural burning of some crops to be burned on a given day to reduce VOCs, NOx, and PM.	Rulemaking not yet initiated.	TBD
SSM #8 - Sulfur Dioxide from Petroleum Code Calcining	Reduce SOx emissions from coke calcining.	Initiated April 2012.	TBD
SSM#9 – Cement Kilns	Further limit NOx and PM from cement production and reduce toxic emissions.	Workshop was held in December 2011. Public hearing expected Sept, 2012.	Expected Sept 2012
SSM #10 - Refinery Boilers and Heaters	Further reduce NOx emissions from refinery boilers, heaters, and steam generators.	Adopted December 15, 2010.	December 2010
SSM #11 - Residential Fan Type Furnaces	Reduce allowable NOx limits for residential furnaces.	Not yet initiated.	TBD

Stationary Source Measure (SSM)	Description	Status	Completion Date
SSM #12 - Large Residential and Commercial Space Heating	Establish NOx limits for industrial and commercial space heating.	Not yet initiated.	TBD
SSM #13 - Dryers, Ovens, and Kilns	Establish NOx limits for industrial dryers, ovens, and kilns.	Not yet initiated.	TBD
SSM #14 - Glass Furnaces	Reduce NOx limits for glass furnaces.	Not yet initiated.	TBD
SSM #16 - New Source Review Addressing PM 2.5	Amend Reg. 2, Rule 2 to address the District's anticipated non-attainment status of the 24-hour PM2.5 National Ambient Air Quality Standard.	Workshop March, 2012. Board hearing anticipated Sept/Oct 2012.	Fall 2012
SSM #17 - New Source Review for Toxic Contaminants	Implement more health-protective permitting requirements in Regulation 2, Rule 5, New Source Review of Toxic Air Contaminants based on revisions to OEHHA risk factors and method.	Adopted January 6, 2010.	January, 2010
SSM #18 – Revisions to Air Toxic Hotspots Program	Revise the District's Air Toxics Hot Spots program to incorporate more stringent risk reduction requirements from existing sources.	Awaiting OEHHA revisions to exposure assessment guidelines expected 2012.	TBD

*To be determined

Pursuant to SSM #6 in the 2010 CAP, Air District staff has embarked upon a thorough review of the general PM rule (Regulation 6, Rule 1) with the objective of imposing more stringent emissions limits based upon the latest control technologies, as discussed in Section 5.

Reducing PM from Mobile Sources

The California Air Resources Board has primary legal authority to regulate emissions from mobile sources, as described above. However, recognizing that on-road and off-road vehicles are major sources of primary PM emissions and PM precursors in the Bay Area, the Air District also works to reduce emissions from mobile sources. The Air District seeks to reduce PM emissions from mobile sources by means of grants and incentives, targeted enforcement of ARB regulations, partnerships, and public education.

In the case of heavy-duty vehicles, the Air District focuses its efforts on ensuring compliance with ARB's diesel regulations in the Bay Area; incentivizing early compliance with ARB regulations; and promoting the use of alternative fuels and technologies. The Air District's efforts to reduce emissions from passenger vehicles include accelerating the repair or replacement of old vehicles

with high emission rates; promoting the use of alternative fuels and technologies, such as zero emissions vehicles; and reducing motor vehicle use by promoting transit use, ridesharing, bicycling, walking, and telecommuting.

Reducing Emissions from Seaports and Goods Movement

Movement of goods and freight is a major source of particulate matter emissions and other air pollutants in major freeway corridors, in ports and rail yards, and in the disproportionately-impacted communities identified by the Air District's Community Air Risk Evaluation (CARE) program. Therefore, reducing emissions from seaports and the goods movement sector has been a major focus of Air District efforts in recent years. To provide a technical foundation, the Air District has developed detailed emissions inventories for each of the five Bay Area seaports (Oakland, Richmond, Redwood City, Benicia, and San Francisco). Much of the emission reduction effort has been directed at the Port of Oakland, since this port handles by far the greatest volume of goods and is located in the impacted western Alameda County area identified by the CARE program.

To develop a comprehensive approach to reducing emissions from port operations, the Port of Oakland, in partnership with the Air District and other stakeholders, developed the Maritime Air Quality Improvement Plan (MAQIP) in 2009, with the overall goal of protecting the local residents and workers by reducing their exposure to diesel PM. The Air District and the Port of Oakland have developed a joint work program that includes outreach to the regulated community to ensure compliance with state and federal regulations; and cooperating to identify and implement projects to reduce emissions, such as replacement and retrofit of drayage trucks; shore power (dockside electrification) for ships; vessel speed reduction; and development of a "marine highway" between the ports of Oakland, West Sacramento, and Stockton to help reduce on-road truck traffic between these ports.

Significant emission reductions at the Port of Oakland have already been achieved through a combination of grants and regulations. For example, over the past several years, ships have been required to switch to low-sulfur fuel. In addition, significant grant funding has been provided to equip drayage trucks that serve the Port with diesel particulate filters or with new cleaner engines, as discussed further below. Additional benefits will be achieved by 2015 as engines in cargo-handling equipment and harbor craft are either replaced or retrofitted, and ships begin using shore power while berthed.

In addition to these efforts to reduce emissions, the Air District also collaborated with ARB, the Port of Oakland, and Union Pacific Railroad in performing the 2008 West Oakland Health Risk Assessment (HRA). The HRA was performed to help understand the potential public health impacts from diesel PM emissions on the West Oakland community. The study addressed the health impacts from maritime activities at the Port, as well as locomotives, non-Port marine vessels and trucks and other significant sources of diesel PM emissions in and around the West Oakland community.

Mobile Source Compliance Plan

As noted above, ARB has adopted a comprehensive set of regulations to reduce emissions of PM from diesel engines. These regulations provide an option for local air districts to play a role in enforcing these regulations within their boundaries. Recognizing that effective enforcement of the diesel regulations is essential to protect the health of Bay Area residents, the Air District executed a Memorandum of Understanding (MOU) with ARB in fall 2009 and established a Mobile Source Compliance Plan (MSCP) which sets forth a comprehensive strategy to enforce specified ARB regulations, including regulations that apply to drayage trucks, commercial vehicle idling, transport refrigeration units, and off-road vehicles.

The goal of the MSCP is to reduce diesel PM health risk in CARE impacted communities through a robust enforcement and compliance assistance program. The initial focus of the MSCP was to provide a strong presence at the Port of Oakland to enforce ARB's 2010 Drayage Truck Rule. As of the first quarter of 2012, MSCP resources have been focused on preventing illegal "drayoffs" whereby drayage trucks switch loads from compliant to dirty trucks. By helping to ensure compliance with ARB's truck rule, the Air District's enforcement efforts have contributed to a major reduction in emissions from drayage trucks in the West Oakland area, as discussed below.

Table 4-4 summarizes MSCP enforcement efforts for calendar years 2010 and 2011.

Table 4-4 Mobile Source Enforcement Summary for Port of Oakland: 1/1/2010-12/31/2011

Inspection Type	# Inspections	# Violations	Compliance Rate
Heavy-Duty Drayage Trucks	3,581	29	99%
Port Truck Terminal Idling	34	0	100%
Commercial Vehicle/Sleeper Berth Idling	267	12	96%
Railroads: Statewide MOU & BAAQMD Protocol	8	0	100%
Off-Road (Construction) Diesel Equipment	7	0	100%
Portable Equipment Registration Program	600	0	100%
Transport Refrigeration Units	434	8	98%
Commercial Harbor Craft	4	0	100%
Oceangoing Vessels: Fuel-Sulfur Limits	41	0	100%
Oceangoing Ships: Onboard Incineration Limits	41	0	100%

Grant and Incentive Programs

To complement ARB's regulations to limit emissions from mobile sources, the Air District provides grants and incentives for projects to reduce emissions from both on-road and off-road vehicles. The purpose of these grant programs is to achieve "surplus" emissions reductions (i.e., over and above regulatory requirements) in order to complement ARB regulations. The Air District awarded a total of $308 million in external grants during a five-year period covering FY 06/07 through FY 11/12. In aggregate, these projects are estimated to reduce emission of over 1,300 tons of PM; 21,000 tons of NOx; 3,100 tons of ROG; and 1,325,000 tons of CO2 over their lifetime. Table 4-5 summarizes key grant programs, projects funded from 2007 through 2011, and the emission benefits of these projects over their lifetime.

Table 4-5 Air District Grant Programs: Projects Funded from 2007 through 2011

Eligible Equipment/Projects	# Projects	$$ Awarded	PM (Tons Reduced)	NOx (Tons Reduced)
Grant Program: Transportation Fund for Clean Air (TFCA)				
Shuttles Ride-Sharing Bicycle Facilities Smart Growth Arterial Management Clean Vehicles Alternative Fuel Infrastructure	499	$111,000,000	470	940
Grant Programs: Carl Moyer Program (CMP), Mobile Source Incentive Fund (MSIF)				
On-road Heavy-Duty Vehicles Off-Road Marine Engines Shore power for Ports/ Ships Locomotives Agricultural Equipment	1,158	$79,373,112	604	13,440
Grant Program: (Vehicle buyback)				
Light-duty scrappage	21,673	$18,094,880	8	565
Grant Program: Goods Movement Emission Reduction Program				
Drayage Trucks Other Trucks Shore power for Ports/ Ships Cargo Handling Equipment Locomotives Marine Engines	1,901	$72,138,878	292	6,606

As discussed later in this chapter, the Air District has developed its Community Air Risk Evaluation (CARE) program to identify communities disproportionately impacted by air pollutants and reduce emissions and

health risks in these areas. One of the most direct ways to improve air quality in CARE communities is to replace or retrofit dirty engines and vehicles that operate in these communities. The Air District has made a commitment to target its grant funds to projects in impacted communities. Figure 4-1 summarizes the Air Districts grant funded project allocations over the last five years by project type. Figure 4-2 summarizes the funding awarded for projects in CARE communities in 2011 when approximately $60 million in Air District grant funds were directed to these communities.

Figure 4-1 Air District Grants Awarded by Project Type from 2007 through 2011 (Total value = $308 million)

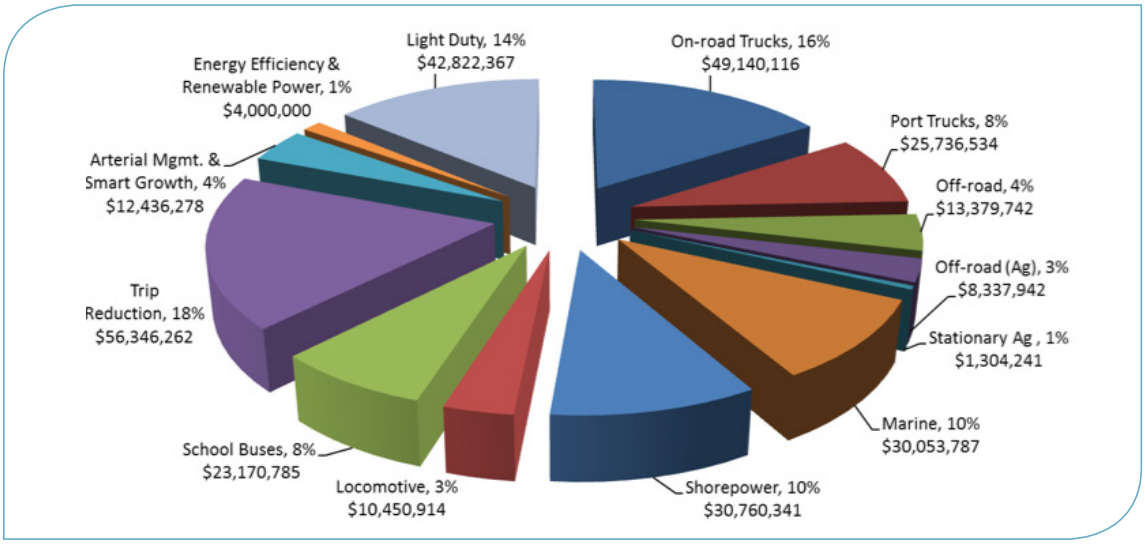
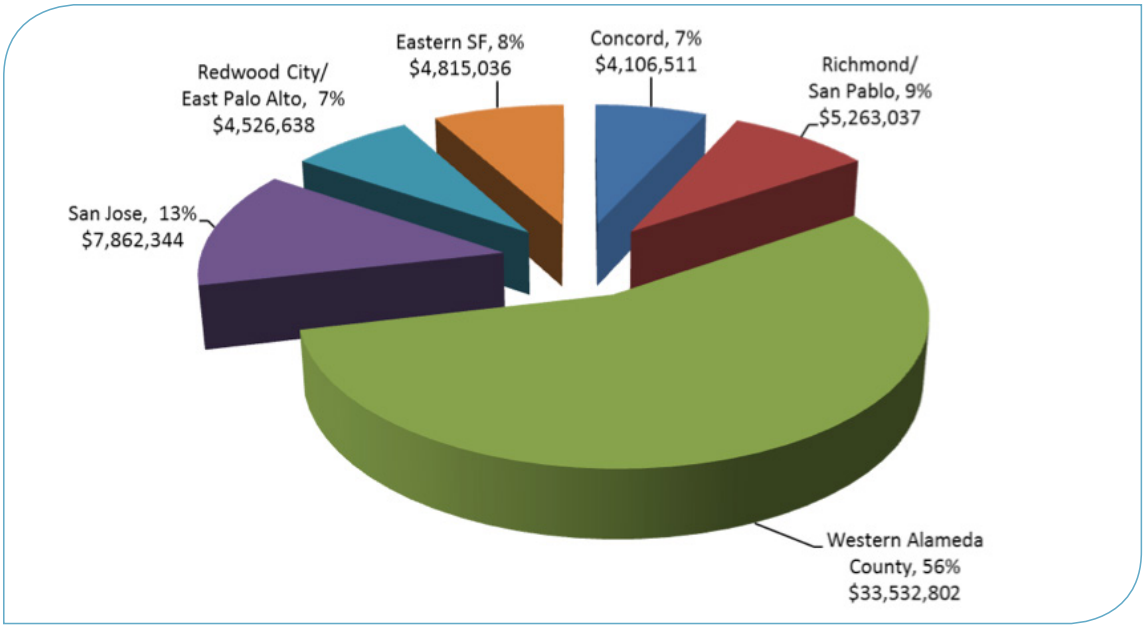


Figure 4-2 Grant Funds Awarded to Projects in Impacted Communities in 2011 (Total value = $60 million)



Key projects funded by the Air District to reduce emissions from mobile sources in recent years are briefly described below.

Drayage trucks

The term "drayage trucks" refers to heavy-duty trucks that handle freight at seaports and intermodal rail yards. The Port of Oakland is served by 2,000-3,000 drayage trucks, many of which were equipped with old uncontrolled engines. Collectively, these trucks were a major source of emissions of diesel PM and other pollutants that endangered the health of people who live or work in West Oakland and surrounding areas included in the western Alameda County CARE community. The Air District and partner agencies therefore prioritized the need to reduce diesel PM emissions from the drayage truck fleet that serves the Port of Oakland. In 2008, the Air District accepted applications for drayage truck retrofit and replacement projects as part of its port truck upgrade program. Through this program the Air District received and awarded a total of $25.8 million in funding from Air District, State, and federal sources. These funds were used to upgrade 1,522 trucks operating at the Port of Oakland, including 1,319 truck retrofits and 203 truck replacements. This program reduces over 14 tons of diesel PM per year at the Port of Oakland. This program reduces approximately 0.3 tons of diesel particulate emissions daily at the Port of Oakland and over 14 tons of diesel PM on an annual basis.

In March 2012 the Air District Board of Directors approved a new initiative that will provide additional grant funds to replace drayage trucks with newer trucks that meet the stringent 2007 engine emission standards. Grants of up to $10,000 will be available to eligible Bay Area truck owners toward the purchase of a truck with a cleaner 2007 model year engine or newer. The Air District Board of Directors committed an intial $1.9 million in funding for this initiative, and Alameda County has committed an additional $1.4 million. In addition, $25 million in State grant funding has been awarded for drayage truck replacement in the Bay Area. This new drayage truck initiative is expected to reduce 1.5 tons of PM and 3,401 tons of NOx over the life of the project. This effort will protect public health in communities adjacent to the Port, help local port truck drivers comply with the ARB drayage truck regulation ahead of schedule, and help maintain the economic vitality of the Port.

There is evidence that the efforts to reduce emissions from goods movement have already improved air quality in the West Oakland area. A recent study performed by UC Berkeley (Dallmann et al. 2011) found substantial reductions in exhaust emissions of black carbon (the primary constituent of diesel PM) and NOx from trucks operating in the vicinity of the Port of Oakland as a result of drayage truck retrofit and replacement projects implemented to date. The average black carbon emission factor for

this drayage truck fleet decreased by approximately 50%, while the average NOx emission factor was reduced by roughly 40%. Emission reductions for black carbon were driven by the retrofit of trucks with diesel particulate filter systems and the replacement of older model year trucks with newer vehicles; reductions in NOx emissions were mainly the result of truck replacement.

On-Road Trucks

Since 2008 the Air District has issued two major solicitations for grant applications for on-road trucks used to transport goods and freight. The first solicitation resulted in the expenditure of nearly $10 million on 211 truck projects (primarily for truck replacements) and reduced more than 109 tons of PM and more than 2,300 tons of PM. The Air District received applications for over 880 eligible on-road emission reduction projects for the second solicitation, and is currently in the process of contracting with truck owners. As part of the second solicitation, the Air District will allocate approximately $15 million to truck owners to assist in replacing existing trucks. The trucks funded from the second solicitation should be on the road by mid-2013, providing estimated emission reductions of more than 55 tons of PM and 1,400 tons of NOx.

Shore Power

Since 2008 the Air District has invested over $31 million in shore power projects in the Bay Area. By eliminating the need for ships to run their engines while docked, these projects will provide significant reductions in the communities adjacent to the ports of Oakland and San Francisco. The shore power installations at the Port of San Francisco (Pier 27) and at the three berths at the APL terminal at the Port of Oakland have been completed. The installation of shore power at twelve more berths at the Port of Oakland are expected to be completed by the end of 2013. Combined, these shore power projects will reduce over 75 tons of PM and 4,000 tons of NOx over their lifetime.

Cleaner School Buses

As noted in Section 1-B, children who go to school in diesel school buses may be exposed to emissions from the bus they ride in, especially if the buses are old models that lack emission controls. The Lower-Emission School Bus Program is one of the most effective ways to reduce exposure of children to diesel PM. Using a combination of funds from its own grant programs, as well as funding provided by the California Air Resources Board, the Air District has allocated over $47 million since the year 2000 for projects to reduce emissions from over 1,100 school buses throughout the Bay Area. This includes $36.5 million to replace old buses with new ones; $10 million to

retrofit 694 buses with diesel particulate control devices, and $676,000 to replace the engines in 25 buses.

Reducing Emissions from Light-Duty Vehicles

Reducing population exposure to PM emissions from motor vehicles requires reducing emissions from light-duty passenger vehicles as well as heavy-duty diesel engines. Although PM emissions from light- and medium-duty gasoline vehicles are very low on a per-mile basis, PM emissions from these vehicles are significant on an aggregate basis because light-duty vehicles account for roughly 95% of total motor vehicle travel in the Bay Area. The Air District is working to reduce emissions from light-duty vehicles. Several of these efforts are described below.

Smoking Vehicle Program

High-emitting vehicles, often called "smoking vehicles", make up a small percentage of the vehicle fleet; however, they account for a much bigger share of total emissions of PM and other pollutants. Fortunately, the number of smoking vehicles has declined in recent years, due to turnover in the vehicle fleet as older, dirtier vehicles are replaced by newer, cleaner vehicles that achieve stringent State emission standards. Retirement of older, high-emitting vehicles has been accelerated by programs to purchase and scrap old vehicles. The Air District administered a successful vehicle-scrappage program from 1996 through 2010, which retired over 55,000 old vehicles from Bay Area roads during this period. Cumulatively, the program reduced over 4,600 tons of ROG, over 2,500 tons of NOx, and over 32 tons of PM. The Air District phased out its program, but Bay Area residents can still participate in the statewide Consumer Assistance Program to scrap old vehicles which is administered by the California Bureau of Auto Repair.

Although their numbers have been reduced, smoking vehicles are still a problem, exposing both the driver and members of the public to harmful pollutants. To help identify these vehicles, the Air District established a smoking vehicle assistance program in the early 1990's. Smoking vehicles can be reported via the 1-800-EXHAUST line, or online at www.800exhaust.org, or via an app for iPhones and Android devices. When smoking vehicle reports are received, the Air District sends an informational letter to the owner describing the harmful effects of smoking vehicles and options for vehicle repair or retirement, and requesting that the owner take appropriate action to rectify the problem. In the two-year period 2010-2011, more than 13,000 smoking vehicle reports were submitted to the Air District.

Electric Vehicles

The long-term solution to improving air quality and reducing emissions of greenhouse gases is to transition to zero-emission vehicles (ZEV), such as battery electric vehicles. Therefore, the Air District is playing a key role in funding projects to accelerate the adoption of battery electric vehicles (EVs) in the Bay Area, with the goal of an adoption of 10,000 ZEVs and 100,000 plug-in hybrid electric vehicles in the Bay Area by 2020. Much of this effort is directed at installing a robust EV-charging network throughout the Bay Area. In FY 2009/10, the Air District allocated $1.3 million for projects to install publicly-available Level 2 chargers in up to 250 locations around the region, six direct current (DC) fast chargers to serve taxi fleets, and a Battery-switch station to test the viability of this advanced technology as a pilot project with taxi fleets. In FY 2010/11, the Air District allocated an additional $5 million to expand this effort, with a goal to install up to 3,000 Level 2 chargers in the Bay Area, and up to 50 DC fast chargers by the end of 2013. Looking forward, the Air District is considering other actions to expand the use of electric vehicles, such as offering grants to encourage cities and counties to expand the use of EVs in their fleets, as well as funds to incentivize the early adoption of electric vehicles in medium- and heavy-duty vehicles used in delivery fleets and similar applications, thus reducing emissions of PM and other pollutants from diesel engines.

Bicycle-Sharing

In recent years, major cities in Europe, Asia, and North America have implemented publicly-available bicycle-sharing programs to reduce traffic and air pollution in the urban core. The Air District is leading a partnership to implement a regional bicycle sharing pilot project in five Bay Area cities, in collaboration with transportation agencies in the counties of Santa Clara, San Mateo, and San Francisco. This project will deploy 1,000 bicycles in the cities of San Jose, Palo Alto, Mountain View, Redwood City and San Francisco for a period of at least 12 months. The goal of the pilot is to test and develop a self-funded regional Bike Share System to complement existing transportation options by providing a convenient option for residents, commuters, and visitors making short trips to and from transit facilities, places of employment and residence, and social and recreational destinations. The current schedule is to launch the project by the end of 2012. If successful, the project may be expanded to additional communities within the Bay Area.

Reducing PM from Wood Smoke

Wood smoke from residential wood-burning is a major component of PM in the Bay Area, especially on winter days when high PM concentrations that exceed the 24-hour PM2.5 standard are most likely to occur. At the local scale, in neighborhoods where wood-burning is prevalent during winter months, wood smoke can expose people to high PM levels, especially if topographical features (e.g., a valley or canyon) and/or weather conditions (an inversion) prevent dispersion of the smoke. Therefore, reducing emissions from wood-burning is a key component of the Air District's efforts to reduce PM levels and protect public health in the Bay Area.

The Air District's efforts to reduce residential wood-burning have evolved over the past two decades. Public education and voluntary compliance were the focus of this effort in the 1990's. The Air District began implementing a voluntary Winter Spare the Air program in 1991, requesting that Bay Area

residents voluntarily curtail wood-burning on days when an exceedance of PM standards was forecast.

In the mid-1990's, the Air District developed a model wood smoke ordinance as a guidance document for cities and counties that wished to regulate sources of particulate matter in their communities. Along with requesting that residents curtail the use of fireplaces and woodstoves in response to Winter Spare the Air alerts, this model ordinance promoted the use of cleaner technologies to reduce wood smoke pollution. Air District staff worked with health agencies and interested residents throughout the Bay Area to promote adoption of the ordinance. To date, 49 Bay Area cities and counties have adopted wood smoke ordinances.

In 2006, US EPA significantly strengthened the national 24-hour PM2.5 standard, lowering the threshold from 65 to 35 mg/m^3. The Air District recognized that further reductions in PM emissions from wood smoke would be needed to achieve the new PM2.5 standard, especially on days when meteorological conditions are conducive to high PM concentrations. Therefore, in 2008 the Air District adopted a stringent wood-burning rule (Regulation 6-3), and amended another rule which regulates open burning (Regulation 5). The Air District also substantially expanded its public outreach and education program for wood smoke reduction.

Summary of Wood-Burning Rule

Key provisions of the wood smoke rule (Regulation 6, Rule 3: Wood-burning Devices) include the following:

- Prohibits operation of any indoor fireplace, fire pit, wood or pellet stove or fireplace insert on specific winter days when the Air District forecasts that PM2.5 levels may exceed the national 24-hour PM2.5 standard. (Regulation 5: Open Burning prohibits outdoor recreational fires during the same periods when elevated PM2.5 levels are forecast.)
- Prohibits excess visible emissions from wood-burning devices.
- Requires cleaner burning technology (EPA-Phase II certified wood-burning device or pellet stove) when wood-burning devices are sold, resold or installed.
- Requires cleaner burning technology if wood-burning devices are permitted for installation in new building construction and remodels. (Installation of new wood-burning fireplaces is prohibited).
- Prohibits burning of garbage, non-seasoned wood, plastics and other inappropriate materials.

- Requires labeling of moisture content for wood sold for use within Air District boundaries, including instructions on how to dry wood that has moisture content greater than 20 percent.
- Requires a label on packages of wood and other solid fuels (such as pressed logs and pellets) instructing the user to check local air quality status before burning these products.

Promoting Compliance with the Wood-Burning Rule

The Air District relies upon both public education and enforcement to promote compliance with the wood-burning rule. In addition to preventing exceedances of the national 24-hour PM2.5 standard, this effort is intended to reduce wood-burning over the long term by educating the public about the hazards of wood smoke.

The public outreach campaign is intended to educate the public as to the requirements of the rule, ensure that people are aware that they need to check air quality status before burning, and explain the public health benefits from reduced wood smoke pollution. The Winter Spare the Air Alert outreach campaign utilizes a wide variety of media and multiple languages to reach the diverse Bay Area population and notify the public when a Winter Spare the Air Alert has been called.

Recognizing that certain areas experience localized impacts of wood smoke, the Air District has conducted targeted mailings, with information about the wood smoke rule and the negative health effects of wood burning, to neighborhoods with high levels of wood smoke complaints and/or burning. In addition, the Air District recently developed a new wood smoke model ordinance that offers local governments a menu of more stringent and innovative options to choose from to reduce neighborhood wood smoke within their jurisdictions. The Air District provided the new model ordinance to all cities and counties in the Bay Area in April 2012.

The Air District is planning to take the following actions to enhance enforcement of the wood-burning rule for the winter 2012-2013 season:

- Use more conservative forecasting to call Winter Spare the Air alerts that trigger the no-burn provision of Regulation 6, Rule 3;
- Add a requirement for first-time violators to complete “wood smoke awareness school” or pay a $100 fine; and
- Increase fines for repeated violations of Regulation 6, Rule 3 for second-time violators, increase the fine to $500, with progressive penalties for subsequent violations.

Survey data and air quality monitoring data both indicate that the Air District’s efforts have helped to reduce residential wood-burning and avoid exceedances of the 24-hour PM2.5 standard. Responses to surveys that the Air District performs to monitor residential wood-burning suggest that Bay Area residents are burning less wood and are burning less often. Monitoring data shows that the number

and severity of high PM days during the winter have decreased, and chemical mass balance data indicate that PM2.5 from wood smoke has decreased by approximately 40% in the past several years.

Reducing Population Exposure to PM

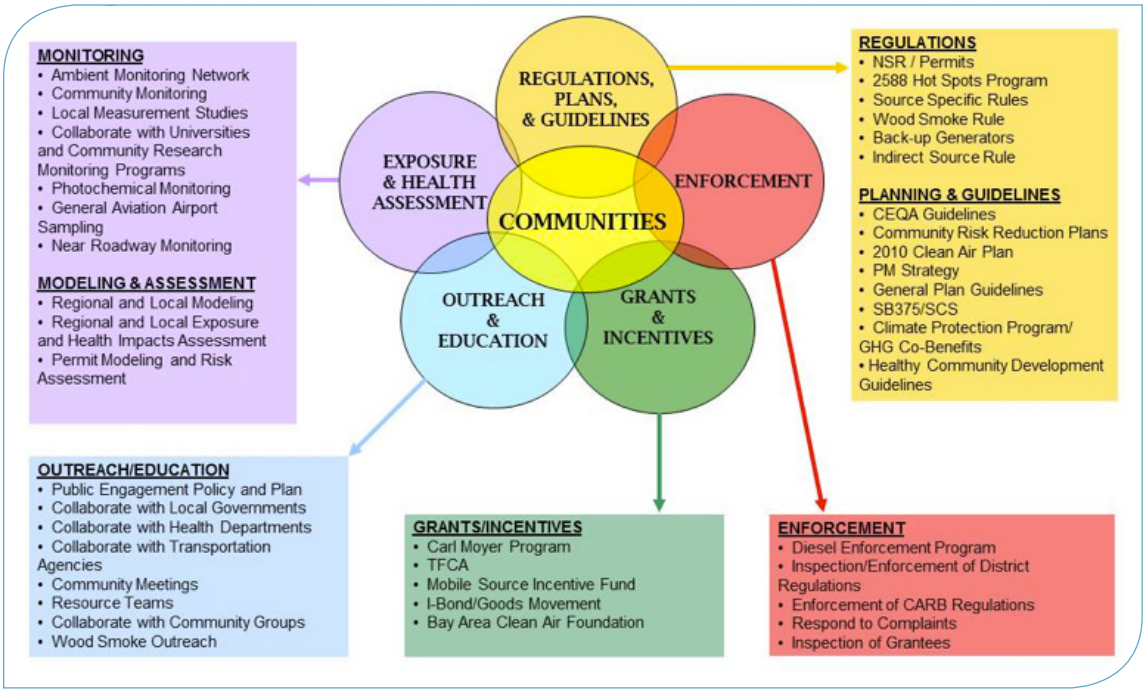
The Air District recognizes that protecting public health means more than just attaining air quality standards at the regional scale. Local concentrations of directly-emitted air pollutants, such as primary PM, may be elevated in proximity to emissions sources such as major roadways, ports and freight distribution hubs, refineries and industrial facilities, airports, and large construction sites. To protect public health, we need to analyze population exposure to air pollution, identify those communities and populations that are most heavily exposed to air pollutants, and develop strategies to reduce population exposure among people who live or work in the most impacted areas.

The Air District's efforts to identify and protect impacted communities have been bundled together under the banner of the multi-faceted **Clean Air Communities Initiative** (CACI). Key elements of the CACI include the following:

- Implementation of the Community Air Risk Evaluation (CARE) program to identify areas in the Bay Area that are disproportionately impacted from transportation and stationary sources.
- New or amended regulations to control emissions from stationary sources that impose disproportionate impacts in CARE communities (e.g., SSM 1, the metal melting rule).
- Implementation of the control strategy in the Bay Area 2010 Clean Air Plan which includes Mobile Source Measures to reduce vehicular emissions; Transportation Control Measures to reduce motor vehicle use, and Land Use and Local Impact Measures to focus on reducing population exposure in impacted areas.
- Performing special monitoring studies to measure ambient concentrations and/or health risks related to PM and/or toxic air contaminants, such as the West Oakland Monitoring Study, the Custom Alloy Scrap Sales (CASS) metals study in West Oakland, and the UC Berkeley study of truck emissions in West Oakland.
- Enforcement of ARB regulations to reduce emissions from diesel engines, via the Mobile Source Compliance Plan described above.
- Providing grants and incentives for projects targeted to reduce emissions within CARE communities, as described above.
- Public education and outreach to encourage compliance with the Air District's wood smoke rule.
- Collaboration with local governments to develop Community Risk Reduction Plans, as described below.
- Collaboration with regional agency partners at MTC, ABAG and BCDC to coordinate regional efforts to promote focused development in a health-protective way via the Air Quality/Priority Development Area working group, as described below.
- Development of on-line analytical tools to help local government agencies to identify and address air quality issues and impacts in their communities.

- Development of a set of standard mitigation strategies to address potential impacts from siting new sensitive receptors near sources of TACs, as described below.
- Reviewing and commenting on air quality analyses in CEQA documents prepared for key plans and projects.
- Development of guidance documents and technical tools to help Bay Area cities and counties address air quality in their General Plans, as described below.

Figure 4-3 BAAQMD Clean Air Communities Initiative



CARE Program to Identify Impacted Communities

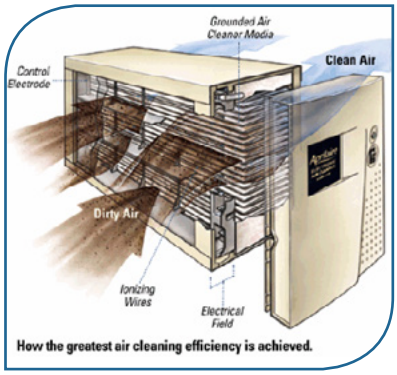
Recognizing that certain neighborhoods and communities in the Bay Area are disproportionately impacted by local emission sources, the Air District launched the **Community Air Risk Evaluation** (CARE) program in 2004. The CARE program was initially focused on identifying risks related to Toxic Air Contaminants (TACs). An analysis of the various TACs in the Bay Area found that diesel PM (identified by ARB as a TAC in 1998) is the TAC that poses by far the greatest health risk in the Bay Area. Based on a combination of major emission sources, high population exposures, and sensitive populations, the CARE program identified six impacted areas as impacted communities: Concord; Richmond/San Pablo; western Alameda County; San Jose; Redwood City/East Palo Alto; and eastern San Francisco. In recent years, recognizing that fine PM of all types is harmful to public health, the scope of the CARE program has been expanded to include PM2.5 as well as TACs. (The Air District is also considering adding other air pollutants, such as ozone, for purposes of identifying and defining impacted communities.)

Community Risk Reduction Plans

Addressing air quality issues in local land use and transportation planning also can help reduce exposure to air pollution. The Air District, in cooperation with Bay Area planning and health agencies,

is developing a new planning tool, known as a **Community Risk Reduction Plan** (CRRP), to help local jurisdictions identify, evaluate, and reduce risks from local sources of toxic air contaminants (TAC) and fine PM. The Air District is encouraging cities, especially those that have been identified by the Air District's CARE program as disproportionately impacted by local pollutants, to prepare a CRRP. The basic approach to develop a CRRP includes several key steps: (1) developing an inventory of TAC and fine PM emissions within a planning area, which may be a whole city or part of a city; (2) using dispersion modeling to map ambient concentrations and risks from local pollutants within the planning area; (3) developing specific goals and objectives to reduce health risks; and 4) defining implementation actions, such as policies and mitigation measures, in order to achieve the goals and objectives. The Air District is providing financial and technical support in a pilot program to assist the City and County of San Francisco and the City of San Jose in developing CRRPs.

The San Francisco Department of Public Health and the SF Planning Department have collaborated with the Air District to develop a city-wide CRRP that encompasses the impacted areas of eastern San Francisco, with the goal of reducing air pollution exposures and associated health risk on a city-wide basis. City staff worked with the Air District to develop a detailed emissions inventory and in applying local-scale dispersion modeling to identify areas with increased risk from air pollution and to produce maps of TAC risks and PM2.5 concentrations from all emission sources. City staff is developing a range of potential policies and programs to reduce residents' exposure to air pollution, such as expanding current air filtration requirements (Article 38 in the San Francisco Health Code), limiting construction emissions, and more.



How the greatest air cleaning efficiency is achieved.

San Francisco Health Code Article 38

Model Ordinance for Cities: San Francisco is the first jurisdiction in the country to create a law, known as Article 38, to protect future residents from exposure to roadway air pollution. The law will prevent avoidable lung disease and premature death in residents living near busy roadways, as well as prevent avoidable health care spending, for example, on hospital charges for prevented asthma attacks.

San Francisco Health Code Article 38, adopted in 2008, requires residential projects with more than 10 units located in "Potential Roadway Exposure Zones" (as defined according to maps provided by the San Francisco Department of Public Health) to prepare an air quality assessment, using modeling tools, to determine whether residents would be exposed to unhealthy levels of PM2.5. The Department of Public Health has defined "unhealthy" levels of PM2.5 as roadway concentrations greater than 0.2 $\mu g/m^3$. If the air quality assessment indicates that the roadway-attributable PM2.5 would be less than 0.2 $\mu g/m^3$, then no further action is required. If the air quality assessment for the residential project indicates that concentrations would be unhealthy, then the project is required to mitigate the traffic-related PM2.5 pollutants, using available technology and design features, to reduce or remove at least 80% of the ambient PM2.5 from indoor spaces.

Meeting the performance standard can be accomplished in several ways, including:

1. Designating lower floors for commercial use and upper for residential use;
2. Setback of buildings from roadway air pollution sources;
3. Locating the intake for fresh air ventilation sources at a non-polluted site;
4. Filtration of fresh air ventilation sources; and/or
5. Recirculation and filtration of indoor air.

Economic Impacts: The City/County of San Francisco's Office of the Controller has determined that the economic impacts of Article 38 on the San Francisco economy, the development community, and future residents of the City are neutral to positive. Although there is a cost associated with implementation of the mitigation measures described above, Article 38 will also prevent avoidable health care spending (for example, hospital charges for emergency room visits for asthma attack) and help to prevent premature mortality associated with exposure to PM. If using a filtration system, the City estimates that costs to install and maintain the system will range from approximately $50-700 per year per unit, while the monetary benefit of the reduction of premature death is estimated to be approximately $2,100 per unit per year. On the basis of this analysis, if installation of a filtration system is required in order to comply with the requirements of Article 38, then the Controller has determined that the net economic benefit of Article 38 would be approximately $1,400 per unit per year.

The Air District has also been providing technical assistance to help the City of San Jose develop a CRRP. The Air District is preparing city-wide emissions inventory for on-road mobile sources on freeways and surface streets, permitted stationary sources, and railroads, airports, and construction projects. Initial air dispersion modeling is underway. The City has also engaged in public outreach, in partnership with the Air District. As a first step on the policy side, the City included several policies in its 2011 General Plan update to analyze and mitigate population exposure from major emissions sources. For example, the air quality section of the General Plan includes policies which (1) require completion of air quality modeling for sensitive land uses such as new residential developments located near emission sources such as freeways and industrial uses; (2) require new residential development projects and projects characterized as sensitive receptors to incorporate effective mitigation into project designs or to be located an adequate distance from sources of toxic air contaminants to avoid significant health risks; and (3) require projects that would emit toxic air contaminants to prepare health risk assessments as part of environmental review and employ effective mitigation to reduce possible health risks to a less-than-significant level. In addition, the General Plan policies mentioned above encourage the use of air filtration devices in existing schools, houses and other sensitive land uses; re-designation of truck routes; and the use of vegetative buffers between emission sources and sensitive receptors.

Promoting Healthy Focused Development

Continued growth in motor vehicle travel could erode the air quality benefits from the ARB and Air District programs described above. We need to better integrate land use, transportation, and air quality planning in order to constrain future increases in vehicle travel and emissions. Therefore, the Air District supports the effort to focus future development in the Bay Area in areas where public transit, biking and walking are viable transportation options. At the same time, however, many of the areas identified as good sites for focused growth already experience high concentrations of air pollutants due to emissions from existing local sources. In fact, a comparison of areas that have been designated as *Priority Development Areas* (PDAs) to date and the impacted communities identified by the Air District's CARE program shows that there is considerable overlap. This emphasizes that we need to plan for focused growth in a way that protects people from exposure to air pollutants, especially local pollutants such as PM and air toxics. To address this issue, the Air District is committing its resources to help planning agencies (cities, counties, MTC, and ABAG) identify, evaluate and mitigate these impacts through the planning and design processes.

The Air District is working actively with partners at both regional and local agencies to support focused development to reduce motor vehicle emissions, while ensuring that development is planned and designed so as to minimize public exposure to air pollutants and protect public health.

At the regional scale, the Air District is engaged with its regional agency partners in the effort to develop *Plan Bay Area*. Plan Bay Area, scheduled for adoption in 2013, will update the Regional Transportation Plan (RTP) and incorporate a **Sustainable Communities Strategy** to better integrate land use and transportation planning, in response to the requirements of Senate Bill (SB) 375. Although SB 375 requirements focus on the need to reduce emissions of greenhouse gases, the Air District worked with its regional agency partners to make sure that the performance targets for Plan

Bay Area include targets to reduce exposure to particulate matter emissions from motor vehicles and to achieve greater reductions of PM in impacted communities.

In addition, Air District staff is participating in the development and environmental review of Station Area Plans where most of the future high-density, transit-oriented development in the Bay Area is projected to occur. The Air District is working to identify potential PM2.5 and TAC impacts and develop plan-level approaches on how to mitigate these impacts, so that subsequent project-level development that conforms to the Station Area Plans is not burdened with costly environmental review.

Since local governments are responsible for land use planning, the Air District is working to develop partnerships and provide technical assistance to the nine counties and 101 cities that comprise the Bay Area to ensure that air quality considerations are addressed in local land use decisions.

Analytical tools: The Air District developed a set of on-line analytical tools to identify and assess the potential impacts from stationary sources, freeways and major roadways in close proximity to a development project (or throughout a plan-area). The stationary source tools can be used to identify all stationary sources permitted by the Air District and to estimate local PM2.5 concentrations associated with each permitted source. The highway tool can be used to identify all highways throughout the Bay Area and to estimate local PM2.5 concentrations associated with each highway. The roadway tool is a set of tables which show the estimated PM2.5 concentrations associated with each major roadway (defined as 10,000 AADT and above) throughout the entire Bay Area. All of the tools are county-specific, meaning the information used in the development of the tool has been customized for each Bay Area county.

Mitigation Strategies: The Air District has also developed a set of recommended mitigation strategies to reduce exposure to PM2.5 concentrations. These mitigation strategies include measures such as:

- Requiring installation of HEPA filtration systems (rated at MERV 16 or higher);
- Designing the project site to minimize population exposure to air pollutants;
- Limiting residential uses on the ground floor;
- Planting trees to buffer and absorb pollutants;
- Reducing emissions, where applicable via measures such as replacing or retrofitting diesel back-up generators; installing electrical hook-ups for diesel trucks; requiring trucks to use transportation refrigeration units that meet EPA Tier 4 emission standards; requiring advanced drive trains or alternative fuels in heavy-duty trucks; and establishing alternative truck routes.

General Plan Guidelines: The Air District is developing a guidance document to help local governments address air quality in their general plans. The general plan is a critically important document for local community planning, because local decisions related to growth and development must be consistent with the policies and objectives contained in the general plan. In addition to elements required by State law, local governments may elect to include additional elements in their general plan, such as health or air quality, to better guide their community's development. The Air District's guidance document provides local agencies with a comprehensive set of air quality-related "model policies" that may be used to build an optional air quality element within their general plan. The guidance document also offers policy recommendations and implementation strategies for community education and outreach, reducing wood burning, improving indoor air quality, and "green" building and contracting practices. The Air District's guidance document should facilitate land use planning to improve air quality and protect public health at both the local and regional scale.

Organizational Changes to Focus on Exposure Assessment & Protecting Public Health: To further its commitment to analyzing air pollution and minimizing population exposure in impacted communities, the Air District reorganized its Planning Division in 2012. The "Special Projects Section", which previously focused on developing emission inventories, was expanded and renamed the "Exposure Assessment and Emission Inventory Section". In addition, the Air District created a Health and Science Officer position in July 2012; this position will bring additional expertise to inform development of Air District policies to protect public health, as well as strengthen the Air District's partnerships with the public health community in the Bay Area. These changes emphasize that the Air District will place a high priority on improving its capabilities in terms of analyzing and reducing population exposure to air pollutants in the coming years.

PM Reductions in the Central Valley: As discussed in Section 2, technical analysis performed by the Air District indicates that transport of PM from the Central Valley contributes significantly to elevated Bay Area PM concentrations during the winter weather pattern typically associated with elevated PM levels in the Bay Area. The San Joaquin Valley Unified Air Pollution Control District is in the process of developing a PM2.5 SIP submittal to demonstrate how it will reduce emissions of primary PM and PM precursors in order to attain the national 24-hour PM2.5 standard. The San Joaquin Valley attainment plan must be submitted to US EPA by December 2012. Monitoring data indicates that the Sacramento air basin recently met the national 24-hour PM2.5 standard. The Sacramento Air Quality Management District plans to develop a re-designation request and maintenance plan to show how it will continue to attain the national 24-hour PM2.5 standard over the next decade. In addition to improving air quality in the Central Valley, implementation of the control strategies set forth in the San Joaquin and Sacramento PM2.5 plans should also help to reduce ambient PM concentrations in the Bay Area during weather patterns that facilitate transport of PM from the Central Valley to the Bay Area.

SECTION 5: LOOKING FORWARD

This final section provides a conceptual framework to guide future Air District efforts to reduce PM in order to protect public health, the climate and the environment. This section identifies several challenges; suggests policy guidelines to inform the development of potential future measures to reduce PM; describes areas where further study and technical enhancements are needed; and provides ideas for how Bay Area residents can reduce their exposure to PM.

As discussed in the preceding sections of this report, the current control programs being implemented by the Air District, the California Air Resources Board, and other partners have reduced substantially ambient PM concentrations in the Bay Area over the past 15-20 years. The Bay Area currently meets the national PM standards and is close to meeting state PM standards. Continued implementation of these programs described in Section 4 is expected to further reduce emissions of primary PM and PM precursors over the next decade. In addition, new initiatives in the final stages of development such as ARB's Low Emission Vehicle (LEV) III standards, should lead to additional PM reductions from targeted emission sectors.

WHY IT'S IMPORTANT TO CONTINUE REDUCING PM

The fact that the Bay Area has made tangible progress in reducing PM levels does not mean that we can rest easy, however. There are compelling reasons why it is important to continue and enhance our efforts to reduce PM.

- Researchers have not been able to establish a safe threshold for population exposure to PM. A robust and growing body of research shows that there are health impacts associated with exposure to PM even below the current standards.
- As new information about the health effects of PM becomes available, the US EPA and/or the ARB may issue more stringent standards in the future.
- Even at the relatively low PM levels that currently prevail in the Bay Area, PM is the air pollutant most harmful to public health, including premature mortality, heart attacks, chronic bronchitis and other key health effects.
- PM levels - and population exposure to PM - can vary significantly at the local scale. Even though the Bay Area currently meets national PM standards (based on the measurements from the regional PM monitoring network), some communities and individuals are exposed to higher concentrations of PM.

- In addition to its detrimental impacts on public health, PM also plays a role in climate change and has negative impacts on ecosystems and visibility.

CHALLENGES WE FACE

Although further PM reductions would benefit the health of Bay Area residents, reducing PM presents challenges, several of which are described below.

- **The Air District's authority is limited**. Emission sources are diverse, and the Air District's authority is limited to a defined set of sources. For example, indoor exposure to ultrafine and fine PM accounts for a significant share of total exposure for many people, but the sources and conditions contributing to indoor PM excposure are complex and the Air District has limited authority to regulate emissions from most indoor sources that contribute to indoor exposures.[5]
- **Low-hanging fruit is sparse**. As described in Section 4, policies and regulations have already been implemented to reduce emissions of primary PM and PM precursors from key sources, such as diesel engines and residential wood burning. It will be a challenge to identify new control measures that achieve significant PM emissions on a cost-effective basis.
- **Wood smoke remains a problem.** The Air District has made a major effort to reduce PM from residential wood burning, as described in Section 4. The evidence indicates that this effort has been effective in reducing PM levels at the regional scale. However, wood smoke is still a significant source of emissions, accounting for roughly one-third of PM2.5 during winter months when the Bay Area experiences its highest PM levels. Moreover, in neighborhoods where wood burning is prevalent during winter months, wood smoke can expose residents to high PM levels, especially if topographical features and/or weather conditions prevent dispersion of the smoke. Achieving further reductions in residential wood burning will be a challenge, however, because the sources are widely dispersed and compliance depends upon public education and cooperation and large-scale behavioral change.
- **Transport of PM from outside the Bay Area**. Analysis shows that on the winter days when the Bay Area experiences its highest PM concentrations, transport of PM by easterly winds from the Central Valley contributes to PM levels in the Bay Area.
- **Coordination challenges**. Many public agencies and other stakeholders have a role to play in reducing PM and protecting public health. The diversity of players and perspectives provides opportunities for collaboration and

5 The Air DIstrict does have authority to regulate emissions from certain indoor sources, including wood-burning cooking, water-heaters and furnaces.

partnership, but also highlights the need to coordinate efforts, identify areas of mutual interest, and reconcile competing objectives.

- R**egional and community needs.** Because certain communities are disproportionately impacted by PM and other air pollutants, the Air District needs to reduce PM at both the regional scale and in the communities most impacted by PM.
- **Protecting public health at the regional and community scale**. Monitoring data show that the Bay Area currently meets the national PM standards. However, health studies show that there are health effects even below these standards, and we know that certain communities and individuals may be exposed to higher levels of PM. GIven this context, how do we determine the appropriate objectives in terms of reducing exposure to PM at both the regional and the community scale?

POLICY GUIDELINES TO INFORM FUTURE PM PLANNING

The discussion in this section provides a conceptual framework to guide the Air District's future efforts relating to PM, based on the best available information to date. This is intended to be a "working" framwork; the Air District recognizes that it may need to be revised as new information is available.

- The Air DIstrict will continue to pursue a multi-faceted approach which combines regulations and control measures to reduce emissions of PM and PM precursors from sources under its jursidiction, targeted enforcement of ARB regulations on sources under ARB control, grants and incentives to achieve emission reductions above and beyond regulatory requirements, efforts to reduce population exposure, partnerships with the health community and other stakeholders, and public education.
- Pursuant to the Bay Area 2010 Clean Air Plan, potential future measures to reduce PM will be evaluated on a multi-pollutant basis, to maximize their overall air quality, health and climate protection benefit.
- Since science has not yet determined precisely which components of PM are the most harmful to public health, the Air District will continue its efforts to reduce PM across the board, including all sizes and types of particles. However, the Air District will continue to monitor the latest research on PM health effects to inform its PM reduction efforts, and will collaborate with the health community to provide information on PM emissions and exposure in the Bay Area.
- Results from the Air District's PM modeling for the Bay Area indicate that reducing emissions of primary PM offers the most direct means to reducing ambient PM concentrations. This is especially true in terms of reducing local PM "hot spots"

which are caused mainly by exposure to emissions of primary PM from motor vehicles, residential wood burning, or major point sources.

- The Air District and its partners will also continue efforts to reduce emissions of precursor pollutants that contribute to the formation of secondary PM, especially to help avoid exceedances of the 24-hour PM2.5 standard during winter months when ammonium nitrate is a major component of ambient PM.
- The evidence indicates that reducing emissions of black carbon particles should provide both health and climate protection benefits. Therefore, the Air District will evaluate potential measures to further reduce combustion of fossil fuels and biomass (wood) in order to decrease emissions of black carbon.
- The Air District will continue to enhance its efforts to reduce emissions from sources, such as motor vehicles, that account for high population to exposure to fine and ultrafine particles.
- The Air District will continue its efforts to better understand local PM concentrations and exposures by, for example, expanding monitoring near roadways and major emission sources, undertaking special studies, and improving methods to estimate population exposure to PM.
- The Air District work to strengthen its partnerships with county health departments, local planning agencies, community groups, academic institutions, and other stakeholders with an itnerest in improving air quality and protecting public health to address the challenges and policy issues identified in this report.

AREAS FOR FURTHER EVALUATION

To inform the Air DIstrict's future efforts to control PM and reduce the negative impacts described in previous sections, we need:

- Better information as to which types and sizes of PM are most harmful to public health.
- More precise analysis of personal exposure to PM in various micro-environments to determine which types of exposures pose the highest risk to health.
- Better understanding as to the interplay between PM and climate change, and how the various types of particles promote or inhibit climate heating.

Several specific areas merit further evaluation: (1) ultrafine PM, (2) the role of ammonia as a precursor to secondary PM formation, and (3) the climate change impacts of black carbon. The Air District will consider each of these areas, as discussed below.

Ultrafine PM

As described previously, ultrafine particles (UFPM) present special challenges since they are hard to measure and extremely dynamic, and because ultrafine PM concentrations tend to be elevated and localized in close proximity to emission sources. The current understanding of ultrafine PM in the scientific community is still very limited. Although evidence suggests that exposure to ultrafine PM may be especially harmful to public health because the particles can penetrate deep into body organs and tissues, there are as yet no ambient air quality standards for ultrafine PM nor requirements for monitoring of ambient ultrafine PM concentrations. Because of the gaps in our understanding of ultrafine PM, efforts to characterize these particles and develop appropriate control strategies are still in the early stages. Key constraints in terms of ultrafine PM include the following:

Emissions inventory: As discussed below, the Air District prepared its first ultrafine PM emissions inventory in August 2012. However, further work will be needed to refine the inventory as emission factors are developed and improved for various many source categories.

Ambient concentrations: The technology to measure ambient concentrations (particle numbers) of ultrafine PM is still evolving. Several ultrafine PM monitors have recently been installed in the Bay Area, but we do not yet have a comprehensive ultrafine PM monitoring network.

Modeling: Given its localized and dynamic nature, modeling ultrafine PM may prove especially valuable. Developing good estimates to where and when ultrafine PM concentrations are high will help identify the types of conditions that are conducive to acute human exposure.

Health studies: Research is on-going to analyze the health effects of ultrafine PM and to determine whether there are distinct health effects related to ultrafine PM as opposed to fine particles (PM2.5). However, the lack of ultrafine PM monitoring networks in most urban areas, and the consequent absence of data on ultrafine particle concentrations, makes it difficult to perform epidemiological studies to better elucidate the health effects of ultrafine PM.

Ambient air quality standards: Despite growing concerns about the health effects of ultrafine PM, there are as yet no State or national ambient air quality standards for UFPM. Nor are such standards likely to be adopted until the gaps described above have been addressed. In the meantime, PM2.5 serves as the closest surrogate for ultrafine PM, despite the fact that evidence indicates that the correlation between PM2.5 mass and ultrafine PM numbers is tenuous at best, and may actually be negatively correlated.

To address the gaps in our understanding of ultrafine PM, the Air District will undertake initiatives in regard to the emissions inventory, monitoring and modeling for ultrafine PM, as summarized in the Technical Enhancements section below.

BAAQMD Advisory Council Recommendations

The Air District's Advisory Council has been studying ultrafine PM over the past two years and receiving presentations from leading experts on ultrafine PM measurement and its health effects. In December 2011, the Advisory Council presented recommendations on ultrafine PM to the Board of Directors. Key Advisory Council recommendations to the Board include the following:

- Integrate ultrafine PM considerations into PM2.5 planning.
- Continue its efforts to characterize ultrafine PM sources, chemical composition, and ambient air levels in the Bay Area.
- Consider development of a ultrafine PM emission inventory and monitoring strategy.
- Consider conducting short-term intensive ultrafine PM monitoring to characterize ambient ultrafine PM levels and speciation at selected key locations (e.g., near heavily traveled roadways), possibly integrating those efforts with upcoming near-roadway continuous NO2 monitoring required pursuant to the 1-hour NO2 national standard.
- Maintain a focus on PM2.5 and ultrafine PM emissions from fuel-burning vehicles, with particular attention to PM emissions from unburned and partially burned fuel and lube oil.
- Continue to investigate and evaluate measures to reduce personal exposure to PM2.5 and ultrafine PM.
- Collaborate with the Association of Bay Area Governments and the Metropolitan Transportation Commission to educate the public on the public health effects associated with on-road and near road ultrafine PM and with PM2.5 exposures; and promote strategies to reduce vehicle miles traveled.
- Collaborate with other agencies (e.g., ARB, South Coast Air Quality Management District) in studying ultrafine PM measurements, and health impacts, fashioning effective public policy strategies and focusing policy development on vulnerable populations and highly impacted areas.

PM and Climate Change (Black Carbon)

As discussed in Section 1-C, the relationship between PM and climate change is complex. A variety of physical processes are involved, and different types of particles have differing impacts on climate. Although it is difficult to determine the net effect of PM on climate, there is strong evidence that black carbon (soot) may be a significant contributor to climate heating. Policy actions to reduce heating effects of PM on the climate should focus on reducing black carbon, as well as brown carbon. Such actions would also yield important health benefits by further reducing exposure to fine particles. Future actions may include the following:

- Develop a Bay Area black carbon emissions inventory; work with the Air Resources Board to obtain black carbon emissions factors for motor vehicles and other mobile sources.

- Collaborate with U.S. EPA, ARB, and other agencies as appropriate, to develop a Global Warming Potential (or a substitute metric) value that places proper weight on the near-term climate protection benefits of reducing black carbon.
- Investigate methods to identify and speciate the types of fine particles that will be reduced by potential control measures in order to target the particles that contribute most to climate heating.
- Consider developing additional control measures to reduce black carbon emissions in the next update of the Bay Area Clean Air Plan.
- In developing measures to reduce particulate emissions, prioritize controls on emission sources that have a high ratio of black carbon compared to organic carbon, sulfates, and nitrates.
- Continue to enhance the Air District's efforts to reduce residential wood-burning and to educate Bay Area residents about the detrimental health and climate effects of wood-burning.
- Encourage Bay Area cities (and other local agencies) to address black carbon in their climate protection plans, and provide technical support to assist in this effort.
- Work with local governments and other stakeholders to estimate the public health benefits of climate protection measures to reduce greenhouse gases, as well as short-term climate forcers such as black carbon.
- Monitor on-going research into the climate impacts of PM, and consider how new findings should be reflected in Air District policies and climate protection efforts.
- Facilitate communications between policy-makers and the scientific community to identify research needs regarding fine particles and climate impacts in order to reduce uncertainties in the policy arena.

Ammonia

As noted in Section 2 of this report, ammonia is a precursor to the formation of ammonium nitrate, a compound which accounts for a significant share of PM concentrations in the Bay Area, especially in winter months when PM concentrations are highest. NOx is converted to nitric acid, which then combines with ammonia to form ammonium nitrate. Ammonia is also a precursor to ammonium sulfate, which accounts for over 10% of Bay Area PM2.5 on an annual basis. For purposes of PM2.5 SIP planning requirements, US EPA guidelines[6] state that certain precursors (e.g., SO2 and NOx) are presumed to be significant contributors to the formation of secondary PM2.5, whereas others, such as volatile organic compounds (VOC) and ammonia are presumed **not** to be significant contributors unless the State makes a finding that the precursor contributes significantly to the PM2.5 non-attainment in the air basin or in downwind areas.

6 See US EPA Clean Air Fine Particle Implementation Rule, April 25, 2007: www.gpo.gov/fdsys/pkg/FR-2007-04-25/pdf/E7-6347.pdf#page=1

In determining whether ammonia is a significant contributor to PM formation, the key question is which pollutant – ammonia, or NOx (in the form of nitric acid) - is the limiting factor in ammonium nitrate formation. Based on the ratio of ammonia to NOx and the dynamics of ammonium nitrate and ammonium sulfate formation in the Bay Area, PM2.5 modeling performed by Air District staff found that reducing ammonia would be the most effective PM precursor to reduce in order to decrease PM2.5 concentrations, as described in Section 2.[7]

To date, PM2.5 SIP plans prepared by other air districts in the state, including South Coast, San Joaquin Valley, and Sacramento, have not treated ammonia as a significant precursor to PM and have not proposed any regulations or policies to control ammonia emissions. It should also be noted that, even if there is a solid technical rationale for controlling ammonia emissions in the Bay Area, there would be challenges in terms of how to control ammonia emissions. The source categories that account for the bulk of ammonia emissions are very different than for primary PM or the other PM precursors. The menu of available control measures appears to be limited, and some of the major sources (e.g. human perspiration and respiration, domestic animal waste) do not lend themselves to regulation.

To better inform a future decision as to whether to consider ammonia a significant contribute to secondary PM formation and pursue measures to reduce ammonia emissions, Air District staff will analyze future PM2.5 modeling results, seek to improve the Bay Area ammonia emissions inventory, and monitor on-going research and policy guidelines that shed light on this issue.

TECHNICAL ENHANCEMENTS NEEDED TO SUPPORT THE AIR DISTRICT'S EFFORTS

As discussed in the preceding sections of this report, the Air District has been building a solid technical and analytical foundation for its PM control efforts in recent years. The Air District has been performing cutting edge work in its efforts to measure, analyze, and characterize PM emissions, concentrations, population exposure, and health effects. However, because PM is such a complex pollutant, there are a number of gaps to be filled. Opportunities to enhance our technical understanding and capabilities in regard to PM include:

- Better measurements and/or estimates of localized PM concentrations;
- Better information as to population exposure to PM; and
- Technical data to characterize ultrafine PM emissions, concentrations, and population exposure in the Bay Area.

7 This is the opposite of results from the Central Valley, where modeling found that the Valley is so rich in ammonia, primarily from agricultural and livestock operations, that reducing ammonia emissions would have little or no effect on decreasing ammonium nitrate formation.

Emissions Inventory

The Air District has a detailed inventory of both primary PM emissions of PM2.5 and PM10, as well as the precursors that contribute to formation of secondary PM. Several potential enhancements to the existing inventory for PM2.5 and PM10 are described below.

Domestic cooking: The Air District PM inventory, like other PM inventories throughout California, currently does not include PM from domestic (residential) cooking. This category would include PM emitted by the both natural gas and electric stoves and ovens, as well as barbeque grills. It is possible that PM from domestic cooking could prove to be a significant source of emissions, given the number of stoves and ovens used in Bay Area homes, as well as the volume of outdoor cooking in summer months. As noted in Section 1-B, indoor PM levels spike when stoves and ovens are in use, and some fraction of this PM finds its way outdoors either by means of stove hood fans, windows, or other types of dispersion. Air District staff will investigate PM emissions from domestic cooking with the objective of developing emissions estimates for this category.

Projections of future wood smoke emissions: As discussed previously, information from speciation of PM collected on filters, as well as Bay Area wood-burning survey results, indicates that the Air District's program has been successful in reducing wood-burning during the winter months. The projections in the PM inventory currently assume that wood-burning emissions will remain constant in future years. However, it seems plausible that PM emissions from residential wood-burning will decrease further in future years in response to continued public education, the gradual phasing out of housing with uncertified wood stoves, conversion of fireplaces to natural gas inserts, and other factors. In order to better understand future wood-burning trends, Air District staff will analyze and research the various factors that influence residential wood-burning, such as the compliance rate during Spare the Air Alerts, the rate at which fireplaces and woodstoves are removed, upgraded, or converted to natural gas inserts, etc. Staff may revise the wood-burning survey to ensure that it provides information to track compliance with all provisions of the wood-burning regulation and overall progress reducing residential wood-burning.

Condensable PM emissions: As mentioned in the emissions inventory discussion, the inventory does not include gaseous emissions that condense to form particles when combustion exhaust cools upon exposure to ambient air. US EPA guidance for PM2.5 planning states that planning efforts should "consider" condensable emissions. This makes sense conceptually; the challenge is to develop test methods to accurately estimate condensable emissions for all the various emission source categories.

Ammonia inventory: As discussed previously, ammonia is one of the precursors to formation of ammonium nitrate, a key component of secondary PM. The Air District has developed an ammonia emissions inventory for purposes of photochemical modeling of PM2.5 in the Bay Area. ARB has developed a separate ammonia inventory for the Bay Area and for other air districts to use in preparing PM2.5 SIP submittals that are due to US EPA by December 2012. There are significant differences between the Air District's ammonia emissions inventory and the one provided by ARB. Air District staff will work to improve the Air District's ammonia inventory and to reconcile the differences

with the ARB ammonia inventory, as methodologies to estimate ammonia emissions from the various source categories are improved and refined.

In addition to improving the existing inventory, the Air District will pursue new initiatives for the emissions inventory in regard to ultrafine PM and black carbon.

Regional ultrafine PM emissions inventory: The Air District released its first-ever emissions inventory for ultrafine PM in August 2012. The ultrafine PM inventory will be an important tool to help in analyzing key emission sources, performing photochemical modeling for PM, and laying the groundwork for a potential control strategy to reduce ultrafube PM. Comparing the breakdown of emission sources for ultrafine PM versus PM2.5 will be very instructive for purposes of informing future control efforts. The Air District will refine and revise the ultrafine PM inventory as new emission factors become available.

Develop black carbon inventory: As noted in the section on PM and Climate, the component of PM known as black carbon is a potent climate heating agent produced primarily by combustion of fossil fuels and biomass. Air District staff will consider the utility and feasibility of developing a black carbon inventory in order to inform future efforts to reduce black carbon emissions.

PM Monitoring / Ambient Concentrations

Ultrafine PM Monitoring: The Air District recently installed several ultrafine PM monitors to provide continuous measurements in various Bay Area locations, as described in Section 3-A. The monitors will serve as the preliminary foundation for the District's effort to develop data as to ultrafine particle number concentrations. Looking forward, the District will consider expanding its UFPM monitoring network, subject to the availability of resources to purchase and operate the monitors.

Monitoring Localized and Episodic Concentrations: The Air District will also pursue new technologies, opportunities, and partnerships to increase the density of PM2.5 measurements in the region, especially in most impacted communities, and near freeways and other major emission sources where PM "hot spots" are most likely to occur. In addition, the Air District will also investigate whether the network can be augmented with accurate, real-time, mobile PM measurement capabilities to determine impacts from short-term episodes and to provide better understanding as to how PM concentrations vary over space and time.

PM Photochemical Modeling

Additional PM2.5 Modeling: The Air District performed initial photochemical modeling for PM2.5 in 2009, as described in Section 2. The 2009 modeling was performed on a 4 km by 4 km grid scale using emissions and meteorological data based upon several high PM episodes in winter months. The Air District is currently performing additional regional-scale PM2.5 modeling to simulate PM formation fat the regional scale for a full year, using emissions and meteorological data from all four seasons in order to be able to simulate PM formation for the entire year. Since most epidemiological studies are based on annual average exposure, this will enable the Air

District to more accurately estimate the health effects related to PM in the Bay Area. In addition, it will provide a better understanding of secondary PM formation, and how the formation of secondary PM contributes to ambient PM concentrations for the entire year, rather than just the winter months. This modeling will also analyze potential impacts of reductions in emissions from key PM sources, such as wood smoke. As resources permit, the Air District may consider performing additional PM modeling using a finer grid resolution in order to better identify local areas with the potential for high PM formation.

Ultrafine PM Modeling: Information as to ultrafine particle concentrations in the Bay Area is currently very limited. The Air District will perform its first-ever ultrafine PM modeling on a region-wide basis on a 4 km by 4 km grid scale. The UFPM modeling will simulate concentrations to identify potential hot spot areas in the Bay Area. This modeling will also establish a relationship between UFPM levels and meteorological conditions.

Analyzing Population Exposure to PM

Reducing population exposure to PM in the Bay Area is the key to reducing its health effects. This can be accomplished both by reducing emissions and by avoiding exposures. However, as noted in Section 1-B, analyzing population exposure to PM requires accurate data as to (1) ambient concentrations of PM at a fine-grained spatial scale throughout the region, (2) personal activity patterns; that is, where and when people are exposed to PM, and (3) estimates of PM concentrations in various micro-environments such as homes, schools, cars, and sidewalks, and how these concentrations are related to ambient levels.

The Air District will consider how to improve its PM population exposure assessment capabilities. Improved exposure assessment methods could potentially be used for any or all of the following purposes:

- To evaluate total population exposure to ambient PM in the Bay Area, and to track progress in reducing population exposure at the regional scale or among defined population sub-groups.
- To estimate the PM exposure from outdoor versus indoor environments, as well as the contribution of key micro-environments, such as in-vehicle, near-roadway, etc.
- To inform future efforts to target and implement the Air District's CARE program and Clean Air Communities Initiative (CACI).
- To inform analyses and policy decisions at the regional and local level to promote focused growth, including the development of station area plans, general plans, specific plans, community risk reduction plans, etc.
- To help Bay Area residents understand the magnitude and the key sources or their personal exposure to PM, and how they reduce their exposure.

Analyzing Health & Climate Impacts

Air District staff will continue to monitor the latest research as to the health and climate effects of PM and incorporate this information into its PM reduction program. In terms of estimating the impact of PM on public health in the Bay Area, the Air District will:

- Update the findings of its September 2011 report on the morbidity and mortality impacts of PM2.5 in Bay Area, and the economic cost of those impacts, based upon the new round of PM2.5 modeling;
- Update the District's Multi-Pollutant Evaluation Method (MPEM) to reflect results of full-year PM2.5 modeling, the latest health risk factors, and the latest information as to the climate impacts of greenhouse gases and the value of reducing GHG emissions; and
- Develop estimates as to the health and economic impacts of ultrafine PM, based on the results of ultrafine PM modeling and health studies.

HOW BAY AREA RESIDENCES CAN REDUCE THEIR PERSONAL EXPOSURE TO PM

In concert with the Air District's efforts, Bay Area residents may decrease their personal exposure to PM by taking simple steps including the following:

- Minimize time spent driving on, or in close proximity to, busy roadways, especially those that carry a high volume of heavy-duty diesel vehicles.
- Avoid opening vents and windows while driving on busy roadways.
- Avoid smoke from tobacco products, incense and candles.
- Avoid exposure to wood smoke. Don't burn wood in a fireplace or stove. Avoid campfires, bonfires, and charcoal fires. Replace wood-burning fireplaces with a natural gas insert.
- Reduce exposure to PM from cooking by ventilating the kitchen when cooking, and switching to electric pilot lights.
- Change filters in furnaces and range hoods on a regular bsais.
- Reduce exposure to PM and other air pollutants from cleaning products by ventilating work areas while cleaning and disposing of used rags promptly.

CONCLUSION

The Air District is committed to analyzing and reducing PM to protect public health, the climate, and the environment. To maintain progress in reducing Bay Area PM levels in the coming years, the Air District will continue to monitor the latest research on PM impacts to public health and the environment, and to enhance its technical capabilities to measure and analyze PM. In addition, the Air District will maintain its efforts to reduce PM by implementing the control measures described in the Bay Area 2010 Clean Air Plan and by considering potential additional measures (to be determined at a future date) in the course of developing future air quality plans.

Appendix A
Bay Area Winter Emissions Inventory for Primary PM + PM Precursors: 2010-2030

SOURCE CATEGORY	Winter Emissions tons/day																								
	PM_{10} 2010	PM_{10} 2015	PM_{10} 2020	PM_{10} 2025	PM_{10} 2030	$PM_{2.5}$ 2010	$PM_{2.5}$ 2015	$PM_{2.5}$ 2020	$PM_{2.5}$ 2025	$PM_{2.5}$ 2030	ROG 2010	ROG 2015	ROG 2020	ROG 2025	ROG 2030	NOx 2010	NOx 2015	NOx 2020	NOx 2025	NOx 2030	SO_2 2010	SO_2 2015	SO_2 2020	SO_2 2025	SO_2 2030
INDUSTRIAL/COMMERCIAL PROCESSES																									
Basic Refining Processes	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	--	--	--	--	--	0.2	0.2	0.2	0.3	0.3
Wastewater (Oil-Water) Separators	--	--	--	--	--	--	--	--	--	--	1.2	1.2	1.3	1.4	1.4	--	--	--	--	--	--	--	--	--	--
Wastewater Treatment Facilities	--	--	--	--	--	--	--	--	--	--	0.5	0.5	0.5	0.5	0.6	--	--	--	--	--	--	--	--	--	--
Cooling Towers	--	--	--	--	--	--	--	--	--	--	0.9	0.9	1.0	1.0	1.1	--	--	--	--	--	--	--	--	--	--
Flares & Blowdown Systems	--	--	0.1	0.1	0.1	--	--	--	--	--	0.8	0.8	0.9	0.9	1.0	1.2	1.3	1.3	1.4	1.5	0.6	0.7	0.7	0.7	0.8
Other Refining Processes	--	--	--	--	--	--	--	--	--	--	0.3	0.3	0.3	0.3	0.4	--	--	--	--	--	--	--	--	--	--
Fugitives	--	--	--	--	--	--	--	--	--	--	0.5	0.5	0.6	0.6	0.6	--	--	--	--	--	--	--	--	--	--
Subtotal	**0.3**	**0.3**	**0.3**	**0.3**	**0.3**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**4.3**	**4.5**	**4.7**	**5.0**	**5.2**	**1.2**	**1.3**	**1.4**	**1.4**	**1.5**	**0.9**	**0.9**	**1.0**	**1.0**	**1.1**
CHEMICAL MANUFACTURING FACILITIES																									
Coating, Inks, Resins & Other Facilities	0.1	0.1	0.1	0.1	0.1	--	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	2.7	2.9	3.0	3.2	3.3
Pharmaceuticals & Cosmetics	0.4	0.4	0.4	0.5	0.5	0.4	0.4	0.4	0.4	0.5	0.8	0.8	0.9	0.9	1.0	1.4	1.4	1.5	1.6	1.7	3.2	3.3	3.5	3.7	3.9
Fugitives - Valves & Flanges	--	--	--	--	--	--	--	--	--	--	0.6	0.7	0.5	0.6	0.6	--	--	--	--	--	--	--	--	--	--
Subtotal	**0.5**	**0.5**	**0.5**	**0.5**	**0.6**	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**	**1.5**	**1.6**	**1.5**	**1.6**	**1.7**	**1.5**	**1.5**	**1.6**	**1.7**	**1.8**	**5.9**	**6.2**	**6.5**	**6.8**	**7.2**
OTHER INDUSTRIAL / COMMERCIAL PROCESSES																									
Bakeries	--	--	--	--	--	--	--	--	--	--	0.8	0.9	0.9	1.0	1.0	--	--	--	--	--	--	--	--	--	--
Cooking(Charbroiling)	2.0	1.8	2.0	2.2	2.4	1.5	1.4	1.5	1.7	1.9	0.9	1.0	1.1	1.2	1.3	--	--	--	--	--	--	--	--	--	--
Cooking(Deep Fat Frying)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	--	--	--	--	--	--	--	--	--	--
Cooking(Griddles)	0.6	0.7	0.7	0.8	0.9	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.2	--	--	--	--	--	--	--	--	--	--
Wineries & Other Food & Agr. Processes	0.5	0.6	0.6	0.7	0.7	0.3	0.3	0.4	0.4	0.4	1.1	1.1	1.2	1.2	1.2	--	--	--	--	--	--	--	0.1	0.1	0.1
Metallurgical & Minerals	2.6	2.8	3.0	3.3	3.5	1.8	1.9	2.1	2.2	2.4	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.3
Waste Management	2.1	2.1	2.2	2.2	2.2	0.6	0.6	0.6	0.6	0.6	3.1	3.1	3.2	3.2	3.2	--	--	--	--	--	--	--	--	--	--
Semiconductor Mfg.	--	--	--	--	--	--	--	--	--	--	0.2	0.2	0.3	0.3	0.3	--	--	--	--	--	--	--	--	--	--
Fiberglass Products Mfg.	--	--	--	--	--	--	--	--	--	--	0.1	0.2	0.2	0.2	0.2	--	--	--	--	--	--	--	--	--	--
Rubber & Plastic Products	--	--	--	--	--	--	--	--	--	--	0.3	0.3	0.3	0.3	0.3	--	--	--	--	--	--	--	--	--	--
Contaminated Soil Aeration	--	--	--	--	--	--	--	--	--	--	0.1	0.1	0.1	0.1	0.1	--	--	--	--	--	--	--	--	--	--
Other Industrial Commercial	0.8	0.9	1.0	1.0	1.1	0.4	0.5	0.5	0.5	0.6	0.9	1.0	1.1	1.1	1.2	--	--	--	--	--	--	--	--	--	--
Subtotal	**8.8**	**9.0**	**9.6**	**10.3**	**11.0**	**4.9**	**5.0**	**5.3**	**5.8**	**6.2**	**7.9**	**8.3**	**8.6**	**9.1**	**9.5**	**0.3**	**0.3**	**0.3**	**0.4**	**0.4**	**0.3**	**0.3**	**0.3**	**0.3**	**0.4**
PETROLEUM PRODUCT / SOLVENT EVAPORATION																									
PETROLEUM REFINERY EVAPORATION																									
Storage Tanks	--	--	--	--	--	--	--	--	--	--	3.3	3.5	3.6	3.8	4.0	--	--	--	--	--	--	--	--	--	--
Loading Operations	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	--	--	--	--	--	--	--	--	--	--
Subtotal	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**	**3.4**	**3.6**	**3.8**	**4.0**	**4.2**	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**	**--**
FUELS DISTRIBUTION																									
Natural Gas Distribution	--	--	--	--	--	--	--	--	--	--	0.7	0.8	0.8	0.8	0.8	--	--	--	--	--	--	--	--	--	--
Bulk Plants & Terminals	--	--	--	--	--	--	--	--	--	--	0.7	0.6	0.6	0.6	0.6	--	--	--	--	--	--	--	--	--	--
Trucking	--	--	--	--	--	--	--	--	--	--	2.6	2.6	2.5	2.5	2.5	--	--	--	--	--	--	--	--	--	--
Gasoline Filling Stations	--	--	--	--	--	--	--	--	--	--	5.2	4.9	4.8	4.6	4.5	--	--	--	--	--	--	--	--	--	--
Aircraft Fueling	--	--	--	--	--	--	--	--	--	--	1.1	1.0	1.0	1.0	1.0	--	--	--	--	--	--	--	--	--	--
Recreational Boat Fueling	--	--	--	--	--	--	--	--	--	--	0.9	0.9	1.0	1.0	1.0	--	--	--	--	--	--	--	--	--	--
Portable Fuel Container Spillage	--	--	--	--	--	--	--	--	--	--	3.8	2.8	2.3	2.0	1.8	--	--	--	--	--	--	--	--	--	--
Other Fueling	--	--	--	--	--	--	--	--	--	--	0.4	0.4	0.4	0.5	0.5	--	--	--	--	--	--	--	--	--	--

Appendix A
Bay Area Winter Emissions Inventory for Primary PM + PM Precursors: 2010-2030

SOURCE CATEGORY	Winter Emissions tons/day																								
	PM_{10} 2010	PM_{10} 2015	PM_{10} 2020	PM_{10} 2025	PM_{10} 2030	$PM_{2.5}$ 2010	$PM_{2.5}$ 2015	$PM_{2.5}$ 2020	$PM_{2.5}$ 2025	$PM_{2.5}$ 2030	ROG 2010	ROG 2015	ROG 2020	ROG 2025	ROG 2030	NOx 2010	NOx 2015	NOx 2020	NOx 2025	NOx 2030	SO_2 2010	SO_2 2015	SO_2 2020	SO_2 2025	SO_2 2030
Subtotal	--	--	--	--	--	--	--	--	--	--	**15.3**	**14.0**	**13.4**	**13.0**	**12.8**	--	--	--	--	--	--	--	--	--	--
OTHER ORGANIC COMPOUNDS																									
Cold Cleaning	--	--	--	--	--	--	--	--	--	--	2.7	2.9	3.1	3.3	3.5	--	--	--	--	--	--	--	--	--	--
Vapor Degreasing	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Handwiping	--	--	--	--	--	--	--	--	--	--	2.3	2.5	2.7	2.8	3.0	--	--	--	--	--	--	--	--	--	--
Dry Cleaners	--	--	--	--	--	--	--	--	--	--	0.6	0.7	0.7	0.7	0.8	--	--	--	--	--	--	--	--	--	--
Printing	--	--	--	--	--	--	--	--	--	--	4.1	4.1	4.2	4.4	4.5	--	--	--	--	--	--	--	--	--	--
Adhesives & Sealants	--	--	--	--	--	--	--	--	--	--	9.7	10.6	11.5	12.8	14.0	--	--	--	--	--	--	--	--	--	--
Structures Coating	--	--	--	--	--	--	--	--	--	--	21.2	16.3	17.1	17.8	18.6	--	--	--	--	--	--	--	--	--	--
Industrial/Commercial Coating	--	--	--	--	--	--	--	--	--	--	8.1	6.8	7.3	7.6	8.1	--	--	--	--	--	--	--	--	--	--
Storage Tanks	--	--	--	--	--	--	--	--	--	--	0.8	0.8	0.9	0.9	0.9	--	--	--	--	--	--	--	--	--	--
Lightering & Ballsting	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Other Organics Evaporation	--	--	--	--	--	--	--	--	--	--	1.5	1.6	1.7	1.8	2.0	--	--	--	--	--	--	--	--	--	--
Subtotal	--	--	--	--	--	--	--	--	--	--	**51.0**	**46.2**	**49.0**	**52.2**	**55.4**	--	--	--	--	--	--	--	--	--	--
COMBUSTION - STATIONARY SOURCES																									
FUELS COMBUSTION																									
Natural Gas(Space/Water Heating/Cooking)	1.7	1.8	1.9	2.0	2.1	1.7	1.8	1.9	2.0	2.1	1.0	1.1	1.2	1.2	1.3	18.3	19.8	20.9	22.1	23.3	0.1	0.1	0.2	0.2	0.2
LPG and Liquid Fuel	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.2	0.2	0.2
Solid Fuel (Woodstoves)	4.0	4.0	4.0	4.0	4.0	3.7	3.7	3.7	3.7	3.7	2.8	2.8	2.8	2.8	2.8	0.5	0.5	0.5	0.5	0.5	0.1	0.1	0.1	0.1	0.1
Solid Fuel (Fireplaces)	13.9	13.9	13.9	13.9	13.9	13.1	13.1	13.1	13.1	13.1	5.3	5.3	5.3	5.3	5.3	1.1	1.1	1.1	1.1	1.1	0.2	0.2	0.2	0.2	0.2
Cogeneration	0.7	0.7	0.8	0.8	0.9	0.7	0.7	0.8	0.8	0.9	1.9	2.0	2.1	2.2	2.3	3.9	4.1	4.3	4.6	4.9	0.3	0.4	0.4	0.4	0.4
Power Plants	0.3	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.4	0.4	0.1	0.1	0.1	0.1	0.1	1.0	1.1	1.2	1.3	1.4	0.1	0.1	0.1	0.1	0.1
Oil Refineries External Combustion	2.5	2.6	2.7	2.8	3.0	2.4	2.5	2.7	2.8	2.9	1.0	1.1	1.1	1.2	1.2	10.5	11.0	11.6	12.2	12.8	14.0	14.7	15.5	16.2	17.1
Glass Melting Furnaces - Natural Gas	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.9	0.9	0.9	1.0	1.0	--	--	--	--	--
Reciprocating Engines	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.5	0.5	0.5	0.5	0.6	2.9	2.7	2.6	2.7	2.9	0.1	0.1	0.1	0.1	0.1
Turbines	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	--	--	--	--	--	0.8	0.8	0.9	0.9	1.0	--	--	--	--	--
Landfill/Cement Plant Combustion	1.6	1.6	1.7	1.7	1.8	1.6	1.6	1.7	1.7	1.8	1.4	1.5	1.5	1.6	1.6	15.4	16.2	17.1	17.8	18.7	3.0	3.2	3.4	3.6	3.8
Subtotal	**24.8**	**25.2**	**25.5**	**25.9**	**26.3**	**23.8**	**24.1**	**24.5**	**24.8**	**25.2**	**14.0**	**14.3**	**14.6**	**15.0**	**15.3**	**55.6**	**58.7**	**61.4**	**64.6**	**67.9**	**18.2**	**19.1**	**20.1**	**21.1**	**22.1**
BURNING OF WASTE MATERIAL																									
Incineration	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.3	--	--	--	--	--
Planned Fires	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.2	0.2	0.2	0.2	--	--	--	--	--
Subtotal	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**0.4**	**--**	**--**	**--**	**--**	**0.1**
Banked Emissions	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Alternative Compliance Allowance	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Subtotal	**34.9**	**35.5**	**36.5**	**37.7**	**38.8**	**29.8**	**30.3**	**31.0**	**31.9**	**32.8**	**97.9**	**92.9**	**96.1**	**100.2**	**104.5**	**59.0**	**62.2**	**65.1**	**68.4**	**72.0**	**25.3**	**26.5**	**27.9**	**29.3**	**30.8**
COMBUSTION - MOBILE SOURCES																									
ON-ROAD MOTOR VEHICLES																									
Passenger Cars	5.1	5.2	5.4	5.6	5.8	2.3	2.2	2.3	2.4	2.5	42.1	21.5	12.4	10.1	9.3	35.5	18.8	11.6	9.8	9.2	0.4	0.4	0.4	0.4	0.4
Light Duty Trucks<6000lbs	2.3	2.3	2.3	2.4	2.5	1.0	1.0	1.0	1.0	1.1	23.4	15.8	10.9	9.0	7.8	27.1	16.2	9.9	7.1	5.8	0.2	0.2	0.2	0.2	0.2
Medium Duty Trucks 6001-8500 lbs	1.2	1.2	1.2	1.2	1.3	0.5	0.5	0.5	0.5	0.5	10.1	9.2	7.9	6.6	5.9	17.9	13.0	9.1	6.5	5.0	0.2	0.2	0.2	0.2	0.2
Light Heavy Duty Trucks 8501-14000lbs	0.7	0.6	0.6	0.6	0.6	0.4	0.3	0.3	0.3	0.3	6.2	5.1	4.2	3.4	2.8	23.1	18.0	13.8	10.6	8.5	0.1	0.1	0.1	0.1	0.1
Medium Heavy Duty Trucks 14001-33000lbs	1.1	0.7	0.6	0.6	0.6	0.8	0.5	0.3	0.3	0.3	2.4	1.3	0.8	0.7	0.7	21.6	13.8	6.6	3.9	4.0	--	--	--	--	--

Appendix A
Bay Area Winter Emissions Inventory for Primary PM + PM Precursors: 2010-2030

Winter Emissions tons/day

SOURCE CATEGORY	PM_{10} 2010	PM_{10} 2015	PM_{10} 2020	PM_{10} 2025	PM_{10} 2030	$PM_{2.5}$ 2010	$PM_{2.5}$ 2015	$PM_{2.5}$ 2020	$PM_{2.5}$ 2025	$PM_{2.5}$ 2030	ROG 2010	ROG 2015	ROG 2020	ROG 2025	ROG 2030	NOx 2010	NOx 2015	NOx 2020	NOx 2025	NOx 2030	SO_2 2010	SO_2 2015	SO_2 2020	SO_2 2025	SO_2 2030
Heavy Heavy Duty Trucks>33000 lbs	2.0	1.0	0.9	1.0	1.1	1.6	0.7	0.5	0.6	0.6	2.8	1.8	1.8	1.9	2.1	51.7	36.5	23.8	15.6	16.5	0.1	0.1	0.1	0.1	0.1
School/Urban Buses	1.0	0.8	0.8	0.8	0.8	0.6	0.5	0.4	0.4	0.4	1.4	1.0	0.9	0.8	0.6	16.9	14.0	11.3	10.2	8.2	--	--	--	--	--
Motor-Homes	--	--	--	--	--	--	--	--	--	--	1.4	1.2	0.8	0.5	0.4	1.4	1.0	0.8	0.6	0.5	--	--	--	--	--
Motorcycles	0.1	0.1	0.1	0.1	0.1	--	--	--	--	--	17.5	13.7	13.0	13.3	13.8	2.3	2.4	2.5	2.6	2.7	--	--	--	--	--
Subtotal	**13.5**	**11.9**	**11.9**	**12.3**	**12.8**	**7.3**	**5.6**	**5.4**	**5.6**	**5.8**	**107.4**	**70.6**	**52.6**	**46.1**	**43.3**	**197.6**	**133.7**	**89.5**	**66.8**	**60.5**	**0.9**	**0.9**	**1.0**	**1.0**	**1.1**
OFF-HIGHWAY MOBILE SOURCES																									
Lawn and Garden Equipment	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	13.6	11.8	10.8	10.8	11.0	2.1	2.0	2.0	2.1	2.2	--	--	--	--	--
Transportation Refrigeration Units	0.6	0.3	0.1	0.1	0.1	0.6	0.3	0.1	0.1	0.1	1.9	0.9	0.9	1.2	1.5	7.7	7.5	7.1	8.4	10.4	--	--	--	--	--
Agricultural Equipment	0.3	0.2	0.1	0.1	--	0.3	0.2	0.1	0.1	--	1.0	0.7	0.4	0.3	0.3	5.9	4.1	2.7	1.7	1.2	--	--	--	--	--
Construction and Mining Equipment	0.6	0.5	0.3	0.3	0.3	0.6	0.5	0.3	0.3	0.3	1.6	1.4	1.0	1.0	1.1	11.7	9.6	5.2	4.2	3.8	--	--	--	--	--
Industrial Equipment	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	1.1	0.9	0.9	0.9	0.9	6.5	5.4	5.0	5.0	5.1	--	--	--	--	--
Light Duty Commercial Equipment	0.6	0.5	0.4	0.4	0.3	0.6	0.5	0.4	0.3	0.3	4.5	3.4	2.8	2.7	2.8	7.4	6.3	4.9	4.1	3.8	--	--	--	--	--
Trains	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.9	0.9	0.9	0.9	1.0	10.7	12.3	13.0	13.8	14.9	--	--	--	--	--
Off Road Recreational Vehicles	--	--	--	--	--	--	--	--	--	--	1.3	1.2	1.3	1.3	1.4	--	--	--	--	--	--	--	--	--	--
Ships	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.3	0.4	0.5	0.6	0.7	0.7	8.3	8.5	7.5	6.1	5.0	1.8	0.7	0.8	0.8	0.9
Commercial Harborcraft	0.6	0.4	0.3	0.2	0.2	0.6	0.4	0.3	0.2	0.2	1.2	1.1	1.1	1.1	1.1	16.1	11.1	9.2	8.9	8.9	--	--	--	--	--
Recreational Boats	0.5	0.7	0.9	1.1	1.5	0.5	0.7	0.9	1.1	1.5	8.5	8.0	7.9	8.3	9.5	2.3	2.3	2.4	2.4	2.7	--	--	--	--	--
Subtotal	**4.1**	**3.4**	**2.8**	**2.9**	**3.3**	**4.0**	**3.3**	**2.8**	**2.9**	**3.2**	**35.9**	**30.7**	**28.6**	**29.3**	**31.3**	**78.7**	**69.2**	**59.0**	**56.8**	**58.0**	**1.9**	**0.7**	**0.8**	**0.9**	**1.0**
AIRCRAFT																									
Commercial Aircraft	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	2.4	3.1	3.7	4.0	4.3	9.1	11.1	14.6	16.6	17.5	0.8	0.9	1.0	1.1	1.3
General Aviation	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	0.6	0.6	0.6	0.1	0.2	0.2	0.2	0.2	--	--	--	--	--
Military Aircraft	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.7	1.2	1.2	1.2	1.3	1.7	4.0	4.0	4.1	4.1	0.1	0.2	0.2	0.2	0.2
Airport Ground Support Equipment	--	--	--	--	--	--	--	--	--	--	0.1	0.1	0.1	--	0.1	0.8	0.7	0.5	0.3	0.6	--	--	--	0.1	--
Subtotal	**0.4**	**0.4**	**0.4**	**0.5**	**0.5**	**0.3**	**0.4**	**0.4**	**0.4**	**0.5**	**3.7**	**4.9**	**5.5**	**5.8**	**6.3**	**11.7**	**15.8**	**19.2**	**21.2**	**22.3**	**0.9**	**1.2**	**1.3**	**1.5**	**1.5**
MISCELLANEOUS OTHER SOURCES																									
Construction Operations	10.1	11.2	12.2	13.6	14.8	1.0	1.1	1.2	1.4	1.5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Farming Operations	1.5	1.4	1.4	1.4	1.3	0.2	0.2	0.2	0.2	0.2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Entrained Road Dust-Paved Roads	23.5	23.5	23.5	23.5	23.5	3.5	3.5	3.5	3.5	3.5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Entrained Road Dust-Unpaved Roads	3.8	3.8	3.8	3.8	3.8	0.4	0.4	0.4	0.4	0.4	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Wind Blown Dust	3.9	3.9	3.9	3.9	3.9	0.7	0.7	0.7	0.7	0.7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Animal Waste	7.3	7.4	7.5	7.5	7.6	0.9	0.9	0.9	0.9	1.0	3.9	3.9	3.9	4.0	4.0	--	--	--	--	--	--	--	--	--	--
Agricultural Pesticides	--	--	--	--	--	--	--	--	--	--	0.6	0.6	0.6	0.6	0.6	--	--	--	--	--	--	--	--	--	--
Non-Agricultural Pesticides	--	--	--	--	--	--	--	--	--	--	0.3	0.3	0.3	0.3	0.3	--	--	--	--	--	--	--	--	--	--
Consumer Products(Excluding Pesticides)	--	--	--	--	--	--	--	--	--	--	44.1	45.3	46.5	47.5	48.6	--	--	--	--	--	--	--	--	--	--
Accidental Fires and Cigarette Smoking	1.3	1.2	1.1	1.2	1.2	1.2	1.1	1.1	1.1	1.1	0.4	0.4	0.4	0.4	0.4	0.2	0.2	0.2	0.2	0.2	--	--	--	--	--
Subtotal	**51.3**	**52.4**	**53.3**	**54.8**	**56.1**	**7.9**	**8.0**	**8.0**	**8.2**	**8.3**	**49.2**	**50.5**	**51.8**	**52.8**	**53.9**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**--**	**--**	**--**	**--**	**--**
GRAND TOTAL EMISSIONS	**104**	**104**	**105**	**108**	**111**	**49**	**48**	**48**	**49**	**51**	**294**	**250**	**235**	**234**	**239**	**347**	**281**	**233**	**213**	**213**	**29**	**29**	**31**	**33**	**34**

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