Vehicular Exposures and Potential Mitigations Downwind of Watt Avenue, Sacramento, CA

Report to
The Health Effects Task Force, Breathe California of Sacramento-Emigrant Trails
October 23, 2006

Based on the "**The Sacramento/Interstate -5 Aerosol Transect Study, December, 2002 – January, 2003**", "**The Arden Middle School Addendum of 2004**", and the Arden Middle School studies of January, 2006.

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Executive Summary

This report is a summary of atmospheric particulate matter (aerosols) downwind of Watt Avenue at Arden Middle School based on the reports to the Breathe California Health Effects Task Force (HETF, 2003, HETF, 2005), recent data (2006), and a more extensive analysis of mitigation options. Literature values of emission rates were collected, and roadway concentrations of both diesel vehicles and automobiles were calculated by two separate methods – tracer and mass balance. These values were displaced downwind via diffusion modeling from linear source to calculate values at the sampling sites. Meteorology data was generated both locally and via trajectory analysis by NOAA's HYSPLIT program. Model results were close to measured values, giving confidence in assigning a wider variety of traffic pollutants to the downwind site than we had been able to measure previously.

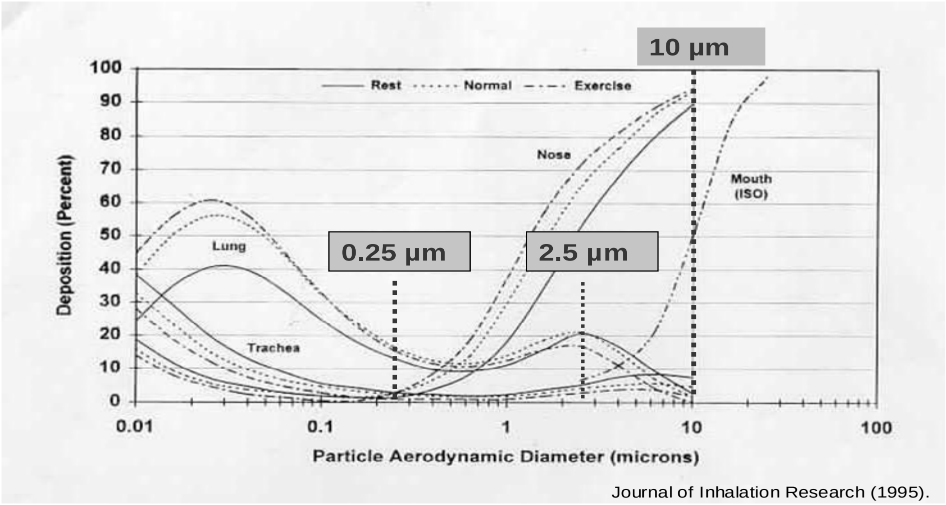
1. This study confirms our previous finding that areas immediately downwind (east) of Watt Avenue, including Arden Middle School, are heavily impacted by Watt Avenue traffic. The mass of very fine and ultra fine particles that are strongly implicated in health impacts by both their size, $D_p < 0.25$ µm diameter lung capture efficiency, and toxic composition (PAHs, other) were:
    a. Mean aerosols - measured - 7.0 ± 1.5 $\mu g/m^3$
    b. Mean aerosol – predicted - 6.7 ± 3.0 $\mu g/m^3$ from Gertler tunnel data
    c. Mean aerosols – predicted - 5.4 ± 3.2 $\mu g/m^3$ from tracer to mass ratio

    with the dominant source of aerosols from automobiles, not diesel trucks (on roadway average) From the Gertler et al 2002 tunnel data and calculation, we predict -

    d. Diesel trucks - 0.8 $\mu g/m^3$
    e. Automobiles - 5.9 $\mu g/m^3$

2. In considering these data, it is important to understand that this study is an ambient exposure study, not a health study. The potential health impacts of automotive particulate matter are poorly known at this time, although they have some degree of similarity (as well as differences) from the health impacts of the better studied diesel particulate matter. Note that diesel particulate matter is responsible for 70% of the potential cancer impacts of all toxic air contaminants combined (California Almanac, 2006).Exhaust from diesels and automobiles, almost all of which lies in particles finer than 0.25 µm, is efficiently captured deep in the lung. Health studies have shown that this efficient capture of very fine and ultrafine particles allows for their transport from the lung into the blood stream, which may result in adverse effects to the heart and brain.

Particle Size versus Percent Deposition



Journal of Inhalation Research (1995).

This figure shows the relationship between particle size and what percent is deposited in different parts of the respiratory tract.

A key unknown is the toxicity of smoking automobile exhaust. Data are presented from the literatures indicating that used spark emission lubricating oil has 10 to 20 times more PAHs than used diesel oil, (Fujita et al, 2005, see Appendix A) but diesel combustion has additional sources of toxicity not anticipated in automobile exhaust. Research is in progress on this matter at the ARB and elsewhere. In addition, roadways emit a variety of other pollutants, gaseous and particulate, with uncertain health impacts.

The particle size and known and potential toxicity of the observed and predicted vehicular pollutants downwind of Watt Avenue support the implementation of reasonable mitigation measures.

3. In considering these data, it is also important to understand that this study is an ambient exposure study, not a regulatory exercise. The DRUM sampler and other

impactors, while well tested and validated, are research instruments that can yield information unavailable from standard approved regulatory air samplers, including detailed size and composition measurements of diesel exhaust in laboratory studies (Appendix A). Impactor data can not be used for official PM_{10} or $PM_{2.5}$ measurements for regulatory purposes. It is noted that neither the DRUM sampler nor the regulatory ambient air samplers at the nearest SMAQMD site, Del Paso Manor, showed any violations of the federal 24 hour $PM_{2.5}$ standard during the study period (SMAQMD, private communication).

4. Mitigation alternatives have been examined in four categories. Some of these would be applicable only to new development and need additional regulations, while some are available immediately:
   a. Mitigation by source reduction on the roadway

      While strategies to reduce pollution from on-road sources are determined by state and federal mobile emission standards, changes made locally, such as adjusting the signal timing at Watt Avenue and Arden Way, as well as encouraging green transportation modes, can reduce congestion directly upwind of Arden Middle School.
   b. Mitigation via improved roadway design

      This is a promising but little examined option, including using vegetation on the median and within the right-of-way to foster both the natural temperature driven plume rise from the roadway waste heat and trap very fine/ultra fine particles on needles and leaves. Studies are in progress on this option by the HETF at UC Davis.
   c. Mitigation from the right-of-way fence to receptors (homes, schools, etc.)

      The most effective mitigation is distance, with many studies giving a 160 m to 240 m distance as adequate to achieving pollution concentrations only 10% greater than upwind values.

      Barriers and vegetation are also included, and limited evidence indicates potential important mitigation is possible. Studies are in progress on this option by the HETF at UC Davis.
   d. Mitigation in the indoor air of the receptors

      Indoor mitigation is both the most immediate and most effective mitigation available, supported by models and data, with the potential of effectively eliminating the impact of Watt Avenue (to a few %) in indoor air at modest cost. The HETF – UC Davis studies of 2006 showed a 75% reduction on very fine/ultra fine pollution inside the Arden Middle School teacher ready room with a standard (non HEPA) upgrade to an electrostatic filter.

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A. Aerosols downwind of Watt Avenue

In addition to the regionally dispersed particulate air pollution, reasonably well represented by the Del Paso Manor Sacramento Metropolitan Air Quality Management District site (HETF 2003), we have previously shown that areas directly downwind of Watt Avenue at Arden Way are seriously impacted by vehicular pollution (HETF, 2003, HETF 2005). This problem has been exacerbated by several factors:

1. the expansion of Watt Avenue into a major north-south connector, with an average of 66,000 vehicles/day, typically 1.5% trucks,
2. the relatively narrow right of way,
3. the stoplights, including that at Watt Avenue and Arden Way,
4. the flat at-grade roadway, without sound walls or major vegetation,
5. the lack of barriers between the roadway and downwind areas, and
6. the proximity of receptor sites (schools, houses) to the edge of the right of way.

The result is that the impact of Watt Avenue at downwind receptors is similar to the more heavily traveled Interstate 5 in downtown Sacramento, (170,000 vehicles/day, 10% trucks) which in part is a depressed freeway, and often has sound walls and mature large trees between the roadway and downwind receptors.

Even though no state and federal air quality standards are violated, the current best information indicates that very fine and ultra fine particles from diesels and smoking automobiles (Harrison et al, 1997, Cadle et al, 2003, Cao et al, 2006) are highly toxic (Devlin, 2003, EPA 2006, ARB Almanac 2006). The ARB Almanac assigns 70% of all impact of toxic air contaminants (TACs) to diesel exhaust alone, and recent results show that automobile exhaust may be more toxic per unit mass than diesel exhaust (Fujita, 2005), although diesel combustion has additional sources of toxicity not anticipated in automobile exhaust. The reasons can be found in the size and composition of diesel exhaust toxics, especially PAHs, whose characteristics allow for the maximum capture in the human lung.

A.1 Modeling exposures downwind of Watt Avenue

Two methods were used to model the amount of traffic derived aerosol at Watt Avenue.

1. Literature values were used for emissions (Gertler et al, 2002), which were then entered into a "sliding box" model (Cahill, 1974, Feeney et al, 1976, Engelbrecht et al 1978), which with measured meteorology and traffic flows, gave $PM_{2.5}$ concentrations of 5.9 $\mu g/m^3$ for cars, 0.8 $\mu g/m^3$ for trucks, for a total of 6.7 ± 3.0 $\mu g/m^3$ at the edge of the right of way. From the results of the diesel exhaust studies (Zielinska et al, 2004), almost all of this is below 0.25 μm in size.

2. An alternative way is to use the zinc mass values from the laboratory diesel studies, 3000 to 1. With the measured (by synchrotron-x-ray fluorescence, Bench et al, 2002) mean downwind very fine $0.26 > D_p > 0.09$ μm zinc, 0.8 ug/m^3 at the Arden Middle School 40 m site, we predict 3.1 $\mu g/m^3$ of very fine mass, or roughly 5.4 ± 3.6 $\mu g/m^3$ of very fine plus ultra fine mass from vehicles, scaled to the right-of-way fence (see below).

A key and untested assumption in this work is that the zinc from smoking automobiles and diesels are roughly equivalent, which is suggested by the common source, lubricating oil, and the emissions of gasoline vehicles by Norbeck et al and Sagebiel et al (above). Nevertheless, since almost all vehicular emissions in $PM_{2.5}$ are actually less than $PM_{0.25}$, this value is consistent with the very different technique given above.

Next, we can use literature values for the fall off of pollutants downwind of Watt Avenue. A published and validated model was developed in Cahill et al 1974, and widely used thereafter. It is shown below in Table 1, with the theory and the validation side by side. This reference was used because it was one of the very few to treat complex roadway configurations, needed for comparison to the Crocker Art Museum site used in previous HETF studies. (HETF 2003, 2005)

Roadway	**Distance**	**27 m**	**40 m**	**100 m**	**160 m**
At grade	*Calculated*	*≡ 1.00*	*0.85*	*0.35*	*0.10*
At grade	Measured	1.0	0.78	0.35	0.09
Depressed	Measured	1.1	0.42	0.065	na
Elevated	Measured	1.2	0.58	0.78	$(0.87)^2$

Table 1 *Effect of roadway distance and configuration on downwind concentrations of fine aerosols, measured from the downwind edge of the nearest traffic lane plus ½ of the height of the mixed box. Each value is the average of two separate freeways.*

A.2 Measuring exposures downwind of Watt Avenue

For the study of 2006, the site was moved closer to Watt Avenue, roughly 12 m from the right of way fence and 15 m from the nearest road edge. The Arden outdoor site was on the roof of the teacher ready room, about 15 m from the edge of the nearest traffic lane and above a small (6 car) parking lot. It was at the same elevation but about 25m closer than the 40 m distance to Watt Avenue that we used in 2002 and 2004. The roof (painted white) was filthy with black soot. The weather during each two week period was roughly comparable. Two DELTA 8 DRUM samplers with ultrafine after filters were placed at Arden Middle School, January 27, 2006. The differences from previous studies are that both samplers had integrating ultra-fine filters. One sampled indoor air, the other sampled outdoor air. The results are given below, with comparison to previous work.

Site	Data Sources For models	Very fine (0.26 – 0.09 μm)	Total Diesel/Car (0.30 – 0.00 μm)
Arden (theory, near Watt)	*Gertler tunnel*		*6.7 μg/m^3*
Arden (theory, near Watt)	*DRI/UCD zinc*		*5.4 μg/m^3*
Arden roof (15 m from Watt)	January, 2006	4.0 μg/m^3	7.0 μg/m^3
Arden indoors (20 m – Watt)	January, 2006	1.0 μg/m^3	1.8 μg/m^3
Arden roof (40 m from Watt)	January, 2004	1.3 μg/m^3	na
Crocker Art (100 m from I-5)	Dec.-Jan., 2001/2	4.1 μg/m^3	na
Fresno 1st Street	Dec. 2001	4.2 μg/m^3	na

Table 2 *Measured and modeled vehicular exhaust downwind of Watt Avenue.*

In Table 2, the measured mass values for very fine mass (0.26 μm > D_p > 0.09) and total diesel added measured ultra fine mass (<0.09 μm) and a portion of larger particles seen as in the Desert Research Institute (DRI) diesel tests.

The measured mass at the Arden roof 15m site, 7.0 μg/m^3, can be compared with the predicted 6.7 μg/m^3 for diesel mass using the results of Table 2 and the size distributions of UCD/DRI, Figure A-1, and the 5.4 μg/m^3 scaling up from the zinc to mass ratio in the Minnesota/DRI/UC Davis diesel tests, also Figure A-1 (Zielinska et al, 2004). The propagated error from the measurements is hard to estimate, but is at least ± 30%, making the agreement adequate.

In summary, both theory and experiment show that high levels of vehicular particulate pollution in very fine and ultra fine particulate modes exist directly downwind (east) of Watt Avenue. According to the ARB Almanac (2006), these particles are responsible for (at least) 70% of all the impact of toxic air contaminants (TAC) in California, deposit deep into the lung, and possess significant risk to human health.

There is also some good news. The value measured and estimated at the eastern side of the school complex, the 40 m site at Arden Middle School, 2.3 μg/m^3, was much lower than the prediction of the at-grade line source dispersion model, which predicted, 5.9 μg/m^3. While there are certainly some modest differences in meteorology, this is most likely a result of the turbulence and mixing caused by the school structures themselves. This helps confirm the degree of mitigation that could be generated by vegetation in the absence of the school buildings.

B. Mitigation

The data above establish that aerosols directly downwind of Watt Avenue are at unhealthy levels for subjects that have to bear long term exposure, even though aerosol mass does not violate any state or federal particulate matter standards. The impact of these aerosols can be mitigated, however, and the following sections will discuss mitigation options.

Mitigation of the aerosols from Watt Avenue can occur in many ways, but we will consider the following four options:

1. Mitigation via source reduction (extensive and current data)
2. Mitigation via roadway design (very few data, weak models)
3. Mitigation from the right-of-way to the receptor (very few data, weak models)
4. Mitigation at the receptor (extensive recent data, fair models)

Each option will entail costs and benefits, and the most likely optimum results will be a combination of these mitigation approaches.

B.1. Mitigation via source reduction

As has been shown above, there are excellent current data for emission rates of vehicles on the open highway and in laboratory conditions, data that allow a good match from vehicles on the highway to aerosols downwind of the highway. From such data, one can easily theoretically modify the source strength by increasing or decreasing the number of cars and trucks as well as increasing or decreasing the emissions per automobile or truck. Of special interest is the fact that a small number of automobiles dominate total automobile particulate emissions ("gross emitting or smoking cars"), some but not all of which emit visible smoke. Removal of a relatively small number of such vehicles would result in a dramatic reduction in automobile pollution. However, realistically, we have little local control over these factors, which are driven primarily by federal and state mandates.

Nevertheless, there are options.

A. Local

1. Giving a greater priority in time to vehicles on Watt Avenue versus Arden Way to avoid congestion and vehicle idling directly upwind of Arden Middle School.
2. Redesigning the intersection so that there are no stop lights, materially decreasing the pollution from the stopped and accelerating cars and trucks.
3. Closing the road to heavy trucks during school hours would have a modest improvement, as diesels are an established source of TACs.
4. Building a parallel road of improved design (see Mitigations B.2) that would reduce traffic on Watt Ave without adding pollution to another site.
5. Establish an infra-red beam detector for gross emitting vehicles, photograph, identify, and send a notice to re-do the smog check. Note: There is typically a 1/3 voluntary compliance in the 1 – 800- CUT SMOG notifications for smoking vehicles (SCAQMD 2003). The same procedures could be used in principle for gross emitting smoking vehicles using a nephelometer.

B. State

1. Any ARB state mandate that decreases emissions/vehicle, including the new CO_2 reduction programs (CO_2 as a pollutant, state CO_2 reductions).

2. A statewide program using sensors (see above) to remove gross emitting vehicles from roadways, including funding vehicle repair/replacement programs from smog checks, which now include a smoke test per AB 1870.
3. Specific ARB control measures targeting very fine and ultra fine particles, including a < 0.25 μm mass standard, a proposed particle area standard (Wilson, 2006) and the European Unions proposed particle number standard.

C. Federal

1. The new national diesel fuel standards will be of some modest assistance on interstate highways from trucks fueling in Nevada, but few of these will use Watt Avenue.

While we support all state and federal actions to lower source emission rates, we believe that much can be accomplished at reasonable cost and in a short time frame by using one or more of the mitigation methods outlined below.

B.2 Mitigation via roadway design

This area provides important long term possibilities for mitigation, but such concepts are not widely supported by either experiments or models.

Mitigation within the right of way

A. Heat and Barriers

Cars and trucks on a highway create a mixed zone due to the turbulence of the vehicles, which is roughly 1.5 times the height of the mean vehicle at freeway speeds, less at low speeds. This mixed zone contains emissions from the vehicles, including waste heat. This waste heat tends to make the road pollution slightly buoyant, as was shown in the extensive studies in Cahill et al 1974. It was found that the cut section Santa Monica freeway (at 250,000 vehicles/day) increased in temperature 1.4 ^{o} F/minute, resulting in a cyclic cleaning of the road edge aerosols on a roughly 9 minute cycle. This was one of the major factors (the other being vegetation at the right of way edge) that the aerosols downwind of the Santa Monica freeway were only 20% of what a line source diffusion model would predict (see Table 2). Thus, roadways should be designed to hinder easy lateral transport of pollution and to enhance the upward motion the excess heat delivers.

This buoyant lift can be modeled by adding a vertical vector to the lateral wind velocity. This may also be the reason that the aerosol mass measured downwind of Interstate-5 at the elevated Crocker Art Museum site was higher than the model would predict. This tendency can be enhanced by placing a barrier to direct lateral motion from the roadway, slowing the lateral velocity and allowing the lift to raise the pollution level and entraining cleaner higher altitude air. This heating could, in summer, be enhanced by a hot roadway surface.

B. Vegetation

This effect can be encouraged by placing barriers, ideally vegetation, in the median strip. This placement will slow transport of pollution from the upwind lane into the downwind lane, further encouraging vertical motion.

The additional advantage of vegetation is that it acts as a deposition surface for the very fine and especially ultra fine particles. HETF studies are in progress to evaluate this effect, especially for the most toxic very fine and ultra fine species generated by diesels and automobiles.

C. Roadway or Intersection Redesign

There are also some very expensive mitigations, such as placing the entire roadway in a cut section as part of an elimination of the Watt Avenue intersection.

B.3 Mitigation from the right-of-way to the receptor

The most important mitigation from the right of way to the receptor is distance. As shown above in Table 2 (Cahill et al, 1974; Feeney et al, 1976, Harrison at al 1997) all the way to recent work, Figure 1 (Zhu et al, 2002), the highway influence for the most toxic materials decreases to about 10% of near highway values at distances between 160 m and 240 m for at grade roads.

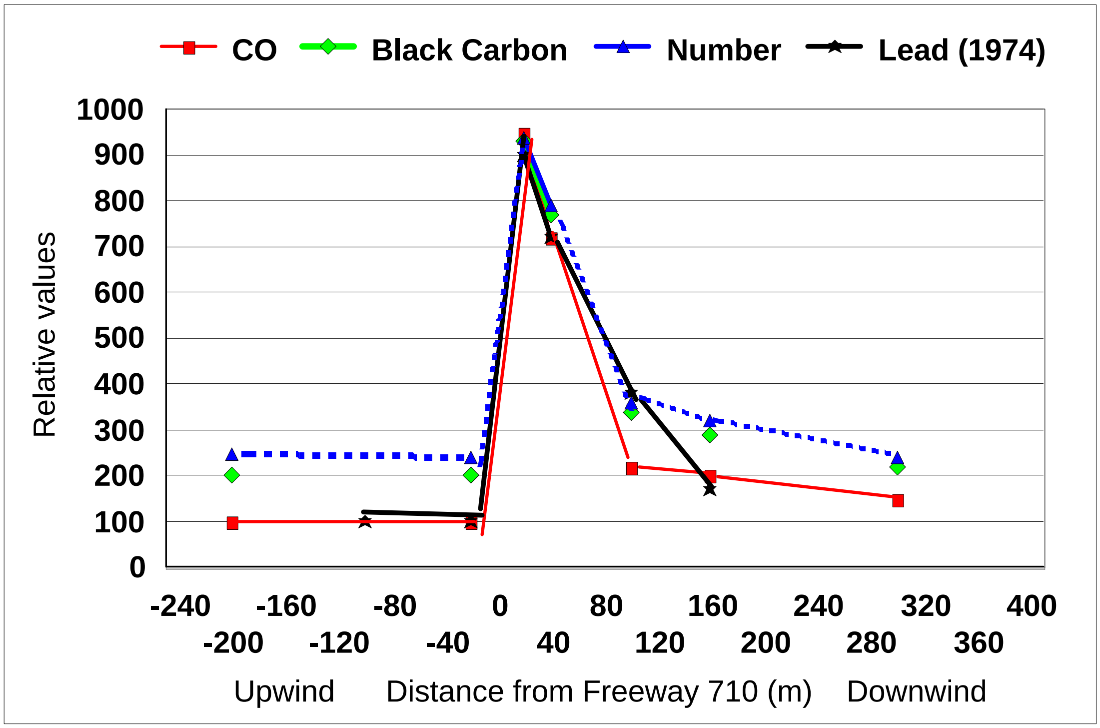

Figure 1 *Profiles across the 710 freeway in an at-grade section in Los Angeles for carbon monoxide (CO), black carbon (BC), and particle number, with the data of Cahill et al 1974 superimposed.*

Recent data (Harrison et al 2004) use the distance of 50 m in Birmingham, England, to separate near roadway from far roadway cohorts for health effect studies. Conversely, the ARB recently reported (2006) that the number distribution did not meet background values for many hundreds of meters in a transect on Highway 50 in stable meteorological conditions in nighttime low velocity winds. However, this result was taken across an elevated freeway section, which has been earlier shown (see Table 2 and Cahill et al, 1974) to disperse freeway particles out to an estimated 2 km. Note that this same plot shows relatively high levels of black carbon and ultrafine particle numbers upwind of the freeway, and many kilometers downwind of the nearest upwind roadway. Thus, it does little good to reduce the roadway impact to very small levels if there is an important upwind background, such as exists in downtown Sacramento. The evidence of the 2004 tests at Sebastian Way show that at the intersection of Watt Avenue at Arden Way, this is not the case (HETF, 2005).

The second form of mitigation is to impose barriers between the right-of-way and the receptor that can force air up and generate mixing, lowering values by dilution, or removing the particles from the air by providing surfaces for deposition, impaction, and settling.

The literature is weak in this area, but one article (Kim et al, 2005) found that sound walls were not very effective barriers to pollution. There is considerable literature, however, on urban street canyons, and the effect of tall buildings on local pollution. The result is that there is a mixing of the polluted ground level air with (presumably) cleaner elevated levels, reducing concentrations by dilution. With a line source like a highway, lateral diffusion is little help, therefore the mixing must be vertical. Turbulence is induced by a pierced barrier, which allows air to pass at some spots but not others, and this would favor an irregular barrier, not a smooth wall with laminar flow of air (and pollutants).

Support for this form of mitigation is given by the anomalously clean masses measured at the downwind edge of the Arden Middle School complex. The mixture of buildings and trees (without leaves) was adequate to lower the roadway aerosols by a factor of 2 or more (see Table 2, pg. 7). Support is also given by the rapid fall off of lead aerosols at the Santa Monica Freeway site (Cahill et al, 1974), which involved passage through a thick barrier of vegetation. Whatever the effect, the combination of roadway heating and vegetative barrier produced a dramatic reduction in lead, over a factor of 5 at 100 m.

But for ultrafine particles, there is an additional option. These particles are so fine that they have long diffusion lengths and the ability to move to a surface, if it is close enough. Thus, we can make these barriers in such a way that air passes through closely spaced structures. As can be seen below from the summary of Seinfeld and Pandas, 1997, particles below about 0.05 µm, responsible for most of the particle number, much of the surface area, and a significant fraction of ultra fine mass, have high diffusion lengths and thus equivalent "settling velocities", which in the case of very fine/ultra fine particles, can be either up, down or sideways, since gravity is not a factor in a Brownian motion dominate system (the system governing the random movements of the smallest particles).

Particle		Theory		Dep vel	settling	Removal	
diameter	D	Diffusion	cp	S&P pg 970		Velocity	/
microns	cm2/sec	mm/sec	cm/sec	cm/sec	cm/sec	cm/sec	
0.002	1.28E-002	0.866	4965	Total			
0.004	3.23E-003	0.435	1760				d
0.01	5.24E-004	0.175	444	0.500		0.500	
0.02	1.30E-004	0.087	157	0.100		0.100	
0.04	3.59E-005	0.046	55.5	0.022		0.022	
0.1	6.82E-006	0.020	14	0.015		0.015	
0.2	2.21E-006	0.011	4.96	0.010		0.010	
0.4	8.32E-007	0.007	1.76	0.015		0.015	
1	2.74E-007	0.004	0.444	0.018	0.004	0.022	
2	1.27E-007	0.003	0.157	0.030	0.015	0.045	
4	6.1E-008	0.002	0.056		0.075	0.075	
10	2.38E-008	0.001	0.014		0.500	0.500	

Table 3 *Deposition velocities for particles.*

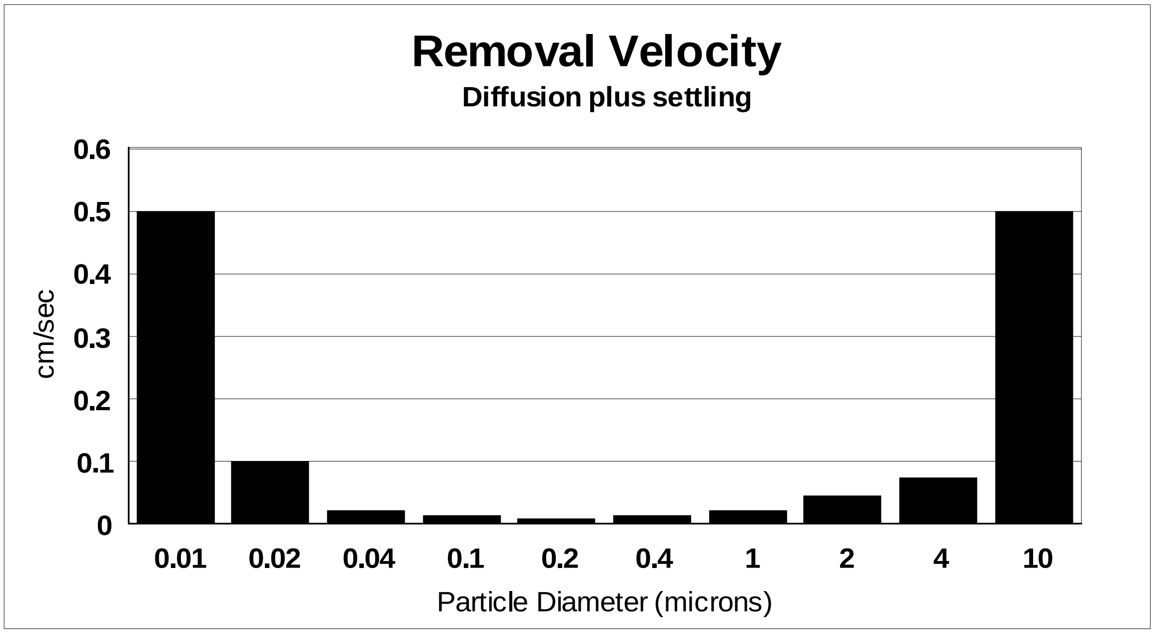

Figure 2 *Plot of deposition velocities for particles. Note the rapid removal for ultrafine particles.*

Using these values, one can calculate the removal of particles passing through finely divided needles or leaves in a tree, with the assumption that these ultra fine particles are generally sticky with oils, and once they contact a surface, they do not easily leave it until washed off.

B.4 Mitigation at the receptor

This area has a large and growing literature, via models and other resources showing that mitigation at the receptor has the proven potential to make the largest improvements in air quality. These improvements may be so significant that the indoor air is much cleaner than even the regional outdoor air for very important pollutants, including very fine particles and ozone.

The state of the field was recently summarized by Morawska (2006), in her recent book. The basic science behind the indoor/outdoor (I/O) ratio of concentrations can be simplified when there are no internal sources (cooking, candles, smoking, etc.)

$$I/O \equiv C_{inside}/C_{outside} = P\ a/(a + k),$$

So that P is the penetration factor, a = the air exchange rate, usually expressed in 1/hours, and k = deposition (removal) of particles within the receptor, likewise expressed as 1/hours. Thus, the air exchange rate varies with the seasons since the heating and cooling systems may be active in winter or summer respectively, minimizing exchange with outside air.

Morawska, while listing the myriad aspects that affect indoor air, summarized that "at times there is very little difference between the characteristics of indoor and outdoor particles. For example, for naturally ventilated buildings the penetration of particles of all sizes with significance to human health is almost 100 percent." From a score of studies, she found that the median Indoor/Outdoor ratio, I/O for naturally ventilated houses was

PM_{10}	I/O = 0.64
$PM_{2.5}$	I/O = 0.85
Particle number	I/O = 0.56, which was also close to the value for ozone.

However, I disagree with her statement in that recent studies and summaries of studies (EPA 2006) focus on the health impacts of the finest particles, which means the sharp reduction in particle numbers shown by an I/O ratio of 0.56 represents a significant health advantage.

Thus, buildings downwind of Watt Avenue would be closely coupled to the emissions from the highway, although with some mitigation occurring in naturally ventilated houses for the most worrisome very fine and ultra fine particles. To go beyond these generalities requires evaluation of each individual receptor site, its use patterns, construction, and other details

Mechanically ventilated buildings provide additional options, so that the indoor air can essentially be as clean as one wishes. An example is a recent study in Fairbanks, AK, (Reynolds and Cahill, 2004) during the heavy forest fires in 2004. The city of Fairbanks lived under a pall of smoke for months, with 24 hr $PM_{2.5}$ levels in the region of 500 $\mu g/m^3$. Studies were made during this period on indoor air cleaning. Two conditions were considered, treated outdoor air and internally circulated air, and two kinds of filters were used, HEPA and a more porous and standard electrostatic filter.

With internally circulated air, the Fantech 3000 HEPA filter lowered particle $PM_{2.5}$ mass of smoke by 98%, which is much less than the 99.97% the manufacturer claimed. A Matrix Air 450 cfm HEPA didn't do nearly as well, with decreases averaging 70%. The less efficient MERV 11 Filter plus pleated carbon, rated at 60 to 65% efficiency, actually achieved 75% reduction.

When the Fantech 3000 was used for outside air in a pressured mode, it reduced aerosols by 92 to 98%. The 90 to 95% MERV 14 reduced outside air, from $PM_{2.5}$ 492 $\mu g/m^3$ to 52 $\mu g/m^3$, or 72% (natural ventilation was 185 $\mu g/m^3$). However, when highly polluted outdoor air was brought into the building through an inefficient filter, it actually raised pollution levels. Thus, pressurization with clean air can be made to work.

In the winter of 2006, the heating system of the teacher ready room, a separate recirculation system at Arden Middle School, was supplied with these improved (but not HEPA) filters. They used MERV 11 filters, rated at 60 to 65% efficiency and rated at 1.0 to 3.0 microns. The result was a dramatic 75% reduction in very fine and ultra fine particles (Table 2). The key point is that the pressure drop across these filters, unlike

HEPA filters, is low enough that standard air conditioning and heating systems can be used, with a major savings in cost.

With air brought in from outside, the HEPA filters have a high pressure drop and require more powerful fans than is normal in air handling systems. However, theoretical analysis indicates that a standard electrostatic filter should get more and more efficient as the particle size drops to 0.1 µm and below, offering the option of a system like a standard attic fan blowing air into a house through such a filter, or more likely a standard furnace filter followed by an electrostatic filter to reduce dust clogging. This would result in a slightly positively pressurized house or school that blocks the input of polluted outdoor air.

This option is being studied under a grant from the Sacramento Metropolitan Air Quality Management District, with results available by January, 2007.

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Other informational resources on the web

Important resources are local meteorology (various sources, from the Sacramento Bee, www.weatherunderground.com, and the US Weather Service.

Trajectory analysis was performed with the NOAA ARL program HYSPLIT, http://www.arl.noaa.gov/ready/hysplit4.html.

Air quality data are available from the California Air Resources Board, including the excellent ADAM site http://www.arb.ca.gov/adam/welcome.html.

Local traffic counts are available from http://www.sacdot.com/ and state wide from www.caltrans.ca.gov/.

The technology used in this study and the data from this study will be posted on the UC Davis DELTA Group web site http://delta.ucdavis.edu

EPA’s Fact Sheet on the new PM standards includes health information: http://www.epa.gov/pm/pdfs/20060921 fact sheet pdf.

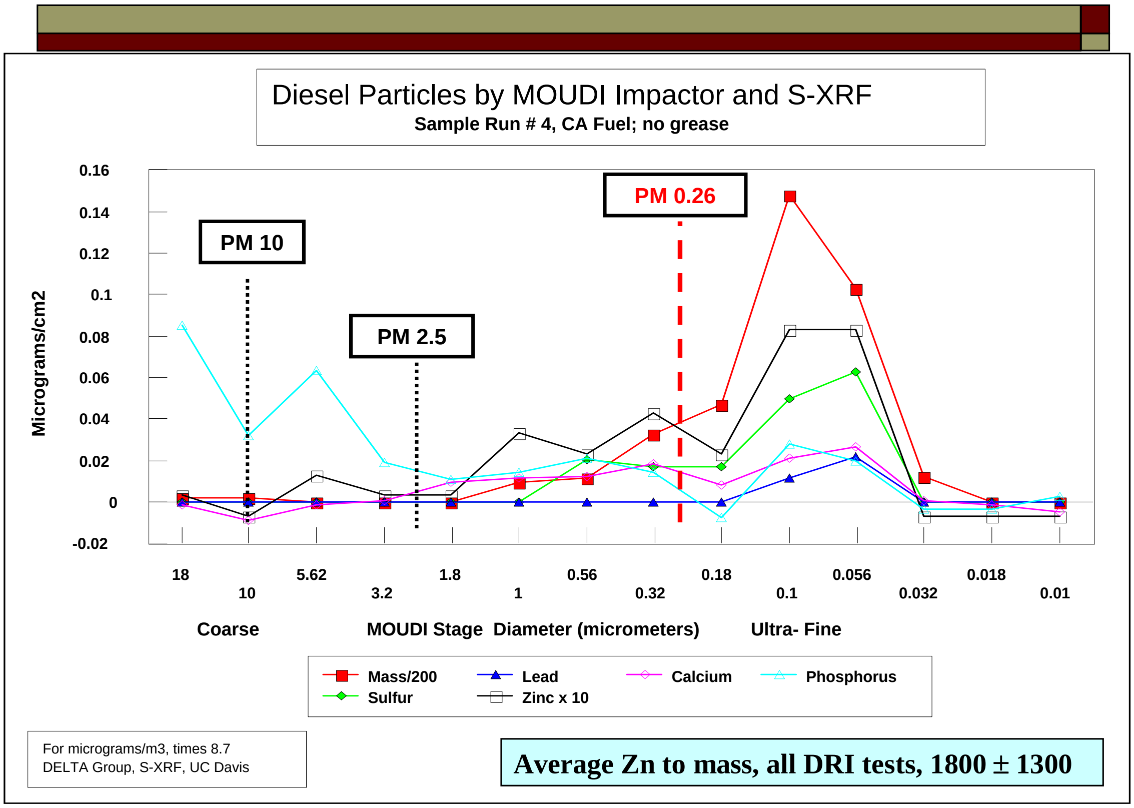
EPA's website on PM and your health: http://www.epa.gov/pm/pdfs/pm-color.pdf

ARB's fact sheet on air pollution (covers both PM and ozone) health effects: http://www.arb.ca.gov/research/health/fs/PM-03fs.pdf

SMAQMD's website on health effects (covers PM and ozone): http://www.sparetheair.com/health.cfm?page=healthoverall

Appendix A   Nature and impacts of roadway aerosols

Aerosols from cars and trucks are concentrated in the finest particles, as shown by these tests of diesels at the U. Minnesota (Zielinska et al 2004).



Diesel Particles by MOUDI Impactor and S-XRF

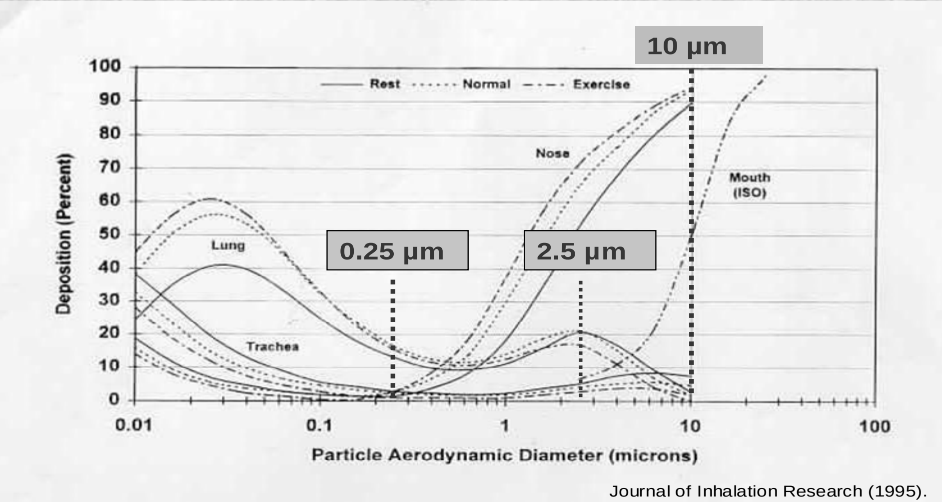
Sample Run # 4, CA Fuel; no grease

For micrograms/m3, times 8.7
DELTA Group, S-XRF, UC Davis

Average Zn to mass, all DRI tests, 1800 ± 1300

Figure A-1 *Size distribution of aerosols from diesel trucks.*

Particle Size versus Percent Deposition

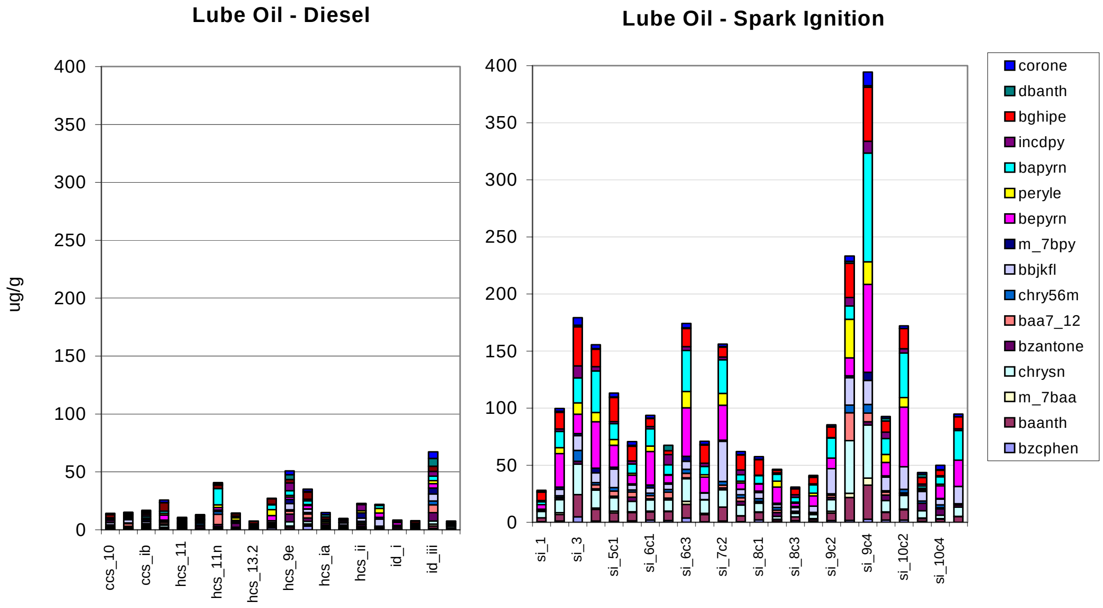


Journal of Inhalation Research (1995).

This figure shows the relationship between particle size and what percent is deposited in different parts of the respiratory tract.

Figure A-2 *Lung deposition rates. Note how diesel exhaust ends up deep in the lung.*

Such particles nicely match the lung deposition curve shown in Figure A-2, so that most of the diesel mass ends up deep in the lung and alveolar region. These diesel particulates are responsible for 70% of all impact from Toxic Air Contaminants (TACs) in California from all sources because they contain known PAH carcinogens.


Lube Oil - Diesel

Lube Oil - Spark Ignition

Figure A-3 *Toxicity of used diesel and spark ignition vehicle oil.*

Recent results in Figure A-3 (Fujita et al 2005) show that aerosols from spark ignition vehicles contain more PAHs than diesels per unit mass, indicating that partially burned auto exhaust may be more toxic than diesel exhaust. Therefore, these studies focus on identifying and mitigating the most toxic components of the aerosols, in the hope that regulations will eventually be upgraded to cover these sources.

Appendix B Modeling downwind concentrations from on road data

Modeling of downwind concentrations from roadway emissions data requires information on meteorology, on site traffic counts, and periodic measurements of truck traffic.

Map of the Arden Middle School site

The month of January 2004, started with foggy weather, poor visibility, and then went into a series of rain storms from late January into February. Good ventilation occurred Jan 25 – Jan 27, and Jan 31 – Feb 4, 2004. In summary, the weather was typical of Sacramento area winters, and also similar to both Winter 2002 (the first study) and Winter 2006 (the last study).

Traffic counts – car and truck

Traffic counts were made by Sacramento County during the winter, 2004 study. The truck fraction was measured by using the school crossing guard.

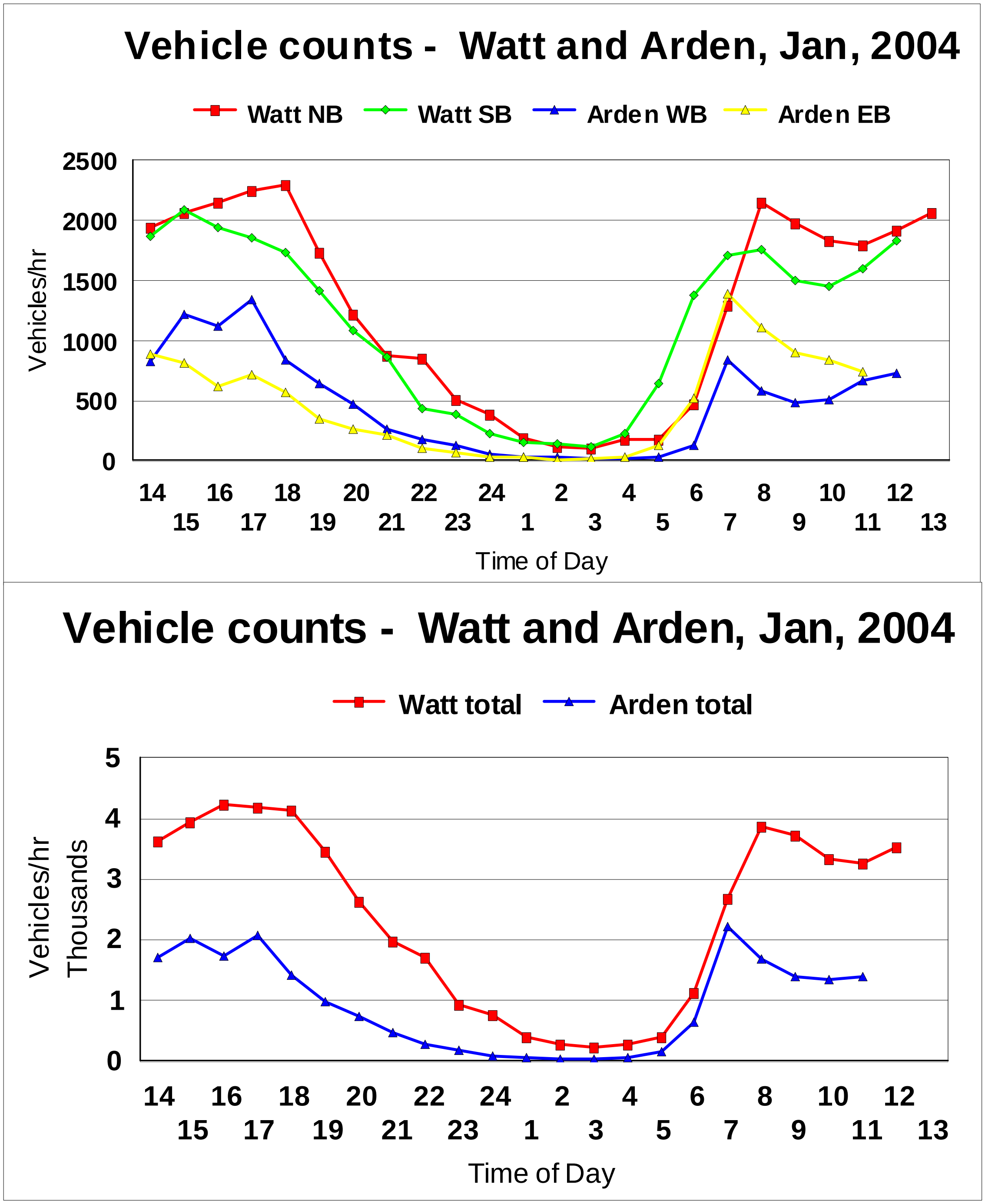


Figure B-1 *Vehicle counts on Watt Avenue and Arden Way, January, 2004. These are weekday counts.*

Truck counts	2004						**Average values**
Watt Avenue	date	# hours	Start time	End time	> 2 axels # trucks	# trucks per hour	**> 2 axel trucks/hr**
Jan	28	3	10:30	17:30	102	34.0	
	29	4	9:30	17:30	172	43.0	
	30	4	9:30	17:30	164	41.0	**Daytime**
Feb	2	4	9:30	17:30	140	35.0	**avg 38.3**
	5	2	6:45	10:30	127	63.5	
	6	1	6:45	8:30	50	50.0	
	9	1	6:45	8:30	75	75.0	**Morning**
	10	1	6:45	8:30	69	69.0	**avg 67.5**
	11	1	6:45	8:30	80	80.0	
Arden							
Way							**Daytime**
Feb	3	4	9:30	17:30	24	6.0	**avg 6.0**

Table B-1 *Truck counts at Watt Avenue and Arden Way. The estimated daily car count was 55,000, estimated daily trucks, 585, or about 1 %.*

The truck counts were for trucks with 3 axels or greater. There were a number of 2 axel diesel trucks that were not included in this count. These data roughly confirmed prior county records indicating a roughly 1% fraction of trucks on Watt Avenue, and less on Arden Way.

Parameter			Heavy duty (mg/km)	Light duty (mg/km)	Mixed (mg/km)
PM$_{10}$ mass	Gertler 2002	Tuscarora	181 ± 13	10 ± 11	87 ± 54
PM$_{2.5}$ mass	Gertler 2002	Tuscarora	135 ± 18	14 ± 13	62 ± 42
PM$_{10}$ mass	Gillies 2001	Sepulveda	na	Na	69 ± 30
PM$_{2.5}$ mass	Gillies 2001	Sepulveda	na	Na	53 ± 27
PM$_{2.5}$ mass	Norbeck 1998	In-use (med)		18 ± 9	
PM$_{2.5}$ mass	Norbeck 1998	In-use (high)		185 ± 50	
PM$_{10}$ mass	Sagebiel 1997	High CO, HC		346 smoke	
PM$_{10}$ mass	Sagebiel 1997	High CO, HC		32 no smoke	

Table B-2 *Comparison to heavy duty and light duty PM$_{10}$ and PM$_{2.5}$ emission rates from the Gertler at al 2002 Tuscarora Tunnel studies and other studies.*

The next problem was the nature of traffic flow on Watt Avenue. The presence of the stop lights meant that roughly ½ the time, automobiles and trucks were stopped and idling just upwind of Arden Middle School, followed by acceleration with visible increases in smoke from almost all diesel trucks. The measured emission of idling diesel truck, circa 1 g/hr, is much less than the emissions at speed, roughly ¼ g/mi. Thus, at 30 mi/hr, emissions are 7.5 g/hr. This idling reduction is counteracted by the smoke under acceleration, and since this number was large and not known, but in a direction to increase the low emission rate for idling trucks, we simply used the emission rate at average speed and ignored both the idling and the acceleration modes.

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Parameter	Units		I-5 at Q St.	I-5 at Q St		Watt Avenue	Watt Avenue.
			cars	trucks		cars	trucks
Emission rate	mg/km		14	135		14	135
Box volume							
Height	m		3.5	3.5		2.5	2.5
Width	m		60	60		40	40
Length	m		1600	1600		1600	1600
Volume	m^3		336,000	336,000		160,000	160,000
Traffic	v/hr		7900	325		3800	53
averaging			AADT/18	AADT/24		AADT/18	AADT/12
speed	km/hr		72	72		32	32
Vehicles, box			176	7		190	3
Emissions/min	mg		3932	1516		4256	572
Conc. box/min	$\mu g/m^3$		11.7	4.6		26.6	3.6
Wind velocity	m/s		2	2		3	3
translation	s		30	30		13	13
Fraction/min			0.50	0.50		0.22	0.22
Conc./highway	**$\mu g/m^3$**		**5.8**	**2.3**		**5.9**	**0.8**

Table B-3 *Car and truck counts and predicted emissions at two sites in Sacramento.*

The predicted total $PM_{2.5}$ concentration at the edge of the right-of-way for Interstate 5 at Q Street is 8.1 $\mu g/m^3$ and for Watt Avenue, 6.7 $\mu g/m^3$.

Appendix C Modeling downwind concentrations from tracer data

In order to find the very fine component of the aerosol, an alternative way is to use the zinc mass values from the laboratory diesel studies, 3000 to 1. With the mean downwind very fine 0.26 > D_p > 0.09 µm zinc, 0.8 ng/m^3 at the Arden Middle School 40 m site, we predict 3.1 $\mu g/m^3$ of very fine mass, or roughly 5.4 $\mu g/m^3$ of very fine plus ultra fine mass from vehicles, again scaled to the right-of-way fence (see below). A key and untested assumption in this work is that the zinc from smoking automobiles and diesels are roughly equivalent, which is suggested by the common source, lubricating oil, and the emissions of high emission gasoline vehicles by Norbeck et al and Sagebiel et al (above). Nevertheless, since almost all vehicular emissions in $PM_{2.5}$ are actually less than $PM_{0.25}$, this value is consistent with the very different technique given above.

An important component of the winter 2004 study was upwind-downwind samplers. Below we show the very fine particle elements characteristic of smoking automobiles and diesels at Sebastian Way and Arden Middle School. The few larger peaks at Sebastian Way are all associated with times when the characteristic upwind-downwind alignment was violated, including winds that came in over Arden Way from the northeast, and on January 26, winds that blew directly north up Watt Avenue. With these data, we could now predict the diesel and smoking automobile aerosols downwind of Watt Avenue, using literature values for the ratio of tracer elements to very fine particulate mass.

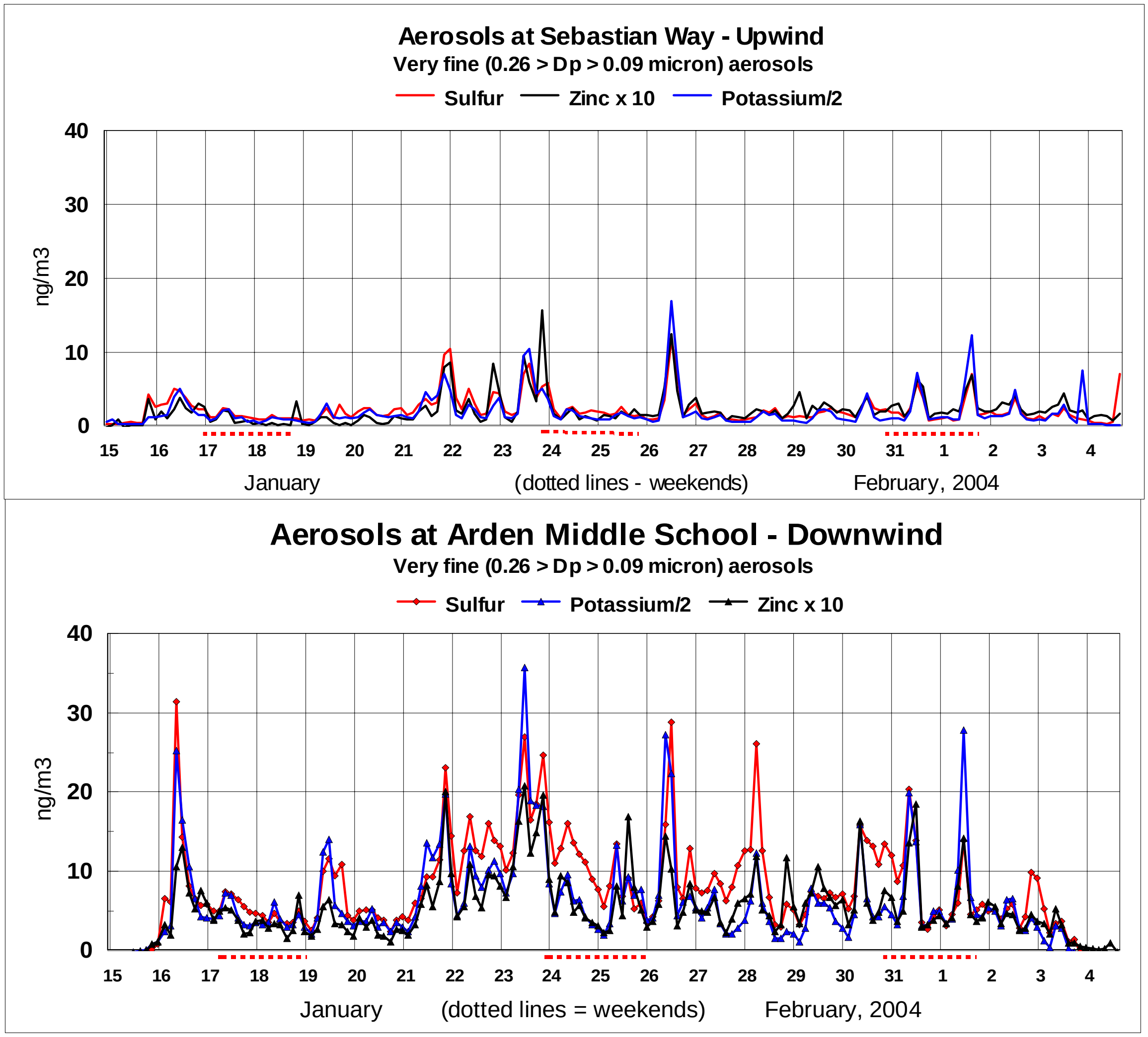

Figure C-1 *Very fine particles from Sebastian Way (top) and Arden Middle School (bottom).*

Roadway	**Distance**	**27 m**	**40 m**	**100 m**	**160 m**
At grade	*Calculated*	*≡ 1.00*	*0.85*	*0.35*	*0.10*
At grade	Measured	1.0	0.78	0.35	0.09
Depressed	Measured	1.1	0.42	0.065	na
Elevated	Measured	1.2	0.58	0.78	(0.87)[2]

Table C-1 *Effect of roadway distance and configuration on downwind concentrations of fine aerosols, measured from the downwind edge of the nearest traffic lane plus ½ of the height of the mixed box. Each value is the average of two separate freeways.*

The original study was based upon lead, and the calculated value was based directly on literature value of emissions, in mg/km. Thus, the exact agreement for the at-grade freeway is fortuitous, and the other configurations are very close. The dramatic impact of freeway configurations in other than at grade conditions requires advanced modeling, including plume lofting from roadway heating and particle settling.[2] The Arden Middle School studies of 2002 and 2004 were at 40 m, the 2006 study was at 15 m. The I-5 at Q Street study site for 2002 was at roughly 100m from a depressed freeway, but at a 20 m elevation.

Appendix D Measuring downwind concentrations

For the study of 2006, the monitoring site was moved closer to Watt Avenue, roughly 12 m from the right of way fence and 15 m from the nearest road edge. The Arden outdoor site was on the roof of the teacher ready room, above a small (6 car) parking lot. It was at the same elevation but about at 1/3 the distance to Watt Avenue than we used in 2002 and 2004. The roof (painted white) was filthy with black soot. Two DELTA 8 DRUM samplers with ultra-fine after filters were placed at Arden Middle School, January 27, operating on a three hour time resolution. The filters were barred filters and integrated the 2 weeks at Arden. One filter collected outdoor air, while the other was brought into the teacher ready room and collected air roughly 2 /12 meters above the floor near the south wall. The outside doors were not used during the test, the windows remained closed, and the one ventilation fan was disabled. An in-room heating system with upgraded filters re-circulated the air in the room.

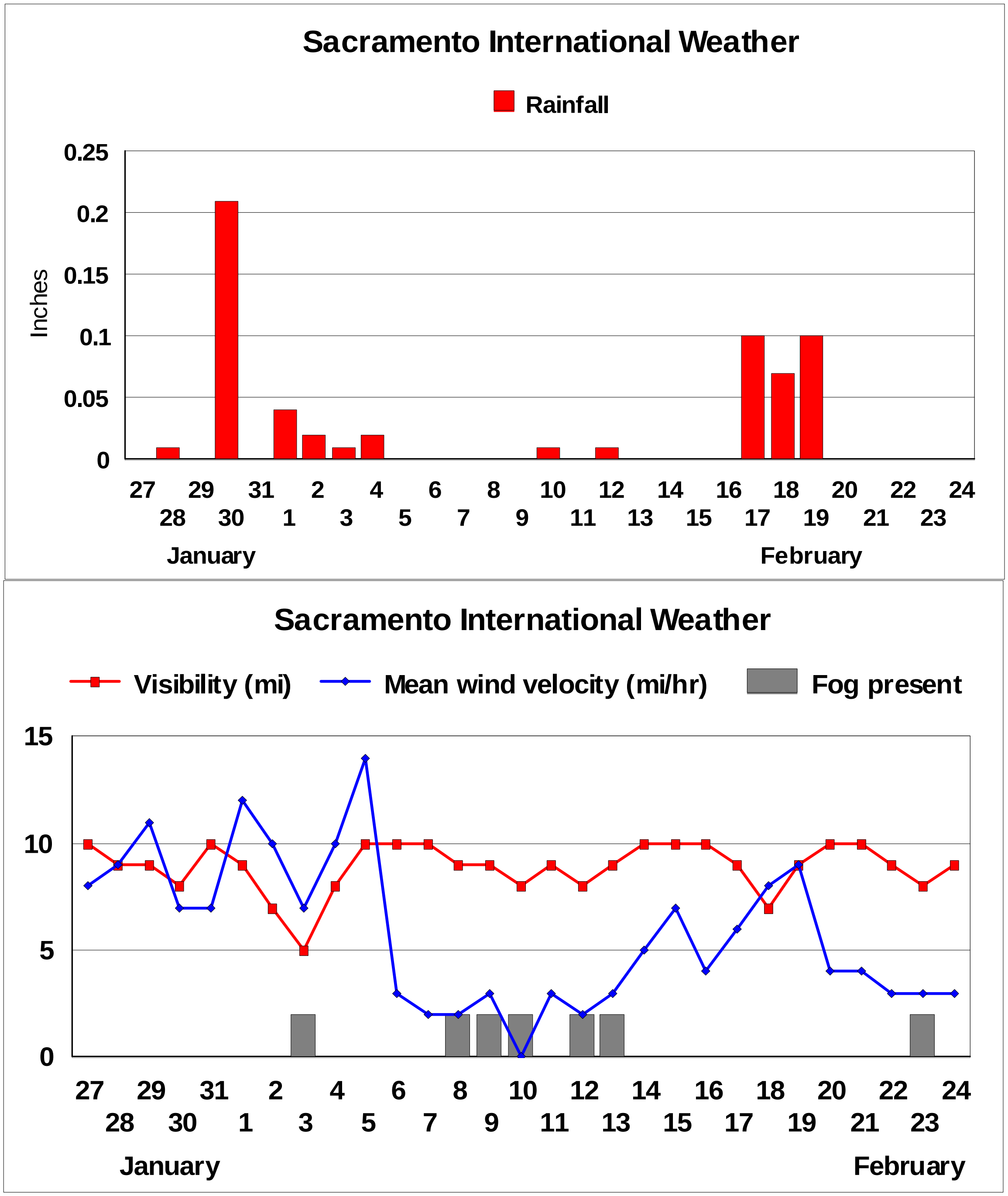

Figure D-1 *Weather data for a two month period in Winter 2006.*

Appendix E Comparison to other sites

On February 10, 2006, both samplers were moved to the Denio monitoring site downwind of the Roseville Railyard in Placer County. This was in conjunction with the Placer County APCD and was not part of the Roseville Railyard Monitoring Program, but the same downwind site at Denio's was used. As shown above, the weather during each two week period was roughly comparable, with Arden having slightly better ventilation. Below we show the actual particles photographed in natural light (hence the bluish tinge to the clean Mylar). There is an obvious soil like component at the Denio site absent at the Arden site, but other than that, the traces seen roughly comparable.

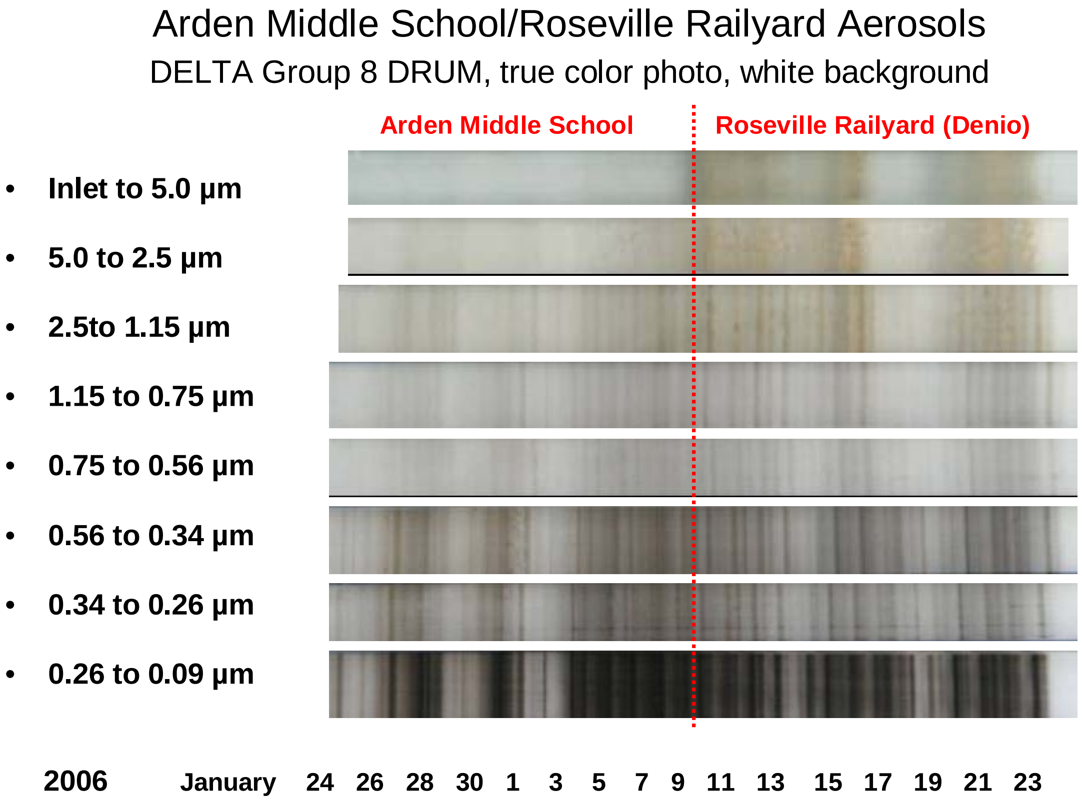

Figure E-1 *Comparative air samples from two different sites.*

Based on the compositional information, the finest 2 stages (< 0.34 µm) are dominated by automobile and diesel exhaust, while there is clearly additional smoke impact on the 0.56 to 0.34 µm stage.

Arden Middle School Very Fine Aerosols

DELTA 8 DRUM, 0.26 > Dp > 0.09 µm

January 16 – February 4, 2004

January 24 – February 10, Arden roof:
February 10 - 24 – Denio site – Roseville rail yard

Figure E-2 *Detailed view of filter at Stage 8, the finest mode.*

Surprisingly, the Stage 8 (0.26 > D_p > 0.09 µm) DRUM sample of 2004 was darker than the Arden sample of 2006, probably because the first two weeks of the 2006 study had more rain.

Mass measurements were made by soft beta ray transmission by the DELTA Group, and these are shown below.

These charts are included only as a point of comparison in measuring very fine and ultrafine particles in the Sacramento region. Further study at Roseville Railyard is ongoing.

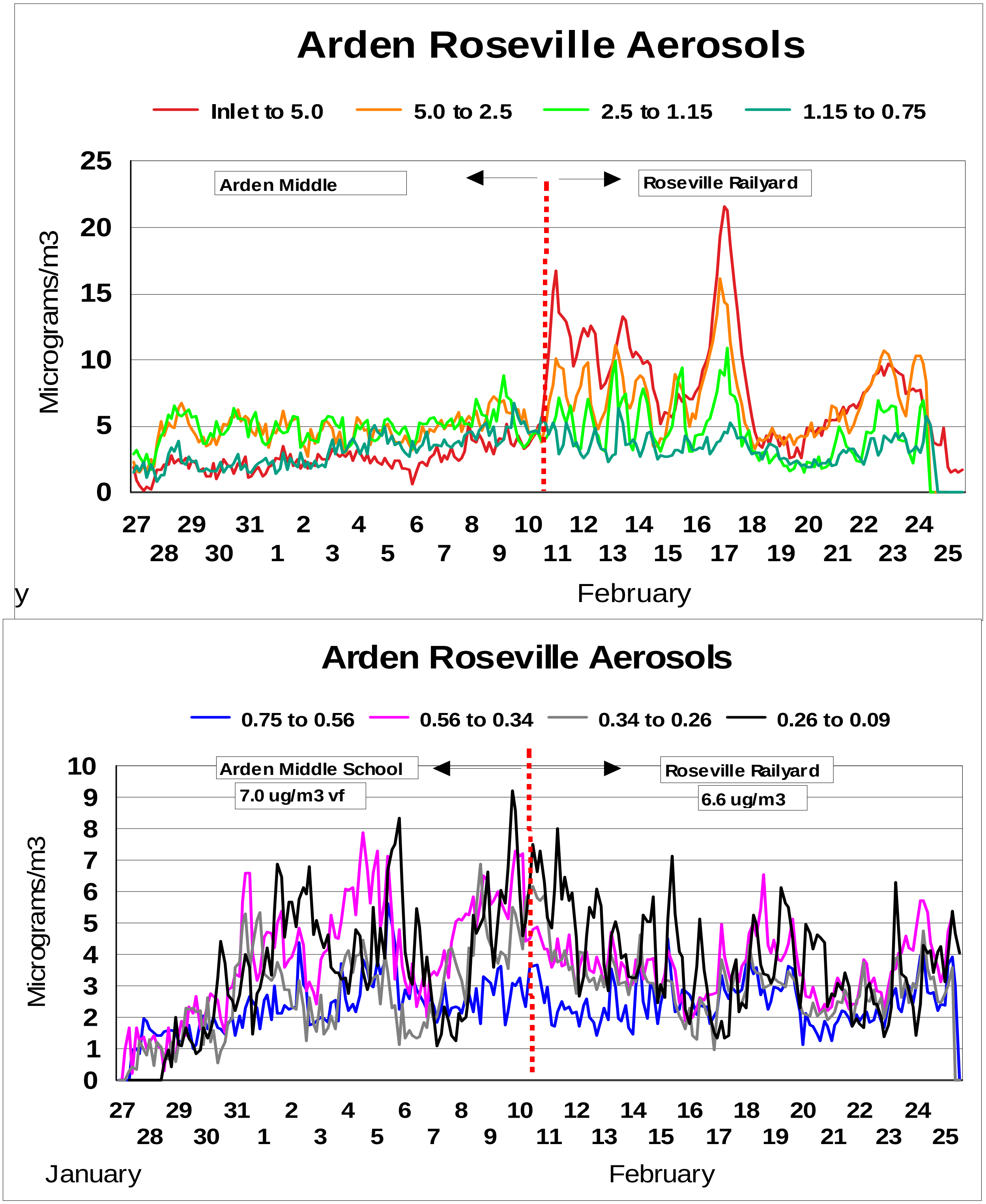

Figure E-3 *Various size mode measurements at both monitoring sites.*