American Lung Association of Sacramento-Emigrant Trails The Sacramento/Interstate-5 Aerosol Transect Study

Winter Months 2003 - 2005

Prof. Thomas A. Cahill, P.I., Lee Portnoff, Dr. Steven S. Cliff, Prof. Kevin D. Perry, (Department of Meteorology, University of Utah), the DELTA Group, University of California, Davis, http://delta.ucdavis.edu, and volunteers of the American Lung Association of Sacramento-Emigrant Trails Health Effects Task Force

An addendum to the Final Report
American Lung Association of Sacramento-Emigrant Trails Health Effects Task Force

The Sacramento/Interstate-5 Transect Study
Part 2: January 2004 – March 2005

Prof. Thomas A. Cahill, P.I., Lee Portnoff, Dr. Steven S. Cliff, Prof. Kevin D. Perry, (Department of Meteorology, University of Utah), the DELTA Group, University of California, Davis, http://delta.ucdavis.edu, and volunteers of the American Lung Association of Sacramento-Emigrant Trails Health Effects Task Force

Note: Part 2 assumes and relies upon all the information in Part 1, including the Quality Assurance sections, much of which will not be repeated herein.

Executive Summary of Part 2:

The Sacramento/Interstate-5 Aerosol Transect Study, Part 1, delivered data of extraordinary scope and utility, and also identified ways to improve the credibility of this report in several ways, which were not possible within the time and resources available in the original study. These include:

1. New information has been published, including
   a. Data on the size and composition of diesel exhaust, with Dr. Zielenska and co-workers at Desert Research Institute (DRI), Nevada, the University of Minnesota, and the National Renewable Energy Lab, Golden, Colorado
   b. Recent tests of the toxicity of diesel and smoking car exhaust by Erik Fujita of DRI, Reno, Nevada,
2. The Arden Middle School 3 DRUM sampler was added to the original study at the last minute, but lacked
   a. Detail size information of the 8 DRUM samplers, especially in the important 0.26 to 0.09 µm mode dominated by diesels and smoking cars.
   b. No DRUM sampler of any kind was available to make simultaneous upwind measurements,
   c. No concurrent truck and traffic data were available.
3. Improved quality assurance data on the DRUM sampler, including
   a. Comparisons of DRUM with IMPROVE samplers at Turtleback Dome, Yosemite National Park,
   b. Quality assurance and inter-comparisons of mass from DRUM samplers, also at Yosemite National Park,
   c. Comparisons with DRI as part of the California Air Resources Board (CARB) Lake Tahoe Atmospheric Deposition (LTAD) program.

The issues raised in the original report led the HETF to, 1) continue studying the air quality impacts of Interstate-5 in more detail, 2) compare the data obtained from this study to other sites in California, and 3) conduct a more thorough study of aerosols downwind of Watt Avenue.

From the new data available from our joint studies with Zielenska and co-workers at DRI, we can identify that:

1. Diesel exhaust almost entirely exists in the 0.25 µm to 0.05 µm size range,
2. Diesel exhaust mass has elemental tracers of sulfur, found in diesel fuel, as well as zinc, phosphorus, and other elements characteristic of lubricating oil.

This information allows the concentration of diesel mass to be inferred from theses tracer elements if the data are available in the < 0.25 mode. These techniques were applied to the data in Part 1 around Interstate-5 and, for comparison, in Fresno.

The second method to identify the particulate matter impact from roadways on surrounding areas uses literature values of emission rates (average of literature 1996-2004), as well as the much more detailed Health Effects Institute Tuscarora Tunnel study (Gertler et al, 2002). Information from these studies allows the roadway concentrations of both diesels and cars to be calculated. The mass concentration of diesel and smoking cars can then be displaced downwind via diffusion modeling from linear source to calculate values at the sampling sites (Cahill et al, 1974; Dunn, 1975; Feeney et al, 1976 ff).

We applied this technique at Watt Avenue, where we collected aerosols in January and February, 2004. We used improved instrumentation (8 DRUM vs. 3 DRUM samplers), which were placed both upwind and downwind of Watt Avenue. The data we gathered is supported by actual car and truck counts. As in the previous study, both mass and elemental values were generated. Meteorology was generated both locally and via trajectory analysis by National Oceanic and Atmospheric Administration's (NOAA) HYSPLIT program.

Thus, in Part 2, two independent methods were developed to find the impact of diesels and smoking cars on near-roadway regions. These are:

1. The elemental tracer method, and
2. The line source diffusion method.

The elemental tracer method can be used in all circumstances, but it suffers from car and diesel interferences. The line source diffusion method separates cars from diesels but requires favorable roadway configurations as well as information on meteorological conditions. From theses methods, the conclusions for Part 2 are below.

A. The Results of the Model Were Similar to Actual Measured Values Downwind of Watt Avenue at Arden Middle School. These Values Include the Resolution of Diesel From Smoking Car Sources

1. This study confirms our previous finding that Arden Middle School is heavily impacted by Watt Avenue. Now each source can be identified:

Mean aerosols - measured	7.0 ± 1.5 μg/m^3
Mean aerosol – predicted	5.4 μg/m^3 to 7.7 μg/m^3 (Gertler et al, 2002 and the average of literature values)

The dominant source of aerosols is from smoking cars, not diesel trucks with automobiles contributing 70 percent and diesel trucks the remaining 30 percent.

2. We can now with confidence predict a wider variety of traffic pollutants at the downwind site than from our measurements alone by using the data of Gertler et al 2002, including toxic materials such as Polycyclic Aromatic Hydrocarbons (PAHs).
3. Although these particles contribute little to total mass values of PM2.5 for which federal Ambient Air Quality Standards (AAQS) exist, recent health research indicates that particles in the ultrafine size range are associated with adverse health effects. While no violations of state or federal ambient air mass standards occurred, the potential toxicity of the observed and predicted vehicular pollutants at Arden Middle School supports reasonable mitigation measures. (ARB Almanac, 2001 p. 326)
4. The suspected enhanced toxicity of smoking car exhaust (Fujita et al, 2005) and the dominance of car exhaust compared to diesel exhaust downwind of Watt Avenue elevates these risks beyond the ARB Almanac estimates.

B. Very Fine and Ultra-fine Particles from Diesels and Smoking Cars Disperse Widely into the Region and are Removed Very Slowly

1. Examples were developed for Sacramento, Fresno, and Los Angeles, including a re-analysis of the ultra-fine results of Zhu et al (2002),
2. Urban areas have high ambient levels of ultra-fine (< 0.1 μm) and very fine (< 0.25 μm) diesel and smoking car exhaust, even well away from the nearest major roadway.

These results were presented as an invited talk at the AAAR/EPA Supersites Meeting in Atlanta, Georgia in February, 2005. (Cahill et al, HETF, AAAR 2005). They reinforce the efforts to control or eliminate these sources, including:

- Changes in fuels and lubricating oils,
- Changes in engine design, including ultra-low spark emission vehicles and post-combustion treatments for diesel,
- High standards for spark emission smog inspections, including an opacity test,
- A statewide smoking vehicle hotline that includes follow up for repeat offenders and quarterly summaries by region as well as by vehicle type,
- The addition of a diesel vehicle smog inspection program, for both diesel cars and trucks, including an opacity test,
- Vehicle repair and removal/exchange programs for gross emitting vehicles.

C. More Extensive Mitigation Analyses

We have initiated a much more extensive analysis of possible mitigation measures, and have planned studies to quantify these mitigation strategies in cases where existing data are sparse or non-existent. Possible mitigation measures include:

1. Reduce on-roadway source strength and toxicity through:

    a. The elimination of gross emitting cars
    b. The control of the toxicity of spark emission lubricating oils
    c. Continuing efforts to eliminate and control diesels
    d. Traffic reduction efforts at critical roadways, especially at critical times throughout the day, such as during peak/rush hours

2. Reduce transport of pollutants from roadways to receptors through:

    a. Roadway design, including median trees and downwind buffer space
    b. Roadway to receptor barriers, including trees and walls

3. Mitigation of receptor sites in order to reduce receptor aerosol exposure including:

    a. appropriately locating building air inputs
    b. installing high-efficiency filtration in buildings
    c. scheduling changes in outdoor activities to avoid peak pollution periods

Table of Contents

Executive Summary, Part 2 1

Abstract of part 1, the original report 8

A. New information included in Part 2:
1. Additional information on diesel exhaust 11
2. Additional information on smoking car exhaust 12
3. Additional studies of the transport of ultra-fine particles from roadways 13

B. New studies
1. Impact of freeways and persistence of fine particles in downtown Sacramento 15
2. Impact of freeways and persistence of fine particles in downtown Fresno 20
3. Watt Avenue study of January – February, 2004
    a. Site 23
    b. Weather 23
    c. Traffic counts – car and truck 24
    d. Aerosol data upwind and downwind of Watt Avenue 26
    e. Execution of the "sliding box" model 28
    f. Line source dispersion modeling 29
    g. Information from size/composition profiles 30

C. Conclusion 31

D. Mitigation
1. Source reduction 31
2. Reducing transport from roadways to receptors 34
3. Mitigation at the receptor 34

Acknowledgements 36

Bibliography 37

Appendices

Appendix A Quality assurance documentation; excerpts from DRUM Quality Assurance Protocols ver. 9/02 39

Appendix B Limitations and advantages of DRUM sampling protocols 45

Appendix C Vehicle emission comparisons from various studies 49

Appendix D Executive Summary of Part 1 50

List of Figures

Figure 1	Site Map and $PM_{2.5}$ aggregated data	8
Figure 2	Sacramento $PM_{2.5}$ mass transect in clear days	9
Figure 3	Diesel size/composition profiles, DRI MOUDI impactor, DELTA S-XRF	11
Figure 4	Diesel size/composition profiles, DRI MOUDI impactor, DELTA S-XRF	12
Figure 5	Toxicity of used oils (Fujita et al, 2005)	13
Figure 6	Study of ultra-fine particles near a major highway Zhu et al (2002); Lead from Cahill et al (ARB, 1974)	14
Figure 7	Fine $PM_{2.5}$ aerosols at 13^{th} and T Streets, Sacramento, 2002	15
Figure 8	Site Map, Sacramento River, Crocker Art Museum and ARB site At 13^{th} and T Streets	16
Figure 9	Very fine aerosol data for sulfur, zinc and phosphorus at Crocker Art Museum site	17
Figure 10	Aerosol mass, very fine and droplet modes, in downtown Sacramento	18
Figure 11	HYSPLIT 72 hourr trajectories for noon, January 4, 2003	19
Figure 12	Very fine aerosols typical of diesel exhaust from the Fresno Supersite, November - December, 2001	20
Figure 13	Soft beta ray mass measurements from the FACES samples	21
Figure 14	Predicted versus measured very fine mass from diesel sources, Fresno, winter, 2001	21
Figure 15	Watt Avenue, Arden Way, and the sites near Arden Middle School	22
Figure 16	Sacramento weather during January and February, 2004	24
Figure 17	Traffic counts on Watt Avenue and Arden Way, January- February, 2004	25

Figure 18	Composition of very fine aerosols at Sebastian Way and Arden Middle School, January – February, 2004	27
Figure 19	Typical soil derived elements downwind of Watt Avenue	30
Figure 20	Sulfur and transition metals downwind of Watt Avenue	31
Figure 21	Aerosol emissions from heavy duty and light duty vehicles over time	33

List of Tables

Table 1	Truck traffic counts at Watt Avenue and Arden Way, January, 2004	26
Table 2	Execution of the "sliding box" model, Interstate 4 and Watt Avenue	28
Table 3	Effect of roadway distance and configuration on downwind concentrations of lead	29

Abstract of Part 1:

During the period December 12, 2002 through January 16, 2003, fine aerosol mass, (fine liquid or solid particles suspended in the air) was collected continuously and measured every three hours along a nine site transect from west of Davis, California, to Shingle Springs, California. The fine $PM_{2.5}$ aerosols were size segregated into either three or six size modes above 0.09 µm diameter. Coarser aerosols were also measured at five of the sites. While no violations of the 24 hour federal $PM_{2.5}$ standard were observed, the highest mass levels observed were associated with winds coming to Sacramento up the San Joaquin Valley under the typical inversion layer.

The direct impact of Interstate-5 on near downwind sites was evident in all weather conditions, while Watt Avenue had a similar impact on Arden Middle School. On many days, aerosol mass values were similar across the entire network, but with an enhancement at the Crocker Art Museum site down wind of Interstate-5, and lesser values at Shingle Springs, which was often above the inversion. Compositional and optical data were generated at the Crocker Art Museum and Arden Middle School sites in order to identify the sources of the observed aerosols. Size and compositional evidence showed a strong presence of diesel and smoking car exhaust at both sites with a minor presence of wood smoke. A large PM_{10} event recorded at the Del Paso Manor Tapered-Element Oscillating Microbalance (TEOM) monitor was shown to be sea salt from the California coast northwest of Sacramento. New Year's Eve fireworks on the Tower Bridge provided distinctive signatures in very fine aerosols at the Crocker Art Museum site and even stronger signatures at Arden Middle School.

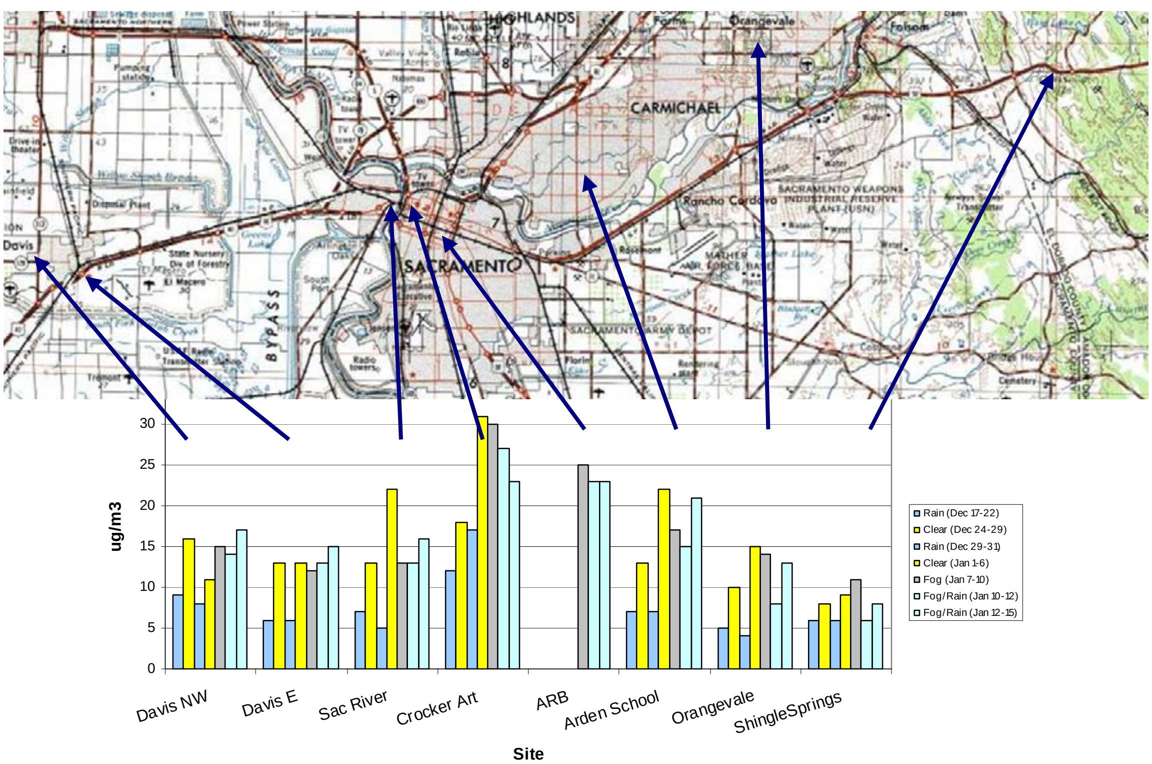


Figure 1. Site map and $PM_{2.5}$ aggregated data

Part 1 Conclusions

1. This Transect Study was an operational success due to the heavy involvement of HETF volunteers, the efforts of the University of California at Davis DELTA[1] Group, and with modest but vital financial assistance.
2. The study was a size, time, and compositionally resolved transect of a major urban area, opening a new approach to urban air quality studies.
3. No violations of the federal 24 hour $PM_{2.5}$ standards were measured.
4. There were extensive periods during which the transect showed spatial uniformity across the region, with rural Davis, Sacramento River, and Orangevale having very similar concentrations of $PM_{2.5}$ particles.
5. The Crocker Art Museum site next to Interstate-5 almost always experienced elevated $PM_{2.5}$ concentrations. The Shingle Springs site, which was often above the inversion layer, usually had lower $PM_{2.5}$ concentrations.
6. The highest levels of $PM_{2.5}$ at all sites measured were generally associated with the typical slow winter drainage winds coming up from the San Joaquin Valley (see Appendix B) that moved parallel to Interstate-5 and Highway 99.
7. During periods of low winds, low inversions, haze and/or dry fog, sharp increases in $PM_{2.5}$ concentrations were seen in measurements immediately upwind compared to downwind of Interstate-5.

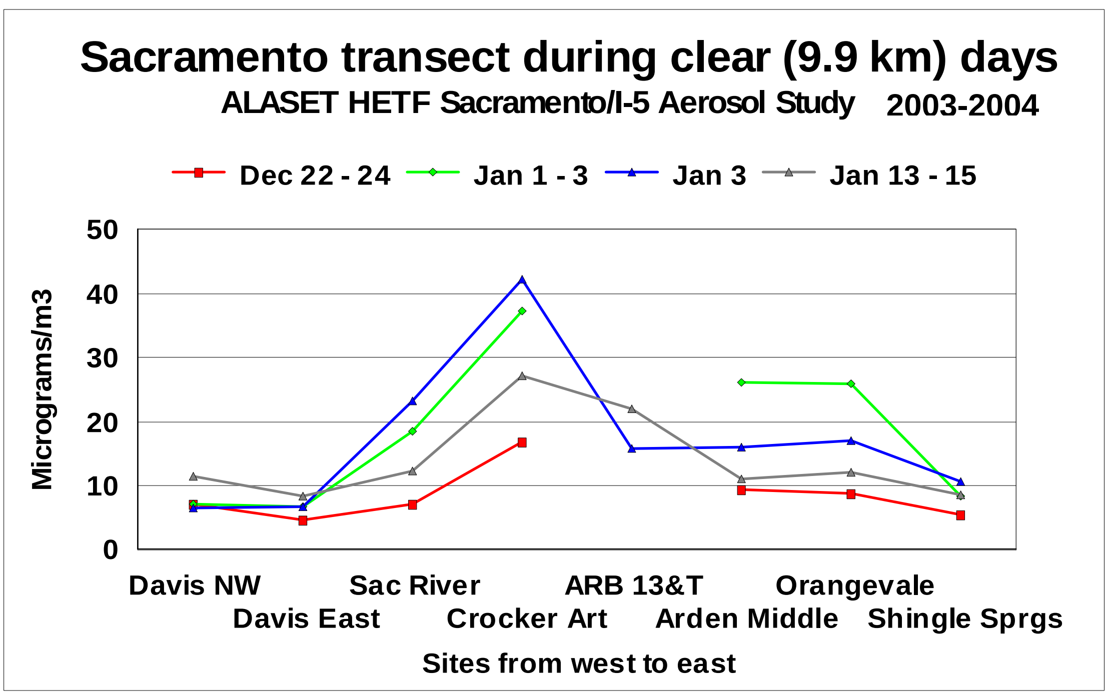


Figure 2. Sacramento $PM_{2.5}$ mass transect during clear days

8. From the high point downwind of Interstate-5, with 11 ± 5 $\mu g/m^3$ of added mass, concentrations fell off relatively smoothly with measurements to the east. On

[1] Detection and Evaluation of Long Range Transport of Aerosols

January 5-6, 2004, HYSPLIT isentropic trajectories showed that the wind came from the east, making the Crocker Art Museum site upwind of Interstate-5 but downwind of the rest of Sacramento, including Highway 99. Concentrations of $PM_{2.5}$ as well as all species fell to low levels, while the now downwind Sacramento River site had high concentrations (see Figure 2).

9. At the Crocker Art Museum site, very fine particles ($0.26 > D_p > 0.09$ µm) were compositionally associated with diesel and smoking light duty gasoline powered vehicle exhaust, as identified through size, color, and the presence of the elements sulfur, phosphorus, and zinc, adding roughly 4.5 ($\pm$ 1.5) µg/m^3 of downwind mass based upon laboratory derived diesel ratios keyed to zinc. About half of this mass is from smoking cars.
10. The Arden Middle School site had a strong local source of mass in the sub-µm size mode that was most likely local in origin. In stable periods, on average, the concentrations measured at Arden Middle School fell between those measured at the ARB building at 13th and T Streets (which is not immediately downwind of a freeway) and Orangevale (a suburb of Sacramento).
11. The direct effect of Watt Avenue was not immediately available in $PM_{2.5}$ mass profiles due to the lack of an immediate upwind site.
12. The effect of the New Years Eve fireworks on the Tower Bridge and a persistent, elevated level of typical diesel and smoking car markers (sulfur, phosphorus, and zinc) was shown in the finest mode, $0.34 > D_p >$ circa 0.15 µm.
13. At Arden Middle School, diesel and smoking vehicle impacts were larger than at the Crocker Museum site despite lower traffic flows. This result is consistent with model predictions, which include the proximity of the school to Watt Avenue as well as the lack of barriers to air motion
14. In addition, I-5 west of the Crocker site is depressed, and data from our Los Angeles work showed that depressed freeways have less influence on nearby sites than at grade or elevated freeways, partially because of the buoyant rise of warm tailpipe emissions. (Cahill et al, 1974; Feeney et al, 1976)

New information included in Part 2

1. Additional information on diesel exhaust

Results from Desert Research Institute and the University of Minnesota/NREL studies of diesel exhaust include information on properly operating diesels as well as information on diesel engines that burn lubricating oil.

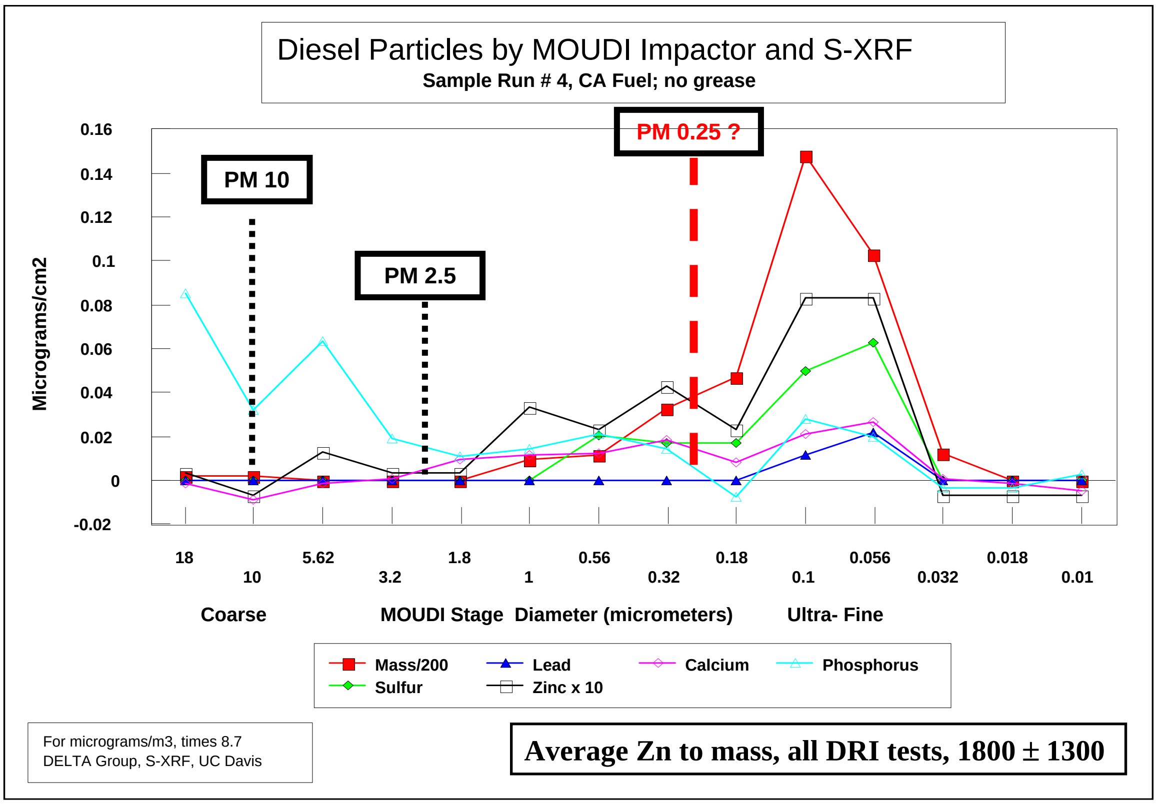


Figure 3. Diesel size/composition profiles, DRI MOUDI impactor, DELTA S-XRF

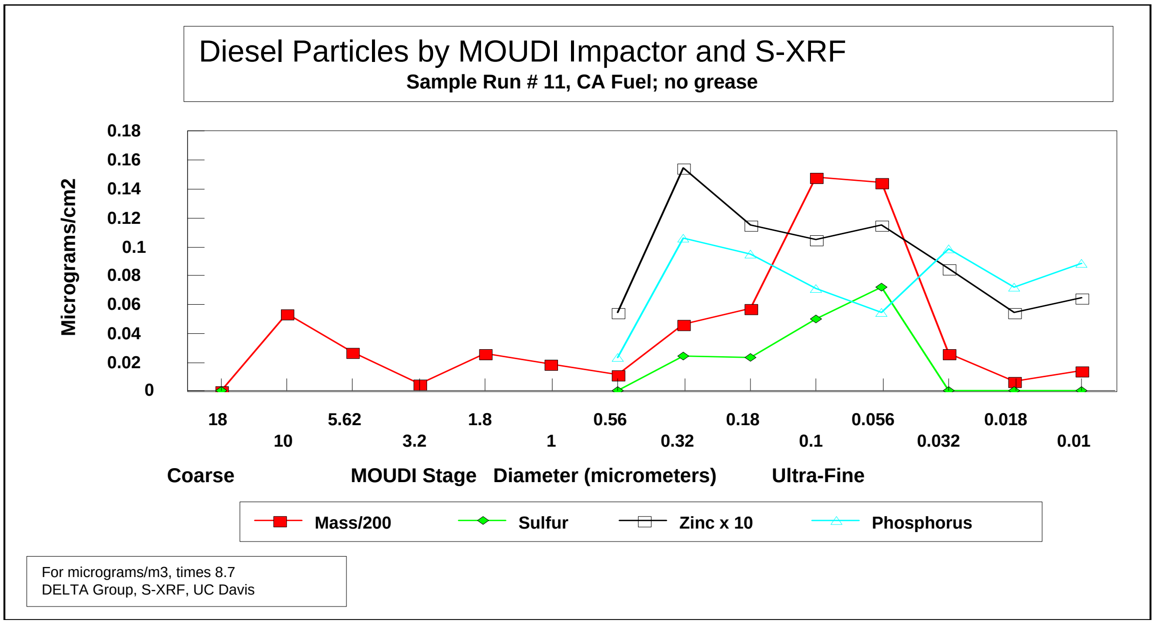


Figure 4. Diesel size/composition profiles, DRI MOUDI impactor, DELTA S-XRF

Figure 3 identifies that the aerosols from the fuel combustion (mass, sulfur) and oil combustion (zinc and phosphate from zinc thiophosphate stabilizer, calcium from calcium carbonate anti-acid additive) have essentially identical size profiles, while over roughly one half (6 out of 11) of all engines tested had the profile similar to that of Figure 4, with major ultra-fine mass and burned lubricating oil. Note that in Figure 4, there is significant mass even at 0.01 µm, representing an enormous number of particles.

From all tests with smoking and non-smoking cars, a zinc to mass ratio in the very fine < 0.25 µm mode of 1800 ± 1300 was derived. When measuring zinc in an urban atmosphere in the very fine size mode, diesel exhaust mass can be calculated, however, this is hindered by the very similar smoking car zinc to mass ratios.

2. Additional information on smoking car exhaust

In 2005, the Department of Energy sponsored a study at the DRI by Eric Fujita that identified the toxicity of oil in spark emission vehicles is greater than that of diesels. This is an expected result because car engines re-circulate oil.

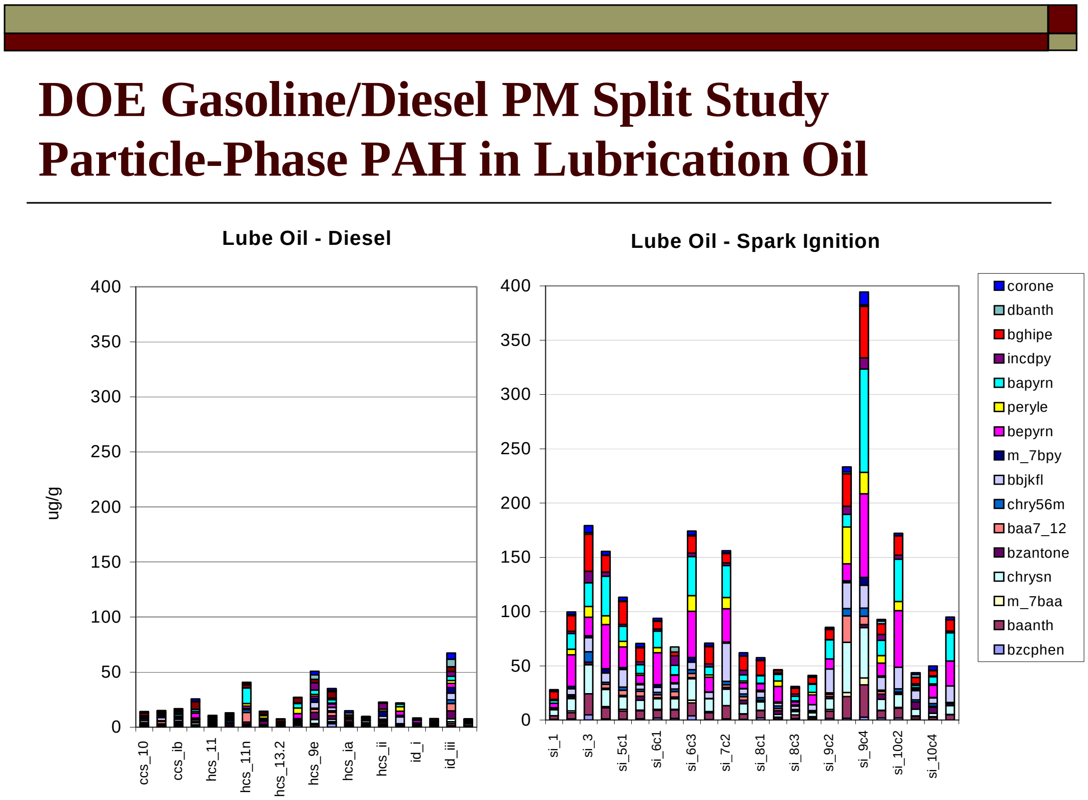


Figure 5. Toxicity of used oils (Fujita et al, 2005)

These results, presented by Erik Fujita at the American Association of Aerosol research/US EPA Supersites Conference in Atlanta, Georgia, February, 2005, show that high levels of PAHs, some of which are emitted into the atmosphere as the oil is burned, in spark emission vehicle lubricating oils are either present initially or increase during driving.

3. **Additional studies of the transport of ultra-fine particles from roadways, especially the results of Zhu et al (2002) in Los Angeles.**

This study concluded that the number of ultra-fine particles, as well as black carbon, appeared to track with carbon monoxide (CO). We added old data on lead, which was also known to be diffusion limited as is non-reactive CO. The implications of these conclusions: results were not developed in the paper, but they lead to several important conclusions:

a. Ultra-fine particles do not appear to coagulate, but instead transport like inert gases or very fine non-reactive particles,
b. The levels of ultra-fine particles upwind of the heavily traveled freeway were about one quarter of the values directly next to and downwind of the freeway. Since the nearest upwind freeway was about five kilometers away, the data implies that large areas of Los Angeles have elevated ultra-fine and black carbon concentrations.

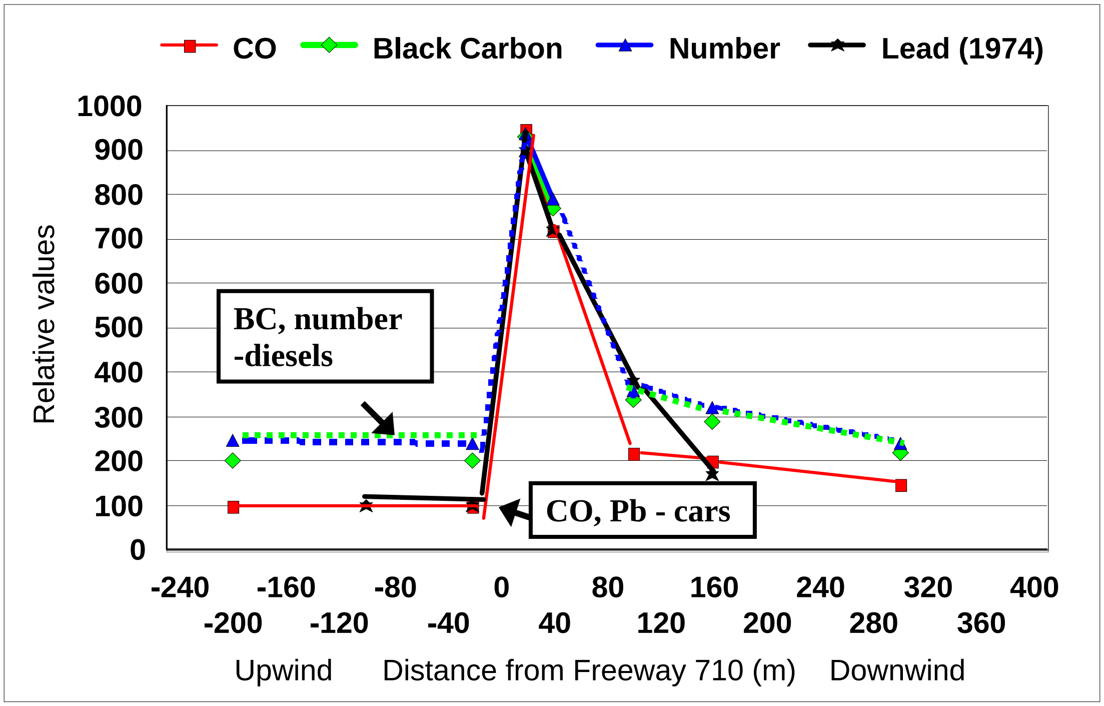


Figure 6. Study of ultra-fine particles near a major highway Zhu et al (2002); Lead from Cahill et al (ARB, 1974)

4. **The EPA Fine Particle Criterion Document December, 2004**
   This document contains a wealth of information, including the most recent data on the health effects of fine (< 2.5µm), very fine (< 0.25 µm), and ultra-fine (< 0.1 µm diameter) particles.

B. New studies

1. Impact of Freeways and the Persistence of Fine Particles in Downtown Sacramento

The Sierra-Delta topography results in Sacramento incorporating a dense freeway nexus, with Interstate-80, Interstate-5, Highway 50 and Highway 99 generating over a million vehicles per day, (including about 75,000 trucks) in an area roughly four miles across. All of these vehicles bring Sacramento close to exceeding the new federal $PM_{2.5}$ standards which are less stringent than the California health-based standards (see Figure 7). However, if this mass is primarily from freeways and roadways, the health impacts may not be truly represented by the federal standards due to the toxicity of diesel and car particulates.

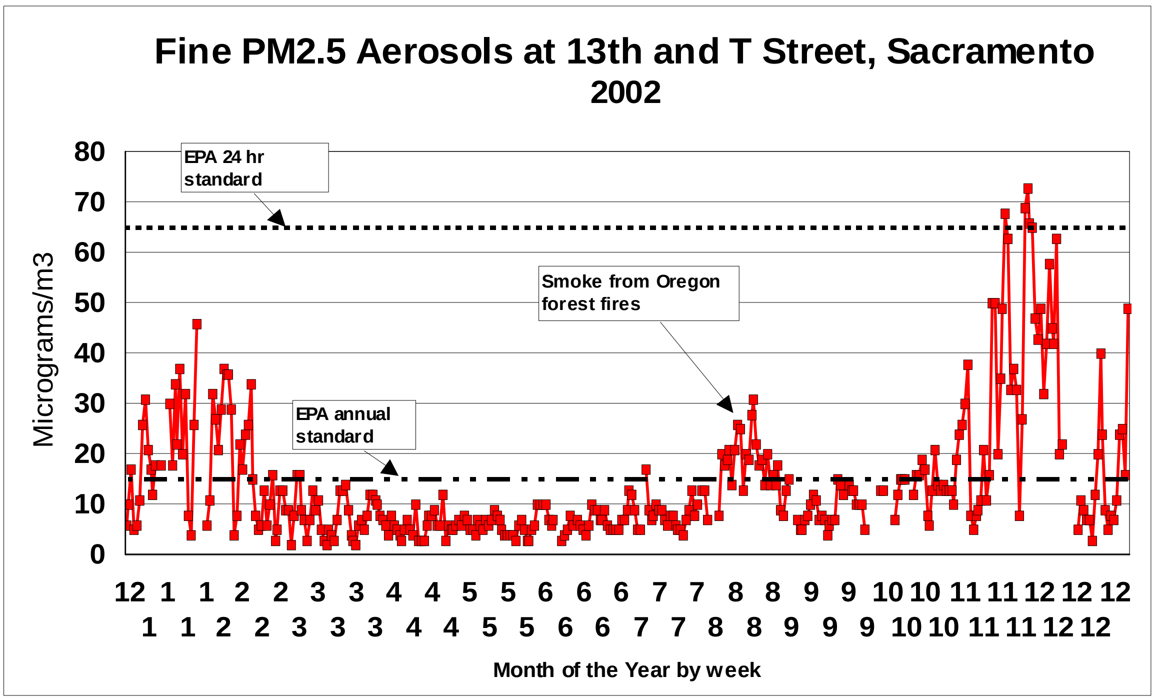


Figure 7. Fine $PM_{2.5}$ aerosols at 13th and T Streets, Sacramento, 2002

In Part 1, we measured aerosols across the entire region, with a focus on Interstate-5 in downtown Sacramento. These three sites are shown in Figure 8. Our measurements documented a very high impact of very fine particles at the Crocker Art Museum site on occasion, including 86 μg/m^3 of $PM_{2.5}$ and a surprising 25 μg/m^3 in the very fine 0.34 to 0.09 μm size range (see Figure 9). However, even with an upwind site and high time and size resolution, direct calculation of highway impacts was difficult due to the complicated topography of the area. Highway 50 crosses the Sacramento River on an elevated bridge, Interstate-5 is below grade, the sampling site is elevated nearly ten meters, and trees are present. Each of these factors complicates our ability to measure the impact of the highways.

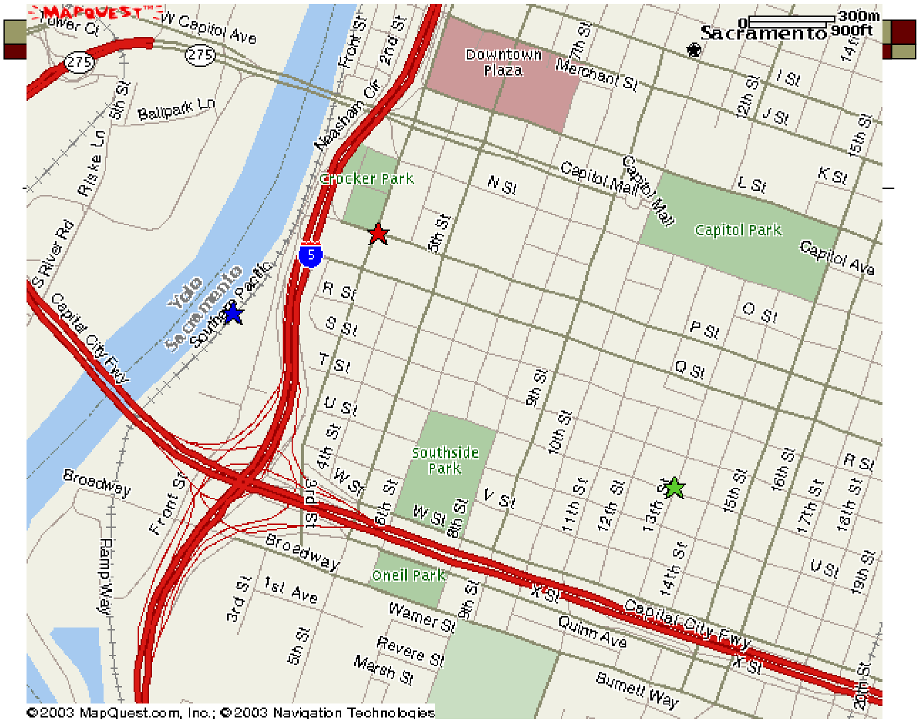


Figure 8. Site map of downtown Sacramento, including the Sacramento River, Crocker Art Museum, and the ARB at 13th and T Streets sampling sites

With the new data on the zinc to mass ratios for diesels from the DRI studies, as well as our < 0.26 µm data to match the DRI size cuts, we can estimate diesel impacts through the ratio of zinc to mass, 1800 ± 1300, for mass < 0.25 µm.

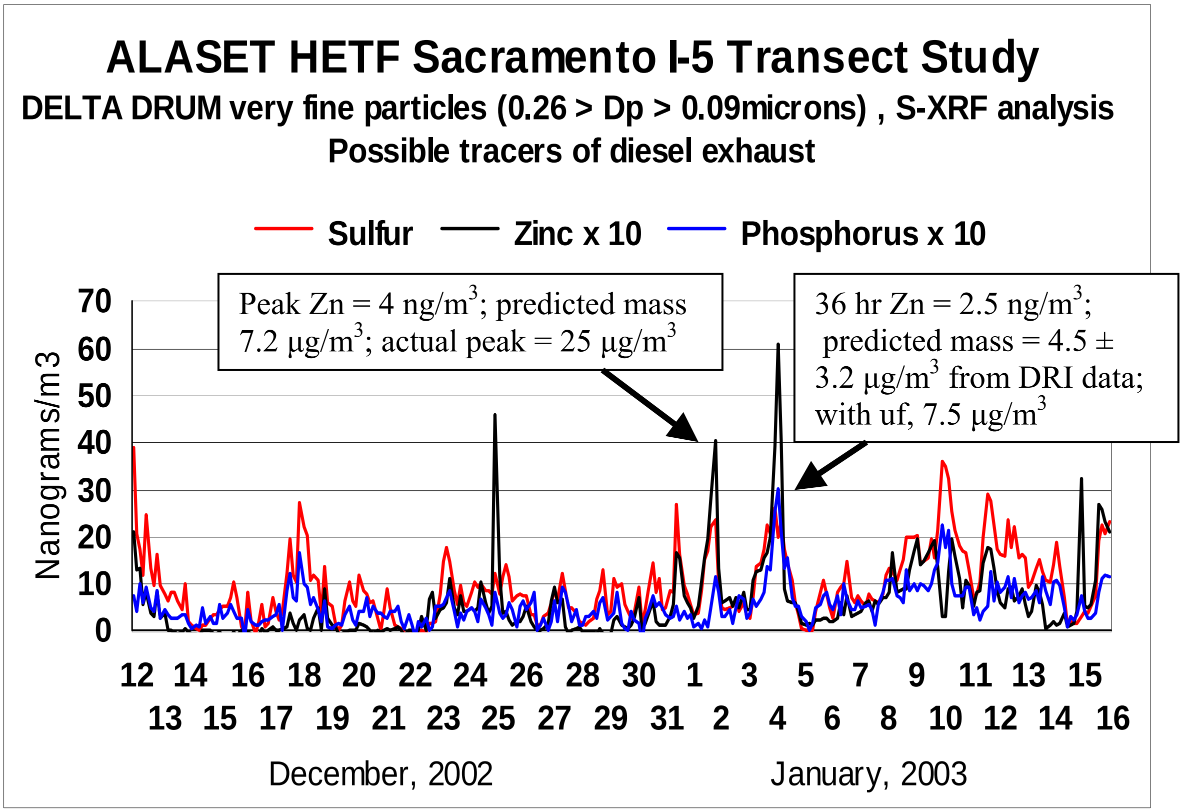


Figure 9. Very fine aerosol data for sulfur, zinc, and phosphorus at Crocker Art Museum site

Below in Figure 10, we show mass values for the two largest modes in the period spanning December 29, 2002 through January 9, 2003. Note the highly variable mass in the "droplet mode" which reflects bound water. Using the Zn/P/S ratio from the DRI study on the data from January 4 to January 5, 2003, we were able to predict 4.3 ± 2.9 $\mu g/m^3$ of diesel mass for the very fine mode, assuming all the trace elements are from the diesels. In fact, we have rather uniform very fine mass of 6 ± 1 $\mu g/m^3$ in the same period at all three sites, including the ARB 13th and T Streets site which is about 0.5 kilometers from the nearest freeway. Since the Tuscarora Tunnel data show that cars have a similar zinc to mass ratio, we can not separate the relative diesel and car contributions. However, cars if anything, are likely to have more toxic smoke than diesels per unit mass, as shown in the DRI studies.

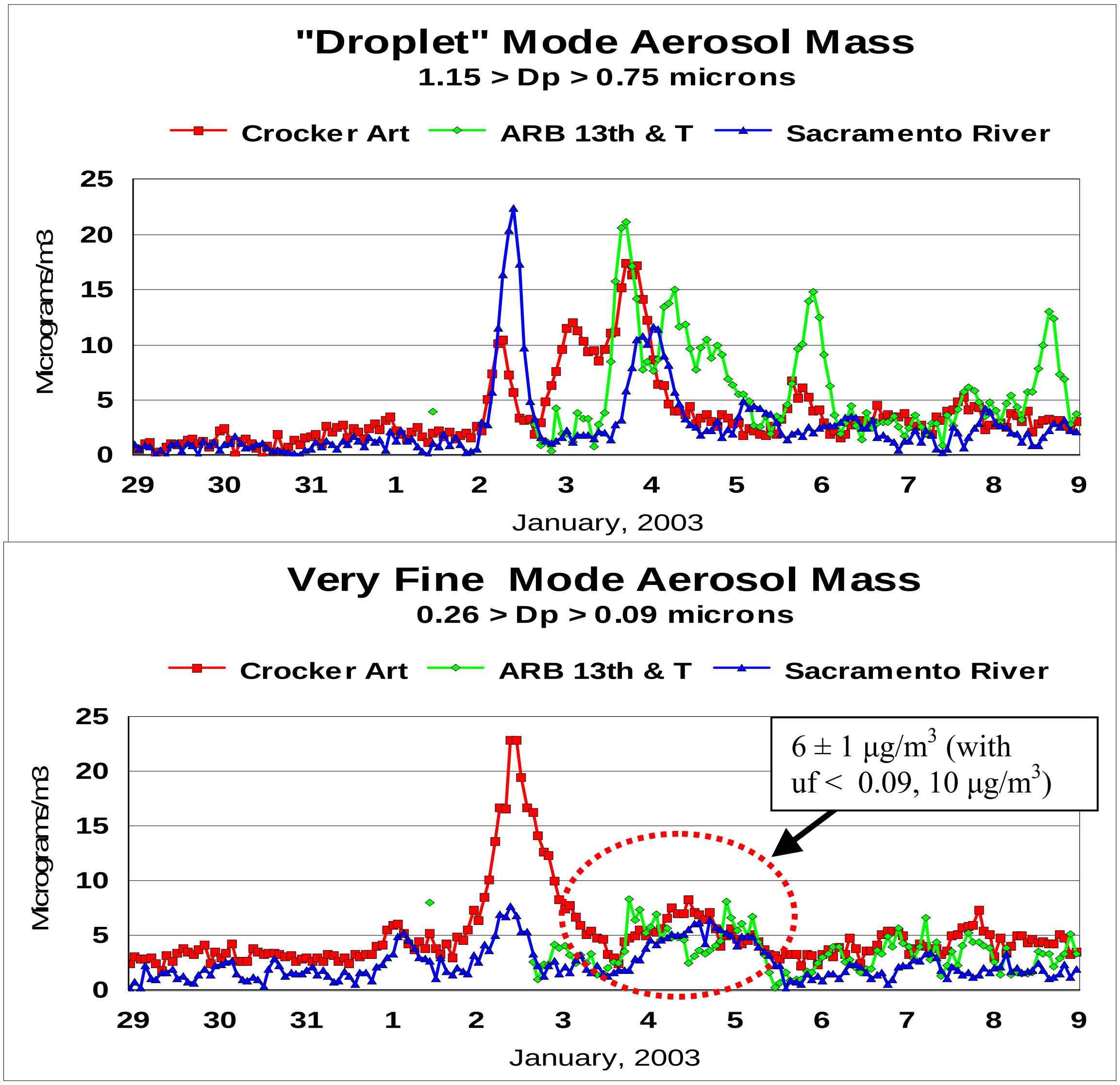


Figure 10. Aerosol mass, very fine and droplet modes, in downtown Sacramento

In conclusion, very fine aerosols and highly toxic diesel and smoking car aerosols persist in the downtown Sacramento region well away from freeways. Very fine roadway mass data at Fresno was measured at 8.8 $\mu g/m^3$ (FACES), and ultra-fines in Los Angeles are widespread (Zhu et al 2002). Thus, very fine and ultra-fine particles from diesels and smoking cars exist in worrisome levels in major California cities. (Cahill et al, 2005)

As mentioned in Part 1, the air present over this 36 hour period came in on slow, low trajectories that traveled essentially parallel to Highway 99 and Interstate-5 from the southeast. These winds consist of part of a drainage flow up from the San Joaquin Valley.

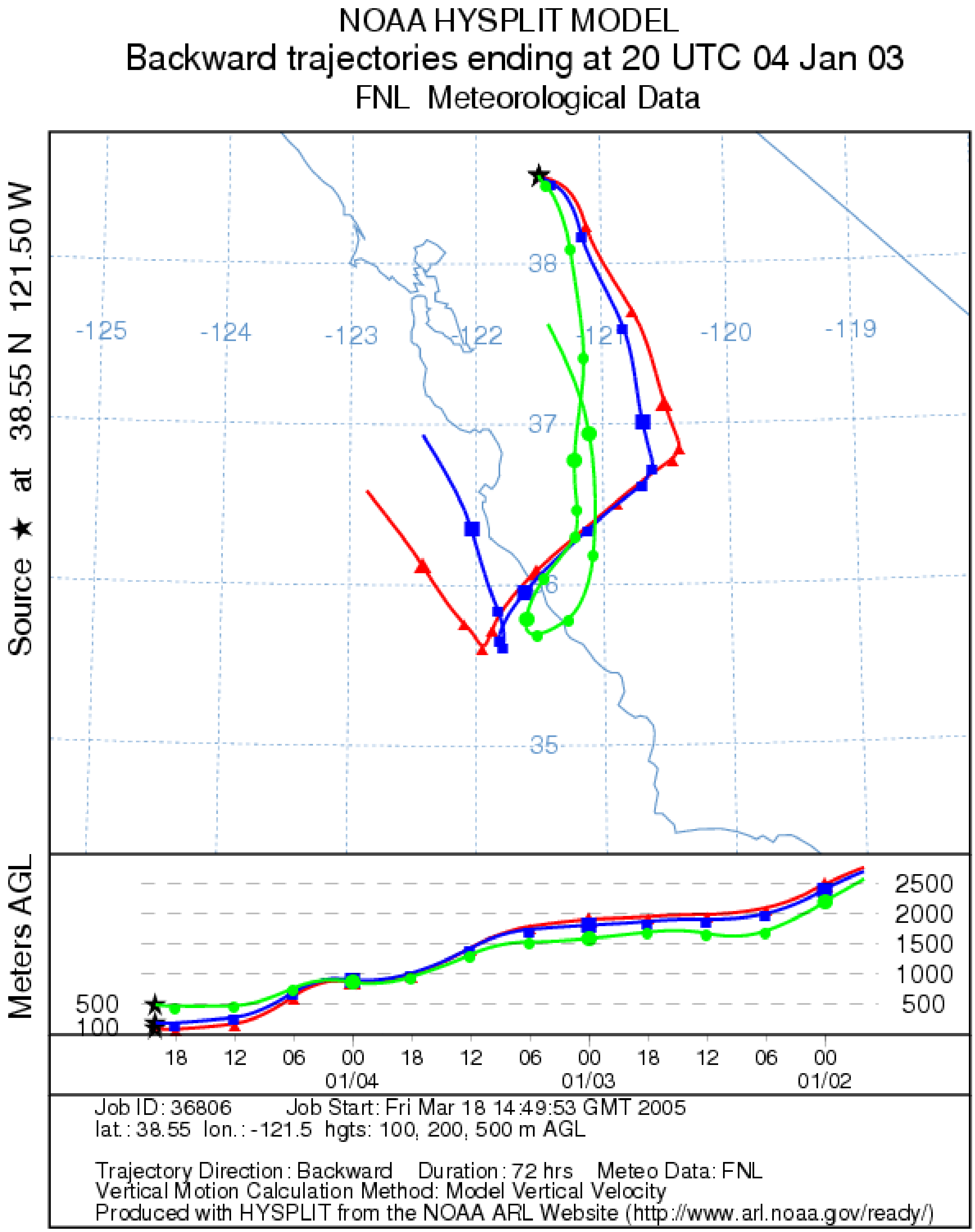


Figure 11. HYSPLIT 72 hour trajectories for noon, January 4, 2003

In the wind conditions illustrated in Figure 11, the Sacramento River site and the Crocker site did not have an upwind-downwind relationship, while Highway 50 was roughly 400 meters south of all sites, and the trajectory essentially paralleled Highway 99 for 24 hours.

2. Impact of freeways and persistence of fine particles in downtown Fresno

The documented impact of the San Joaquin Valley on downtown Sacramento encourages an analysis of San Joaquin Valley air and, in particular, the very fine diesel and smoking automobile components. In Figure 12, shows data from the 2001 FACES study that utilized much of the same technology as the present studies. (Cahill et al, 2005). The very same components seen in the DRI diesel studies occur in Fresno in the winter.

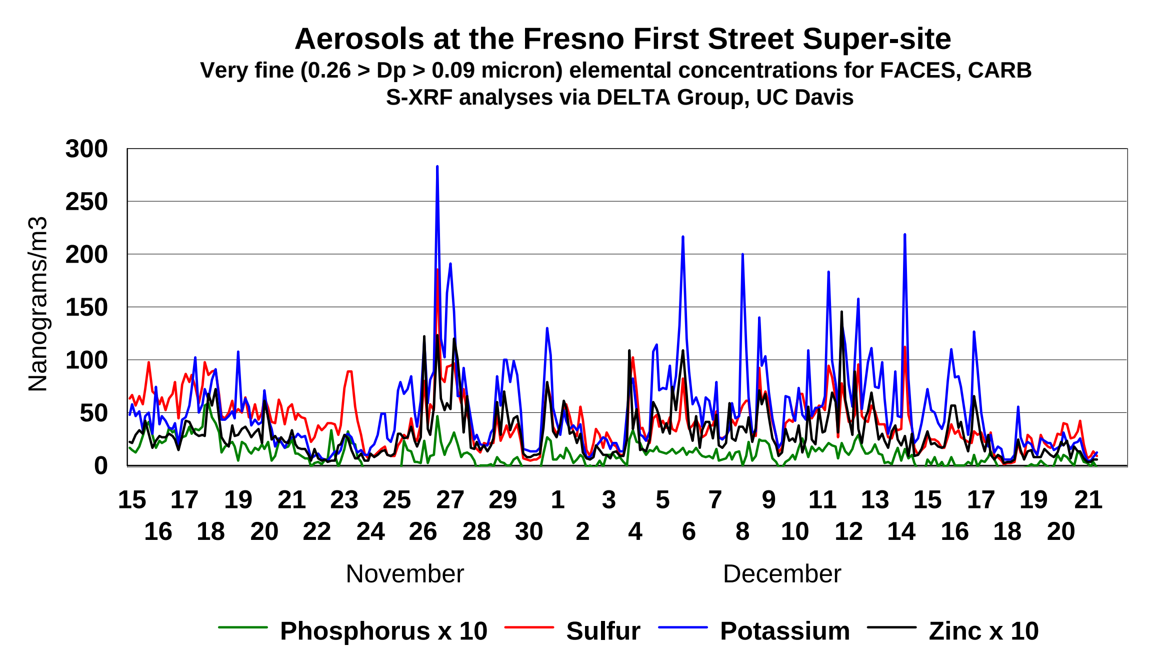


Figure 12. Very fine aerosols typical of diesel exhaust from the Fresno Supersite, November - December, 2001

In Fresno, we see these values over an extended period of time, with a three week average instead of a 36 hour average used in Sacramento. Using the very fine zinc to mass ratio from the DRI studies (1800 ± 1200) and correcting for the unmeasured mass below 0.09 µm, we predicted a very fine mass, < 0.26 µm, to be 9 ± 6 µg/m^3 over the entire period from November 25 through December 17, 2001.

Since the 2001 FACES study, the DELTA Group has developed and validated mass measurements from DRUM samples. We ran the soft beta mass system on the original FACES samples that were archived for the same period. The results are shown below in Figure 13.

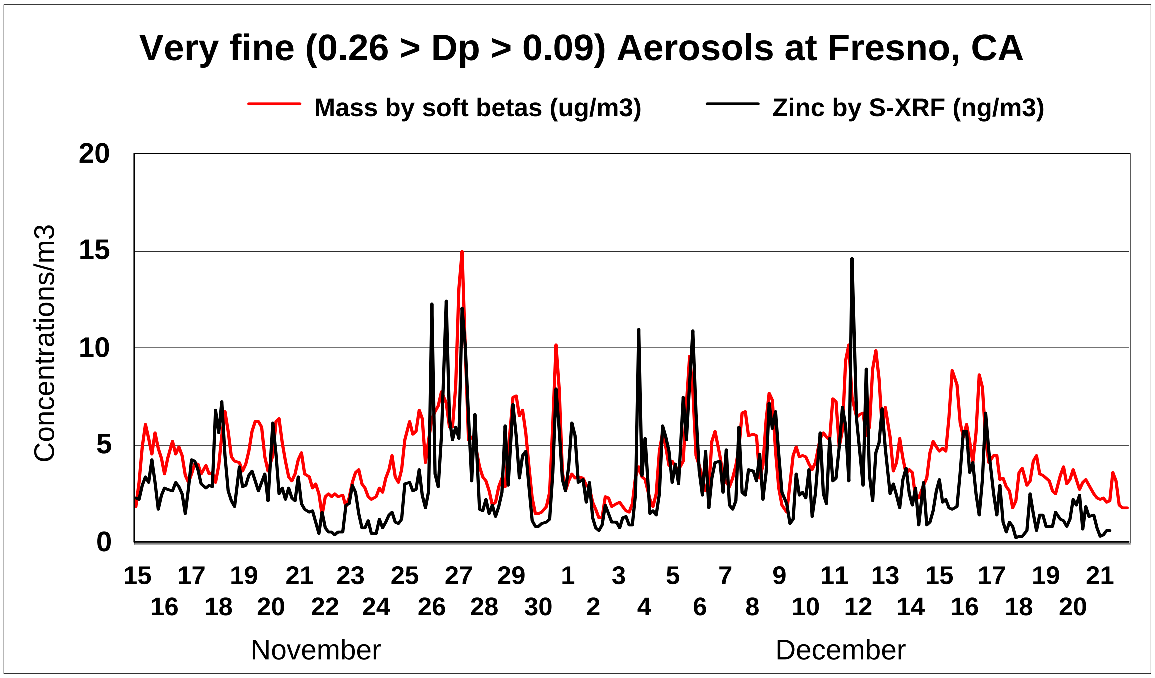


Figure 13. Soft beta ray mass measurements from the FACES samples

Combining these results, we can then match the measured mass to the predicted mass in the very fine mode, as shown below in Figure 14.

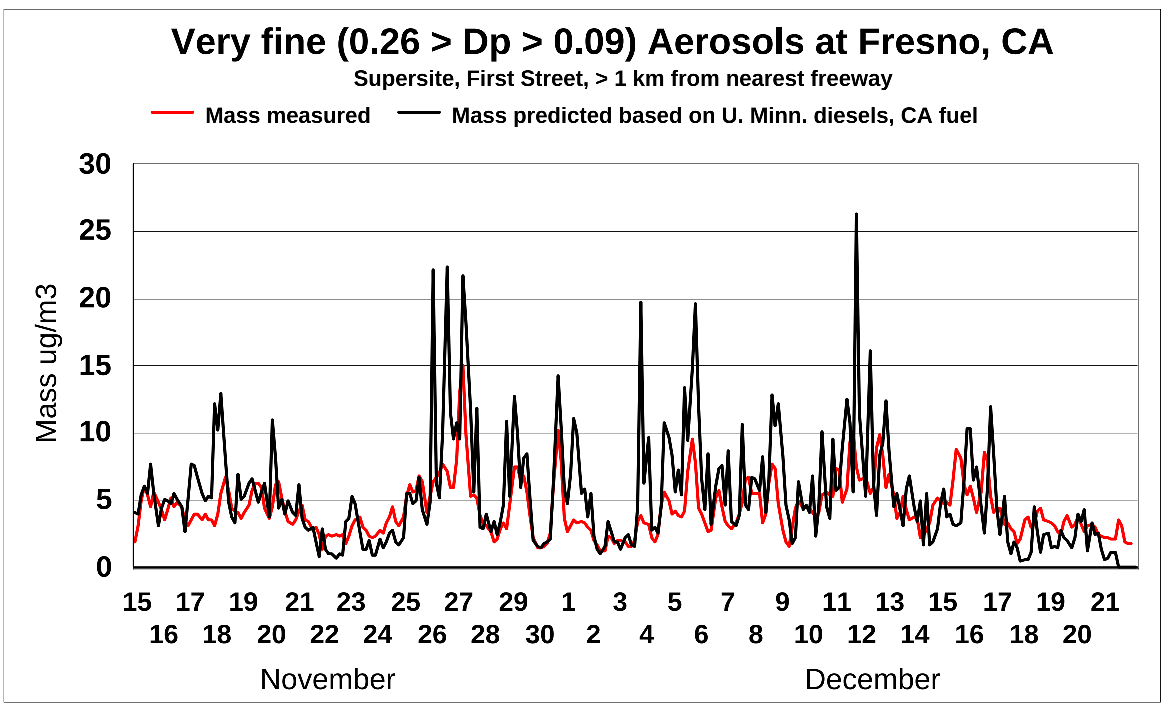


Figure 14. Predicted versus measured very fine mass from diesel sources, Fresno, winter, 2001

For the period November 25 through December 17, 2001, the measured mass was 4.8 ± 1.0 μg/m^3, versus a predicted mass in the same size mode of 6.6 ± 4.8 μg/m^3 from the DRI zinc to mass ratio. From this, the total measured very fine mass $D_p < 0.26$ μm of 8.2 ± 1.7 μg/m^3) is found to be very close to the zinc tracer method value of 9 ± 6 μg/m^3. This agreement assumes that cars have the same zinc to mass ratio as diesel trucks, an assumption for which data are lacking. However, the values measured in the $PM_{2.5}$ samples in the Tuscarora Tunnel (Gertler et al, 2002) were found to be similar to ours.

While there are relatively large uncertainties in the actual values of the Tuscarora study, the conclusion is similar to that in Sacramento. Despite the fact that the Fresno Supersite is roughly 1 kilometer from the nearest freeway, very fine aerosols typical of freeways are present and even abundant in residential neighborhoods. This reinforces our re-analysis of Zhu et al (2002) in the Los Angeles area, leading to the conclusion that very fine and ultra-fine particles behave like a diffusion limited non-reactive gas, persisting because they are too small to settle and too hydrophobic to grow.

3. Watt Avenue study, January – February, 2004

Figure 15. Watt Avenue, Arden Way, and the sites near Arden Middle School

a. Site

Information from the Watt Avenue site near Arden Middle School was enhanced by the establishment of the upwind Sebastian Way site, which was located in a residential backyard roughly 200 meters west of Watt Avenue. DELTA Group 8 stage DRUM samplers were used at both sites. Sacramento County provided traffic counts on Watt Avenue just south of Arden Way.

b. Weather

The month of January 2004 started with foggy weather resulting in poor visibility. Directly following this foggy weather were a series of rain storms from late January into February. Good ventilation as shown by higher wind velocities occurred January 25 through 27, and January 31 to February 4, 2004. See Figure 16.

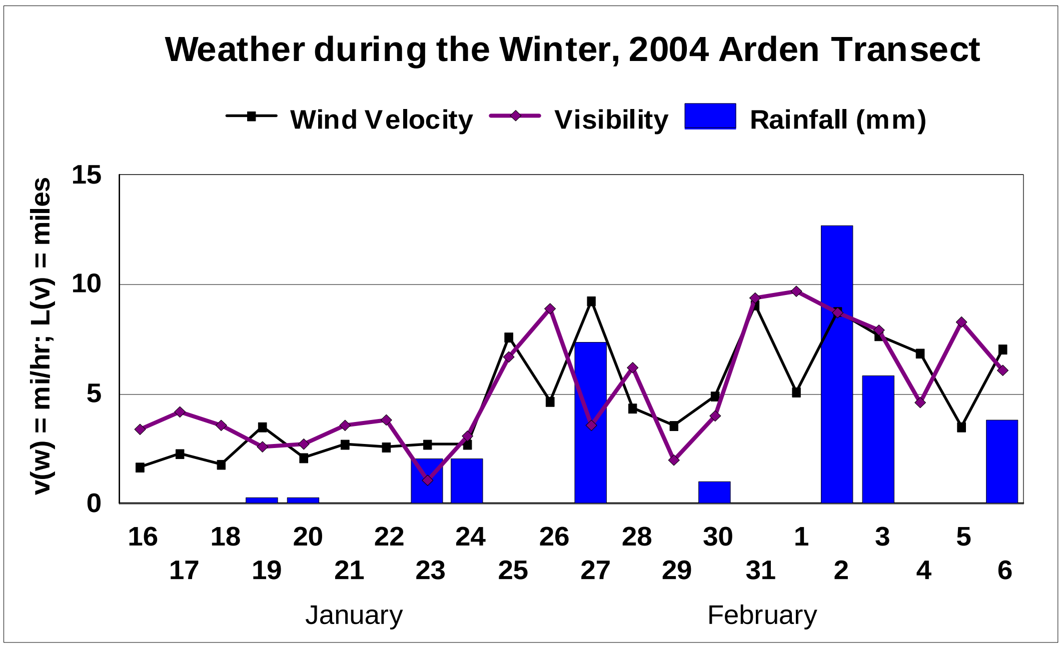


Figure 16. Sacramento weather during January and February, 2004

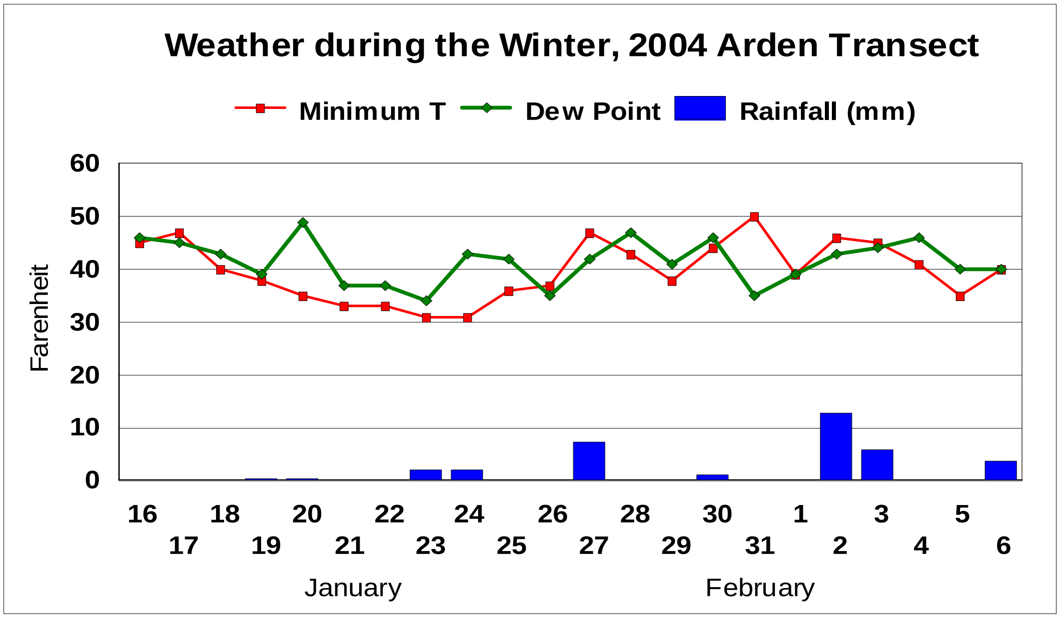


Figure 16. Sacramento weather during January and February, 2004

c. Traffic counts of cars and trucks

Figure 17 shows traffic counts made by Sacramento County during the study**.** The truck fraction was measured by the school's crossing guard.

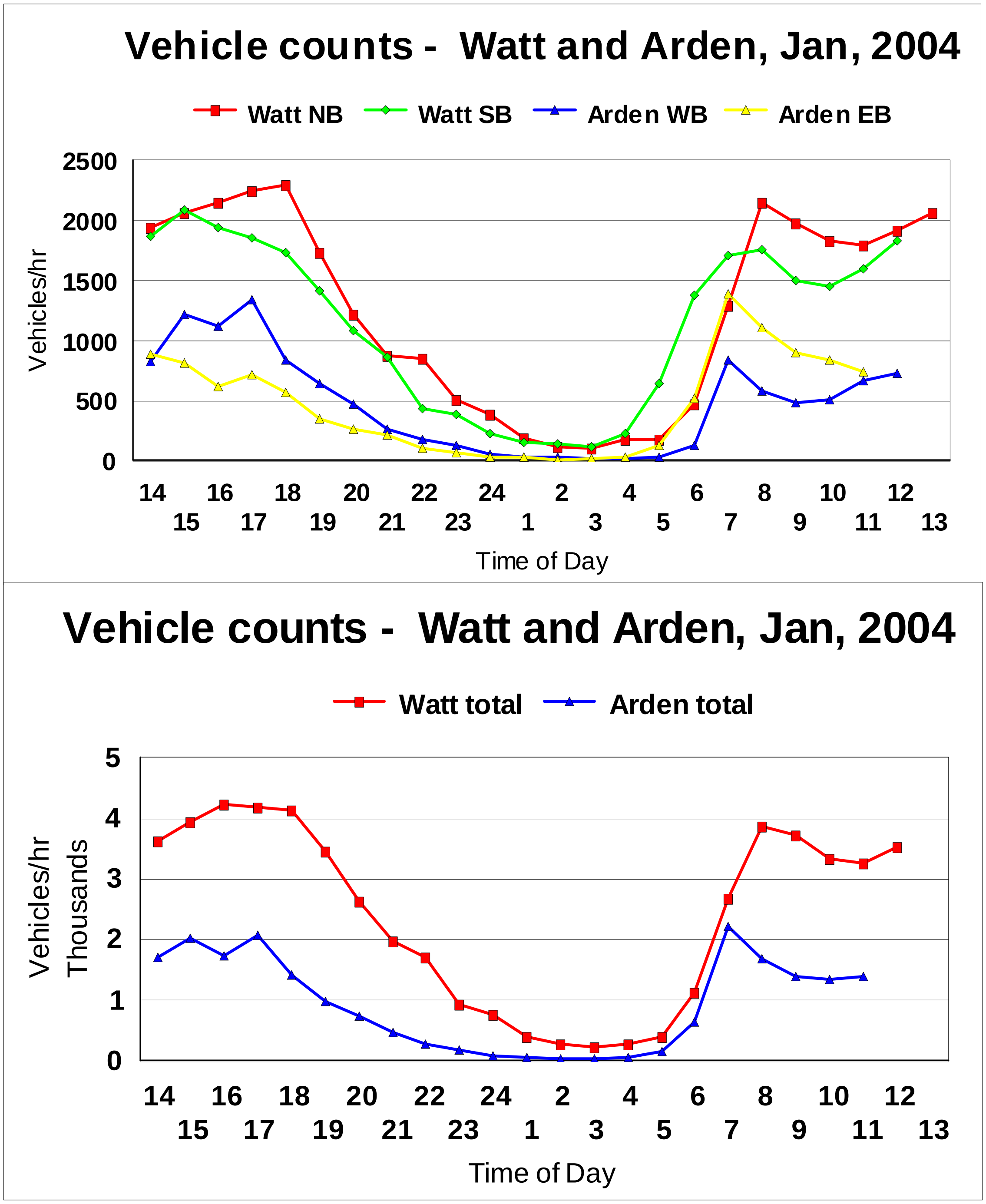


Figure 17. Traffic counts on Watt Avenue and Arden Way, January- February, 2004

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 1. Truck traffic counts at Watt Avenue and Arden Way, January, 2004

The estimated daily car count was 55,000 and the estimated daily truck count was 585. The traffic counts confirmed prior county records, indicating that roughly one percent of all vehicles on Watt Avenue are trucks, and an even smaller percentage on Arden Way.

In addition to traffic counts, another item of interest was the nature of traffic flow on Watt Avenue. The presence of the stop lights meant that cars and trucks were periodically stopped and idling at this intersection which is just upwind of Arden Middle School (ARMI). This period of idling was then followed by acceleration when the lights changed, and visible increases in smoke from nearly all diesel trucks could be seen. The measured emissions of an idling diesel truck, circa 1 g/mi, are much less than the emissions at speed, roughly .25g/mi. Thus, at 30 mi/hr, diesel truck emissions are 7.5 g/hr. This reduction is counteracted by the smoke produced during acceleration. However, since values for this idling/accelerating process are large and unknown, we simply used the emission rate at average speed and ignored both the idling and the acceleration modes.

d. Aerosol data upwind and downwind of Watt Avenue

The most important difference between Part 1 of the study compared to Part 2, was the presence of an upwind site monitor on Sebastian Way. In Figure 18, we compared the Arden Middle School (ARMI) site, which was generally downwind of Watt Avenue, with the Sebastian Way (SEWA) site, which was normally upwind of Watt Avenue, and looked at values in relation to the weather for that period shown in Figure 16. Interestingly, the highest values at the normally upwind SEWA site occurred when the wind was almost exactly south to north, so that SEWA was at least partially downwind of Watt Avenue. Note that the highest levels occurred during low wind and poor visibility conditions on January 23 and 24 as well as the effect of weekday versus weekend traffic volume and flow.

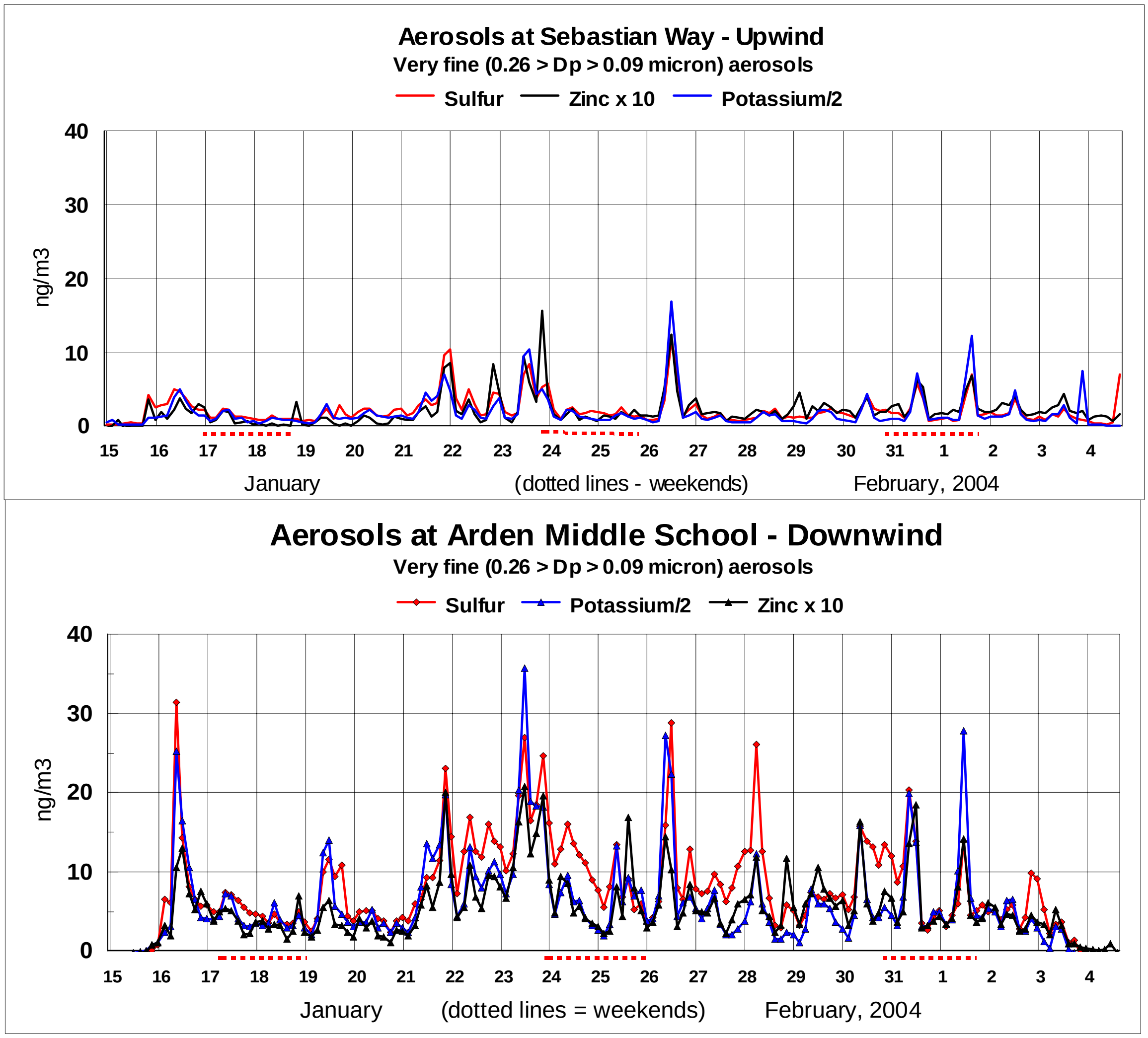


Figure 18. Composition of very fine aerosols at Sebastian Way and Arden Middle School, January – February, 2004

With the addition of mean wind velocities, and assuming a lateral movement from west to east across Watt Avenue, we were able to model the roadway and predict concentrations of both diesel and smoking cars. In the model we used the data of Gertler et al (2002) collected in the Tuscarora Tunnel study and a value which was the average of all published data after 1997.

Finally, we were able to take into account the geometrical and physical attributes associated with Watt Avenue, which has nine traffic lanes directly west of the school. The street is at grade, and no barriers exist at its downwind edge. All these factors give us confidence that we can use literature mass emission rates for diesels and cars to estimate $PM_{2.5}$ mass present downwind of roadways and ascribe the mass to cars and trucks separately. The technique used is the well tested "sliding box" model of the roadway, (Feeney et al, 1976, ff) with the top of the virtual "box" representing the top of the traffic mixed zone. The box is filled with emitted pollutants while it is being slid across the highway by the lateral component of the wind, only to be replaced by a new box filled with upwind air.

e. Execution of the "sliding box" model

Applying the "sliding box" model to Watt allows particulate values to be estimated for that edge of the roadway. Then, using data from published diffusion models, downwind particulate concentrations can be obtained based on atmospheric stability assumptions. Neutral stability (Pasquill C) was used for these calculations.

Box Model Calculations									
	Parameter	Units	Freeway 1974 Cars	I-5 cars Crocker	I-5 trucks Crocker	I-5 cars Pocket	I-5 trucks Pocket	Watt Ave cars	Watt Ave trucks
	Parameter		Lead	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
		mg/mi	48	11.52	398.4	11.52	398.4	11.52	398.4
		mg/km	30	7.2	249	7.2	249	7.2	249
"Box"	Height	m	3.5	3.5	3.5	3.5	3.5	2.5	2.5
	Width	m	60	60	60	60	60	40	40
	Length	m	1600	1600	1600	1600	1600	1600	1600
	Volume	m^3	336,000	336,000	336,000	336,000	336,000	160,000	160,000
Traffic	Daytime	veh/hr	5000	7900	325	3400	540	3800	53
	averaging		Normalized per hour	AADT/ 18 hr	AADT/ 12 hr	AADT/ 18 hr	AADT/ 12 hr)	AADT/ 18 hr	AADT/ 12 hr
Speed		mi/hr	60	45	45	60	60	20	20
		km/hr	96	72	72	96	96	32	32
# vehicles	in "box"	#	83	176	7	57	9	190	3
Emissions		mg/min	4000	2022	2877	653	3586	2189	1056
Concentration per minute	in "box"	$\mu g/m^3$	11.9	6.0	8.6	1.9	10.7	13.7	6.6
Wind	lateral	m/s	3	2	2	2	2	2	2
"Box" translation	lateral	s	20	30	30	30	30	30	30
	Fraction of minute		0.33	0.5	0.5	0.5	0.5	0.5	0.5
Concentration	in "box"	$\mu g/m^3$	3.97	3.0	4.3	1.0	5.3	4.6	2.2
			(lead)	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$	$PM_{2.5}$
Concentration all vehicles	in "box"	$\mu g/m^3$	3.97		7.3		6.3		6.8
Measured all vehicles	at edge	$\mu g/m^3$			10.0		na		7.0

Table 2. Execution of the "sliding box" model, at Interstate-5 and Watt Avenue (just south of Florin Road)

Actual traffic data were used, but estimates are made on diurnal traffic patterns. Wind estimates are from the NOAA HYSPLIT regional model and local weather data (Weatherunderground.com). The height of the "box" is based on measurements of truck fraction and velocity (ARB Freeway Report 1974) is uncertain to at least 30%. Emission rates are from the Gertler et al (2002) Tuscarora Tunnel data, which assumes freely moving traffic and warmed engines that are not a good representation for Watt Avenue.

f. Line source dispersion modeling

We used the measured fall off for lead at a neutral stability class Pasquill stability class C (x 0.75) to predict the values at the Arden Middle School sampling site (which sits roughly 40 meters from the downwind edge of the roadway).

Roadway	**Distance**	**27 m**	**40 m**	**100 m**	**160 m**
At grade	*Calculated*	*4.0*	*3.4*	*1.4*	*0.41*
At grade	Measured	4.0	**3.1**	1.4	0.35
			Arden		
Depressed	Measured	4.5	1.7	**0.26**	
				Crocker	
Elevated	Measured	4.8	2.3	3.1	(3.5)

Table 3. Effect of roadway distance and configuration on downwind concentrations of lead

Predictions
Average of literature values 7.7 μg/m^3
Gertler et. al values 5.4 μg/m^3
Observed
ARB's upwind values 7.0 ± 1.5 μg/m^3

Considering the uncertainties in the literature data and atmospheric stability, these results are in about as good agreement as one can expect. Nevertheless, we can now, with some confidence, predict that the unmeasured parameter on the earlier ARB report on Watt Avenue (2002), the presence of diesel exhaust, can be set at 2.3 μg/m^3. Primary particulate pollution from cars can be set at roughly 4.7 μg/m^3.

From these values, one can calculate the lifetime risk of cancer using the estimates in the ARB Almanac, which assigns roughly 70% of all toxic air contaminants risk in California to diesel exhaust. We will not do this, however, since there is the additional complication of twice as much fine particle mass from cars than from diesel trucks. These fine particulates are of unknown toxicity. However, recent reports (Gertler at al, 2002; Fujita et al, 2004) find higher levels of known toxic compounds in car smoke than diesel smoke.

g. Information from size/composition profiles

A more complete analysis of downwind aerosols at Watt Avenue was conducted in Part 2 of the study. With these values, we will be able to directly compare the results of the Gertler et al 2002 Tuscarora Tunnel study with the ambient aerosols at Arden Middle School. With this comparison, we also gain access to extensive compositional measurements in the Tuscarora Tunnel Study, including toxic air contaminants such as PASHs which could not be measured as part of the present study.

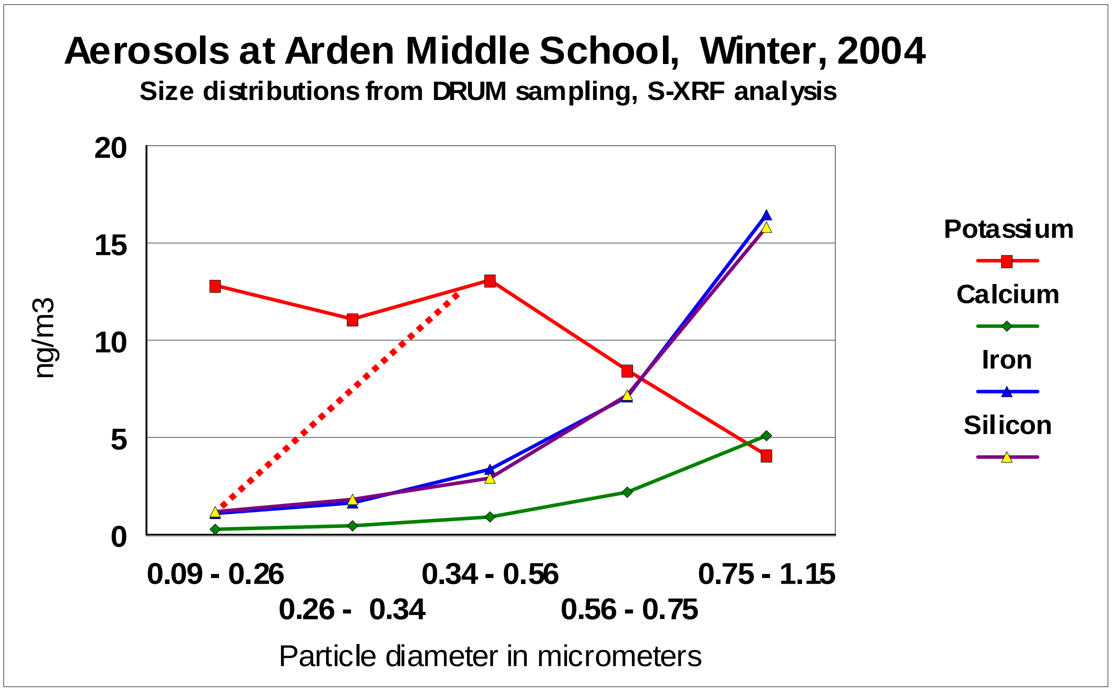


Figure 19. Typical soil derived elements downwind of Watt Avenue

In Figure 19, note that all the elements except potassium, reach very low levels in the fine size mode. This is a validation that the DRUM sampler is operating properly and not allowing particles to be mis-sized as a finer stage. Note also that potassium strongly deviates from the other crustal elements, on the order of 25 in the size mode 0.34 to 0.56 µm. This measurement is the signature of biomass smoke, with the typical extension to finer particles shown by the dashed line (Turn et al, 1997). Note that the very finest potassium sharply deviates from the other elements, with massive enhancements in the 0.09 to 0.26 µm mode. This is the signature of high temperature combustion such as from diesels and smoking cars.

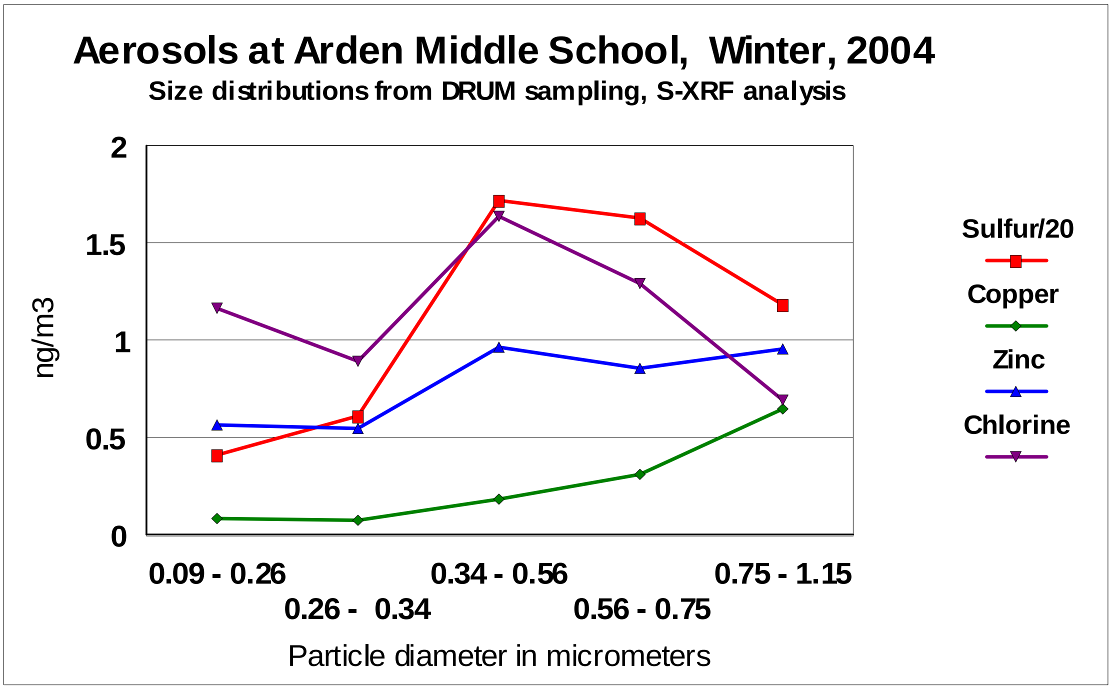


Figure 20. Sulfur and transition metals downwind of Watt Avenue

Figure 20 confirms the presence of direct automotive emissions of very fine particles. The zinc captured in the larger size modes has several sources, including tire wear. However, in the very finest modes, it is dominated by zinc thiophosphate, a stabilizing agent in lubricating oils.

C. Conclusion

Highways and heavily traveled urban arterials are impacting people living near them. Very fine, harmful and toxic particles largely from smoking cars, are spreading farther from their sources than anticipated. However, these effects can and should be mitigated, both immediately and over time in conjunction with long term planning.

D. Mitigation

Three methods to minimize the impact of these aerosols are suggested. They include: reduction of the source (the best way), reduction of source to receptor transport and reduction of pollutant concentrations at the receptor, especially in indoor environments.

1. Source reduction

Source reduction can involve a wide range of activities that reduce emissions from within the right-of-way of the roadway, including reducing the emissions/vehicle, reducing the number of vehicles, and designing roadways in ways to enhance dispersion.

a. Reduction of on-roadway source strength and toxicity.
This involves efforts by the ARB and EPA to control emissions via fuel and engine changes. The success achieved to date with spark ignition vehicles in California is stunning, with 2/3 of all cars contributing only about 10 percent of the automotive pollution. (see Appendix C and references therein)

b. Control of gross emitting cars.
From the information in Figure 21 and Appendix C, it appears that a small fraction of all cars on the roadway contribute almost all automotive pollution. This encourages techniques to identify these vehicles on the highway such as through call-in numbers for smoking vehicles. Additionally, road side emission testing via infrared beams, and the addition of a smoking test to vehicle inspections, can be combined with a financial incentive for lower-income car owners to fix their cars.

c. Control of the toxicity of spark emission lubricating oils.
Efforts to identify cars that use excessive oil, most also likely gross emitters of many pollutants, and have them repaired will help address this problem. The advantage of this approach is that many "gross emitters" don't know that their exhaust is smoky, but they all are of necessity sensitive to oil use.

d. Continued efforts at eliminating and controlling diesels.
Efforts to reduce emissions from diesel-powered heavy duty on-road and off-road vehicles should include: stringent emission standards for new diesel engines; strong requirements for retrofitting and replacing existing engines with the best available technologies; utilization of cleaner alternative fueled vehicles and advanced technologies such as CNG, fuel cell or electric vehicles where feasible, especially in centrally fueled fleets; and increased funding for incentive programs such as the Carl Moyer Program and the Lower Emission School Bus Program.

e. Use of cleaner technologies.
Increase production and utilization of cleaner technologies for light-duty vehicles such as hybrid and natural gas technologies in the short term, and hydrogen fuel cell technologies in the future.

f. Smog Check program improvements.
Adopt improvements to the smog check program to achieve much needed reductions in light duty in-use emissions through updating program design, improving the accessibility of repair funds for lower-income car owners that fail smog check, and adding a smoke opacity standard to the test.

Figure 21 shows that the improvements in diesel engines have not been shared by the average automobile fleet, whose emissions are dominated by a small fraction of gross emitting cars with and without visible smoke. Additional data on these engines can be found in Appendix C.

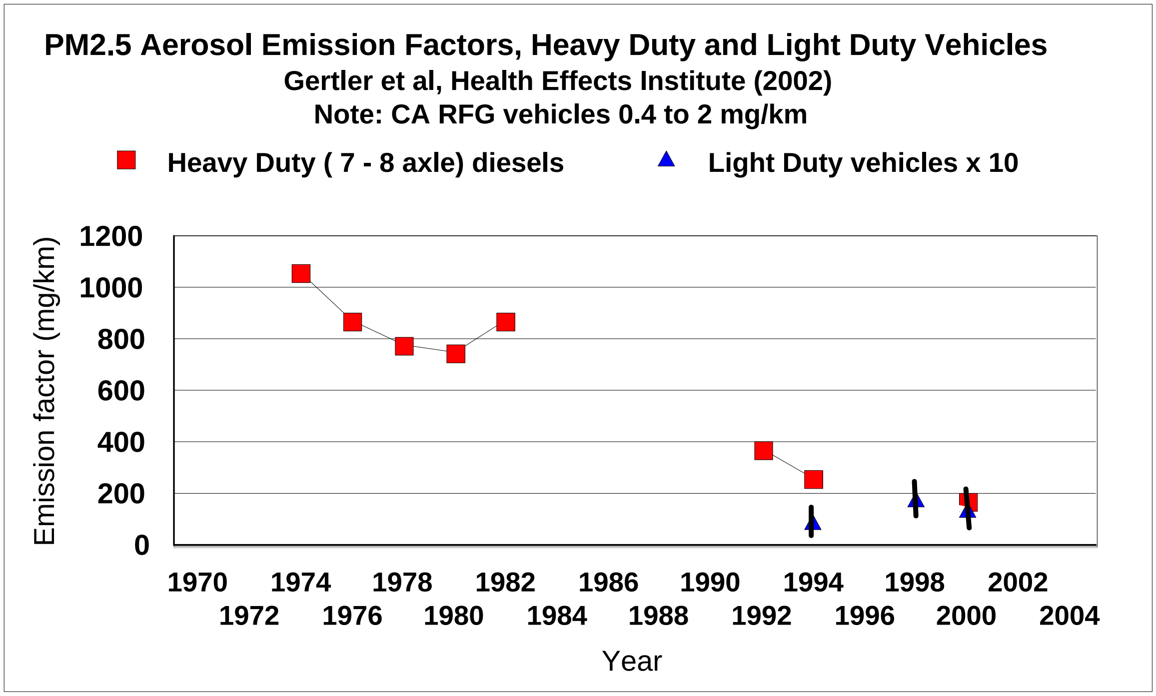


Figure 21. Aerosol emissions from heavy duty and light duty vehicles over time

g. Instituting a statewide call-in phone number for visibly smoking vehicles, with follow up programs and quarterly summary of smoking cars by type for each air basin.

h. Changes should be made in roadway design for all new roads with predicted traffic volumes above some agreed upon level. These designs, including depressed roadways and median vegetation, can encourage ventilation and diffusion that enhance the natural tendency for the warm vehicular exhaust to loft above the roadway and downwind areas.

The aerodynamics of roadways are rarely, if ever, considered in roadway design. However, we must assume under the "precautionary principle" that there will always be some pollutants from roadways merely because a great deal of energy is involved in transportation. The effect of highway design can be seen in early work on lead. From Table 3 (see page 30), it can be seen that the at-grade section matches models to measurement, but the depressed section for several reasons has far less effect on the immediate downwind neighborhood than the at-grade section.

Conversely, the elevated freeway was by far the worst in propagating pollutants into downwind neighborhoods. In a previous report, (Cahill et al, 1974) the temperature rise of the depressed freeway, circa 1 ^{o} C /min at 250,000 vehicles/day, lofted pollutants upward and drew clean air down the embankment to fill the partial vacuum.

i. Traffic reduction efforts, including alternative transportation, high occupancy vehicle lanes, especially at critical roadways, including at critical times.

2. Reducing transport from roadways to receptors

Transport of pollutants from roadways to receptors can be sharply and quickly reduced in a number of ways, but far less work has been done on this topic than for source reduction.

a. Roadway design changes in typically downwind directions, including downwind buffer space. The recent requirement that any school within 500 feet of a heavily traveled road must analyze air impacts is a step in the right direction.

b. Sound walls by themselves have been shown to be relatively ineffective, but clearly help to some degree.

c. Trees, especially non-deciduous trees with high surface area (deodars, redwoods, junipers, ..) can both remove particles, especially the most dangerous very fine particles, in air that passes through the vegetation, while tending to force pollutants up and away from ground level receptors

In the example of the depressed freeway (Cahill et al, 1974), there were also walls of vegetation at the embankment lip, which provided both a direct pollutant transfer barrier and enhanced the chimney effect of the warm, depressed freeway. Regretfully, the recent literature lacks much analysis of pollutant transfer across barriers.

3. Mitigation at the receptor

Finally, actions can be taken at the receptor to reduce exposure. These include:

a. Appropriately locating building air inputs

Clearly, having an open window look out directly into a traffic source enhances pollutant transfer and thus exposure.

b. High efficiency filtration

Particulate pollutants can be reduced to extremely low levels by filtering input and ambient indoor air. This should be done in conjunction with effort to eliminate indoor sources.

c. Scheduling outdoor activities to avoid peak pollution periods

This is particularly important for sports, during which particles can be more easily drawn into the lung when breathing hard. High pollutant periods can often be identified by hazy periods with low wind velocities and high particulate drive Air Quality Index (AQI) reports, often in winter.

d. Avoidance

Problem locations can be avoided when pollutant levels are predicted to be elevated.

Acknowledgements

This report is a product of the American Lung Association of Sacramento-Emigrant Trails Health Effects Task Force, whose members were integral to the project from the beginning to the end, including contributions to the final report.

Members are: *Jananne Sharpless, Chair, Michael Lipsett, M.D., Glenna Trochet, M.D., Earl Withycombe, PE, Helene Margolis Ph.D., Tom Cahill, Ph.D., Bonnie Holmes–Gen, Ralph Propper, MS, Charles Plopper, Ph.D., Linda Davis-Alldritt, R.N.*

We could not have done this study without the support of personnel at the Arden Middle School and San Juan Unified School District who permitted placement of the drum sampler directly downwind of Watt Avenue and supervised collection of truck traffic counts on Watt Avenue, the Sacramento County Department of Transportation which provided traffic count data of both Watt Avenue and Arden Way, and Warren Harding whose back yard served as the upwind site for this study.

The preparation and loan of the air samplers and part of the analysis of the samples was volunteered by members of the DELTA Group, Departments of Applied Science, Chemical Engineering/Materials Science, and Land, Air and Water Resources, University of California, Davis. The equipment was bought and prepared as part of NSF grant ATM 0090225 for ACE-Asia.

Finally, this project was supported and funded by the Sacramento Metropolitan Air Quality Management District, and the Yolo-Solano Air Quality Management District.

Bibliography

Bench, Graham, P.G. Grant, D. Ueda, S.S. Cliff, K.D. Perry, and T. A. Cahill. The use of STIM and PESA to respectively measure profiles of aerosol mass and hydrogen content across Mylar rotating drum impactor samples. 2001 *Aerosol Science and Technology,* 36:642-651.

Cadle, S.H., Gorse, R.A., Bailey, B.K., and Lawson, D.R., Real-Eorld Vehivle Emissions: A summary of the Twelth Coordinating Research Council On-Road Vehicle Workshop. J. Air and Waste Management Assoc. 53, 152-167 (2003).

Cahill, T. A., P. Feeney, R.G. Flocchini, and T. Dunn, Particulate Matter from California Freeways. Final Report to the California Air Resources Board (1974).

Cahill, T.A., C. Goodart, J.W. Nelson, R.A. Eldred, J.S. Nasstrom, and P.J. Feeney. Design and evaluation of the drum impactor. *Proceedings of International Symposium on Particulate and Multi-phase Processes.* Teoman Ariman and T. Nejat Veziroglu, Editors. Hemisphere Publishing Corporation, Washington, D.C. 2:319-325. (1985).

Cahill, T. A, and E. Gearhart, Atm. Science 274, Davis Transect Report (1994).

Cahill, T.A., PI and Project Manager, Steve Cliff, Michael Jimenez-Cruz, and Kevin Perry, Elemental analysis of diesel particles from MOUDI samplers. Final Report to Barbara Zielenska, Desert Research Institute/NREL, March 15, 2002.

Cahill, Thomas A., Steven S. Cliff, Kevin D. Perry, Michael Jimenez-Cruz, Graham Bench, Patrick Grant, Dawn Ueda, James F. Shackelford, Michael Dunlap, Michael Meier, Peter B. Kelly, Sarah Riddle, Jodye Selco and Robert Leifer, Analysis of Aerosols from the World Trade Center Collapse Site, New York, October 2 to October 30, 2001. Aerosol Science and Technology Feb, (2004)

Courtney, W.J., S. Rheingrover, J. Pilotte, H.C. Kaufmann, T.A. Cahill, J.W. Nelson. Continuous observation of particulates during the general motors sulfate dispersion experiment. *Journal of the Air Pollution Control Association.* 28:225-228 (1978).

Devlin, Robert B, "Health effects of PM; What we know and what we think we know. Is it enough?" Plenary Invited talk, AAAR meeting, Charlotte, NC (October, 2002).

Dutcher, Dabrina D, Kevin D. Perry, Thomas A. Cahill and Scott Copeland. Effects of indoor pyrotechnic displays on the air quality in the Houston Astrodome. *Journal of the Air and Waste Management Association*. Vol. 49:156-160 (1999)

Feeney, P.J., T.A. Cahill, R.G. Flocchini, R.A. Eldred, D.J. Shadoan, and T. Dunn. Effect of roadbed configuration on traffic derived aerosols. *Journal of the Air Pollution Control Association.* 25:1145-1147 (1975).

Fujita et al (2005)

Gertler, A. W., J.A. Gillies, W.R. Pierson, C. F. Rogers, J.C. Sagebiel, A-A. Mahmoiud, W. Coulombe, L. Tarnay, and T.A. Cahill. Emissions of Diesel and Gasoline Engines measured in Highway Tunnels. HEI Research Report 107, pg 2 - 56 (2002).

Norbeck, J.M., T.D. Durbin, and T.J. Truex, Measurements of Primary Particulate Matter Emission From Light Duty Motor Vehicles. Final report to the Coordinating Research Council, South Coast Air Quality Management District (SCAQMD) (1998).

Perry, Kevin D**.** Effects of outdoor pyrotechnic displays on the regional air quality of western Washington state. *Journal of the Air and Waste Management Association*. Vol. 49:146-155 (1999).

South Coast Air Quality Management District (SCAQMD), Results of the 1-800 CUT SMOG Program, http://www.aqmd.gov/smog/cutsmog.html, SCAQMD (2003).

Turn, S.Q., B.M. Jenkins, J.C. Chow, D. Campbell, T. Cahill, and S.A. Whalen, Elemental characterization of particulate matter emitted from biomass burning: Wind tunnel derived source profiles for herbaceous and wood fuels. Journal Geophysical Research Vol. 102, No. D3, pgs 3683 – 3699 (1997).

Zielenska et al (2004).

Zhu et al (2002).

Other informational resources

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

Appendix A

(new sections only; consult "DRUM Quality Assurance Protocols DQAP ver 1/05" at http://delta.ucdavis.edu for the full text)

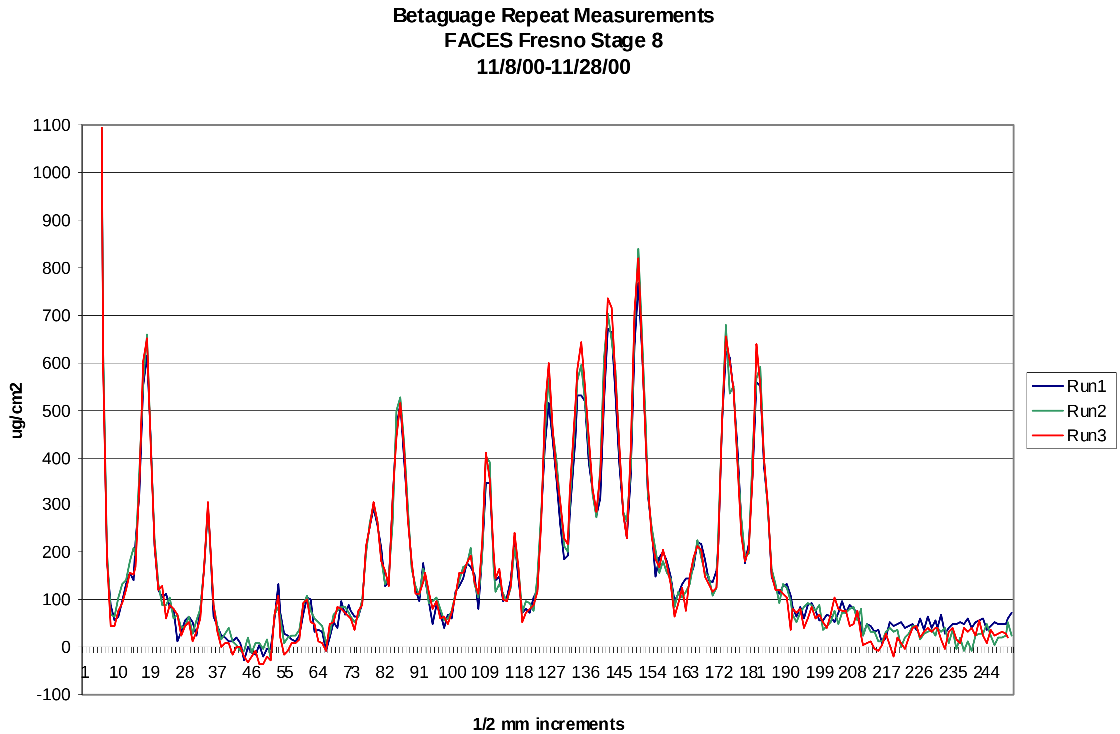
Quality Assurance and Documentation

All data on sampler operation and analytical protocols are contained in DELTA Group DRUM Quality Assurance Protocols ver. 9.02, (DQAP ver 9.02) one copy of which will be transmitted to ALASET. A few relevant pages are given below.

Mass by soft beta ray transmission

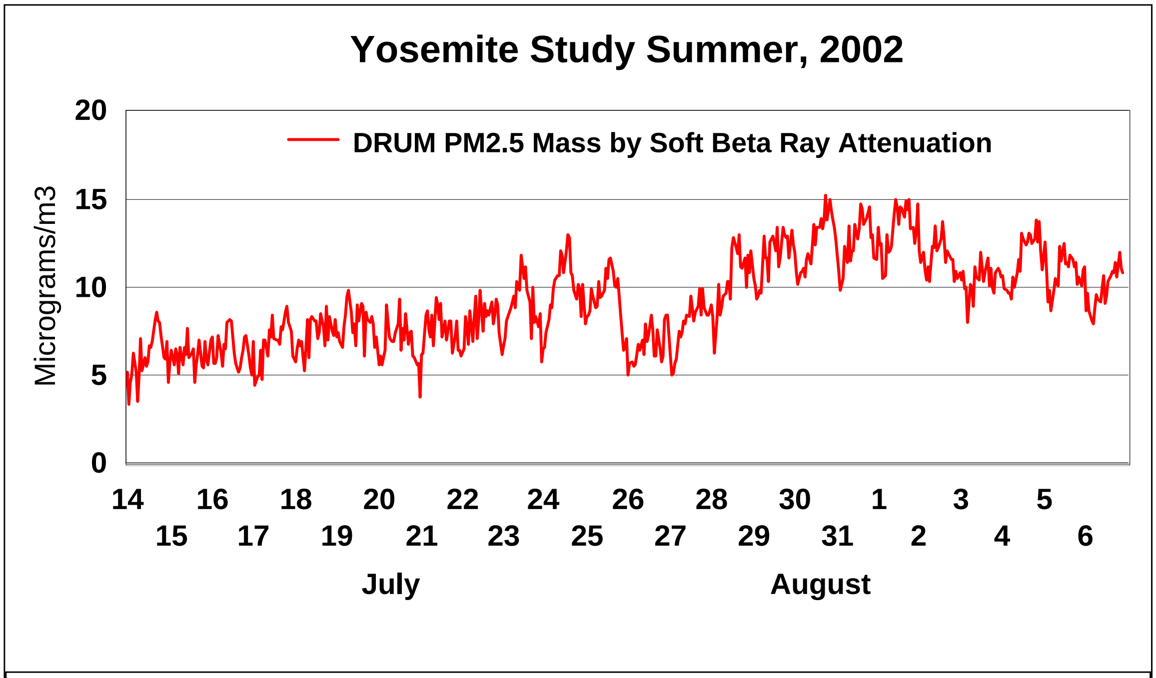
One of the major barriers to wide use of impactors in aerosol research is the difficulty of measuring mass as a function of size and time. The DELTA Group has developed a soft beta ray transmission mass technique, very similar to common devices such as the commercial BAMS beta ray mass units. In both cases, mass is inferred by examining the decrease in electron flux as it passes through a sample. This decrease is only a very weak function of composition, and can be calibrated by mass standards. For the DRUM impactor, the energy of the beta was greatly reduced to match the thin substrates used, with the choice being 70 keV Ni^{63}. This results in a 30 percent decrease in flux for a few 100 μg/cm^2 of mass. The sample is stepped through the unit in increments that can range from 500 μm (3 hr) to 125μm (45 min), but the latter is not achievable in practice since the impactor slots are also about 125 μm wide and thus blur the time resolution.

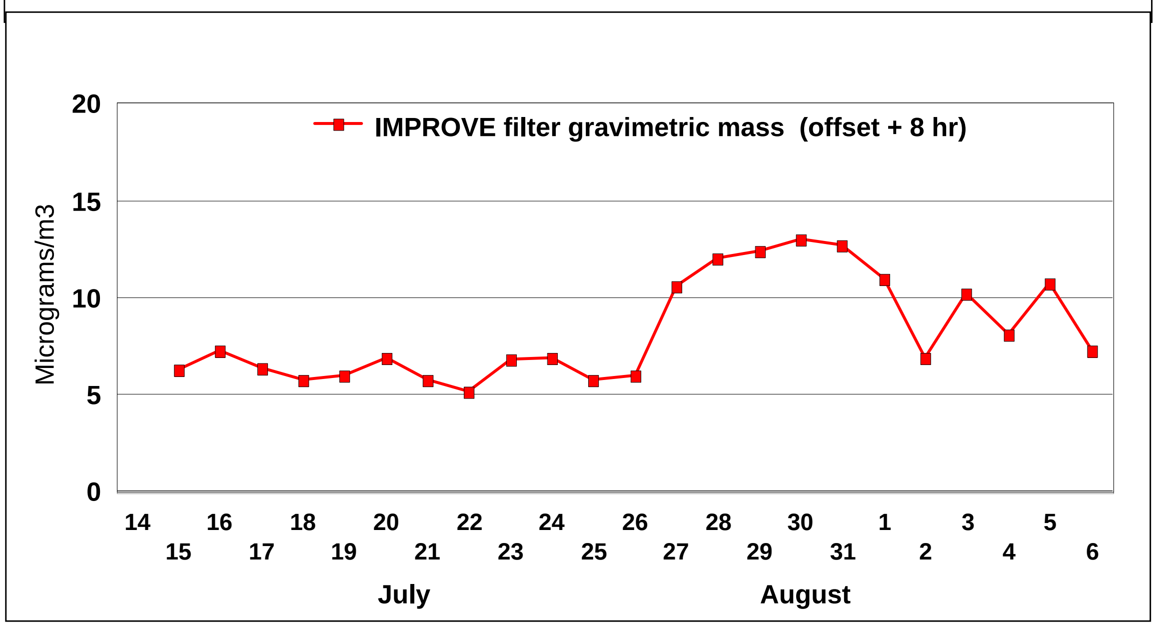
The accuracy and precision of mass by soft beta ray transmission are shown below. These samples are from the very fine mode of the DELTA 8 DRUM, the same configuration used for the ARB 13 & T site and reported in Bench et al 2002 as part of pre-study test for FACES, November, 2000. The masses were highly correlated with the STIM data. The largest peak at location 150 is equivalent to approximately 18 μg/m^3. The off-scale reading at the far left is from a timing marker.

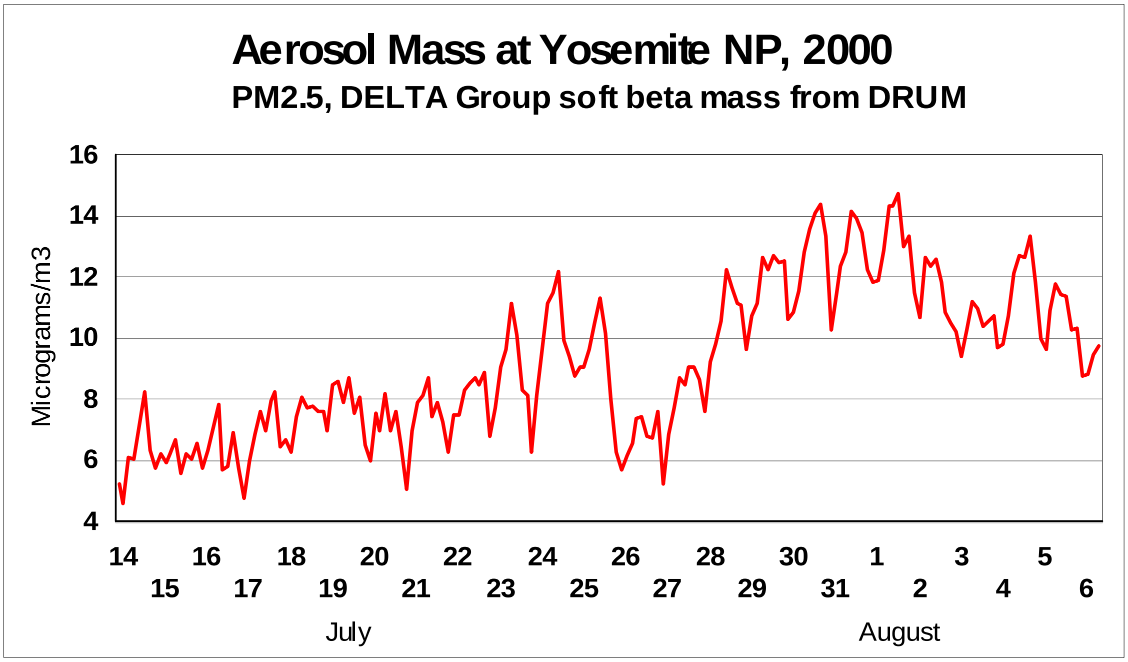


A recent comparison of mass by IMPROVE and mass by soft beta ray transmission (β – mass) from an 8 DRUM sampler was performed at Yosemite NP, summer, 2002. Note that it took 96 individual mass measurements from the DRUM (6 stages below PM2.5 times 16 measurements/day) to equal a single measurement from IMPROVE, which would emphasize any off-set error in the β – mass values. Note also that the total masses were quite low at the Turtleback Dome IMPROVE site around 6,000 ft elevation.

The mass and optical data were originally proposed at a very high time resolution, 1 hr, but the small amount of mass required averaging to 3 hr. Below we show the mass measured on the 8 DRUM sampler by soft beta ray transmission versus gravimetric mass by IMPROVE filters at the TUDO site. Recall that it takes 144 individual 1 hr mass values measurements to equal a single 24 hr $PM_{2.5}$ filters. It is clear from these data that there is no large systematic error involved.


Yosemite Study Summer, 2002
DRUM PM2.5 Mass by Soft Beta Ray Attenuation
Micrograms/m3
0
5
10
15
20
14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6
July
August


IMPROVE filter gravimetric mass (offset + 8 hr)
Micrograms/m3
0
5
10
15
20
14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6
July
August



Comparisons of S-XRF to CARB XRF and RAAS data (from DQAP ver 1/05)

As part of the CARB FACES study in Fresno, Dichot filters (Coarse and $PM_{2.5}$) and RAAS data ($PM_{2.5}$) were provided to insure inter-comparability of data versus S-XRF filter data

In summary, there was excellent agreement between ARB Dichot and DELTA S-XRF Dichot analyses:

> Ratio 1.02 $\pm$ 0.11, 16 measurements, with the minimum ratio 0.7 and the maximum ratio 1.7.

However, ARB Dichot and ARB RAAS data had much poorer inter-comparison,

> Ratio 1.29 $\pm$ 0.63, 16 measurements, with the minimum ratio 0.6 and the maximum 4.35.

as did the DELTA S-XRF Dichot and the ARB RAAS,

> Ratio 1.29 $\pm$ 0.58, 16 measurements, with the minimum ratio 0.42 and the maximum 3.86.

The comparison of ARB Dichot to ARB RAAS for lead was poor,

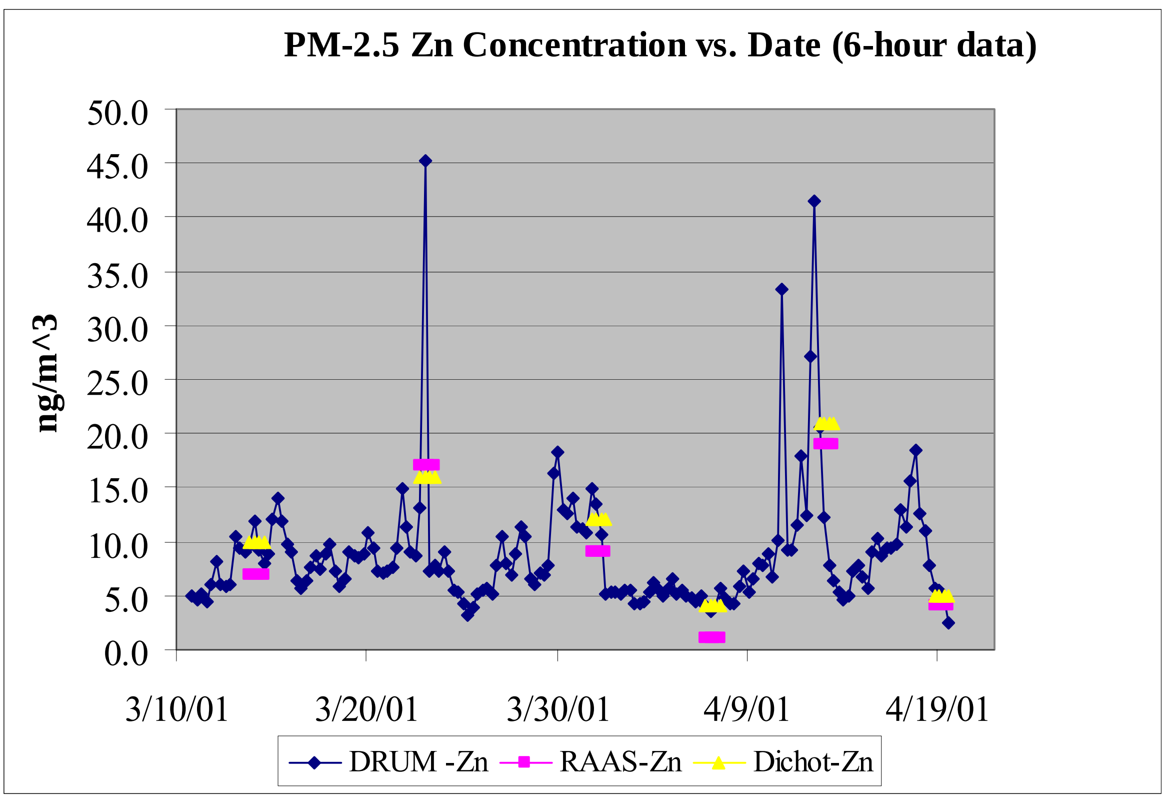
> Ratio 2.83 $\pm$ 1.37, 4 measurements, with the minimum ratio 1.16 and the maximum 4.94.

Examples of these data are plotted below. The one to one line is plotted in each case. It is not a fit to the data.

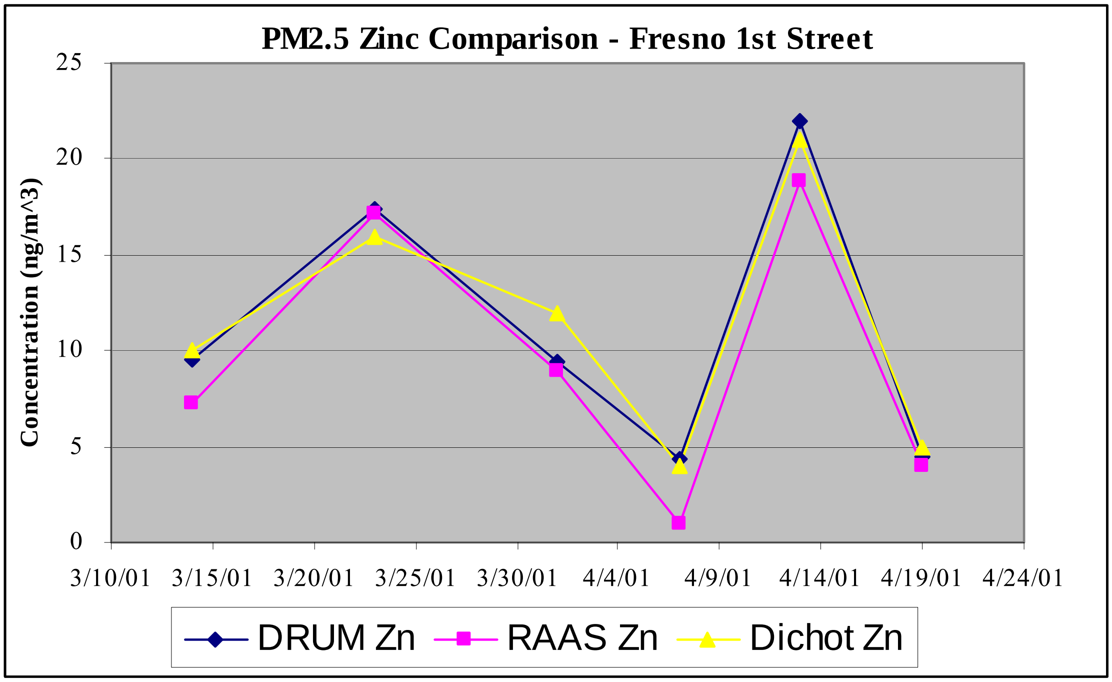
The FACES program also provided a direct comparison of UC DELTA Group DRUM data with ARB Dichotomous sampler and RAAS data. We use for this comparison zinc, since a) all analytical methods agreed for zinc, b) it had an extreme variability in time and was thus a severe test of timing for the DRUM, and c) it is an important tracer of diesels and smoking cars via the zinc thio-phosphate stabilizing agent in most lubricating oil.

Below we show a time series of $PM_{2.5}$ Zinc concentration. Note large spike of Zn of short duration on April 13, 2001. The 24 hour average concentration for 4/13/01 is approximately 20 ng/m^3 according to DRUM, RAAS, and Dichot data. The 24-hour filter data are superimposed for comparison.

Originally, in the preliminary data, we had made an error of 6 hr in DRUM timing, which made a factor of 2 error in the DRUM concentration on April 13. This is an inherent problem with continuous drum sampling, It is very hard to exactly match 24 hr filters when species such as zinc (below) vary so wildly in time. However, this "wild variation" is totally hidden in 24 hr filter sampling, even though it might be critical to short time health responses such as asthma.



In the figure below, we show the time corrected PM2.5 comparison for zinc at Fresno site. Note similarity between 3 independent sampling methods.



For more details and many other examples, please consult DQAP ver 9.02.

Appendix B

Limitations and Advantages of DRUM sampling protocols

The HETF of ALASET used DRUM sampling protocols for the Sacramento/I-5 Transect Study in preference to filter sampling protocols. This choice presented both advantages and limitations in regard to more standard filter based techniques, which we will summarize in this Appendix. Detailed comparisons are found in the DRUM Quality Assurance Protocols ver. 9/02, which is an integral part of the study.

The key reason for our choice was the well recognized inadequacies of filter based techniques for research in aerosol source identification and impacts on health and welfare. These include:

1. Integration over particle sizes, originally 35 µm to 0 µm (TSP), then 10 µm to 0 µm (PM_{10}), and now 2.5 µm to 0 µm ($PM_{2.5}$). Both visibility (Mie Theory) and human health research indicate that portions of these size ranges are far more important than the integrated range (EPA PM Criteria Document 600-P, 1996, Devlin, 2002).

2. Integration over time, with massive diurnal changes and sharp episodes of mass hidden in the daily average. This is even more of a problem when a one-day-in-three or other such limitation is imposed on sampling frequency.

3. Integration over composition to get mass. Both federal and state regulations for aerosols are based on mass data generated from filter based technology, when all evidence shows that health effects are compositionally dependent. For this reason, first IMPROVE under UC Davis and now the US EPA have instituted compositional measurements on a national grid.

There are additional problems with filters, including artifact mass loss, mass gain, and compositional changes, problems that become more acute as one moves away from mass and into compositionally segregated data. In addition, infrastructure requirements and analytical costs/filter make large filter based studies costly. These limitations are so severe that in one recent review article (Watson, AWMA 2002) a prediction was made that in the not to distant future filter methods would be almost entirely supplanted by continuous methods. Many groups, including both UC Davis and the ARB, are moving to newer continuously sampling protocols.

The UC Davis DELTA Group approach to continuous sampling is through DRUM (Davis Rotating-drum Unit for Monitoring) protocols which consist of three components:

1. Particle size separation by inertial impaction and collection onto slightly sticky substrates,
2. Slow translation of impaction surfaces on a drum, and
3. Non-destructive mass and compositional techniques designed for the small amounts of mass collected on the substrates.

Inertial impaction. Particle size separation for the UC Davis DRUMS follows the well established theory and validations of Marple, Rao, and co-workers at the University of Minnesota, (1974 – 1981) and the theory and validations for the UC Davis DRUM sampler of Cahill et al (1985), Raabe et al, (1989) and Cahill et al (1992), the latter as part of the ARB MSAM Project. The important point is that for the two configurations used at UC Davis, the single circular orifice and the semi-infinite slot, the theory is simply basic aerodynamics and can be solved analytically and exactly. Thus, calibrations merely confirm the theory, unlike samplers such as the U. Minnesota MOUDI where every stage must be studied separately as it can not be solved analytically. Note that the sampler is only 18" high, weighs 20 lbs, and uses only 350 watts, allowing easy siting in back yards and roof tops.

Impaction results in a difference from filters in that the impactor cuts are much sharper than the typically softer cut points of filter samplers, so that if much mass lies around a given cut point (say, $PM_{2.5}$) the impactor will give a different value than a filter based system. This was the reason that the US EPA went to the sharper double-cut WINS well impactor for the national $PM_{2.5}$ sampler. A final limitation of the present DRUM is that we are unable to continuously sample particles smaller than 0.09 µm, which are either not sampled (the present study) or collected on manually-changed filters (DELTA Group current practice), which then requires additional costs and labor.

Slow translation. The slowly moving substrate of the DRUM sampler allows continuous sampling, typically for 6 weeks at a time (4 mm/day). The advantage of this protocol is that one can later establish any desired time resolution (down to about 1 hr) any time within the 6 week period. The limitation is that the small amount of stretch in the thin Mylar substrate results in a time error, typically 1 mm/6 weeks, which turns into 6 hrs. Thus, what is simple with a filter (say, midnight to midnight, ± 1 second) is impossible for the DRUM, which can do no better than about ± 1 hr in a 6 week sample, even using our new timing protocols, since the impactor slot is about 1 hr wide.

DRUM analyses. The rotating drum impactor was first designed by Lundgren in 1967, yet has been used only sparingly and in research modes for the past 35 years (key exceptions: ARB, 1973-1977, and US EPA, 1977 -1979). This was mostly because analytical protocols were inadequate to give mass and composition from the miniscule deposits delivered by a rotating drum impactor. This limitation is inherent, for one can not put too much mass on an impaction surface without risking miss-sizing by particle bounce (hence the sticky substrates used by UC Davis). The early rotating drum analyses were almost entirely done by particle induced x-ray emission (PIXE) which required an accelerator and was thus of limited availability and quite expensive.

The UC Davis DELTA Group was formed in 1997 with an explicit goal to further develop DRUM protocols, sampling and analysis, to achieve higher accuracy and precision and improved compositional analytical capabilities, including mass which heretofore was not done with DRUM samplers.

For mass measurements, the problem is compounded by the nature of continuous size resolved sampling. For example, to match a single 24 hr $PM_{2.5}$ filter mass measurement, a DRUM protocol has to make 8 measurements/day (3 hr time resolution) on each of the 6 sub-2.5 μm DRUM stages, or 48 individual mass measurements. The propagation of error requirements are thus extreme. However, there is one advantage because mass measurements on impactor samples on Mylar substrates are largely insensitive to relative humidity, a major problem with both discrete and continuous filter based mass measurements.

For compositional analysis, a good XRF measurement of 30 elements costs commercially somewhere between \$50./sample and \$200./sample, depending on the sensitivity desired. Even using the lowest cost, a single 24 hr day of 3 hr time resolved composition by commercial XRF from a DRUM sampler would cost roughly \$2,500., even if they could achieve the sensitivity of DELTA Group S-XRF (which they can not). Thus, cost reduction was a major goal that had to be achieved for continuous size resolved compositional analysis could become widely useable.

The present DELTA Group protocols include: (see DQAP ver. 9/02)

Mass by soft beta attenuation (β-mass) (Portnoff et al, in prep, 2003)
Mass by scanning transmission ion microscopy (STIM) and
Hydrogen by proton elastic scattering analysis (PESA) (Bench et al, 2002)
Elements by synchrotron-x-ray fluorescence (S-XRF) (Cliff et al, prep. 2003)
Optical attenuation versus wavelength (λ-optical) (R. Miller, thesis, 2003)
Single particle analysis (SEM, TEM) (Shackelford et al, 2003 in prep)

Most of these were featured in just published articles on the large NSF ACE-Asia Study (Seinfeld et al, 2003) and the World Trade Center aerosols study (Cahill et al, 2004), which also included other techniques, including organic matter (GC/MS and LDIOTPF/MS) that are under development. Users of DELTA Group DRUM protocols in the most recent 3 years includes US EPA (2 programs), NPS (2 programs), USFS, NASA, NOAA (2 programs), DOE (2 programs), and DOD (3 programs), multi-state organizations LADCO, NESCAUM, and TRPA, plus California and Alaska.

Detailed comparisons of S-XRF DRUM results with filter based analyses (IMPROVE, ARB, …) in blind tests are included in DQAP ver. 9/02, showing excellent agreement (average ratio, 3 extensive recent comparisons, 1.08 ± 0.10) with the most accepted standard protocols and higher sensitivity than any alternative method. Earlier results with prior versions of the DRUM sampler also showed good agreement with IMPROVE (Cahill et al, ARB Final Report, 1992, Cahill and Wakabayashi, 1996, and ARB Bakersfield Study 1996), typically within 10% of unity despite the limitations of a single jet impactor and PIXE analyses, which had a precision of only $\pm$ 15%. In the ARB Bakersfield comparison of 1996, the prototype slotted DRUM using the PIXE analyses agreed with filter based measurements for sulfur within 10% while providing the only continuous measurements of sulfur, soils, and smoke tracers. However, precision and sensitivity were only fair, which helped accelerate the development of S-XRF analysis.

The cost of analysis on a per-day basis (β-mass, λ-optical, STIM, PESA, S-XRF) for a single day of < $PM_{2.5}$ DRUM sampling (6 Stages, 8 measurements/day) giving in excess of 4500 data/day (48 mass, 96 STM, 96 PESA, 2000 elements, 2,500 optical attenuations) is $42.

The HETF ALASET Sacramento/I-5 Transect Study has shown the wisdom in these choices:

- The very fine (0.26 µm > D_p > 0.09 µm) spikes as high as 23 µg/m^3 downwind of I-5,
- Valley wide coherence across the 80 km array for most periods,
- Previously unanticipated mass spikes, most likely from a local source, at Arden Middle School,
- Dramatic compositional changes versus time, with the very fine mode having great similarities to previously published diesel aerosol data (and presumably smoking cars),
- Probable identification of a large PM_{10} mass peak at the Del Paso TEOM site with sea salt from the California coast near Mendocino.
- Detailed analysis of transport into Sacramento from the San Joaquin Valley.

Finally, there is no way that any other than UC Davis DELTA Group DRUM technology and our volunteers could have delivered even 1% of the data of the HETF ALASET Sacrameto/I-5 Transect Study within the total costs allocated, $4,800.

Appendix C

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

Comparison of heavy duty and light duty PM_{10} and $PM_{2.5}$ emission rates from the Gertler et al 2002 Tuscarora Tunnel studies, and other studies

Appendix D

Executive Summary of Original Report, Part 1

With the essential and enthusiastic assistance of ALASET HETF volunteers, we have collected aerosol samples at 9 sites on a rough line from northwest Davis across Sacramento, including sites near I-5 and Watt Avenue, to Shingle Springs, in the period December 12, 2002, through January 16, 2003. Collection was accomplished continuously on lightly greased Mylar strips by rotating drum impactors with either 3 stages (2.5 to 1.15, 1.15 to 0.34, 0.34 to circa 0.15 µm diameter) or 8 stages (circa 12 to 5.0, 5.0 to 2.5, 2.5 to 1.15, 1.15 to 0.75, 0.75 to 0.56, 0.56 to 0.34, 0.34 to 0.26, 0.26 to 0.09 µm diameter). Analyses were performed on all samples for mass (soft beta ray attenuation) and optical transmission (350 – 850 nm) in 3 hr increments. All samples at Arden Middle School and the very fine particles ($0.26 > D_p > 0.09$ µm) from the Crocker Art Museum site were in addition analyzed by synchrotron x-ray fluorescence (S-XRF) for 32 elements sodium through molybdenum, plus lead. Detailed quality control and quality assurance tests were conducted on all collection and analysis protocols and are summarized in the report (Appendix A and Appendix B) and fully presented in the DRUM Quality Assurance Protocols ver 8/02 (2002) presented as part of this study.

The weather was typical for the period, with strong rainstorms in December and periods of hazy stagnation around Christmas week and in most of January. The results show $PM_{2.5}$ aerosol masses never violated 24 hr federal standards. During many periods, concentrations across the entire network were similar, although the aerosol enhancement caused by Interstate-5 was always evident. Much of this mass was in very fine particles that, near I-5, during periods of stagnation approached values seen in Fresno at the First Street EPA Super-site (Cahill et al, 2002). The estimated impact of diesel/smoking car exhaust from I-5 was about a quarter of the $PM_{2.5}$ mass seen nearby. There was direct influence of Watt Avenue on the Arden Middle School that was comparable to that of I-5 on the Crocker Art Museum site. This impact was successfully modeled using prior roadway studies in California and explained by the very short distance and flat terrain between the heavily traveled road and the school buildings.

Trajectory analysis through use of NOAA's ARL HYSPLIT model has allowed specific features of the aerosols to be tracked to source regions. The elevated levels of pollutants seen starting Jan 2, 2003, were associated with stagnant conditions, with haze and "dry" and saturated fogs seen repeatedly. Highest aerosol concentrations were seen on winds from the south during periods of inversion, winds that blew along the freeways from the San Joaquin Valley. Heavy biomass smoke signature was also seen on these trajectories that started in down slope winds from the Sierra Nevada, a site of heavy wood burning.

While we present working hypotheses and conclusions in this report, this enormous data set can provide the base for a great deal of future analysis.

Ambient Elemental Signatures of Diesel and Automotive Particulate Matter by Size, Time, and Composition.

[1]Thomas A. Cahill, [1]Earl Withycombe, Steven S. Cliff, Michael Jimenez-Cruz, Lee Portnoff, and [2]Kevin D. Perry,
DELTA Group, University of California, Davis, http://delta.ucdavis.edu,
[1]The Health Effects Task Force, American Lung Association, Sacramento-Emigrant Trails,
[2]Dept. of Meteorology, University of Utah

Mitigation at Arden Middle School

While this study recorded no violations of state or federal ambient air standards, the efficient transport of pollutants from heavily traveled Watt Avenue into the Arden Middle School is not a good idea, especially with the documented presence of diesel and/or smoking automobile pollutants, some of which are toxic.

The typical westerly winds push Watt Avenue emissions into Arden Middle School during much of the year. The problem is that there is no barrier to air flow from Watt Avenue into the school grounds, a problem which was probably exacerbated sometime in the past when Watt Avenue was widened and a school buffer of distance and vegetation lost while traffic volumes increased. However, some mitigation is still possible.

The following suggestions are being proposed as worthy of further study and potential implementation:

1. Sound wall. A sound wall on Watt Avenue would prevent straight line transport of pollutants from Watt to the classrooms, forcing the air up and over, mixing the roadway pollutants with cleaner air above.
2. Trees. A line of closely spaced redwood trees directly behind the sound wall would continue the barrier to roadway effluents, while adding particle removal to the foliage. It also would provide afternoon shade.
3. Mysterious mass spikes. These are large, and efforts should be made to understand the source, since it may be so local as not to impact the children. If it is serious, locate the source and remove or control it.

4. Furnace Air Filters. If they are not in use already, high efficiency electrostatic furnace filters would reduce classroom concentrations when outdoor air is used.
5. Ventilation Establish where it is that the air in the classrooms comes from, and make sure it is not directly impacted by Watt Avenue.
6. Trees on site. Always a good idea, especially if they have a dense foliage and are not deciduous.

Suggested Research Project

One of the greatest uncertainties is the vehicle mix on Watt Avenue. Vehicles should be counted by type during selected daytime hours. An inventory of the number and type of vehicles with visible smoke would also be useful.