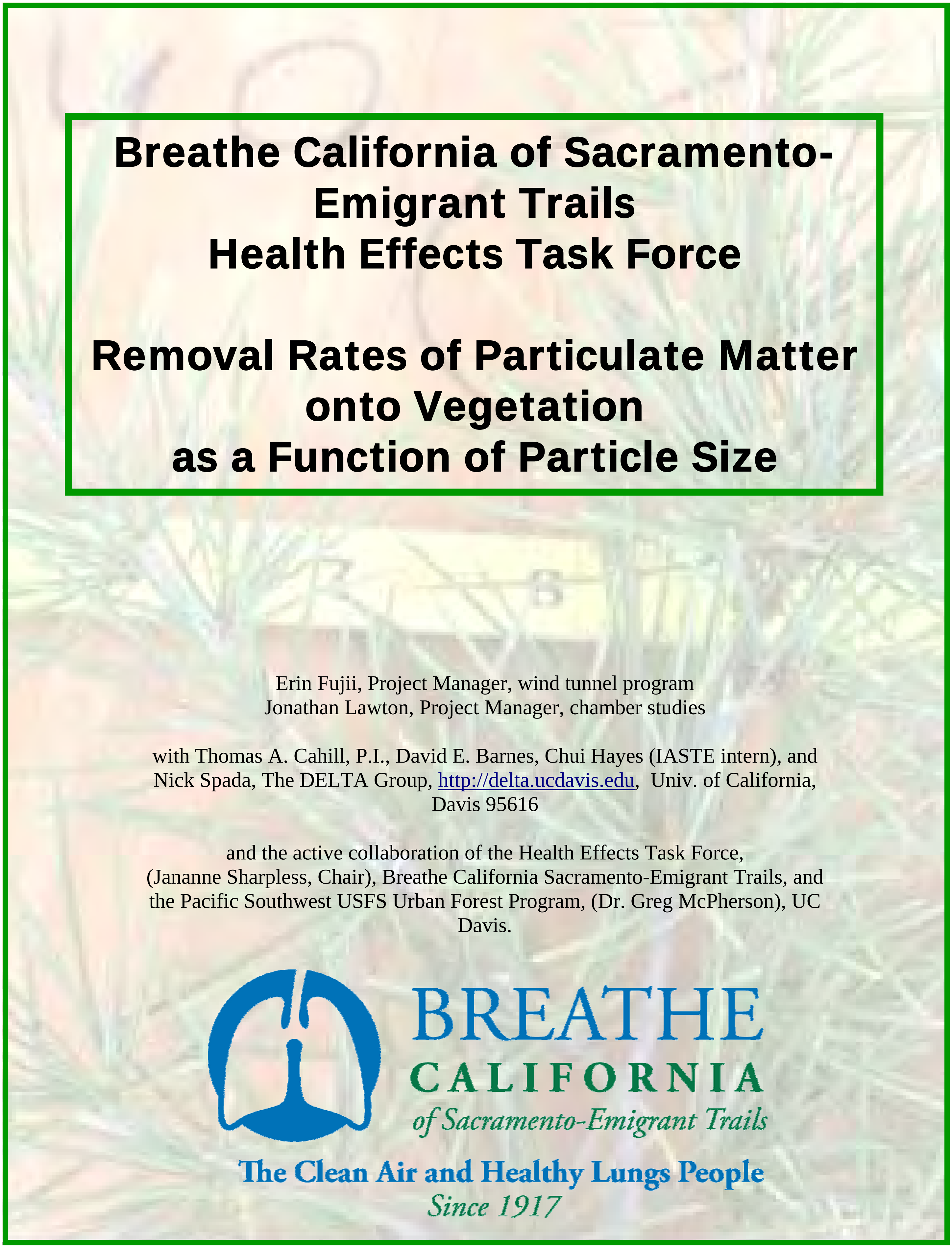

Breathe California of Sacramento-Emigrant Trails
Health Effects Task Force

Removal Rates of Particulate Matter onto Vegetation as a Function of Particle Size

Erin Fujii, Project Manager, wind tunnel program
Jonathan Lawton, Project Manager, chamber studies

with Thomas A. Cahill, P.I., David E. Barnes, Chui Hayes (IASTE intern), and Nick Spada, The DELTA Group, http://delta.ucdavis.edu, Univ. of California, Davis 95616

and the active collaboration of the Health Effects Task Force, (Jananne Sharpless, Chair), Breathe California Sacramento-Emigrant Trails, and the Pacific Southwest USFS Urban Forest Program, (Dr. Greg McPherson), UC Davis.

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CALIFORNIA
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Removal Rates of Particulate Matter onto Vegetation as a Function of Particle Size

Final Report to
Breathe California of Sacramento-Emigrant Trails' Health Effects Task Force (HETF)
and Sacramento Metropolitan Air Quality Management District

April 30, 2008

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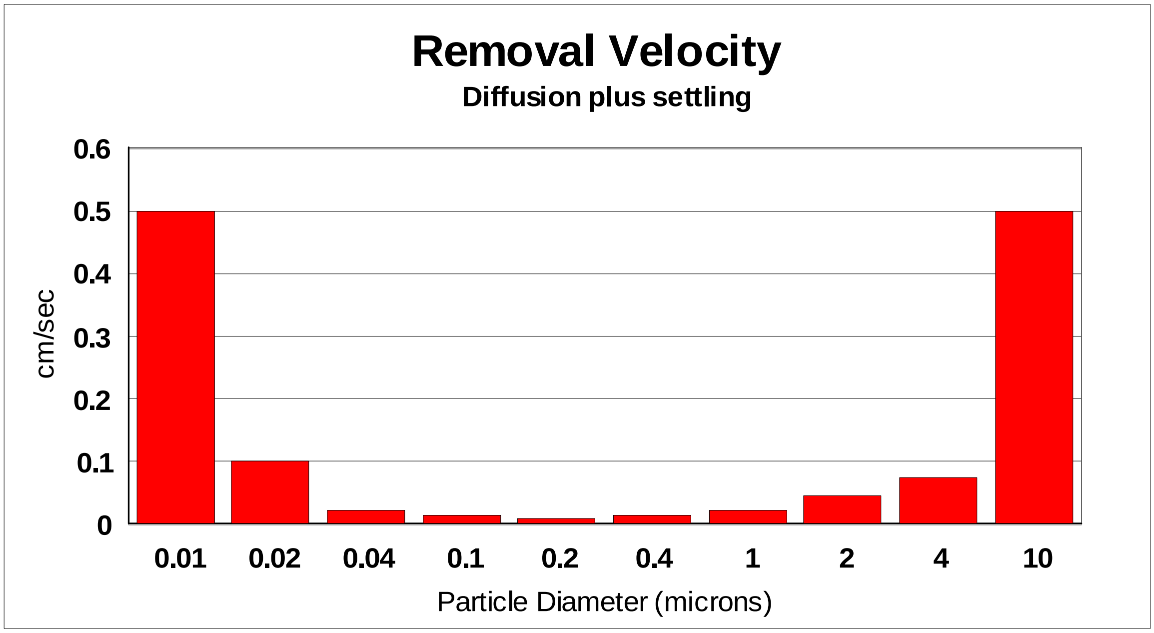
EXECUTIVE SUMMARY

Recent measurements of diesel and smoking car exhaust identify that almost all mass is below 0.25 µm in diameter (very fine) and that many of the most toxic Polycyclic Aromatic Hydrocarbons (PAH) are below 0.10 µm (ultra fine) in diameter (Gertler et al, 2002, Zielinska et al, 2004 for trucks, Cahill et al 2007 for trains). This mode matches a region of very efficient lung capture, but also results in particles that are able to diffuse to surfaces, if such are provided. Below we show a summary of removal velocity versus particle size.



Our hypothesis is that vegetation near very fine particle sources can be effective in removing some of the most toxic particles in the air before they get mixed into the regional air mass.

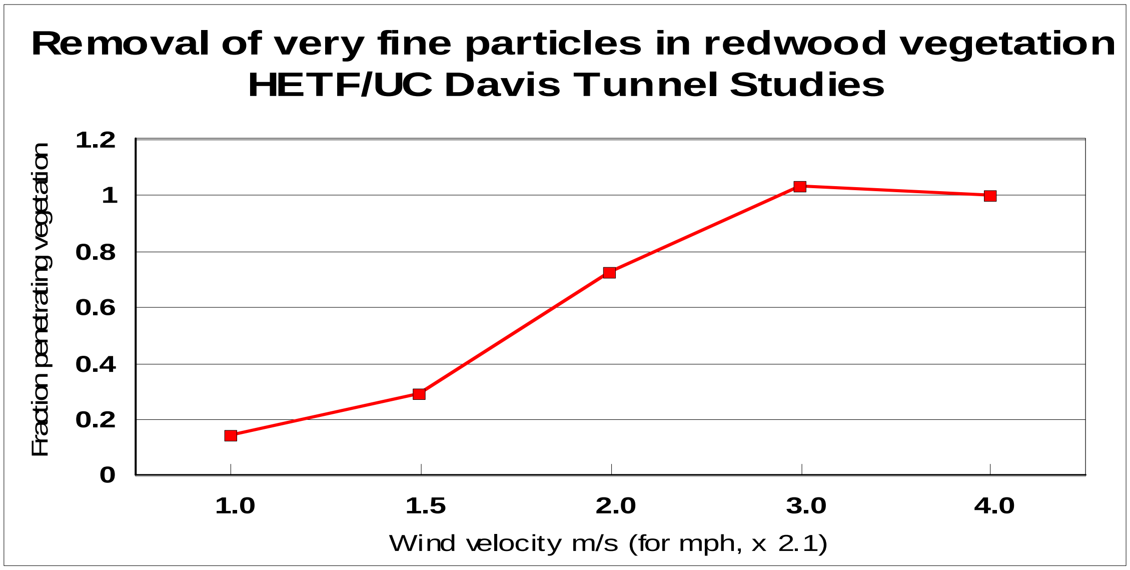
We have measured the removal rate of particulate matter passing through 2 m of leaves and needles in realistic vegetation configurations as a function of particulate size. Two methods were used:

1. We generated fine to very fine particles in the UC Davis instrumented wind tunnel and collected them by size with 8 particle size modes before and after they passed through vegetative layers (redwood, deodar, and live oak) at low wind velocities (4.0 to 0.5 m/s, or 9 to 1.1 mph) in 54 separate runs, and
2. We generated particles into a 3.4 m^3 static chamber and allowed particles to diffuse to vegetation (redwood, deodar, live oak, and oleander), followed by decay in time of mass concentrations, in 8 size modes, over the next 2 to 3 hours. Twenty separate runs were performed in this part of the study.

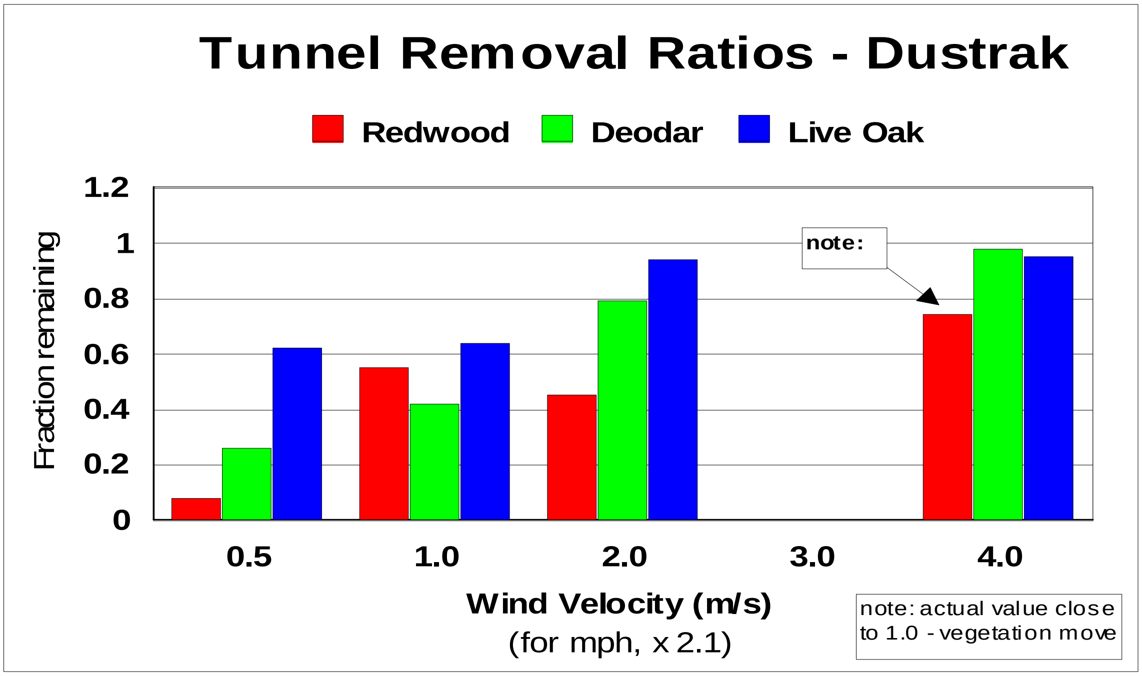
We especially focused on the ability of finely needled and leaved trees suitable for removing the most dangerous highway pollutants from diesel and smoking cars near roadways.

Wind tunnel study

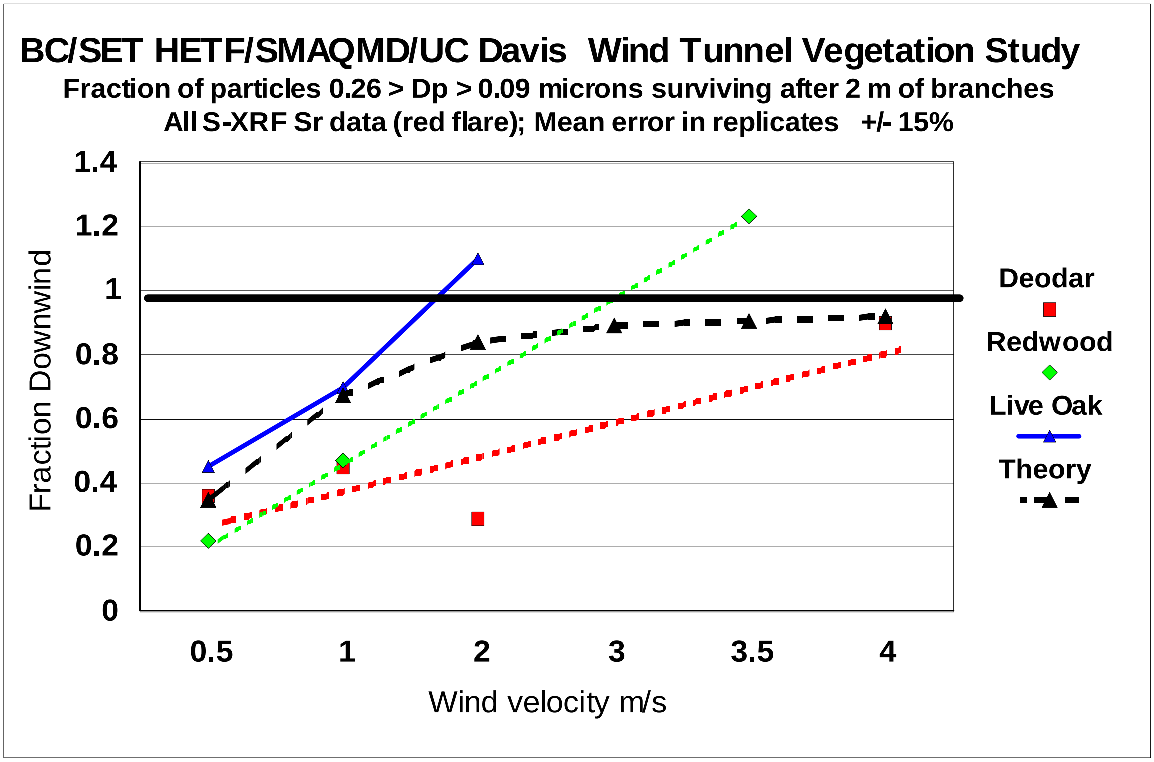
Three methods were used to test removal rates in the tunnel – direct measurement of the dilution of the source versus wind velocity, and upwind-downwind measurements, with Dustrak nephelometers and 8 stage DRUM samplers. Below are examples. The dilution method (below) was tested to insure that losses to the tunnel walls were negligible. The data were taken from mass measured on the 0.26 to 0.09 µm DRUM stage after the vegetation. The results, however, require assumptions about the flare intensity and length, and are thus considered semi-quantitative. Nevertheless, the sensitivity to wind velocity is clear.



The second method involved TSI Dustrak™ nephelometers which have the advantage of upwind-downwind ratios, but do not measure very fine particles well.



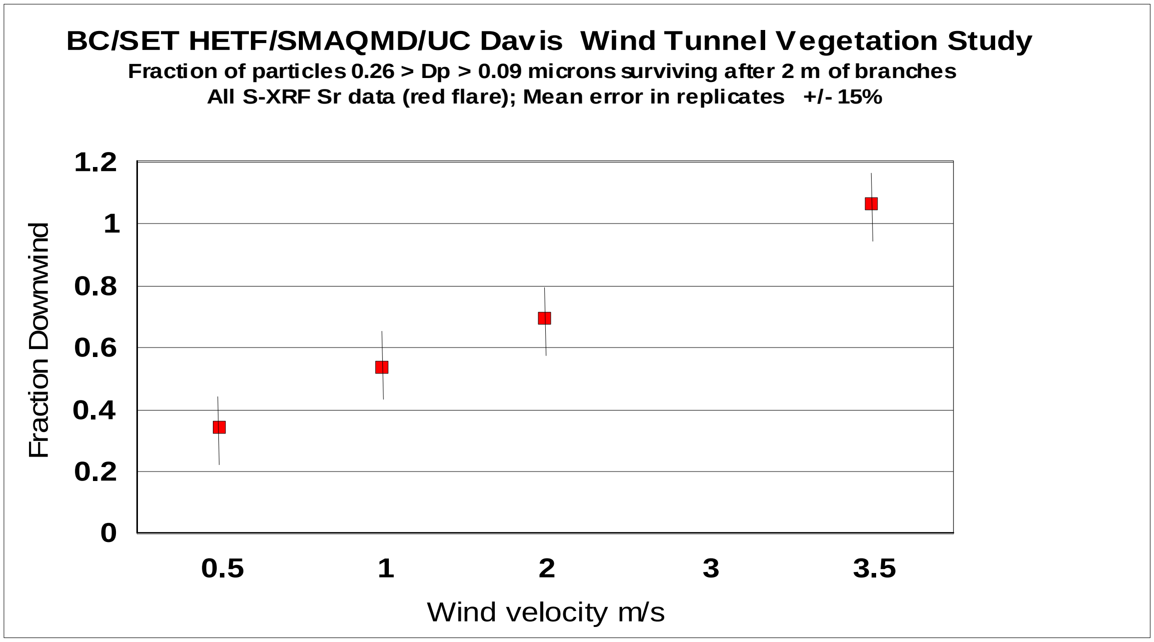
The paired DRUM samplers have both upwind-downwind comparisons as well as particle size down to 0.09 µm, the upper levels of the ultra fine (< 0.1 µm) range, but because of all the additional variables, the variance is higher run to run.



The line marked "Theory" is merely the scaled residence time of the particles near the vegetation, which is proportional to removal rate.

This tunnel study showed that all forms of vegetation were able to remove 30% to 80% of very fine particles at wind velocities below about 1.0 m/sec (roughly 2 mi/hr) during the 2 to 4 seconds in which the particles were within the vegetation chamber. Redwood and deodar were about twice as effective as live oak

Standard highway safety flares, all bought from a single supplier, proved a reliable source for fine and especially very fine (< 0.25 μm) particles, thus mimicking diesel exhaust. Below we summarize all the results with the flare sources for all types of vegetation. The 3.0 m/s and 4.0 m/s results have been averaged.



From the measured data for $0.26 > D_p > 0.09$ μm particles and the 0.5 m/s (1.1 mph) wind velocities, which gives 4 second exposure times in the vegetation, and using the more conservative S-XRF elemental data, we are able to match these fractional removal rates to the measured and extrapolated deposition velocities as found by Seinfeld and Pandis, 2004, and predict fractional removal into the ultra fine (< 0.1 μm) size mode.

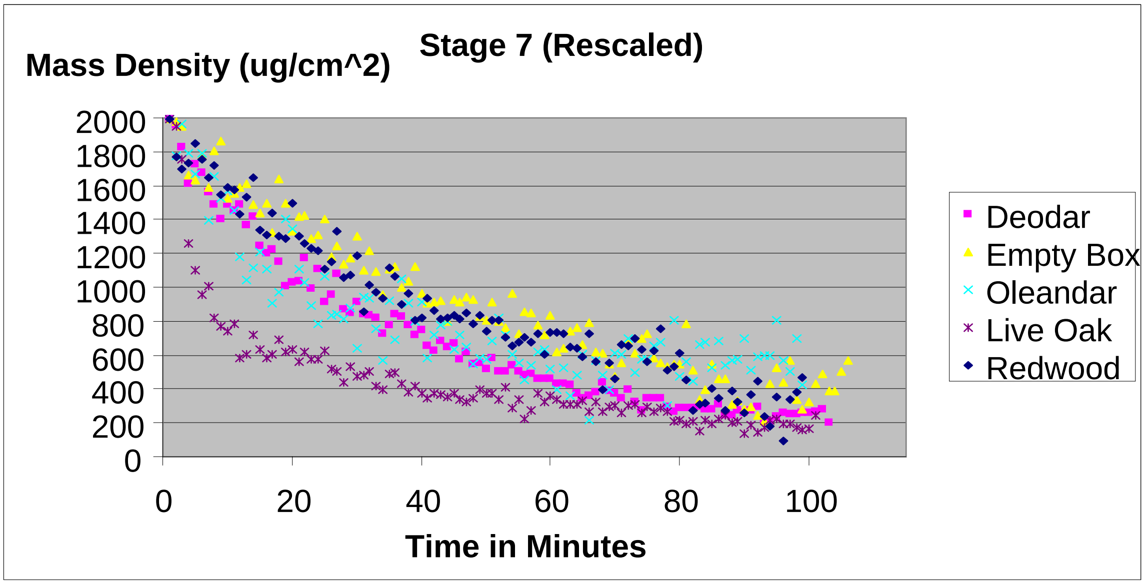
Particle diameter	v_d	Redwood	Deodar	Live oak	
(μm)	(cm/s)	Fraction removed	Fraction removed	Fraction removed	
0.17	**0.01**	**0.79**	**0.65**	**0.55**	**Measured**
0.10	0.0125	0.83	0.72	0.64	Estimated
0.075	0.015	0.86	0.77	0.70	Estimated
0.050	0.02	0.90	0.83	0.78	Estimated
0.035	0.045	0.95	0.92	0.90	Estimated
0.015	*0.25*	*0.99*	*0.99*	*0.98*	*Extrapolated*

We also measured removal for wood smoke, which was about 30% less efficient removal rate than with the flares and on air filters (Appendix I)

Static chamber studies

The static chamber studies were performed with effective wind velocities less than 0.1 m/sec to allow diffusion to surfaces without the impaction that occurs in the wind tunnel. However, the very fine particles were essentially removed from the chambers during filling period, in comparison to the flare data from the tunnel study. We interpret this as due to coagulation because of the much higher particulate concentrations involved, and diffusion to chamber walls in the 1 minute equilibration time allowed in the experiment. By sharply reducing the amount of vegetation (to roughly a few percent of that used in the tunnel studies), and using shorter flare durations (10% of prior protocols), we were able to obtain adequate particles in the slightly coarser 0.26 to 0.34 μm size mode and follow the decay of these particles in time. Twenty separate runs were made in this final configuration.

In this test, the live oak runs were not repeatable, but some were very good (see below). The deodar had the best decay in time, up to100 minutes, better than the redwood which was, surprisingly, essentially the same as the empty chamber. However, most aerosol mass had already been removed in the redwood study before the decay measurements had started.



This shows fast removal in the empty chamber, which makes it difficult to draw conclusions about tree species performance, even though the data are very suggestive. The gross non-uniformity of the branch distribution in the chamber negated our attempt to perform a model of deposition rate as we had originally planned when the chamber was essentially full of vegetation at a roughly uniform spacing.

Conclusions

These studies thus confirm the theoretical predictions that vegetation is highly effective in removing some of the most toxic components in the ambient atmosphere, namely diesel and smoking car exhaust. The effectiveness is greatest at low wind velocities and in configurations such that the vegetation is very close to the source. We showed that the particles, once impacted onto vegetation, were not easily removed at low wind velocity in “shake-off” tests.

We also note that many of the lighter PAHs (many of which have a significant volatility) and other material from diesels and smoking cars have even higher diffusion rates than the heavy PAHs and transition metals studied in this work and thus should be even more efficiently removed onto vegetation.

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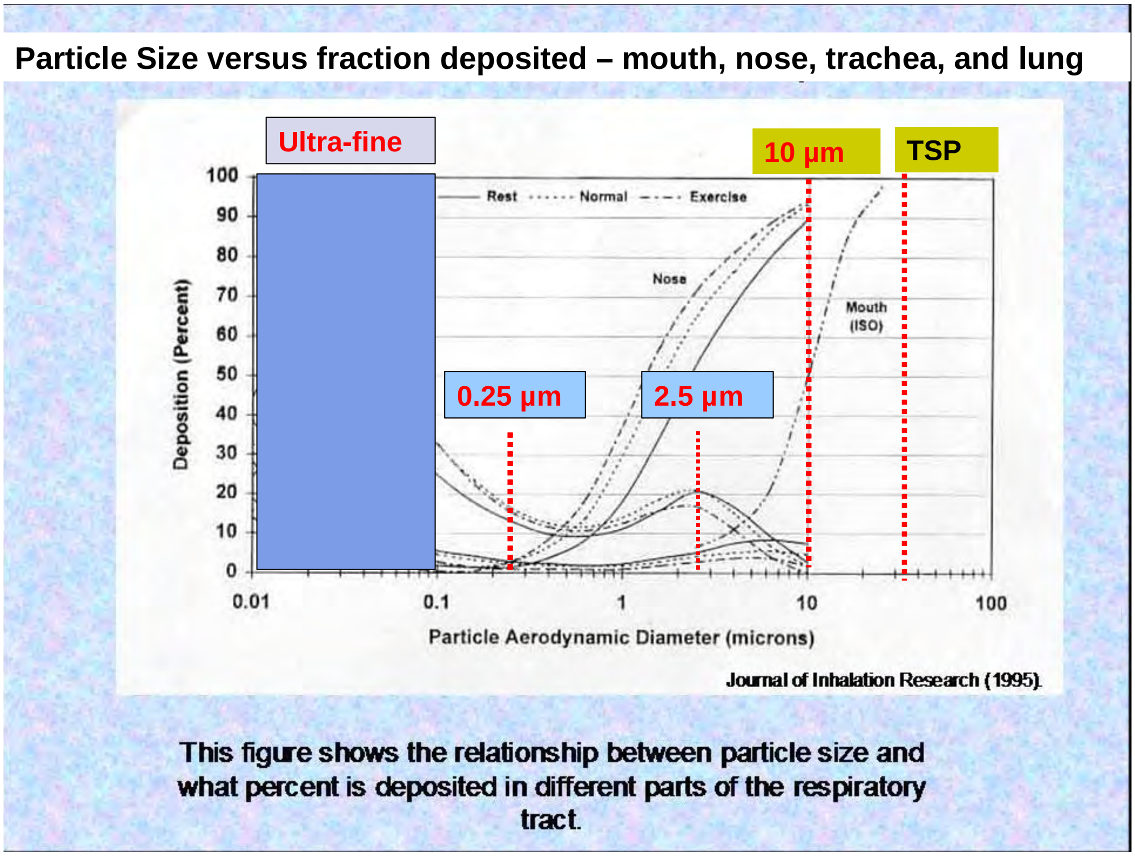
A. Introduction

Trees enhance particle deposition, as well as absorbing ozone, and as such can be a factor in removal of air pollution. The effect on PM_{10} particles can be significant over an entire urban area (McDonald et al, 2007) and downwind of highways (Baldauf, 2007). However, the health impacts of PM_{10} particles are not as great as for $PM_{2.5}$ particles (US EPA Fine Particle Criterion Document 2005), with impact abundantly documented in over 100 studies. However, recent data support greater health impacts from the even finer components, very fine (< 0.25 µm) and ultra fine (< 0.10 µm) diameter particles that include within their size regimes substances such as diesel exhaust.

The enhanced role of very fine (<0.25 µm) and ultra-fine (< 0.10 µm) particles is partially because of their enhanced deposition in the lung, as shown below.


Particle Size versus fraction deposited – mouth, nose, trachea, and lung

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.

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Figure 1 Particle Size versus Percent Deposition in the Lung

The second factor is growing evidence that diesels and smoking cars generate most of their mass in sizes that closely match the lung deposition probabilities. These particles, which include carcinogenic compounds (PAHs) and transition metals, match the peak of deep lung capture (above), and thus pose a grave health risk (70% of all the impact of all California Toxic Air Contaminants (TACs) combined – CA ARB Almanac).

Below we show a plot of data taken as part of a large National Renewable Energy Laboratory (NREL) – U. Minnesota – DRI – UC Davis study (Zielinska et al, 2004). The presence of mass and tracers or burned lubricating oil (zinc, phosphorus) in the ultra fine modes is matched to recent data (Cahill et al, 2007) from the Roseville rail yard, ultra fine lubricating oil from CNG busses (Cahill, AAAR, 2006). Note that about 1/3 of all engines tested had this enhanced ultra fine component.

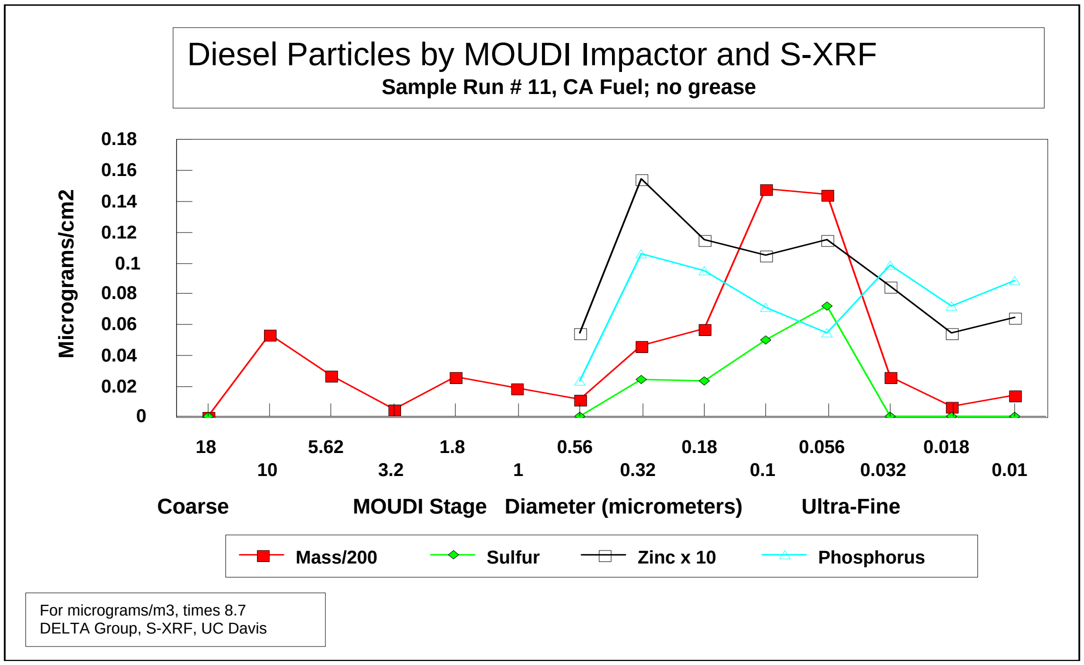


Figure 2 Size distribution of diesel exhaust showing lubricating oil smoke in ultra fine modes

Another example is taken from work at the Roseville rail yard (Cahill et al, 2007) and work in progress on Watt Avenue. Organic matter was measured on both sides of Watt Avenue (65,000 v/day, 1.5% diesel trucks) from February through June, 2007. The example below is from the February – March (winter) sample, and was taken on Apiezon-L coated drums to ensure no mis-sizing occurred, and the comparison data were taken downwind of the Roseville rail yard July – August, 2005.

The data below in Figure 3 show two components of benzopyrene. The more dangerous benzo[a]pyrene, BaP, has the same size distribution as benzo[e]pyrene, but lower values often give poorer precision. The BaP and BeP in the accumulation mode (0.56 > Dp > 0.26 μm) at Watt Ave were tagged to wood smoke by simultaneous measurements of levoglucosan, which also peaked in that size range. The very fine BaP and BeP were attributed to diesels and smoking cars from 0.26 to 0.00 μm by zinc and phosphorus from zinc thio-phosphate, a stabilizing agent in almost all lubricating oils. Essentially all the heavy PAH’s at Roseville were associated with diesel sources, based upon upwind-downwind mass, NO, and black carbon data from Roseville Railyard Aerosol Monitoring Project (RRAMP). The equivalent BeP values in the vf/uf modes are an anomaly due to the seasonal meteorology.

In June, 2007, the Watt Ave. BeP had dropped to a total of all stages of 6 pg/m^3. In comparison, summer Roseville rail yard data showed 58 pg/m^3.

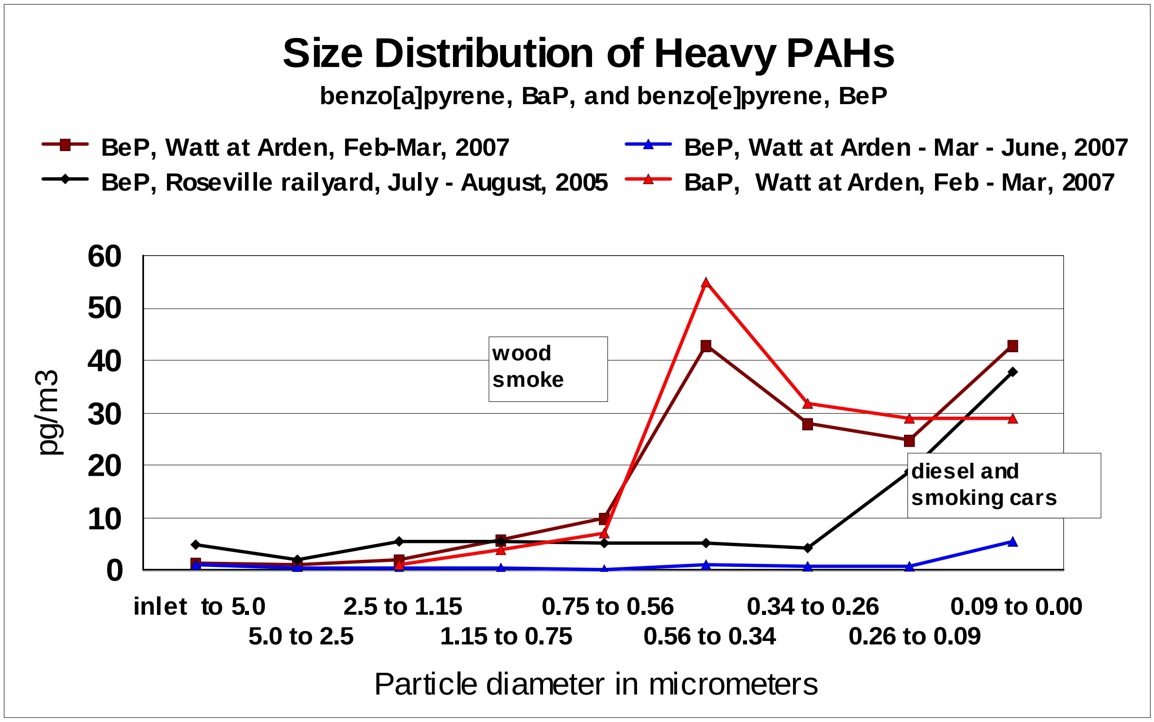


Figure 3 Heavy PAH size distributions from Watt Avenue and the Roseville rail yard.

Thus, we have direct evidence that some of the most carcinogenic components of traffic lie in the very finest particle sizes with a mass median diameter on the order of 0.075 μm in diameter. In addition, many insoluble ultra fine metals are also seen in this size (Figure 3), with potential health impacts.

Roads are always going to act as pollution sources to nearby areas. Our work with the Breathe California of Sacramento-Emigrant Trails (née American Lung Association) Health Effects Task Force (HETF) has shown high impacts of very fine and ultra fine particles from both freeway and non-freeway arterials, such as Watt Avenue, on schools and residences. Since we can not assume all pollution can or will be eliminated, the HETF, working with the DELTA Group, CalTrans, and Sacramento County, is studying the effectiveness of vegetation both in the roadway right of way and between the roadways and schools and residences. The recent realization that almost all the most dangerous roadway particles are in the very fine (< 0.25 μm) and ultra fine (<0.1 μm) modes offers the possibility of using vegetation as a removal mechanism, based on the relatively high diffusion lengths and sticky nature of these particles. Such information is sparse in the literature, but the results could have a major impact on roadway design in future as well as offering retrofit possibilities in the present.

Thus there are two problems – identify and measure these particles in the community (our reports, 2002 and 2005 for Breathe California plus EPA PMREC and

Supersite, and ARB work at UCLA and USC), and find ways to remove them from the air.

The mitigation of these particles falls into 4 classes, and represents the heart of the effort of the Breathe California of Sacramento-Emigrant Trails work for 2005-2007:

1. Mitigation at the source – cleaner cars and trucks, traffic reductions, and support toxics reductions from particles, smog check, etc.,
2. Mitigation in highway design – our “Green Highways” initiative with CalTrans and the ARB,
3. Mitigation for the right of way fence to the receptor dwelling, i.e. school, house, and
4. Mitigation via indoor air control.

In these efforts, vegetation may be able to play a role. But quantitative data to support this hypothesis is limited.

B. Theory of Particle Deposition

Particle removal rates for the ultra fine particles (< 0.1 µm) are greatly enhanced over accumulation mode particles (~ 0.5 µm) because the finer particles can diffuse more easily to surfaces. Since they are oil-rich, they then stick and are removed from the air. This has the result that the most important particles for human health are also those that can be most easily removed by diffusion to a surface, assuming such a surface is available. Removal of these particles occurs at later times in rainfall, sloughing of leaves and needles, etc. Below we show a summary from Seinfeld and Pandis 2004

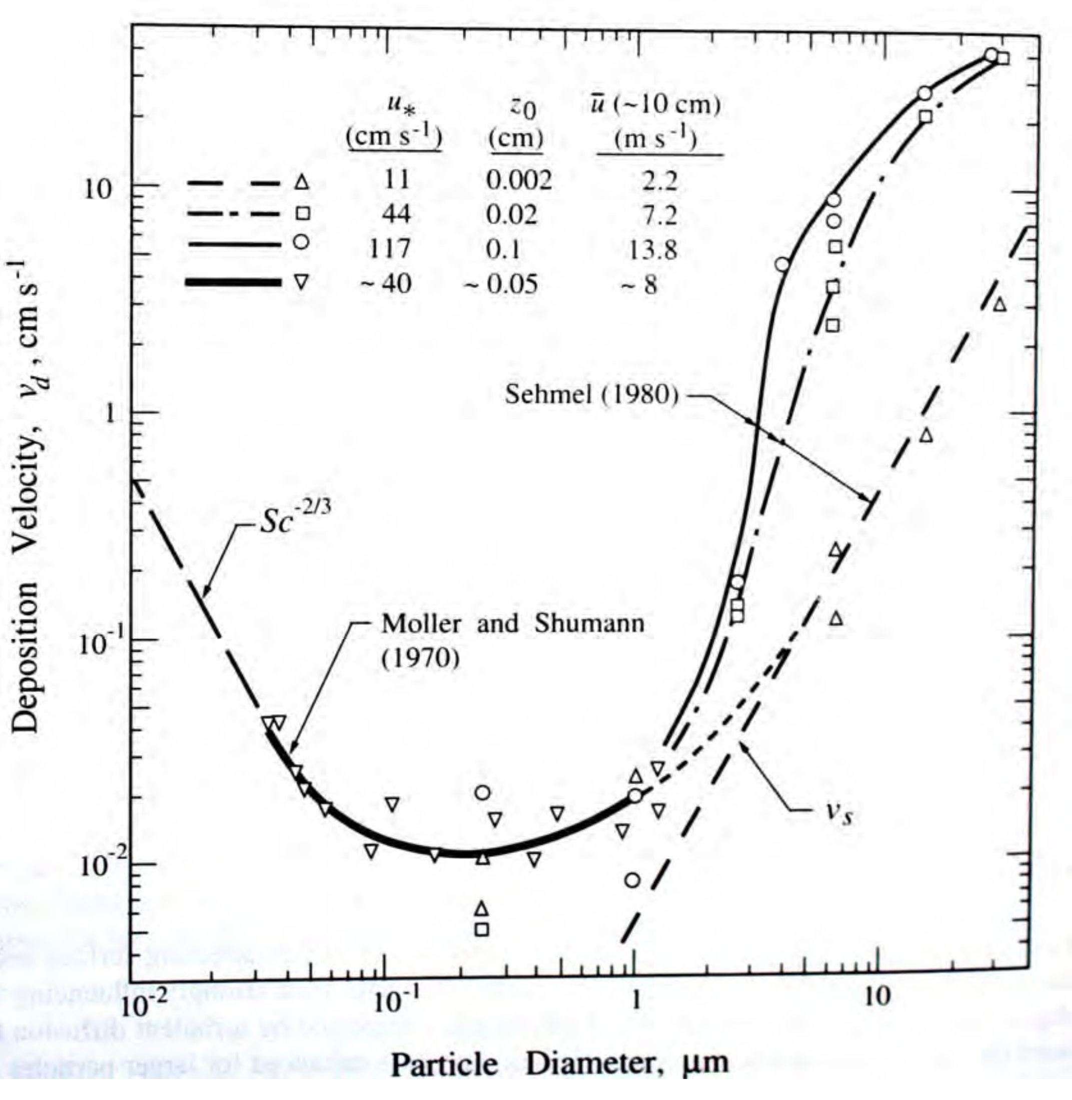


Figure 4 Deposition velocity versus particle diameter

The basic physical parameters are summarized in Seinfeld and Pandis, 2004, pg 970, which have then been extended to our situation in Table 1, column 7.

Particle	Diffusion	Diffusion		Dep. vel.	Settling	Migration
diameter	Theory	Theory	cp	S&P pg970	velocity	v = 1 m/sec
Microns	cm2/sec	mm/sec	cm/sec	cm/sec	cm/sec	10 m veg.
0.002	1.28E-002	0.866	4965	Total		10 sec
0.004	3.23E-003	0.435	1760			distance cm
0.01	5.24E-004	0.175	444	0.500		5.0
0.02	1.30E-004	0.087	157	0.100		1.0
0.04	3.59E-005	0.046	55.5	0.022		0.2
0.1	6.82E-006	0.020	14	0.015		0.2
0.2	2.21E-006	0.011	4.96	0.010		0.1
0.4	8.32E-007	0.007	1.76	0.015		0.2
1	2.74E-007	0.004	0.444	0.018	0.004	0.2
2	1.27E-007	0.003	0.157	0.030	0.015	0.3
4	6.1E-008	0.002	0.056		0.075	0.8
10	2.38E-008	0.001	0.014		0.500	5.0

Table 1 Basic parameters of particulate diffusion to a surface.

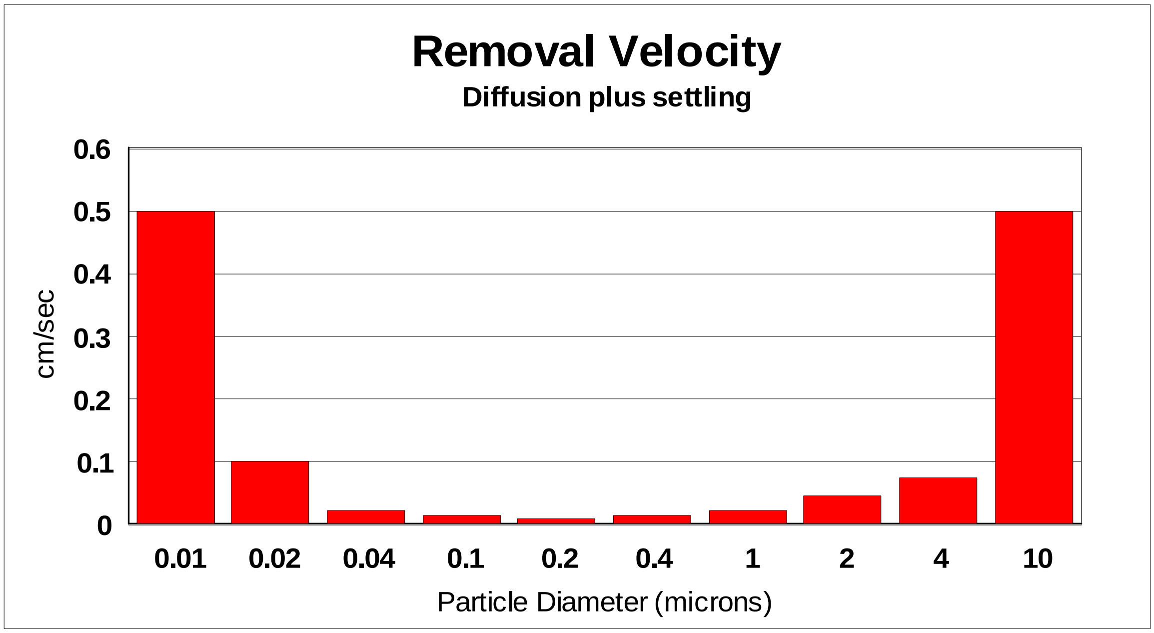


Figure 5 Removal velocity versus particle size

Calculations for removal rate in realistic conditions are complex, and involve both the residence time of the particles in the 3 dimensional arrays of surfaces and the deposition velocity. If the average spacing of the surfaces is, for example, 1 cm, then a 0.1 μm particle would require 50 seconds to reach the surface (100% removal rate). One would then have a 50% removal rate with 25 seconds residence time, etc.

If one considers smaller particles at the peak of the number and surface area distributions, 0.02 µm, the time becomes 10 seconds, and for 0.01 µm particles, 2 seconds.

Thus, provision of a high surface area of vegetation adequate to slow (but not stop) wind motion will maximize particle removal rates. This effect is in addition to the wind transfer function effect, with the lateral wind resistance of the vegetation tipping the wind transport vector to a more vertical direction driven by the waste heat (engine exhaust plus hot pavement) of the highway. (Cahill et al, 1974; Feeney at al, 1976).

C. Experimental operations

The design utilized two complementary approaches:

1. Removal of particles in a vegetation section in a low velocity wind tunnel, and
2. Removal of particles in a static chamber.

The former has the advantage of mimicking natural processes including all aspects of dry deposition – settling, impaction, and diffusion – in low wind velocities typical of winter conditions in Sacramento that have the highest fine particle levels. It is also the most complex to instrument and requires the availability of the fully instrumented wind tunnel.

The latter isolates only the diffusion component at winds that approximate stagnation - < 0.1 m/s, but allows estimates directly of the dry deposition rate unavailable from the wind tunnel.

The wind tunnel studies were conducted via the following protocol:

1. The wind tunnel was configured with particulate inputs, two particulate 8 - DRUM samplers, and two TSI Dustrack™ nephelometers, one before and one after a removable frame holding various kinds of vegetation. The frames included screens to preclude losses of materials into the tunnel. The tunnel operated at up to 5 wind low velocities, 0.5 m/s to 4.0 m/s, with a return to the lowest at the end for a QA check. After the first 4.0 m/s run, baffles were added around the edges to preclude wind passing by rather than through the vegetation at the higher wind speeds.
2. Originally it was planned to use smoke from a small diesel engine as input prior to the laminating section of the tunnel. We were unable to obtain this unit, and instead used NAPA highway flares that in a 15 minute burn produced abundant and unique aerosols down to (and almost certainly below) 0.09 µm.
3. The DRUM samplers operated intermittently for each test, collecting line deposits of particles on greased substrates in the size modes from > 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, and 0.26 to 0.09 microns. A < 0.09 micron filter was added to some of the flare runs.
4. All samples were analyzed for mass using the DELTA Group soft beta ray mass system matched to the periods on constant wind velocity in the tunnel. Selected

samples were also analyzed for elements by synchrotron induced x-ray fluorescence (S-XRF) at the Advanced Light Source, Lawrence Berkeley NL.

5. The tunnel was also used with wood smoke to compare removal rates for the flares.
6. Because of the interest in indoor air pollution, 3 types of standard furnace filters were also studied.
7. A Final Report was prepared on all aspects of the project, including an extensive section on the Quality Assurance of the results.

The chamber studies were not called for in the original proposal, but form a way to study process at very low wind velocities typical of winter stagnation periods in the Sacramento valley. The could in principle also provide a way to calculate deposition velocities without the effect of impaction, assuming a uniform spacing of deposition surfaces and a very low wind velocity.

1. Equipment and technological resources

The primary studies were based on the 20 m long UC Davis Department of Mechanical and Aeronautical Engineering's wind tunnel, designed and built by Prof. Bruce White, which we reconfigured as a low velocity wind tunnel, and a 3.5 m^3 static chamber for diffusion removal studies. The technical resources available include trained faculty, staff and student personnel, plus:

1. Two TSI Dustrak™ nephelometers
2. Two DELTA Group 8 stage rotating drum (DRUM) impactors, with size collection from > 5 µm to 0.09 µm particle aerodynamic diameter.
    a. For the flare aerosols, an after filter was occasionally used to collect from 0.09 to 0.0 µm continuously.
3. DELTA Group's recently developed soft beta ray mass measurement system for DRUM Apiezon-L coated Mylar substrates.
4. DELTA Group Synchrotron induced X-Ray Fluorescence (S-XRF) capabilities at the LBNL Advanced Light Source Beam Line 10.3.1 (presently operated by UC Davis by Dr. Cliff at DAS)
5. DELTA Group optical attenuation vs wavelengths, 350 nm – 820 nm (in final development phase; not included in this report)
6. The USDA Urban Forest Center's LAI-2000 plant surface area analyzer

Sample collection

The DELTA Group 8 DRUM sampler collected particles by impaction into 8 size modes; inlet 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, and 0.26 to 0.09 µm diameter Cahill et al, 1985; Raabe et al, 1988; Cahill and Wakabayashi, 1993). Particles smaller than 0.09 µm must be collected onto filters. Impaction is on to lightly greased (Wesolowski et al, 1978; Cahill 1979) Mylar strips to avoid bounce off, particle loss, and mis-sizing.

For more on our technology, see http://delta.ucdavis.edu .

Figure 6 DELTA Group 8 DRUM sampler - case open, inlet off.

The size distribution of a properly running diesel engine (about ½ of all those tested) is shown below. Note that the finest stage of the 8 DRUM, Stage 8, 0.25 > D_p > 0.09 µm, collects about 60% of such diesel exhaust, with the rest onto an after filter.

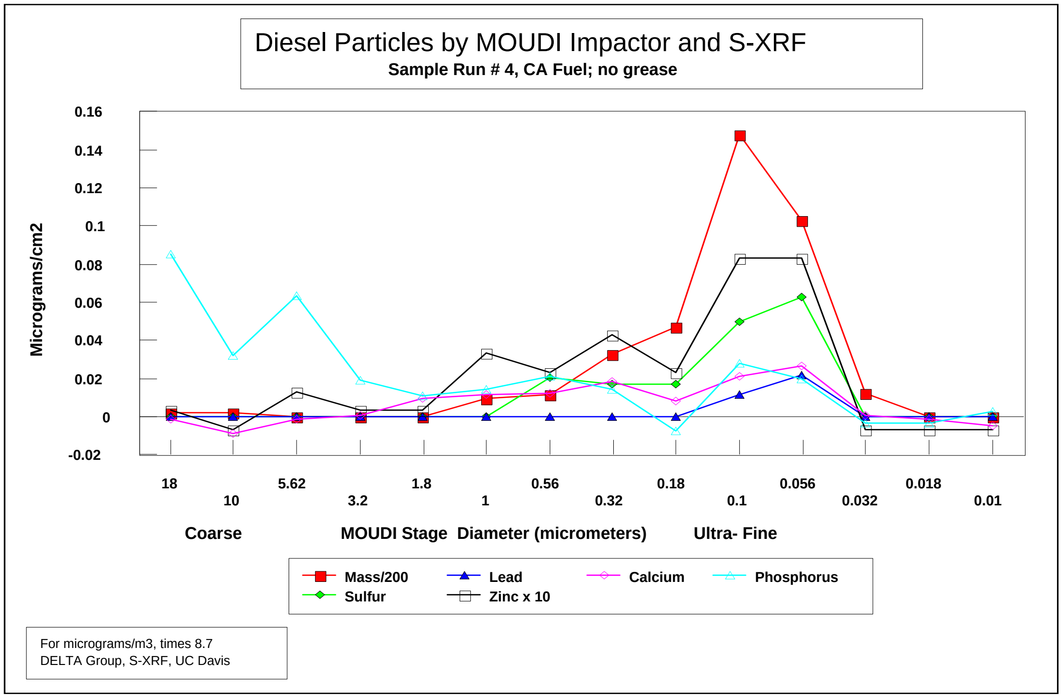


Figure 7 Particle size and composition from a properly operating diesel engine

Sample analysis

Analysis was performed on all samples by soft beta ray transmission, and on selected particles by synchrotron induced x-ray fluorescence (Bench et al, 2001) . These are described briefly in Appendix B and in far more detail in DRUM Quality Assurance Protocols DQAP ver 1/08, an integral report of this Final Report. Details can also be found under the Technology section of the DELTA Group web site, http://delta.ucdavis.edu

Wind tunnel

With the assistance of Prof. Bruce White, his graduate student Dave, and funding from the grant, we were able to clean, repair, and modify the UC Davis low velocity wind tunnel for the vegetation studies.

Figure 8 The 60 ft UC Davis low velocity wind tunnel. The collimators on the entrance are shown, then the 20 ft section for flow treatment, and in the distance the end of the tunnel and outside exhaust.

The wind tunnel was instrumented with wind flow measurers and profilers, a pair of DELTA Group 8 drum samplers, from circa 12 µm down to 0.09 µm diameter, two Dustrak nephelometers, all placed in front of and after the vegetation section.

Figure 9 DELTA staff (Dave, John, and Erin, plus miniature assistant) are setting up the diagnostic equipment. John is calibrating the wind flow devices while Erin is mounting the sampler inlets on the exit section.

Figure 10 Dave Barnes next to the inlet DRUM and Dustrak, with the vegetation section beside him. The exit DRUM and Dustrak can be seen behind him.

Figure 11 Redwood vegetation in place. Erin monitors wind velocity.

Figure 12 Exit inlets for DRUM and Dustrak.

Figure 13 Use of a road flare to generate accumulation mode and very fine aerosol. The flare lasted 15 minutes with the output integrated on the 8 non-rotating stages, inlet and exit. The mean aerosol level before the tests was 13 µg/m^3, and in the test 250 µg/m^3.

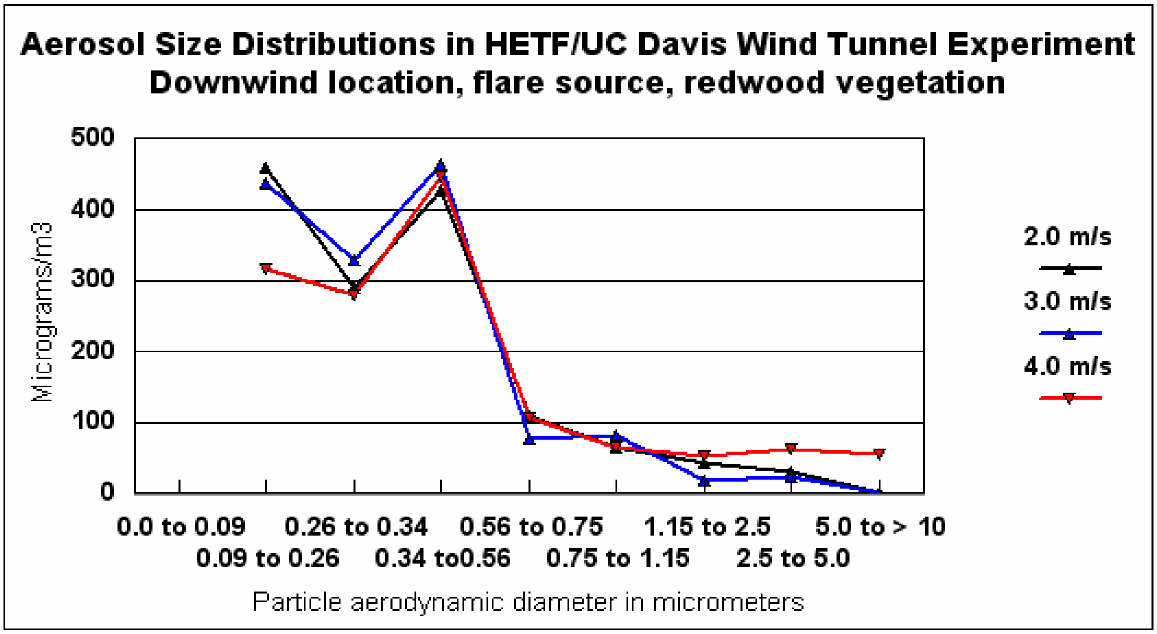


Figure 14 Three runs on flare particles with an empty tunnel. Note that the differences reflect both differences in the flare burn and all uncertainties associated with the beta gauge measurements.

The vegetation was weighed to find the total mass of vegetation in the 2 m section. The vegetation leaf area was estimated manually and by the USDA Urban Forest Center's LAI 2000 plant surface area analyzer. (Smolander and Stenberg 1996, Baldwin et al 1997, Clark et al 1998)

Figure 15 Example of measurements made to determine branch and needle area.

Wind Tunnel Run Summary Data

Vegetation studies
Erin Fujii, Project Manager

Set: (front	Run # and back,	Date stages 1-8)	Vegetation and age (hr)		Wind Velocity (m/s)	Length of Run (s)	Turbulence enhancement	Comments
1	1	09/18/2006	Redwood (6)	flare	1.03	875	none	
	2	9/18-9/19	Redwood (15)	no PM	1.06	1750	ard scaffold/pie plate	
	3	19-Sep	Redwood (28)	flare	0.49	1110	as above	
	4		Redwood (29)	flare	1.99	1150	as above	
	5		Redwood (29)	flare	4.08	1150	as above	
	6		Redwood (30)	flare	1.015	1115	as above	
	7		Redwood (31)	no PM	1.975	3960	as above	
2	8	09/20/2006	Redwood	wood smoke	2		as above	
	9		Redwood	wood smoke	4		as above	
	10		Redwood	wood smoke	1.05		as above	
	11		Redwood	wood smoke	0.54		as above	
	19	09/25/2006	live oak	flare	0.94	480	as above	
	20		live oak	flare	1.99	360		
				flare				
4	21		live oak	flare	3.13	360		
	22		live oak	flare	0.53	360		
	23		live oak	flare	1.04	360		
	24		live oak	wood smoke	1	900		
	25		live oak	wood smoke	2.02	1200		
	26		live oak	wood smoke	3.95	1200		
	27		live oak	wood smoke	0.56	900		
	28		live oak	wood smoke	0.98	900		
	29	09/26/2006	deodar	wood smoke	1.01	900		
	30		deodar	wood smoke	2	900		
5	31		deodar	wood smoke	3.91	1200		
	32		deodar	wood smoke	0.5	903		
	33		deodar	wood smoke	0.95	885		
	34		deodar	flare	0.97	390		
	35		deodar	flare	2	360		
	36		deodar	flare	3.82	360		
	37		deodar	flare	0.52	360		
	38		deodar	flare	1.02	360		

Table 2 Summary of wind tunnel measurements. Runs12 through 18 were tests of air filters.

2. Results of tunnel studies

Three types of data are available from the tunnel study tests. First, since we have a direct measurement of the volume of air in the tunnel, and since the flares proved surprisingly uniform in their ability to generate fine particles, (Figure 14), we can simply measure the particle mass after the vegetation to detect removal, with the concentrations corrected for the dilution rate. Second, we placed TSI Dustrack nephelometers before and after the vegetation, and calculated the ratio. Finally, we placed 8 stage DELTA Group 8 DRUM samplers before and after the vegetation, and again measured particle removal rates but now with the additional capability of information on particle size and elemental composition.

Dilution data

Figure 16 shows an example of the dilution type of test. This test requires, however, assumptions on the equivalency of the flares which were hard to establish. Thus, their result is viewed as semi-quantitative.

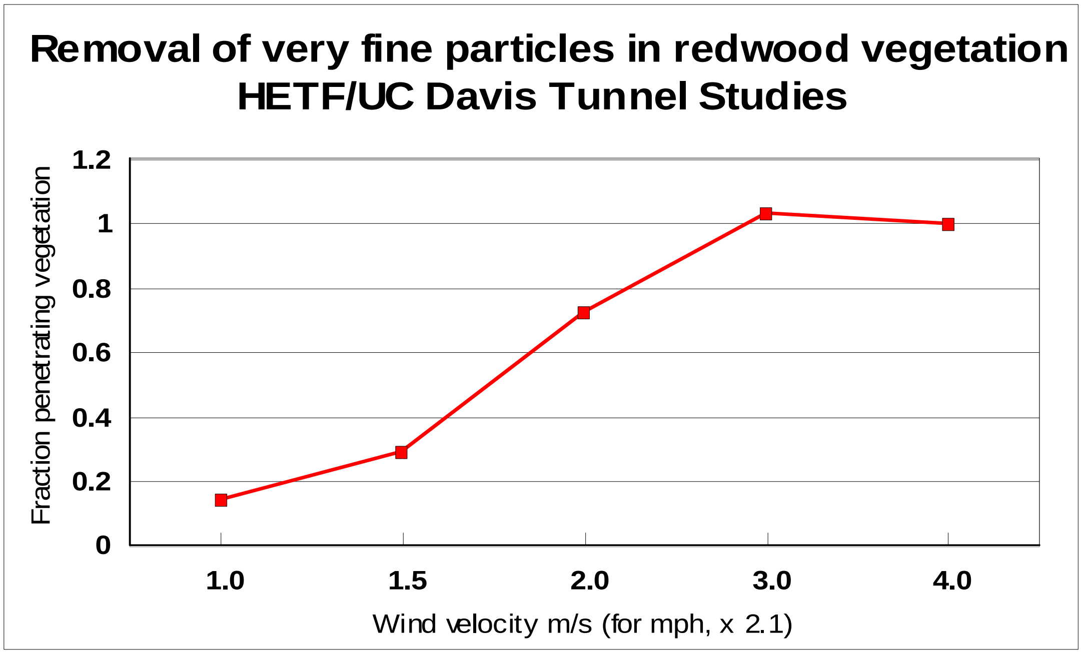


Figure 16 Removal rate of very fine particles on redwood branches via the dilution method.

Dustrak data

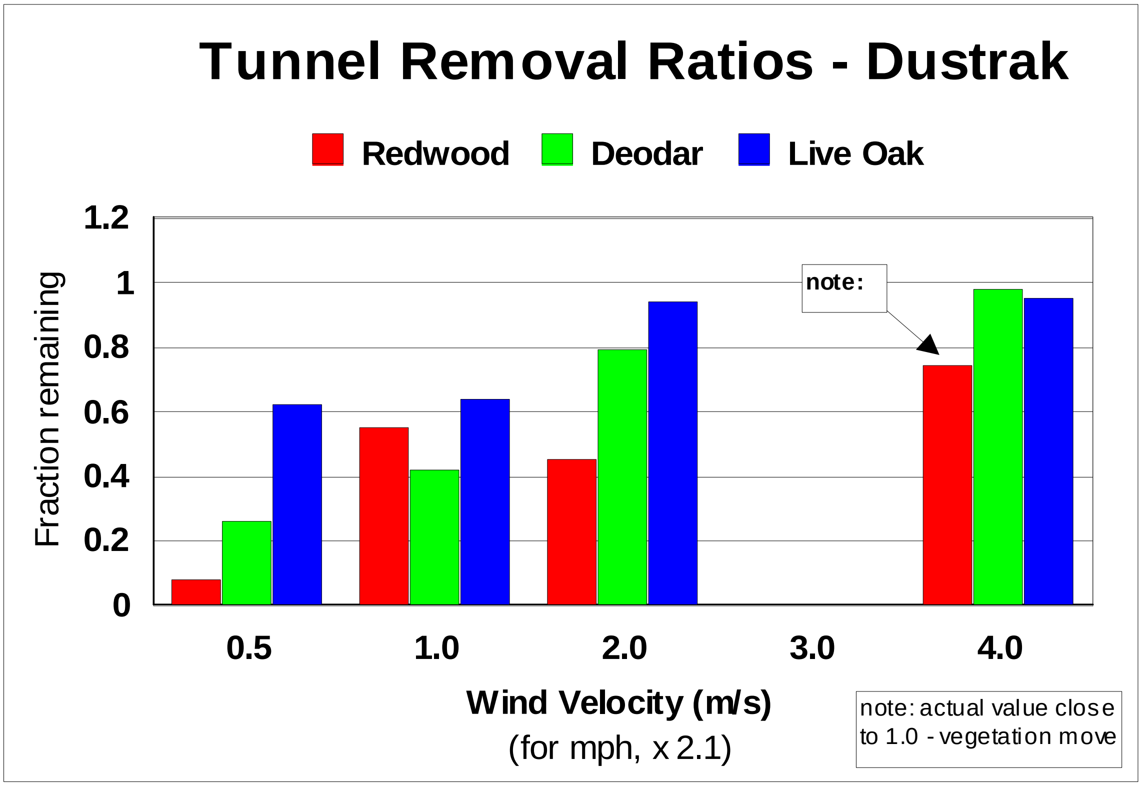
In the second type of measurement, TSI Dustrak™ nephelometers were placed before and after the vegetation of filters on the centerline of the wind tunnel. Recall that the Dustrak does not measure very well very fine (< 0.25 μm) and ultra fine (<0.10 μm) aerosols, so the data represents the heart of the accumulation mode with the upper point set by the flares at about 1 μm and the lower level at roughly 0.2 μm.

The aerosol source, flares or wood smoke in a small open flame combustor, were started, and data were taken typically every minute until the flares was exhausted, typically 12 to 15 minutes. Ratios were calculated for each measurement, and the mean of ratios and standard deviations were calculated and are presented below.

Aerosol sources	Filtering media	Wind Velocity				
		0.5 m/s	1.0 m/s	2.0 m/s	3.0 m/s	4.0 m/s
Flare		Ratio	Ratio	Ratio	Ratio	Ratio
Runs 3 - 7	Redwood	0.08±0.01	0.55±0.14	0.45±0.06		0.74±0.06*
Runs 34-38	Deodar	0.26±0.07	**0.42±0.06**	0.79±0.05		0.98±0.05
Runs 19-23	Live oak	0.62±0.05	**0.64±0.05**	0.94±0.05		0.95±0.05
Wood smoke						
Runs 8 - 11	Redwood		0.39±0.09	0.62±0.10		0.98±0.08
Runs 29-33	Deodar	0.49±0.17	**0.55±0.07**	0.92±0.11		1.11±0.07
Runs 24-28	Live oak	0.65±0.06	**0.69±0.04**	0.78±0.07		0.95±0.05

Table 3 Ratio of particulate concentrations before and after the vegetation or filter, measured with Dustrak nephelometers. Uncertainties are the standard deviations of 7 to 15 individual measurements within one run over time, while values in bold are the mean of repeated runs. Relatively few runs were made at 3.0 m/s.

* At 4.0 m/s, branches bowed to wind pressure allowing mass to avoid the vegetation; cured in all subsequent runs via edge blocking inserts.



note:

note: actual value close to 1.0 - vegetation move

Figure 17 Tunnel test removal ratios from Dustrack data

First, except for the known problem with the first 4.0 m/s redwood run, the 4.0 m/s (9 mi/hr) values represent essentially no removal of particles, with the before to after ratio 1.01 ± 0.10.

Second, on all occasions, reducing the wind velocity from 1.0 m/s to 0.5 m/s improved particle removal rates. This is the opposite behavior one expects for particle removal by settling and impaction, but exactly what one expects from diffusion phenomena that scale by the amount of time the particles are close to a surface.

Third, for the average of the two lowest wind velocities, the redwood runs (0.31) or, based on expected uncertainties (0.25), are roughly equivalent to the deodar runs (0.34), both of which are better than live oak (0.63).

Fourth, the removal rates for the flare particles are slightly better than for wood smoke, which is expected because the flare particles are finer and therefore more subject to diffusion losses than typical wood smoke.

Finally, the predicted removal rate at these wind velocities is far better for the unmeasured ultra fine (< 0.1 μm) particles, with predicted ratios of 0.10, 90% removal rates, in the 4 seconds it takes for the particles to traverse the vegetation.

8 DRUM data

The third type of measurement involves comparison of the upwind versus downwind 8 DRUM sampler data. These results had higher uncertainties, partially caused by the ± 15% uncertainty in replicates, part by suspected non uniformities in the particle distribution after moving through the vegetation. Efforts were made to reduce this by placing air barriers at all edges designed to avoid air passing around the vegetation rather than through it, but variations were still much higher than via the dilution method.

Figures 18 and 19 show the results of these tests for very fine particles. S-XRF strontium data were used, as it was unique to the flare and did not occur in background air, but mass data are also available from all runs.

The plot marked “theory” was based on a deposition velocity (Figure 4) of 0.1 cm/sec, but suffers from the wildly non-uniform leaf and branch configuration that makes quantitative calculation unreliable. It should merely be used as a qualitative measure of expected behavior versus exposure time in the vegetation array.

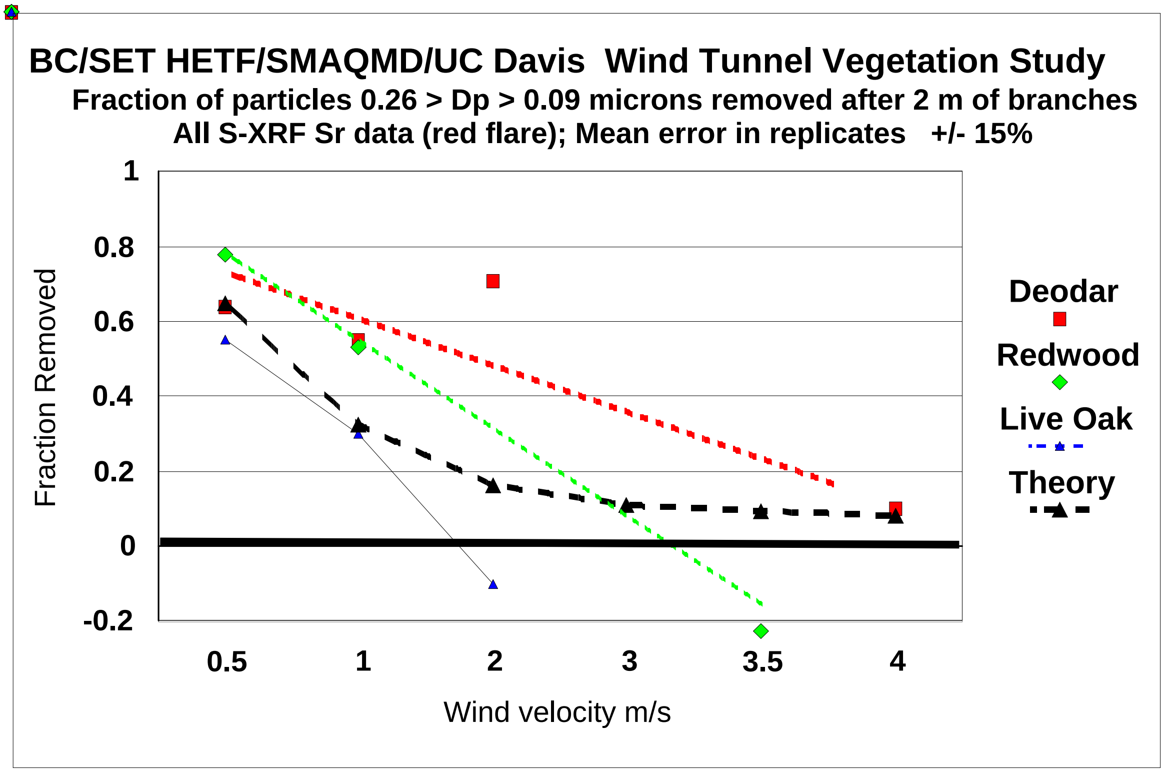


Figure 18 Fraction of particles removed versus wind velocity and vegetation type.

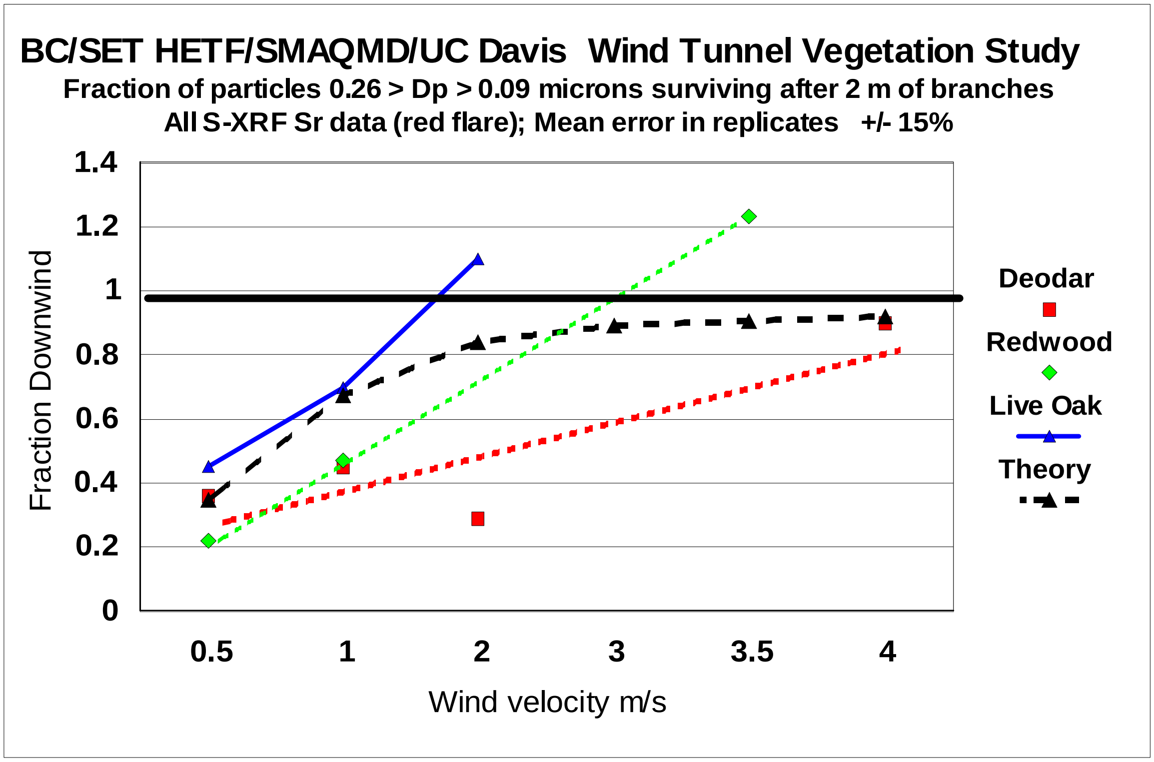


Figure 19 Fraction of particles surviving versus wind velocity and vegetation type.

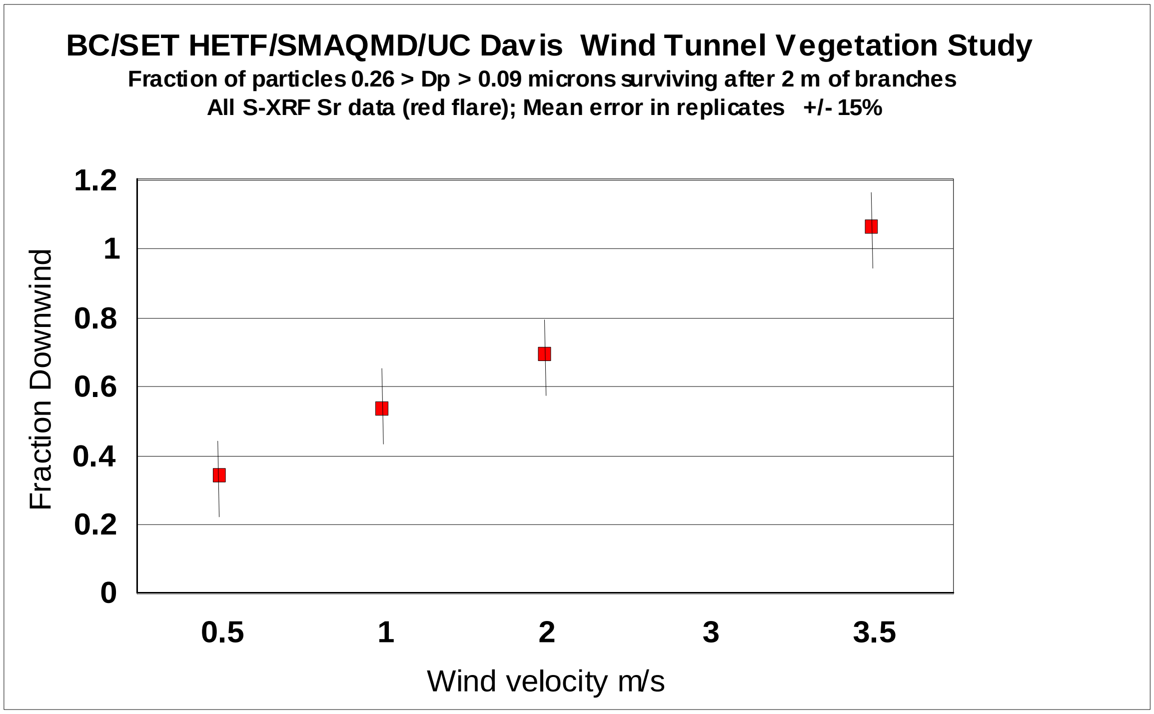


Figure 20 Fraction of particles surviving versus wind velocity – average of all vegetation types

From the measured data for 0.26 > D_p > 0.09 µm particles and the 0.5 m/s (1.1 mph) wind velocities, 4 second exposure time in the vegetation, and using the more conservative S-XRF elemental data, we are able to match these fractional removal rates to the measured and extrapolated deposition velocities of Figure 4 (Seinfeld and Pandis, 2004) and predict fractional removal into the ultra fine (< 0.1 µm) size ranges.

Particle diameter	v_d	Redwood	Deodar	Live oak	
(µm)	(cm/s)	Fraction removed	Fraction removed	Fraction removed	
0.17	**0.01**	**0.79**	**0.65**	**0.55**	**Measured**
0.10	0.0125	0.83	0.72	0.64	Estimated
0.075	0.015	0.86	0.77	0.70	Estimated
0.050	0.02	0.90	0.83	0.78	Estimated
0.035	0.045	0.95	0.92	0.90	Estimated
0.015	*0.25*	*0.99*	*0.99*	*0.98*	*Extrapolated*

Table 4 Measured and estimated removal fractions for very fine and ultra fine particles versus vegetation type.

In summary, three different ways of examining particle removal by vegetation come up with consistent behavior as a function of wind velocity and support for the greater efficiency in the redwood and deodar tests.

The wood smoke data shows slightly poorer removal rates resulting from the flares, which is expected because the wood smoke does not extend to the very fine particle range. Nevertheless, it is clear that as wood smoke passes through a forest, particles are removed from the air. This is especially important for low temperature prescribed fire during which the smoke stays within the tree canopy.

3. Chamber studies

The chamber studies were based on an attempt to perform a diffusion-limited particle removal study without the complexity of air motion and impaction of particles inherent in the wind tunnel studies.

A plastic chamber 1.5 m/side (3.5 m^3) was constructed, with a removable side wall and a frame at the bottom into which was placed fresh vegetation: oleander, redwood, deodar, and live oak, derived from prunings for the UC Davis grounds program. The placement was designed to provide a reasonable natural mass of vegetation far less dense than the vegetation array used in the tunnel study.

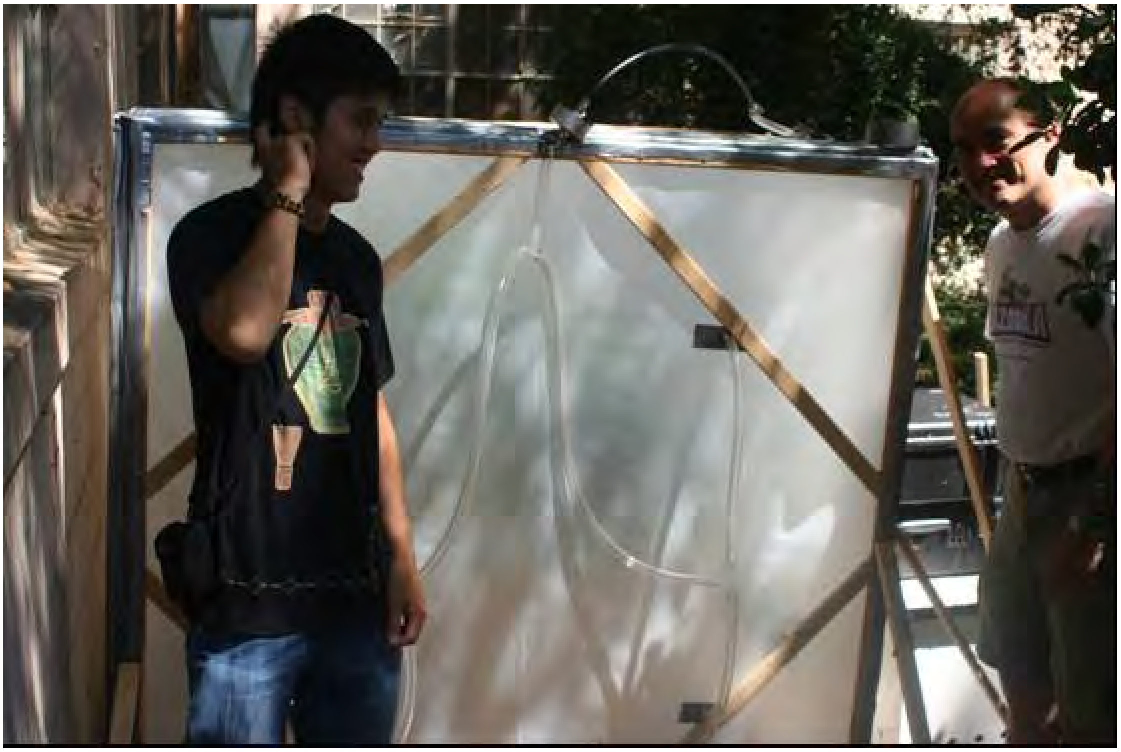


Figure 21 Chui Hayes and David Barnes at the static chamber, with the filtered air make-up air ports visible.

Figure 22 First attempt at vegetation in the static chamber. Even this much oleander absorbed particles so rapidly the chamber could not be filled.

Leaf area

To allow model calculations leaf area had to be obtained. This was done through both the leaf area meter of the USDA Urban Forest Program at UC Davis for the tunnel study and by hand for the static chamber studies. The leaves and branches were calculated separately. As an example, below is the protocol uses for live oak.

Leaves:

1. 32 leaves with petiole were removed at random from the oak branches.
2. The surface area of the leaves was measured:
    a. a calibration sheet was printed with squares of various sizes,
    b. the squares were measured with calipers and the sheet scanned,
    c. the sizes of the scanned squares were measured with Scion Image in pixels and compared to the caliper measurements to establish a calibration,
    d. the leaves were scanned in the same manner along with a calibration target, and
    e. the surface area of the leaves and calibration target was computed
3. The thickness of the leaves was measured with calipers.
4. The mass of the leaves was measured.
5. The density of the leaves was computed using the surface area, thickness, and mass.
6. The remaining leaves were removed from the oak branches and weighed in bulk on a triple beam balance.

7. Using the measured mass, computed density, and previously measured thickness, a total surface area was computed:

$$SurfaceArea = 2\frac{Mass}{Density(Thickness)}$$

Branches:

1. 32 small, straight, sections of oak were cut at random.
2. The diameter and length of each section was measured with calipers.
3. The mass of each section was measured.
4. The density of the sections was computed.
5. The remaining oak branches were cut roughly into straight segments.
6. A large number of the segments were measured with a ruler and then weighed.
7. The surface area of the segments was computed:

$$SurfaceArea = 2\pi(Length)\sqrt{\frac{Mass}{\pi(Density)(Length)}}$$

8. The surface area of another large batch of segments was computed in the same manner.
9. The surface area per unit mass was calculated for each batch and averaged.
10. The remaining segments were weighed and their surface area determined by the above relationship.

From these measurements, the final leaf areas for the static chamber were:

Redwood	7.1 m^2
Deodar	6.3 m^2
Live oak	9.0 m^2

Static chamber operations

As in the tunnel study, particles were derived from highway flares placed in a sealed combustion chamber. Air was inserted into this chamber at the rate of roughly 10 L/min, and the smoke pushed through a 10 cm diameter plastic tube into the center of the chamber. The velocity of the incoming smoke was a few cm/sec, and it fell like slow motion stream of water towards the bottom of the chamber during the fill process. After the flare was burned (originally for the full 15 min, later reduced to 1.5 min), the input air was stopped from the burn chamber.

After 1 min, the DRUM sampler was started (10 L/min and 10 L/min of new filtered stretched Teflon) ambient input air was added at 4 points in each near corner of the chamber on the vertical wall opposite the smoke input. The purpose of this was to provide clean make up air for that lost into the DRUM sampler and provide low velocity mixing. The DRUM input was a 5 cm diameter aluminum tube in the center of the chamber.

Example of drums from 3 redwood chamber runs

Particle diameter (μm)

10 to 5.0 **Not shown**

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

Figure 23 Flare aerosols from 3 redwood static chamber tests. The vegetation for this test had a leaf area roughly 1/10 that shown in Figure 22

Note the absence of particles in the $0.26 > D_p > 0.09$ μm size range in the chamber studies. These are present abundantly in the flare emissions (see Figure 13) but the higher concentrations in the combuster and long residence times appears to have depleted particles below about 0.34 μm. Recall that the exposure time in the chamber before measurements even start was 60 seconds, while the exposure time in the tunnel study was never more than 4 seconds.

Table 4 shows the measurements made during the chamber studies. Each study involved multiple runs of the 8 stage impactor, generally 1 to 3 hr in duration. Typically 3 measurements were made on a single set of drum strips. The samples were then beta gauged, and mass profiles provided.

Static box summary

Date	**Run**	**Foliage**	**Flare Time (min)**	**Sample Time (min)**	**Notes**
?	1	Empty	15	1:03	Foliage support not installed.
7/27/07	2	Empty	16.5	3:00	Foliage support not installed. Stages 1-3 little deposit.
7/30/07	3	Oleander	15	3:00	Stage 7 blockage, gap in box seal
8/01/07	4	Oleander	16.5	3:03	Extra foliage added
8/02/07	5	Empty	18	2:05	Foliage stand in; Stages 1-5 too much mass
?	6	Empty	?	?	Foliage stand in
8/08/07	7	Live Oak	15 (?)	1:30	
8/09/07	8	Live Oak	10 (?)	3:07	Leakage on cyclone, flaking on stage 4, only stage 7 and 8 survive download
8/10/07	9	Live Oak	2	3:00	
8/13/07	10	Live Oak	N/A	0:45	Run with make up air only to see if particles are coming off foliage. Deposit not visible.
8/13/07	11	Live Oak	1	2:00	
9/13/07	12	Deodar	1.5	3:00	Strange “fingerprint” on st. 8.
9/13/07	13	Deodar	1.5	4:45	
9/14/07	14	Deodar	1.5	2:30	
9/20/07	15	Redwood	1.5	3:00	
9/20/07	16	Redwood	1.5	3:00	
9/21/07	17	Redwood	1.5	3:00	
1/02/08	18	Empty	1.5	3:08	
1/02/08	19	Empty	1.5	3:00	
1/03/08	20	Empty	1.5	2:00	
1/03/08	21	Empty	3.0	2:00	
1/03/08	22	Empty	3.0		Lots of smoke leaking from BBQ; Raining.

Table 5 Summary of static chamber tests

The initial set runs were done with the empty chamber and a 15 minute flare burn. The chamber was visually observed to be uniformly filled with flare smoke, which then decreased in time. Note that the removal rate of the DRUM impactor, 10 L/min, would take 350 minutes, almost 6 hr, to empty the chamber. The first runs were on oleander branches, essentially loosely filling the chamber (10 to 12 m^2 of branch and leaf surface area). Two points were immediately evident. The mass of aerosols present in the filled chamber was a small fraction, circa 10%, of the mass of aerosols in the empty chamber. Second, almost all particles in the very fine ($0.26 > D_p > 0.09$ µm) size mode were absent.

Since this occurred also for the empty chamber, this argues for a serious role for coagulation in reducing the aerosol concentrations.

In a way, these measurements by themselves proved the effectiveness of vegetation in removing very fine aerosols from the flare smoke. The process was so fast that it was invisible to the DRUM, so the experiment was modified in two ways:

1. the amount of vegetation was greatly reduced, until the leaf area was on the order of 1.5 m^2, rather than 10 m^2.
2. the length of the flare burn was reduced to 1.5 min.

The empty chamber runs were then duplicated, now with lower concentrations. With this revised protocol, the concentrations in the chamber seen with the branches in place were increased to the point where measurements could be made.

From these runs, two quantitative results are available. First, the concentration seen at the beginning of each run was a measure of the effectiveness of particle removal by the vegetation during the fill and 1 minute delay before the DRUM started to sample. Second, the decay versus time was then available to examine the removal process.

The static chamber studies were performed with effective wind velocities less than 0.1 m/sec to allow diffusion to surfaces without the impaction that occurs in the wind tunnel. However, the very fine particles were essentially removed from the chambers during fill and in the 1 minute equilibration time allowed in the experiment by coagulation, diffusion to chamber walls, and vegetation. By sharply reducing the amount of vegetation (to roughly a few percent of that used in the tunnel studies), we were able to obtain adequate particles in the slightly coarser 0.26 to 0.34 μm size mode and follow the decay of these particles in time. Twenty separate runs were made in this final configuration.

Two measures of success were developed:

1. The amount of mass present in the chamber after the 1 minute delay after filling and mixing, and
2. The decay of the remaining mass in time.

From the particles remaining after fill, the values were (relative units):

Deodar	2000	relative removal	=	0 %
Live oak	1400	relative removal		30 %
Redwood	500	relative removal		75 %
Oleander	400	relative removal		na

The actual removal rates will of course be higher, since there was certainly some removal of particles by the deodar.

The relatively poor removal rate of deodar in the chamber tests contrasts sharply from the excellent results achieved in the tunnel studies. Examination of the needle and branch structure shows that a large fraction of the surface redwood area occurs in flat branchlets with needles side by side, leaving relatively larger gaps empty of vegetation between the branches. Deodar, on the other hand, has a much more diffuse structure (see Figure 15) similar in some ways to live oak.

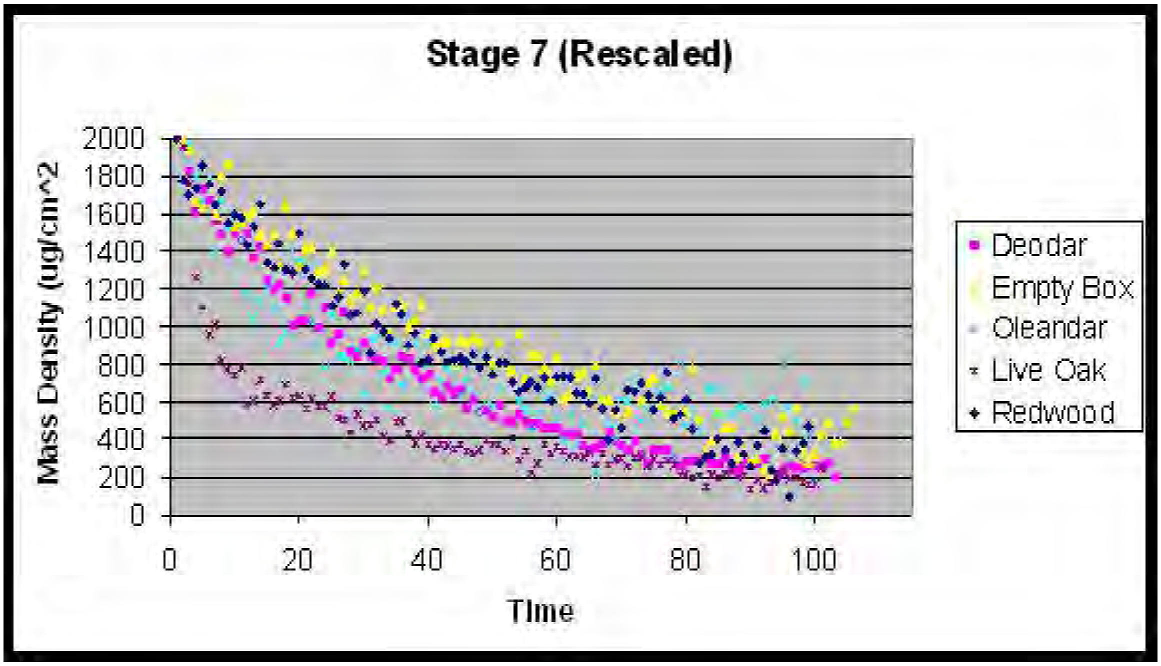


Figure 24 Decay of aerosols (in minutes) in the static chamber versus types of vegetation

The second measure was the decay of the remaining particles in time. In this test, live oak was anomalous while deodar was best. Redwood was, surprisingly, essentially the same as the empty chamber, but recall that it was the best at particle removal during the fill process.

D. Interpretation and Conclusions

The data above show that the basic premise of the study has been confirmed. Vegetation does remove particles from the atmosphere, especially very fine particles such as diesel exhaust, and that removal is semi-quantitatively predicted by theory. These data thus encourage the use of vegetation to not only disperse but to capture and remove the most toxic components of aerosols, very fine (< 0.25 µm) and ultra fine (< 0.1 µm), from the air. When vegetation is placed near sources, such as along roads, there will be mitigation at the source before it is dispersed into the local and regional air mass.

The differences in the two types of study are intriguing, and a clear and unique explanation is not derivable from the present data alone. However, there are important points to note in the information from each study that can help in interpretation.

1. The air velocity of the tunnel study was from 0.5 m/s to 4.0 m/s, that of the chamber study circa 0.05 m/sec.

2. In the tunnel study, redwood and deodar were the most effective removal agents, twice as good as live oak. Redwood and deodar were also more effective than live oak in the static chamber tests, as the live oak had replication problems that reduced our confidence in the data as a whole. .
3. In the chamber studies, particle removal was so rapid that the chamber could not be filled with aerosols (as in the empty chamber) until the branch area had been reduced almost by a factor of 10 from a filled chamber. The differences beyond that are difficult to interpret and may be closely tied to branch structure

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Appendix I

In order to evaluate the ability of air filters to remove very fine and ultra fine particles from indoor air, the tunnel study added a comparative analysis of three “furnace filter” types, all with sizes roughly 20” 25” x 1”:

1. Standard paper based furnace or central air filter
2. ACE Spun glass air filter for furnace or central air, Model 44768, and
3. The Wed Plus filter with micropest control, 3 phase (passive) electrostatic filter, washable and re-usable (“traps up to 91%”)

Wind Tunnel Run Summary Data

Filter studies

Erin Fujii, Project Manager

Set:	Run #	Date	Vegetation and age (hr)		Wind Velocity (m/s)	Length of Run (s)	Turbulence enhancement	Comments
(front and back, stages 1-8)								
	12	09/24/2006	pun glass filte	flare	0.99		as above	* filter wrong
	13		spun glass filte	flare	2		as above	* filter wrong
3	14		spun glass filte	flare	1		as above	** filter ok,
	15		spun glass filte	flare	1.97		as above	
	16		spun glass filte	flare	3.91		as above	
	17		spun glass filte	flare	0.51		as above	
	18		spun glass filte	flare	0.98	480	as above	*** block removed
	39		electrostatic filt	flare	1.01	315		
	40		electrostatic filt	flare	1.98	330		
					* filter facing wrong way			
					** filter facing ok, filter blockages, stg. 7/8			
					*** blockages in stg. 7/8 removed			
6	41		electrostatic filt	flare	4	360		
	42		electrostatic filt	flare	0.51	331		
	43		electrostatic filt	flare	0.5	360	small fan added	
	44		electrostatic filt	flare	0.97	315	as above	
	45		paper filter	flare	0.93	360	as above	
	46		paper filter	flare	1.88	360	as above	
	47		paper filter	flare	2.55	360	as above	
	48		paper filter	flare	0.5	348	as above	with afterfilter
	49		paper filter	flare	1.95	373	as above	
	50		spun glass filte	flare	0.97	360		
7	51		spun glass filte	flare	2.04	360		
	52		spun glass filte	flare	3.97	420		
	53		spun glass filte	flare	0.49	285		
	54		spun glass filte	flare	0.98	345		
					**** small fan added in mouth of tunnel,			
					blowing perpendicular to tunnel flow			

The data for air filters are best summarized in the Dustrack data.

Aerosol sources	Filtering media	Wind Velocity			
		0.5 m/s	1.0 m/s	2.0 m/s	3.0 m/s
		Ratio	Ratio	Ratio	Ratio
Flare	Filters				
Runs 45-49	Paper	0.59±0.09	**0.77±0.10**	0.72±0.08	0.67±.07
Runs 50-54	Spun glass		**0.63±0.06**	**0.71±0.10**	
Runs 13-19	Spun glass	0.37±0.09	**0.46±0.05**	**0.83±0.04**	
Runs 39-44	Electro-static	0.45±0.02	**0.75±0.15**	0.53±0.03	

Table I - 1 Ratio of particulate concentrations before and after the filter, measured with Dustrak nephelometers. Uncertainties are the standard deviations of 7 to 15 individual measurements within one run over time, while values in bold are the mean of repeated runs.

Note that the pressure drop across the filters was so great we could not run at 4.0 m/s

All filters exhibited improved particle removal at lower wind velocities. Both the spun glass and electrostatic removed more particles than the standard paper filter. The fact that they removed fewer particles than the vegetation could well be tied to the much smaller time of residence in the filter counteracting the closer proximity of the particles to the fibers.

Appendix II

Excerpts from DRUM Quality Assurance Protocols DQAP ver 1/08

The DRUM cuts are sharp and fully predictable by standard aerodynamic principles, and mis-sizing by bounce-off is reduced to less than 1 part in 5,000 by mass by a light grease coating (Wesolowski et al, 1979, Cahill 1979, Cahill et al, 1985).

A side by side comparison study of DRUM and other samplers was done on October 2 – 14, 2005, at Davis as part of the Quality Assurance component of the new EPA Particulate Matter Research Center grant to UC Davis which will be using DELTA Group DRUM samplers and analysis, 2005-2010.

However, an error in the modification in old DRUM #4, (1987) the Pool site sampler, resulted in an internal leak in that could not be detected during field sampling at RRAMP using standard vacuum and flow audit devices. It was discovered after analyses of the co-located sampling for quality assurance purposes at the Denio site and confirmed by disassembly of the unit. This invalidated all size modes from the Pool sampler except the finest, $0.26 > D_p > 0.09$ µm, which as a critical orifice has separate quality assurance checks. The side by side comparison yielded an average of 0.72 µg/m^3 for the Denio sampler, 0.68 µg/m^3 for the Pool site.

Comparison between data on DRUM samplers to standard PM is difficult due to:

1. Sharper size cut profiles, DRUM vs filters, especially important near the PM_{10} and $PM_{2.5}$ cut points,
2. Differences in the way impactors handle aerosols, since air is not drawn through the deposit, preserving chemical information sometimes lost in filters (i.e., sulfuric acid, Cahill et al, 1996)
3. Lack of ultra fine data below 0.09 µm. This latter problem is especially important near strong combustion sources.
4. Time registration. DRUM samplers have errors in timing inherent to continuous sampling. The finite width of the impaction slot introduces an irreducible averaging over 1 ½ to 3 hr, the stretching of the Mylar onto the analysis frame adds typically 6 ± 3 hr of uncertainty. The relative time uncertainty is very small, 10 min/day, so that alignment of DRUM data with high precision gas and particulate data (such as NO) is an essential next step in data reduction.
5. Propagation of error problems. To match a single 24 hr $PM_{2.5}$ RRAMP filter, one has to sum 96 individual 1 ½ hr mass measurements or 48 3 hr elemental values from the DRUM samplers.
6. Dilution of the mass signal. The aerosols are spread over 8 size modes, resulting in almost a reduction of 10 in the amount of mass available to analyze on each stage.

1. Analysis

The UC Davis DELTA Group performs analyses by 7 different non-destructive methods, also described in publications and the 135 page DRUM Quality Assurance Document, latest version 1/2005 (DQAP ver. 1/05), posted on the DELTA web site http://delta.ucdavis.edu.

c. Mass

Analysis was completed for mass values every 1 ½ hours in 8 size modes for the entire period. Each strip was analyzed at least 2 times, and the standard deviation of the data are included in the data file. An example of the precision repeated measurements of DRUM strip is shown below.

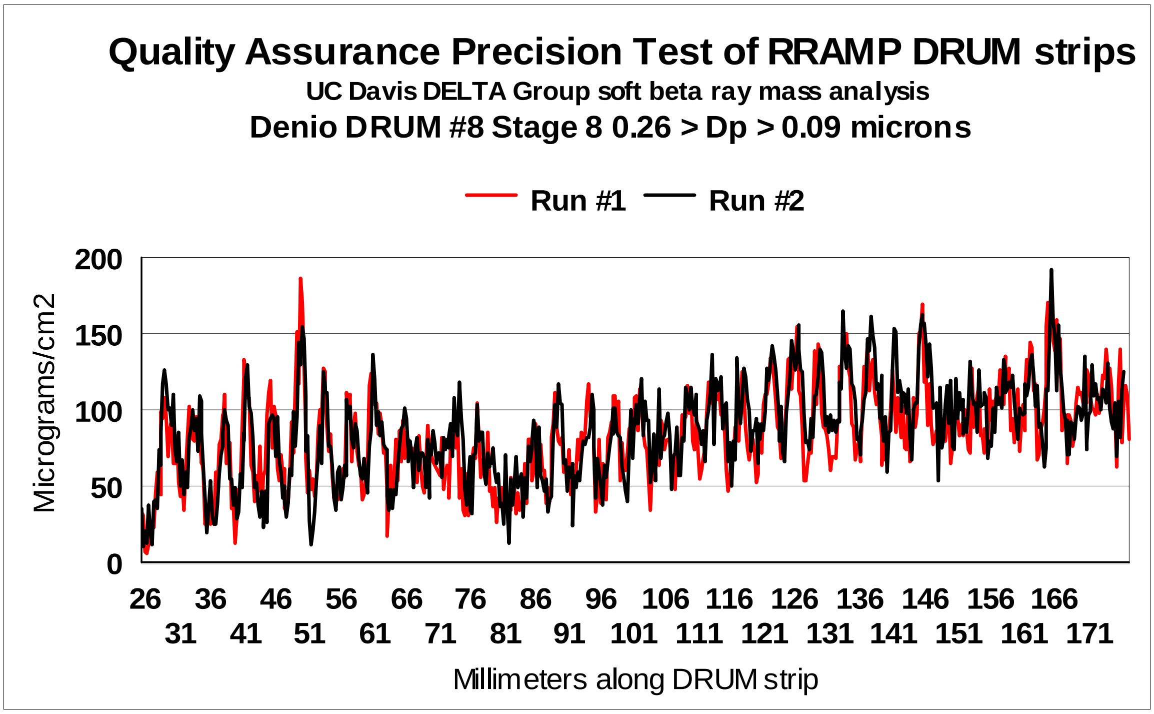


Figure 1 Precision test for mass

Note that since the strip was remounted, the test also validates relative time precision. Any measurements where the analysis differs by more than ± 10% are independently re-run until agreement is achieved.

As mentioned above, comparisons with 24 hr filters are difficult. There have been 2 recent comparisons completed and one in progress (the US EPA PMRC Center tests at Davis) in rural conditions where the lack of ultra fine particulate mass should not be a major effect. The first was with IMPROVE and the National Park Service at Yosemite NP, 2002. (Final Report, 2004) Despite having to average 144 soft beta mass measurement (data taken every hour in 6 size modes), there is good overall agreement ($r^2 = 0.74$, slope = 1.14). However, the worst agreement occurred on 4 successive days with the arrival of fresh forest fire smoke from massive fires in Oregon.

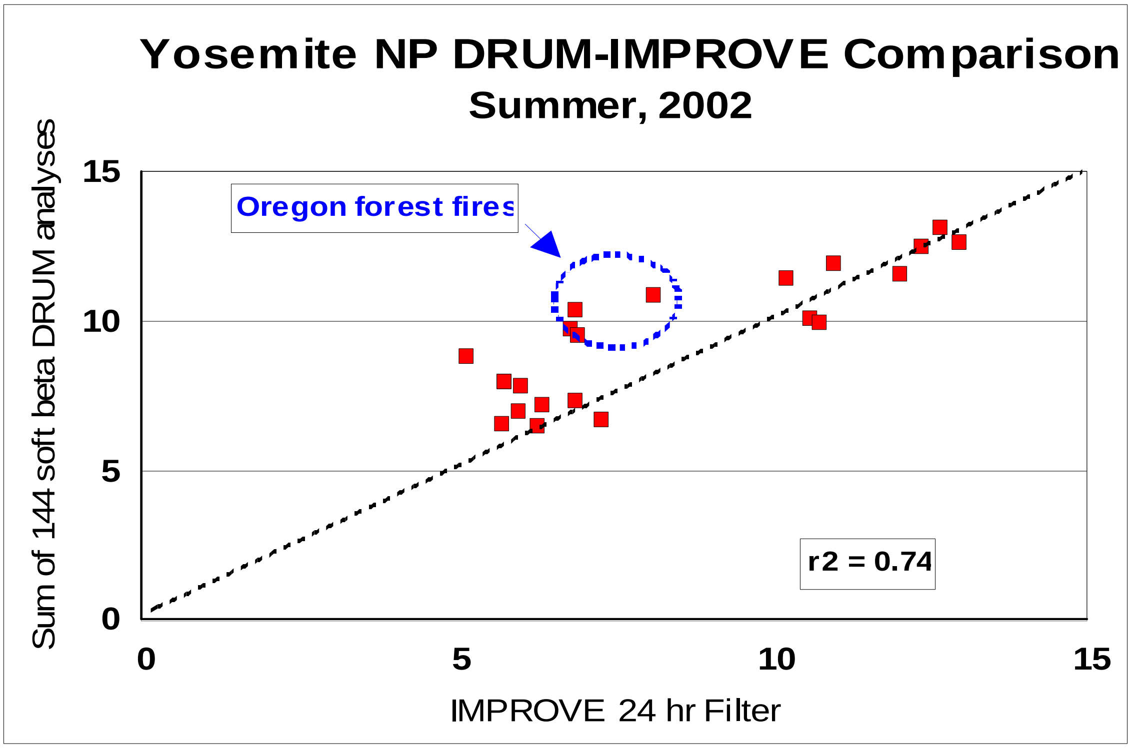


Figure 2 DRUM mass versus filters at Yosemite NP

A second recent test involved a comparison of DRUM mass at Davis to the district $PM_{2.5}$ data at Woodland, roughly 10 miles away.

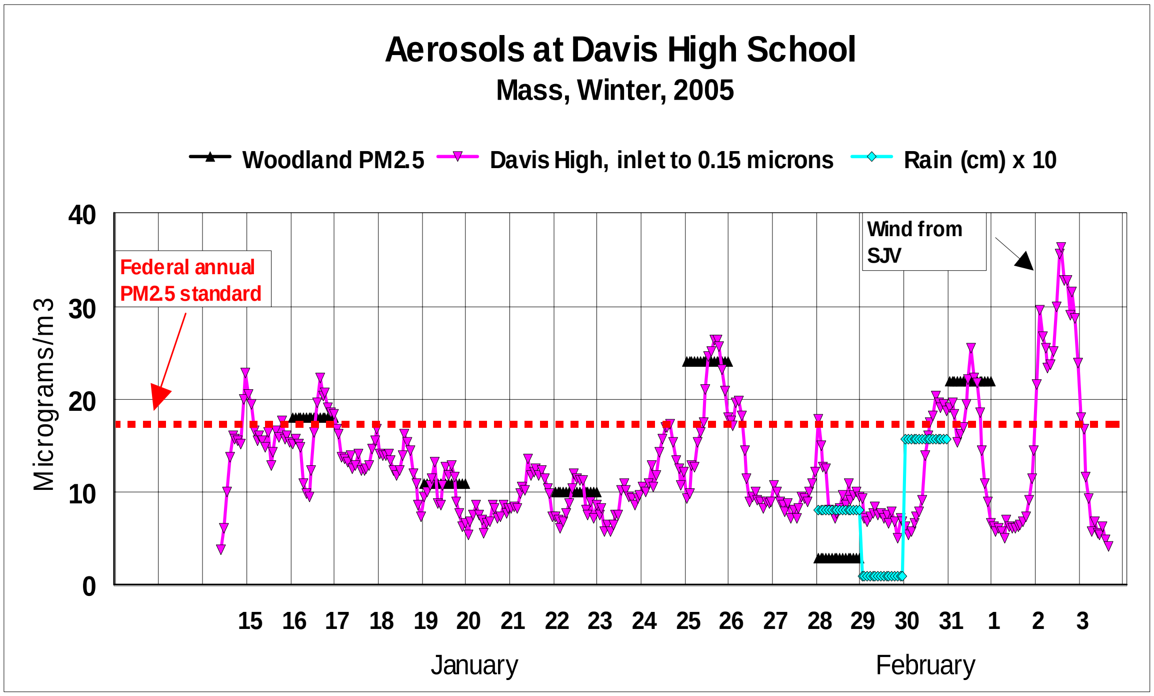


Figure 3 DRUM versus district filter sampler, Yolo County

In summary, DRUM mass data are vital for elucidating temporal and size behavior of aerosols while suffering some loss of accuracy and precision when compared to standard filter methods.

c. **Compositional Analysis of Elements**

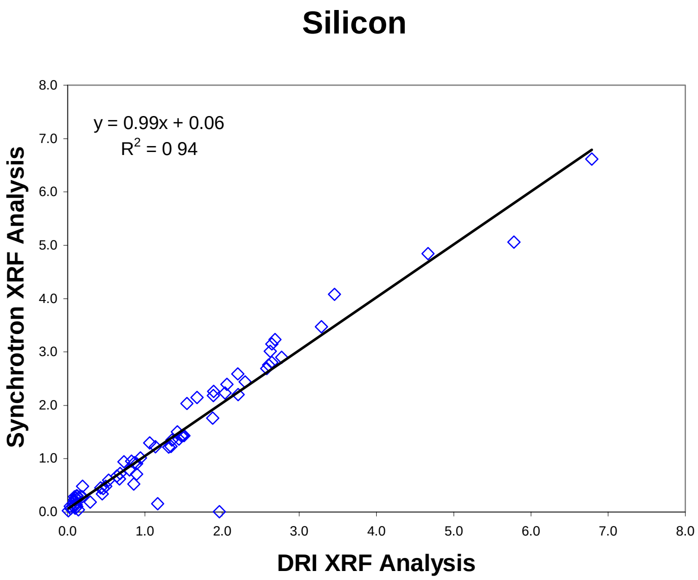
The samples collected by the DRUM sampler are designed to allow highly sensitive elemental analysis by the new DELTA Group designed aerosol analysis system of the x-ray micro beam of the Advanced Light Source, Lawrence Berkeley NL (Bench et al, 2002). The method, synchrotron-induced x-ray fluorescence (S-XRF) has been used by the DELTA Group since 1992, (Cahill et al, 1992) but in its present form since 1999.

Study and date	Methods	**Average ratio, Al to Fe**	Std. dev.	**Average ratio, Cu to Pb**	Std. dev.
BRAVO, 1999	PIXE vs S-XRF	**0.99**	0.04		
BRAVO, 1999	CNL XRF vs S-XRF			**1.24**	0.14
FACES, 2001	ARB XRF vs S-XRF	**0.93**	0.21	**1.02**	0.08
FACES, 2001	ARB RAAS vs S-XRF	**(0.98)**	0.27	**(0.74)**	0.23
ARB LTAD 2005	DRI XRF vs S-XRF	**1.037**	0.085	**0.907**	0.009
All prior studies	**Average**	**0.984**	**0.15**	**0.977**	**0.115**

Table 2 S-XRF comparison, all blind tests since 1999

The S-XRF system has been tested in blind inter-comparisons since 1999, and all of these are shown above. Typically 32 elements are recorded for each analysis, all of which can be traced back to NIST primary (SRM # 1832, SRM # 1833) or secondary (Micromatter thin film) standards. Over 250,000 S-XRF analyses have been done by the DELTA Group since completion of the system in 1999.

An example of a recent comparison for very clean particles from Lake Tahoe is shown below versus DRI's excellent multi-anode XRF system. This was part of the ARB funded Lake Tahoe Atmospheric Deposition (LTAD) project of 2002 - 2005. The units are μg/cm^2.



The sensitivity of S-XRF is typically about 10 x better than standard XRF since the polarized x-rays eliminate over 90% of the x-ray background and the beam intensity is almost unlimited. This allows the standard analysis duration of 30 seconds to achieve a sensitivity for a DRUM sampler of about 0.01 ng/m^3 for elements between titanium and bromine, and roughly 0.03 ng/m^3 for most other elements reported. Below we show the MDLs for Stage 8 (0.26 to 0.09 μm diameter) of the 8 DRUM impactor.

S-XRF analysis			
Elements	MDLs (ng/m^3)	Elements	MDLs (ng/m^3)
Sodium	2.0	Cobalt	0.02
Magnesium	0.14	Nickel	0.02
Aluminum	0.09	Copper	0.03
Silicon	0.15	Zinc	0.05
Phosphorus	0.20	Gallium	0.001
Sulfur	0.20	Arsenic	0.001
Chlorine	0.02	Selenium	0.002
Potassium	0.02	Bromine	0.005
Calcium	0.05	Rubidium	0.01
Titanium	0.015	Strontium	0.02
Vanadium	0.003	Yttrium	0.15
Chromium	0.003	Zirconium	0.15
Manganese	0.005	Molybdenum	0.25
Iron	0.05	Lead	0.15