Estimation of Particulate Highway Impacts – diesels and smoking cars

- **What kind of data do we need?**
  - Near highway (< 200 m) impacts of traffic
  - Sub regional (200 m to few km) impacts of traffic
- **Why do we need the data?**
  - Concerns over health impacts of very fine/ultra fine particles
  - Requirements of visibility at Lake Tahoe – air and water
- **Sources of information**
  - Laboratory studies – NREL/U. Minnesota/DRI diesels; Lawson et al
  - Field data – prior ARB/UC Davis work on lead from freeways
  - Field data – HEI/DRI Tuscarora Tunnel studies; Gertler et al
  - IMPROVE/UC Davis OC/EC studies – 1989 - present
- **Applications**
  - Interstate 5 on downtown Sacramento – ALA (Lung Association)
  - Watt Avenue on Arden Middle School, Sacramento - ALA
  - Highway 50 in South Lake Tahoe – TRPA (Tahoe Regional Planning Agency)

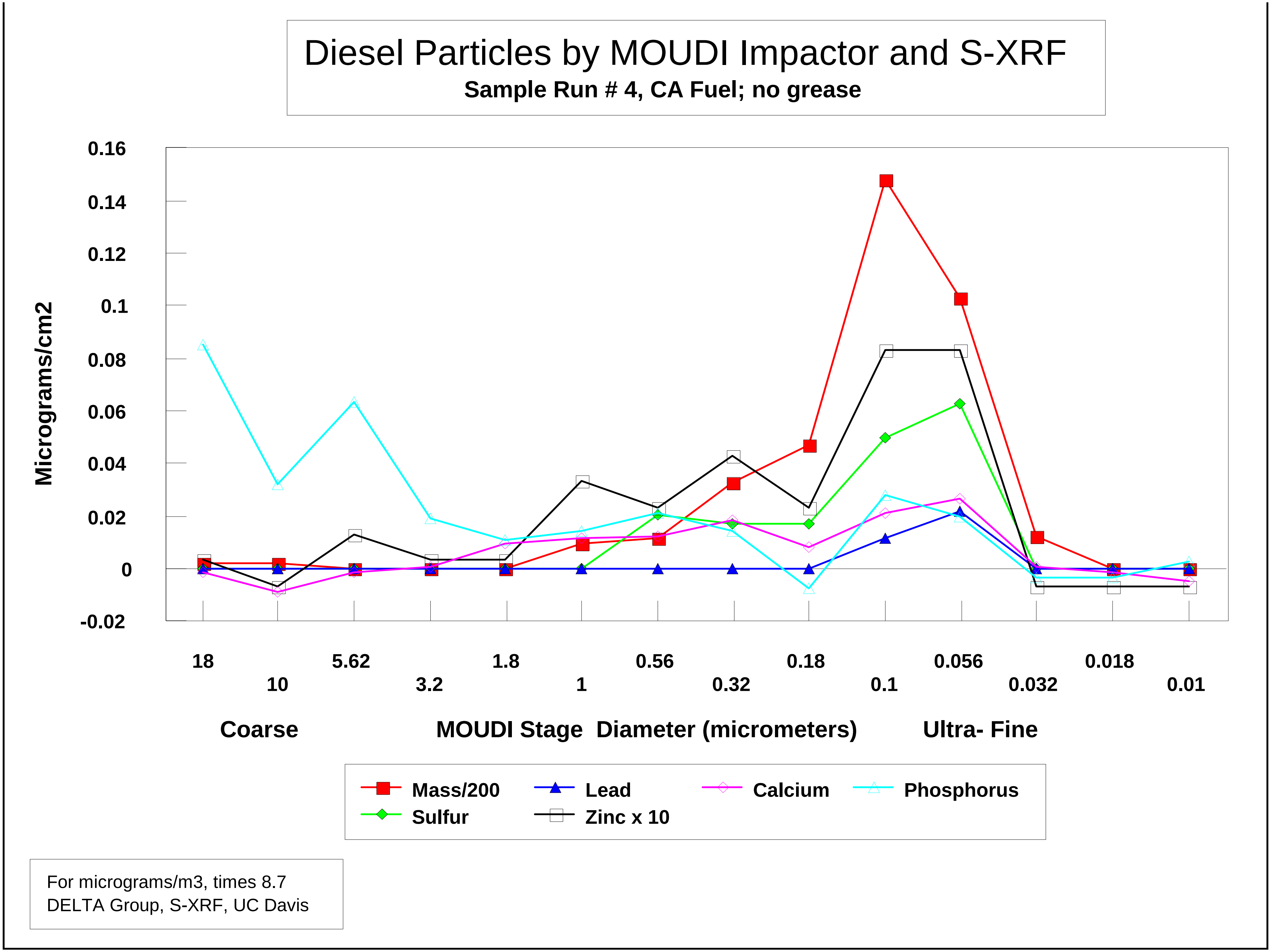
Characteristics of diesel engines

- **High Carnot efficiency derived from high temperature combustion**
  - Fixes Nitrogen from the atmosphere – NO
  - Very fine refractory particles

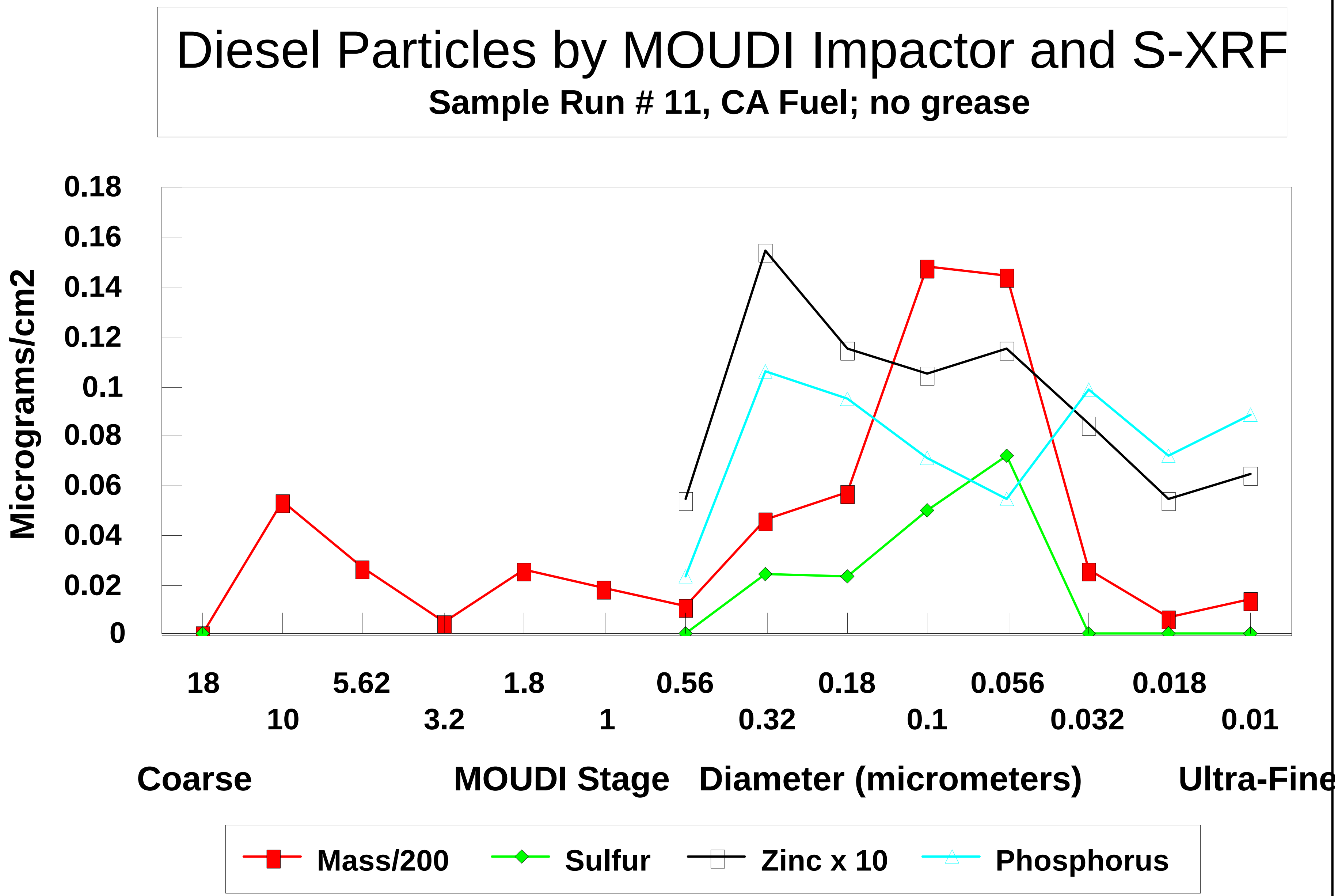
- **High compression needs high molecular weight fuel**
  - Partial combustion near cylinder wall – soot and complex organics
  - Tight clearances need excellent lubrication - Zn, P, S, organics to avoid serious cylinder wall wear – Fe, Mn,…
  - May still contain sulfur since less refined
    - Very fine/ultra fine sulfates during dilution

Laboratory data of Watts et al from the diesel dynamometer tests – NREL (Lawson) / U. Minnesota (Watts et al) /DRI (Zielinska et al)/UC Davis (Cahill et al)

- A series of 11 tests using both California and "road" (US average) fuels
- Particles collected with nano-MOUDI samplers with greased (DELTA Group Apiezon-L) Mylar substrates
- Analysis by mass, ions (DRI) and S-XRF (DELTA Group, UC Davis)
- Some diesel test measurements at UC Davis
- Final Report not yet released



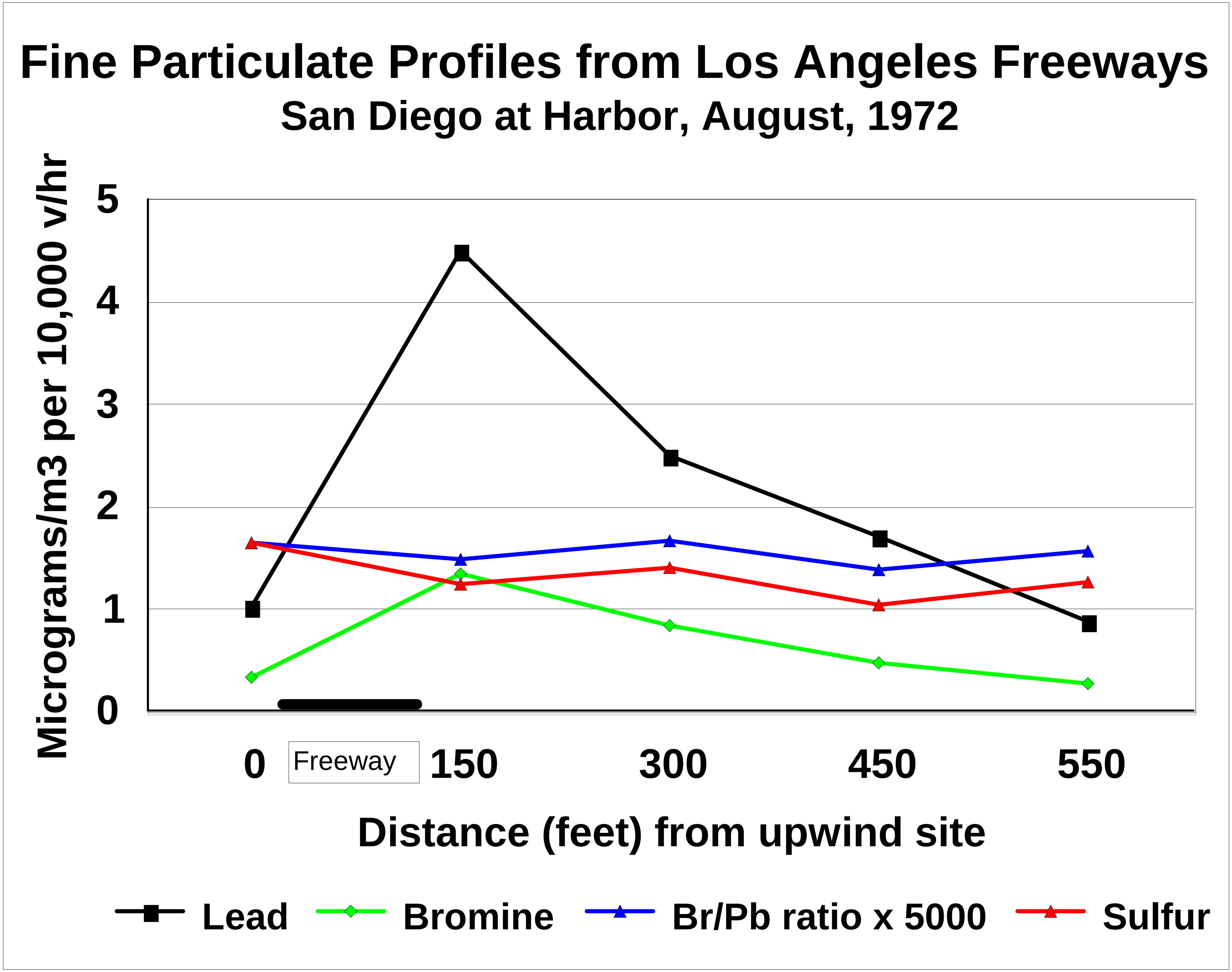
Diesel Particles by MOUDI Impactor and S-XRF
Sample Run # 4, CA Fuel; no grease
Micrograms/cm2
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
18
10
5.62
3.2
1.8
1
0.56
0.32
0.18
0.1
0.056
0.032
0.018
0.01
Coarse
MOUDI Stage Diameter (micrometers)
Ultra- Fine
Mass/200
Lead
Calcium
Phosphorus
Sulfur
Zinc x 10
For micrograms/m3, times 8.7
DELTA Group, S-XRF, UC Davis



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

Field Studies:
1) 5 Prior UCD aerosol/lead transects (1970s):
2) Gertler et al (1999) at the Tuscarora Tunnel, PA HEI/DRI/UC Davis

- 21 individual tests on tunnel exit exhaust versus tunnel input
- A wide variety of gasses and particles collected, including IMPROVE mass balance and DELTA Group 8 DRUM
- Traffic monitored – heavy duty 7 – 8 axle trucks from 15% (daytime) to 83% (nighttime)
- Report released by HEI Jan, 2002


Fine Particulate Profiles from Los Angeles Freeways
San Diego at Harbor, August, 1972
Micrograms/m3 per 10,000 v/hr
5
4
3
2
1
0
0
Freeway
150
300
450
550
Distance (feet) from upwind site
Lead
Bromine
Br/Pb ratio x 5000
Sulfur

Effect of roadway distance and configuration on downwind concentrations of lead [1].

Roadway	Distance	27 m	40 m	100 m	160 m
At grade	*Calculated*	*4.0**	*3.4*	*1.4*	*0.41*
		* not scaled!			
At grade	Measured	4.0	3.1	1.4	0.35
Depressed	Measured	4.5	1.7	0.26	
Elevated	Measured (2 sites)	4.8	2.3	3.1	(3.5) (one site)

PM10 Emission rates from Tuscarora Tunnel Study

Gertler et al, 2002

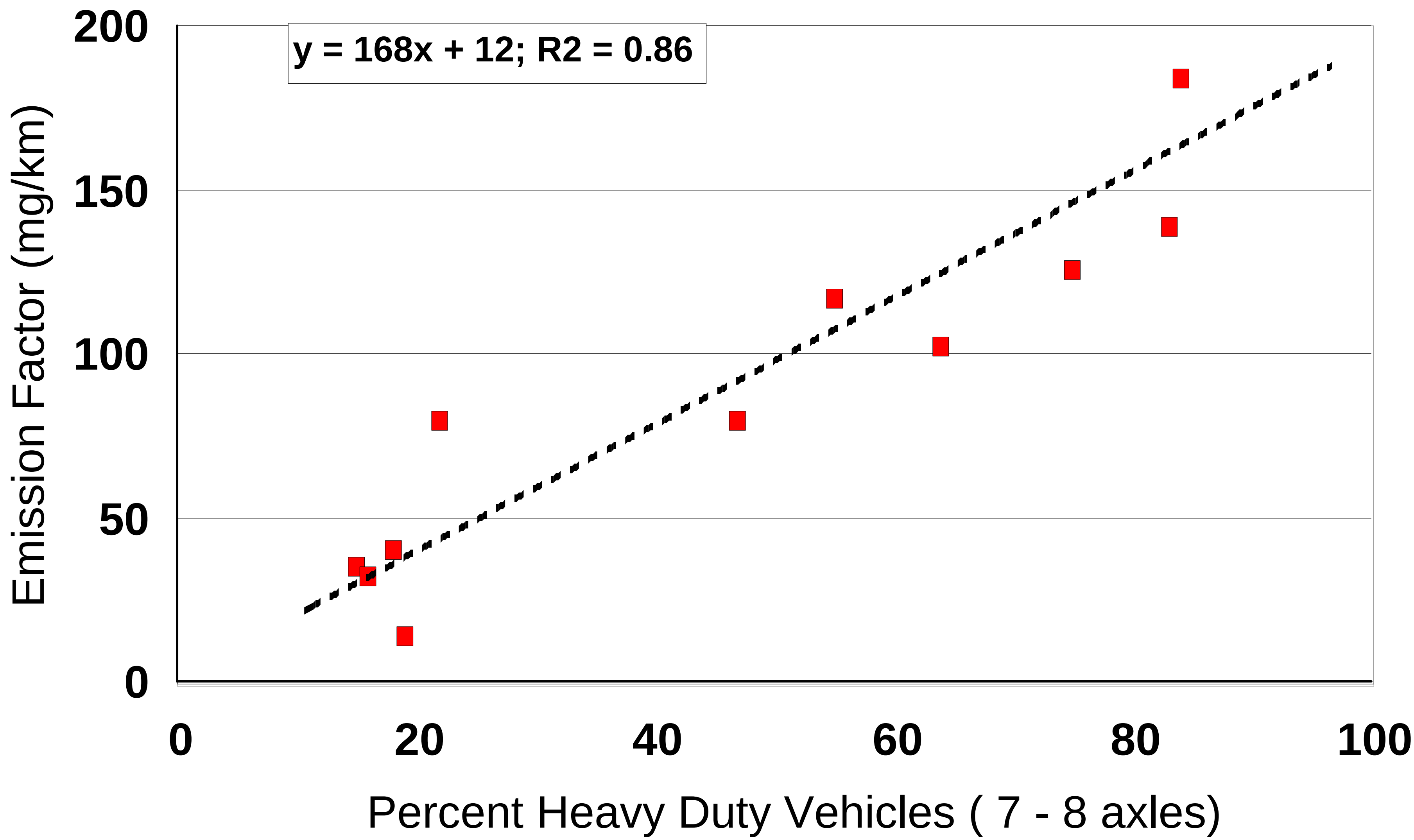


Table 1 Comparison to heavy duty and light duty PM_{10} and $PM_{2.5}$ emission rates form the Gertler at al 2002 Tuscarora Tunnel studies and other studies.

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

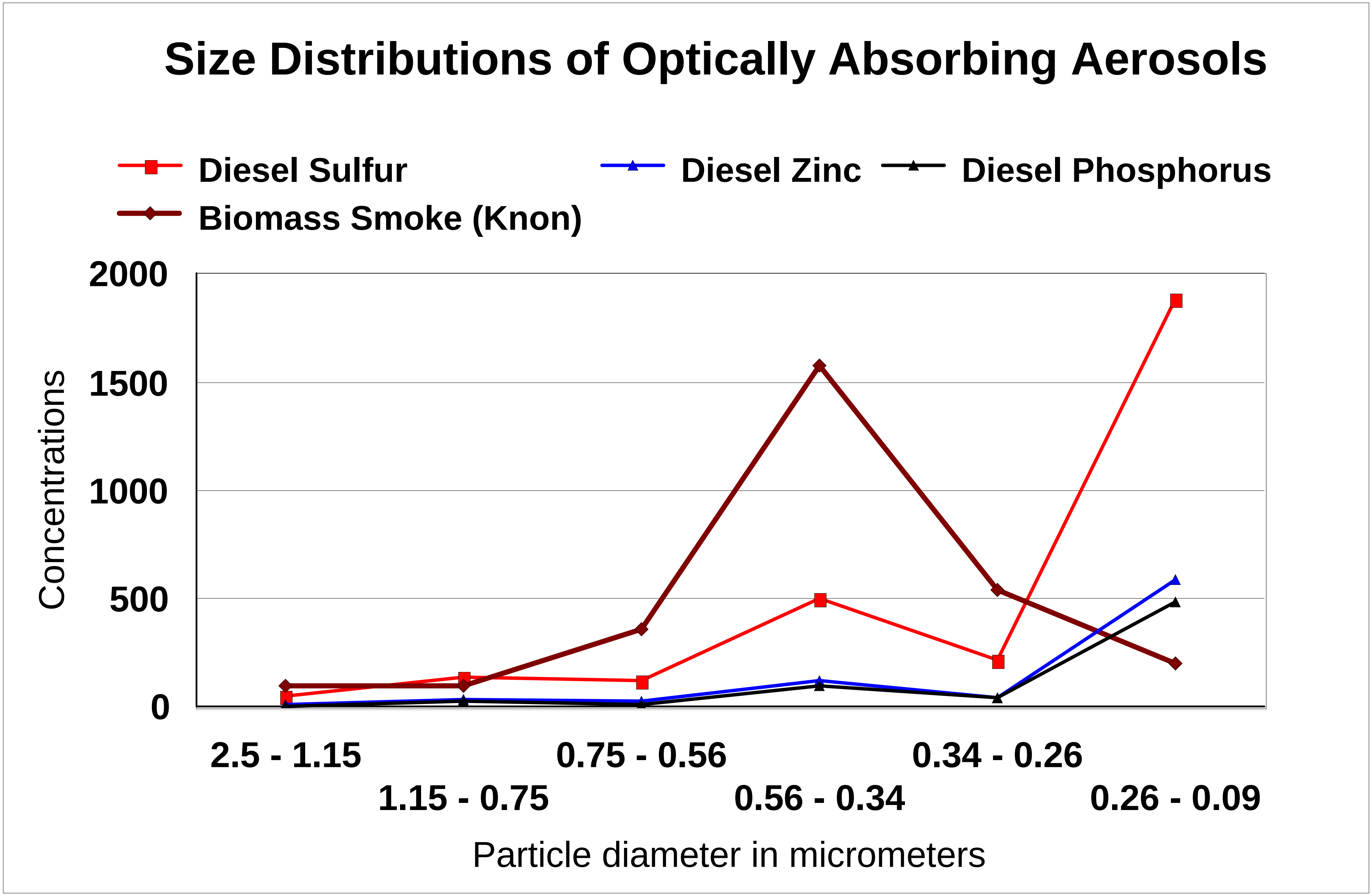
From these results, we see that diesel is about 18 times worse than light duty vehicles fo PM_{10} emissions and 10 times worse than light duty vehicles for $PM_{2.5}$ emissions, and tha the worst case smoking car is about the same as the average diesel. Incidentally, these emission values are sharply lower than occurred only a decade ago.

Table 2. Light duty and heavy duty $PM_{2.5}$ emission rates for numerous particulate species as taken from the Tuscarora Tunnel studies (Gertler et al, 2002).

Vehicle	Light duty avg	Light duty SE	Heavy duty avg	Heavy duty SE	Ratio, HD/LD
$PM_{2.5}$ rate	(mg/mi)	(mg/mi)	(mg/mi)	(mg/mi)	
Species					
Org. Carbon	4.5	1.7	179.8	69.1	40.0
Elem. Carbon	5.3	1.9	296.2	106.5	55.9
NH_3	55.1	28.2	42.6	22.6	0.77
Silicon	1.2	1.2	1.4	1.4	1.17
Sulfur	1.9	1.1	0.43	0.24	0.23
	(µg/mi)	(µg/mi)	(µg/mi)	(µg/mi)	
Manganese	644	200	4454	1387	6.9
Iron	335	145	3194	1386	9.5
Copper	23.7	29.6	141.6	176.7	6.0
Zinc	73,2	49.1	219.6	147.3	3.0
Mercury	2.7	0.7	18.0	4.7	6.7
Lead	17.7	12.3	59.7	41.3	3.4
Gasses	grams/mi	grams/mi	grams/mi	Grams/mi	grams/mi
CO_2	249	24	1197	117	4.8
CO	3.1	1.1	< 1	na	< 0.3
NO (as NO_2)	0.68	0.11	19.1	3.1	28.1
THC	0.65	0.34	2.4	1.3	3.7

The problems with Elemental Carbon (EC) as a diesel tracer

- The definition of EC is operational and arbitrary (Sunset Labs, R&P OC/EC; DRI 8 components)
- Optical absorption also occurs in partially pyrolized organic matter
- From IMPROVE, 3 components correlate:
  - O1, O2 (< 250C) volatile, often natural, no absorption
  - O3, O4, E1 (250 to 550C, 2% O_2) biomass smoke, complex organics, considerable absorption (esp. in blue, so appears brownish)
  - E2, E3 (550 to 800 C, 2% O2) non-volatile, amorphous/graphitic mixture, absorbs light equally blue to red (so appears black)
- TOR (DRI) about 2 x TOT (Sunset,…) Chow et al 2001



Size Distributions of Optically Absorbing Aerosols
Diesel Sulfur
Diesel Zinc
Diesel Phosphorus
Biomass Smoke (Knon)
2000
1500
1000
500
0
Concentrations
2.5 - 1.15
1.15 - 0.75
0.75 - 0.56
0.56 - 0.34
0.34 - 0.26
0.26 - 0.09
Particle diameter in micrometers

The problems with Organic Carbon (OC) as a diesel tracer

- The definition of OC is operational and subject to considerable uncertainties (positive and/or negative artifacts, volatility, …)
- Measurements are difficult and costly
- Field data show wild variations in specific OC constituents, test to test
  - of the 92 species examined by Gertler et al, only a few had both high HD/LD ratios and standard errors significantly less than the LD/HD differences.
- The stability of organic tracers in oxidizing ambient atmospheres is problematical

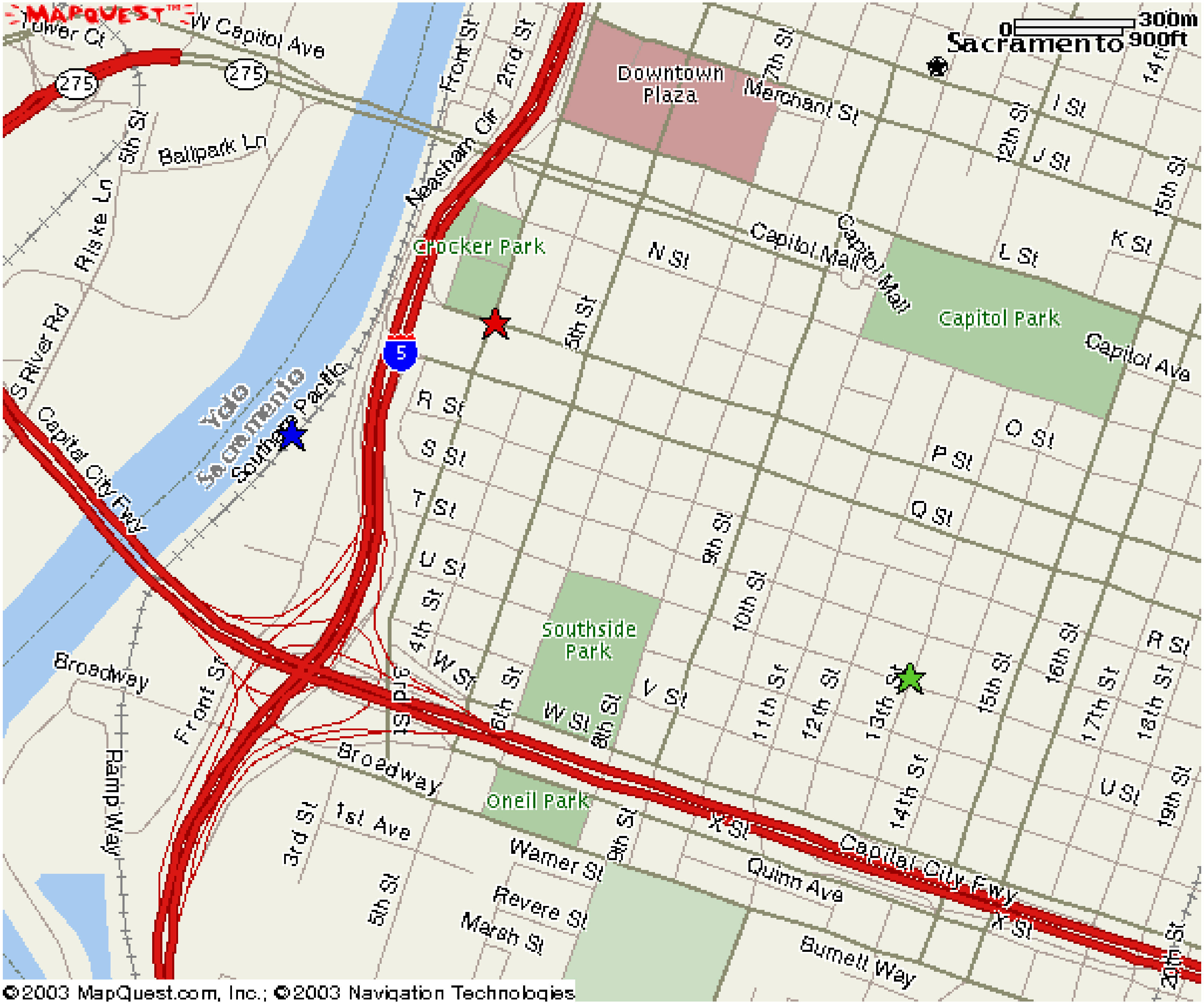
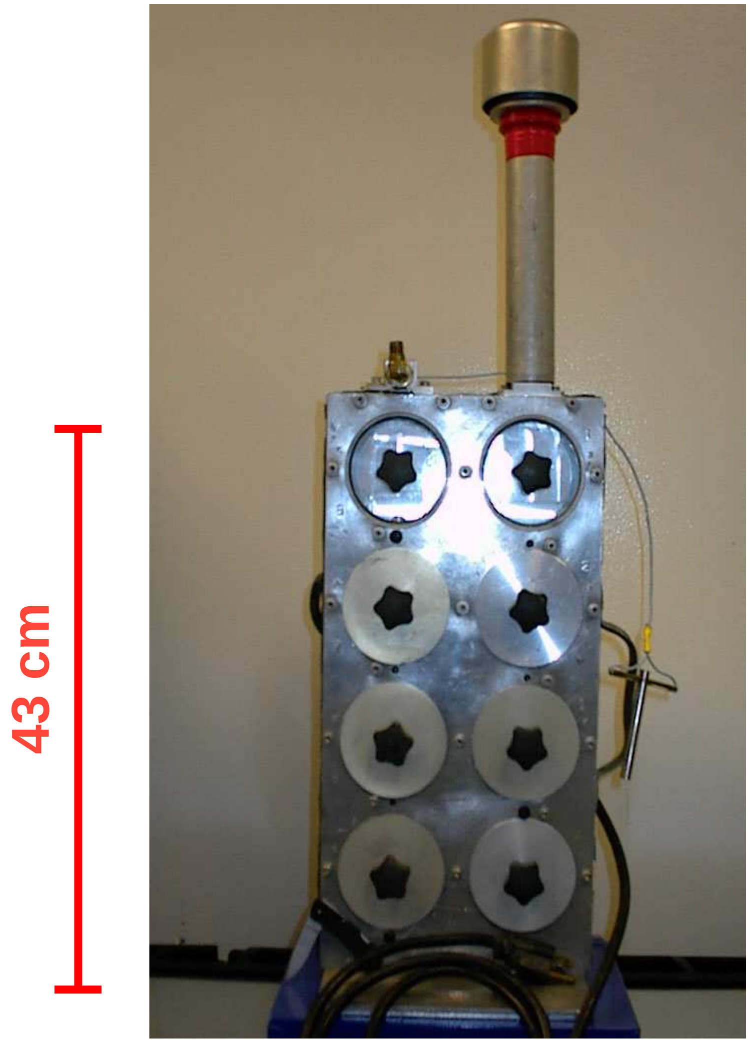

Sacramento
0 300m 900ft
Downtown Plaza
Capitol Park
Crocker Park
Southside Park
Oneil Park
Capitol Mall
Capitol Ave
Capital City Fwy
Sacramento
Yolo
Southern Pacific
W Capitol Ave
Broadway
Front St
2nd St
3rd St
4th St
5th St
6th St
7th St
8th St
9th St
10th St
11th St
12th St
13th St
14th St
15th St
16th St
17th St
18th St
19th St
20th St
I St
J St
K St
L St
N St
O St
P St
Q St
R St
S St
T St
U St
V St
W St
X St
Merchant St
Neasham Cir
1st Ave
Quinn Ave
Burnett Way
Warner St
Revere St
Marsh St
Ballpark Ln
Riske Ln
S River Rd
Ramp Way
Tower Ct
275
5

Table 3 Effect of roadway distance and configuration on downwind concentrations of lead [1].

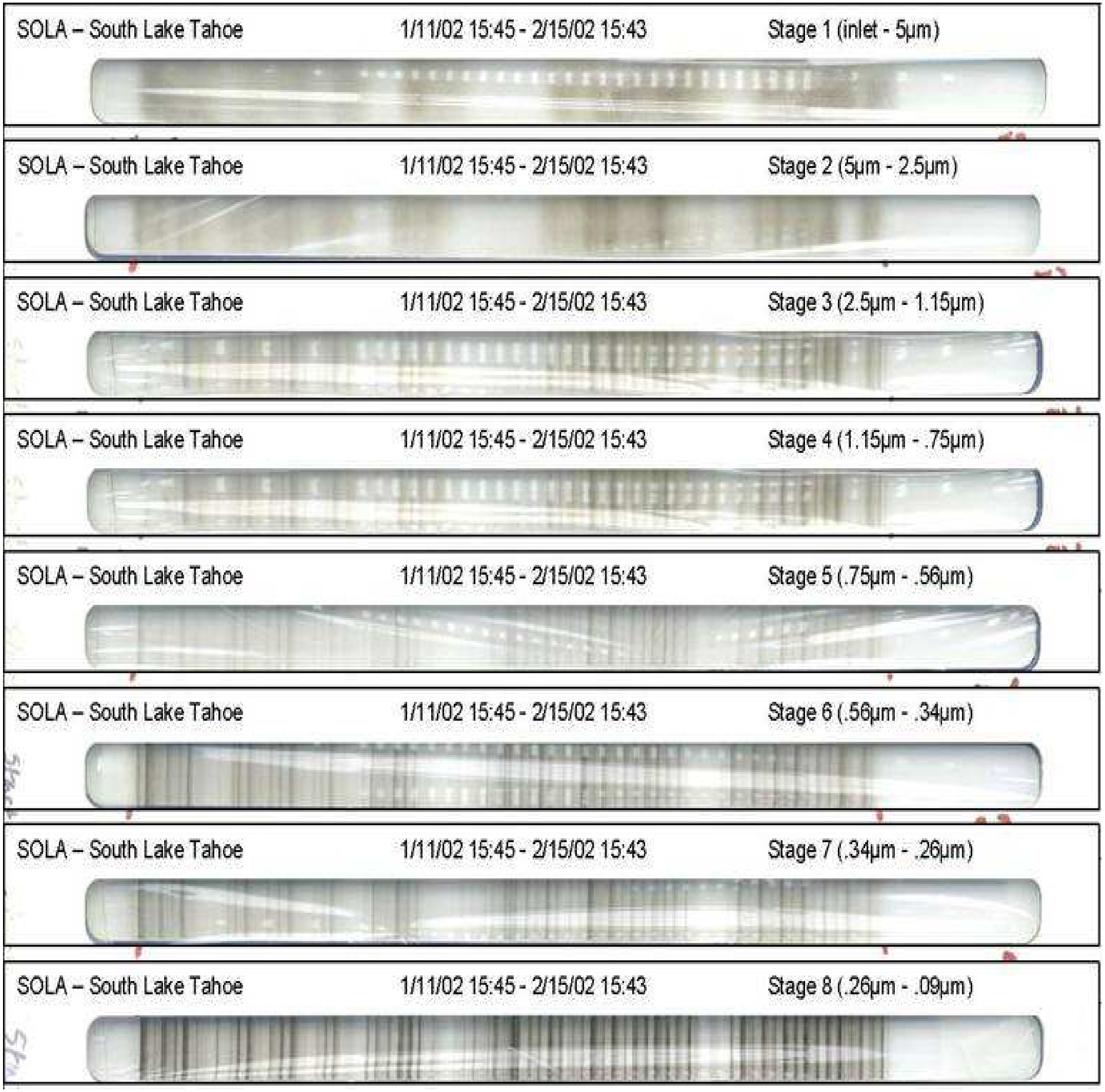
Roadway	**Distance**	**27 m**	**40 m**	**100 m**	**160 m**
At grade	*Calculated*	*4.0*	*3.4*	*1.4*	*0.41*
At grade	Measured	4.0	**3.1**	1.4	0.35
			Arden		
Depressed	Measured	4.5	1.7	**0.26**	
				Crocker	
Elevated	Measured	4.8	2.3	3.1	(3.5)

Thus, the relative effect of I-5 on the Crocker Art Museum site versus Watt Avenue on Arden Middle School site is governed by both distance and roadway configuration, a ratio of 3.1/0.26 = 12, and by traffic volume, which is 4.5 times greater on I-5 than Watt Avenue. This gives a net effect of 12/4.5 = 2.6, with the Arden Middle School site higher than the Crocker Art Museum site despite the higher traffic volume on I-5. This calculation, while only approximate, assumes non-reactive gasses and very fine particles with sizes similar to lead, including diesel/smoking car particles, which transport like a gas.

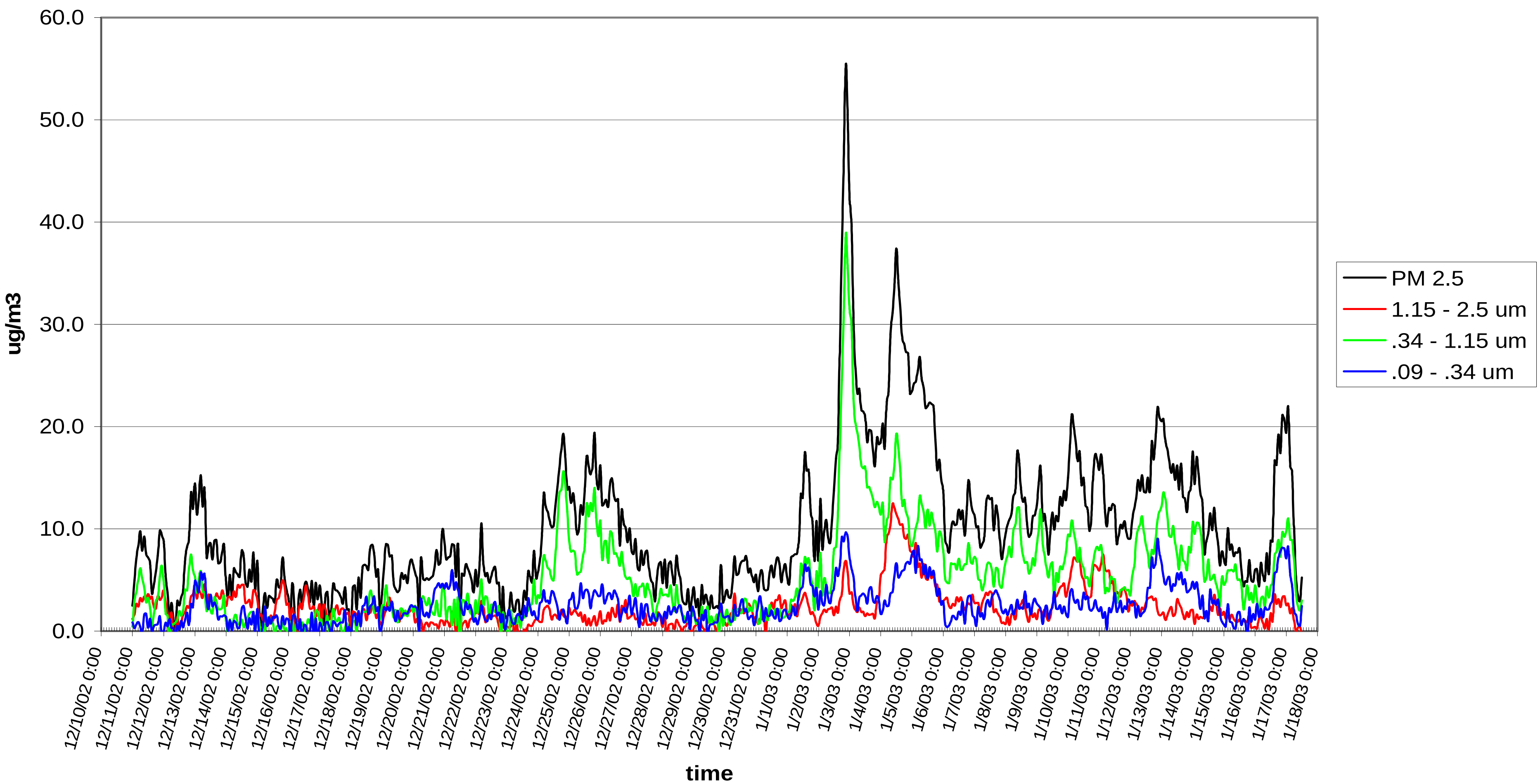
DELTA Group slotted 8 DRUM Impactor

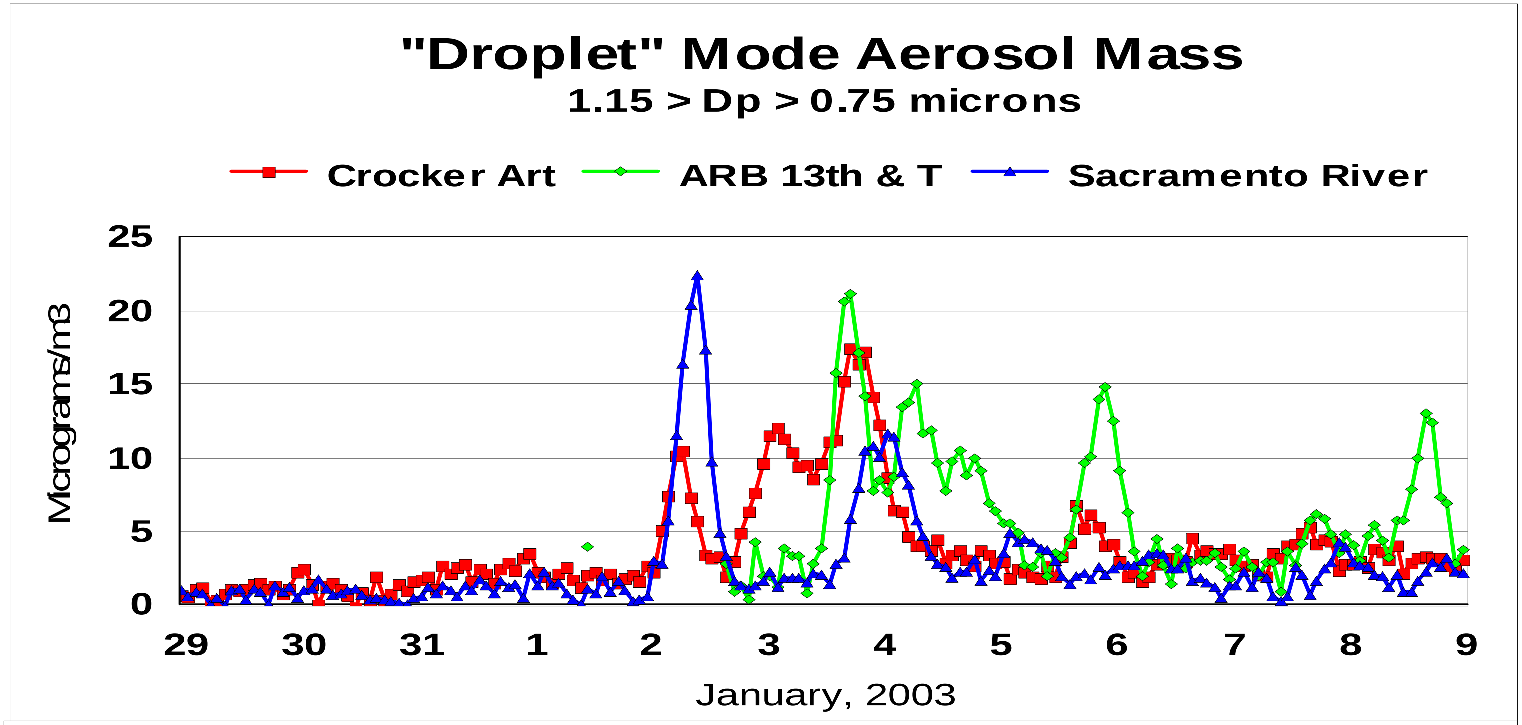


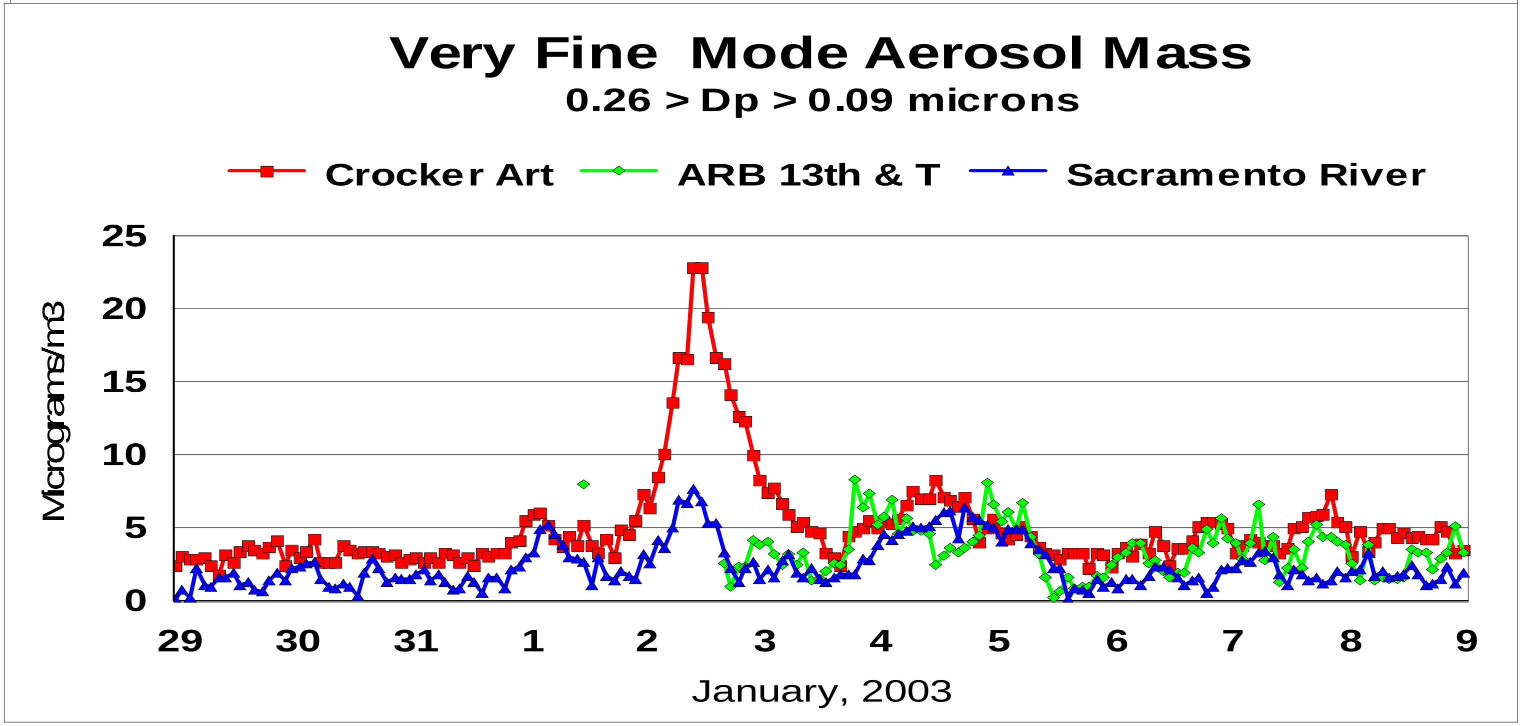
- **8 size ranges:**
  - **Inlet (~ 12) to 5.0 μm**
  - **5.0 to 2.5 μm**
  - **2.5 to 1.15 μm**
  - **1.15 to 0.75 μm**
  - **0.75 to 0.56 μm**
  - **0.56 to 0.34 μm**
  - **0.34 to 0.26 μm**
  - **0.26 to 0.09 μm**
- **10.4 l/min, critical orifice control, ¼ hp pump**
- **6.5 x 168 mm Mylar strips**
- **For 42 day run, 4 mm/day, time resolution = 1 hr.**
- **Field portable**
  - **10 kg, 43 × 22 × 13 cm**

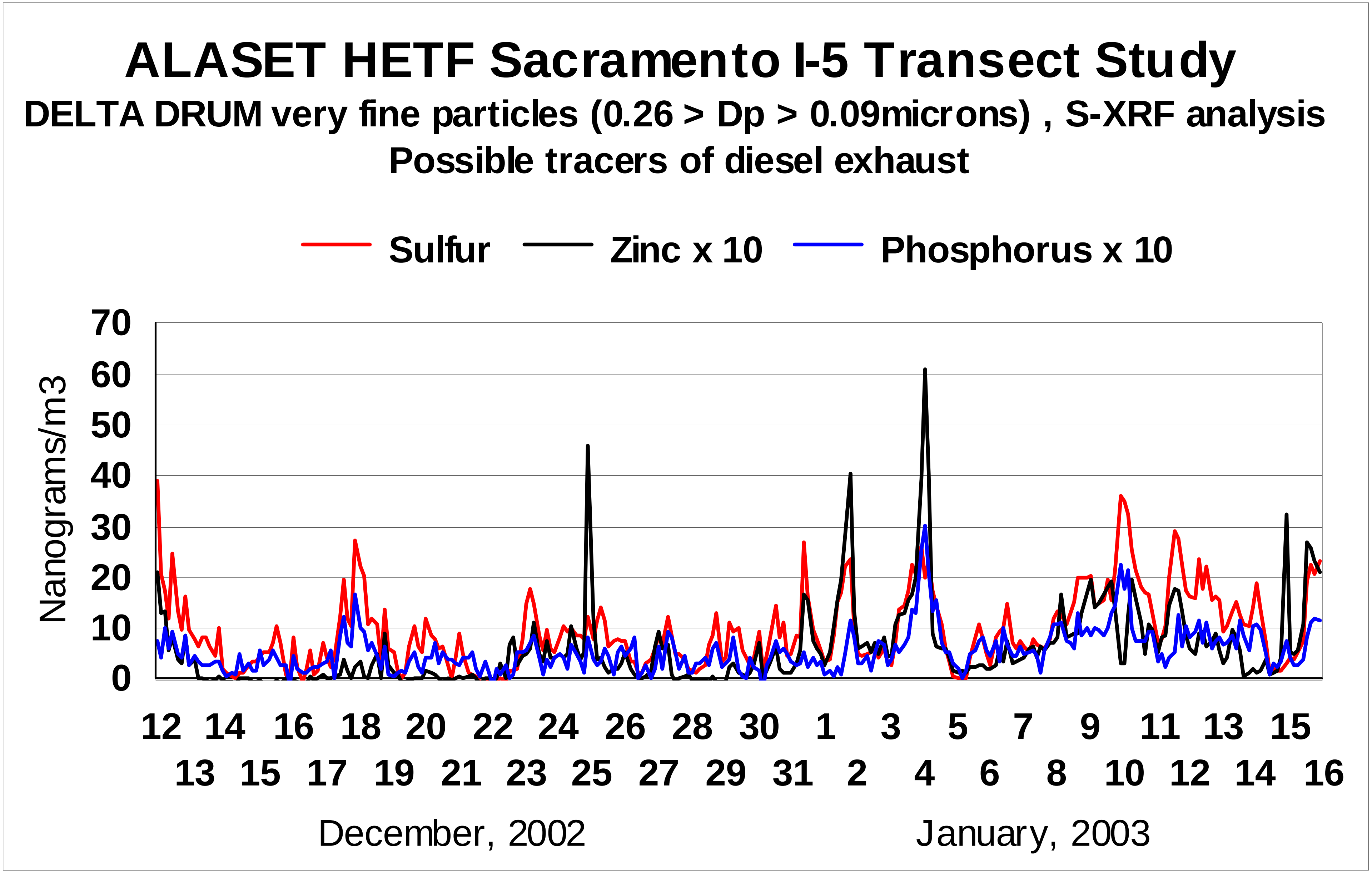

SOLA – South Lake Tahoe
1/11/02 15:45 - 2/15/02 15:43
Stage 1 (inlet - 5µm)
SOLA – South Lake Tahoe
1/11/02 15:45 - 2/15/02 15:43
Stage 2 (5µm - 2.5µm)
SOLA – South Lake Tahoe
1/11/02 15:45 - 2/15/02 15:43
Stage 3 (2.5µm - 1.15µm)
SOLA – South Lake Tahoe
1/11/02 15:45 - 2/15/02 15:43
Stage 4 (1.15µm - .75µm)
SOLA – South Lake Tahoe
1/11/02 15:45 - 2/15/02 15:43
Stage 5 (.75µm - .56µm)
SOLA – South Lake Tahoe
1/11/02 15:45 - 2/15/02 15:43
Stage 6 (.56µm - .34µm)
SOLA – South Lake Tahoe
1/11/02 15:45 - 2/15/02 15:43
Stage 7 (.34µm - .26µm)
SOLA – South Lake Tahoe
1/11/02 15:45 - 2/15/02 15:43
Stage 8 (.26µm - .09µm)

Sacramento Transect Study
12/12/02 - 1/16/03
Sacramento River

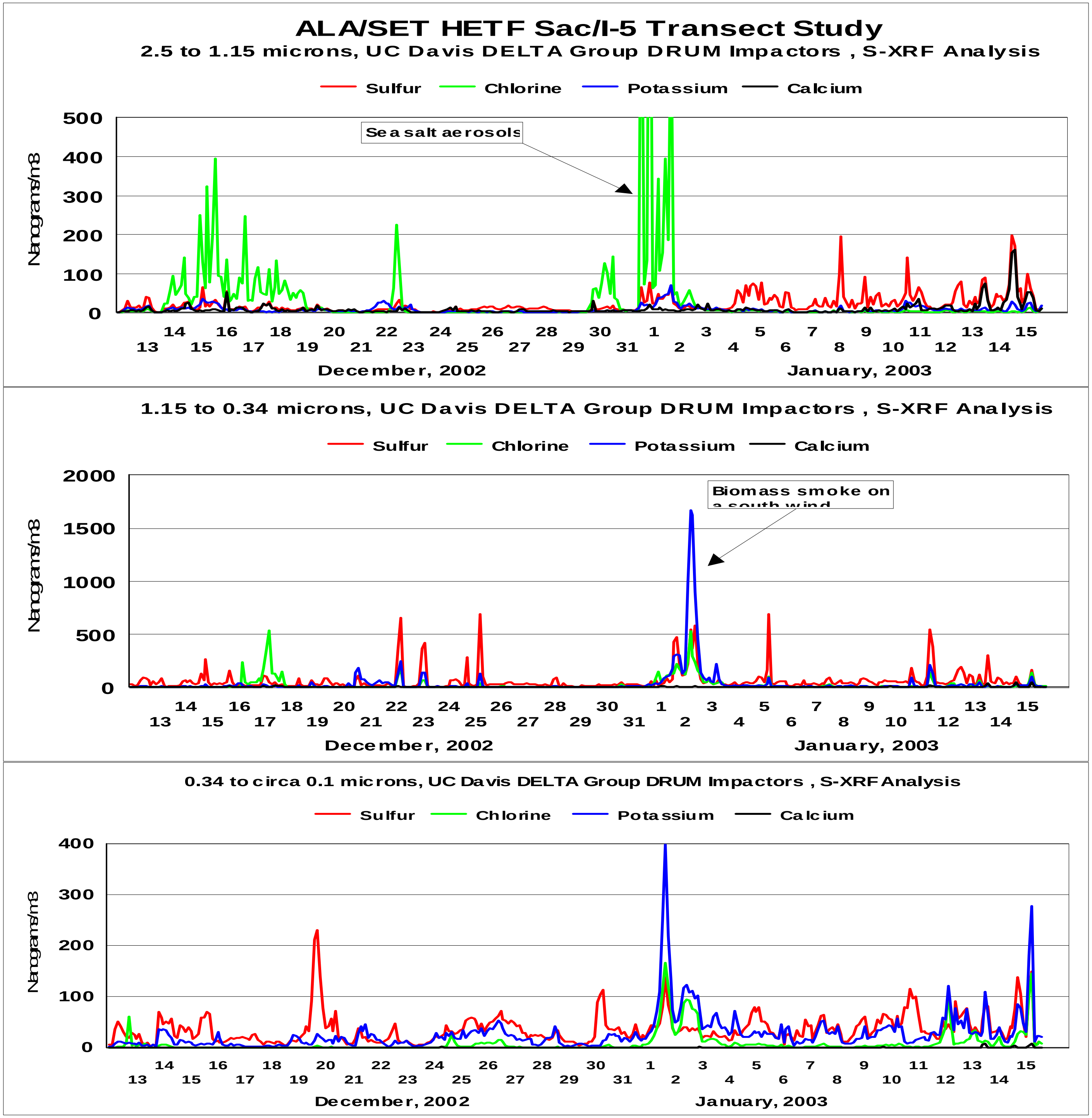


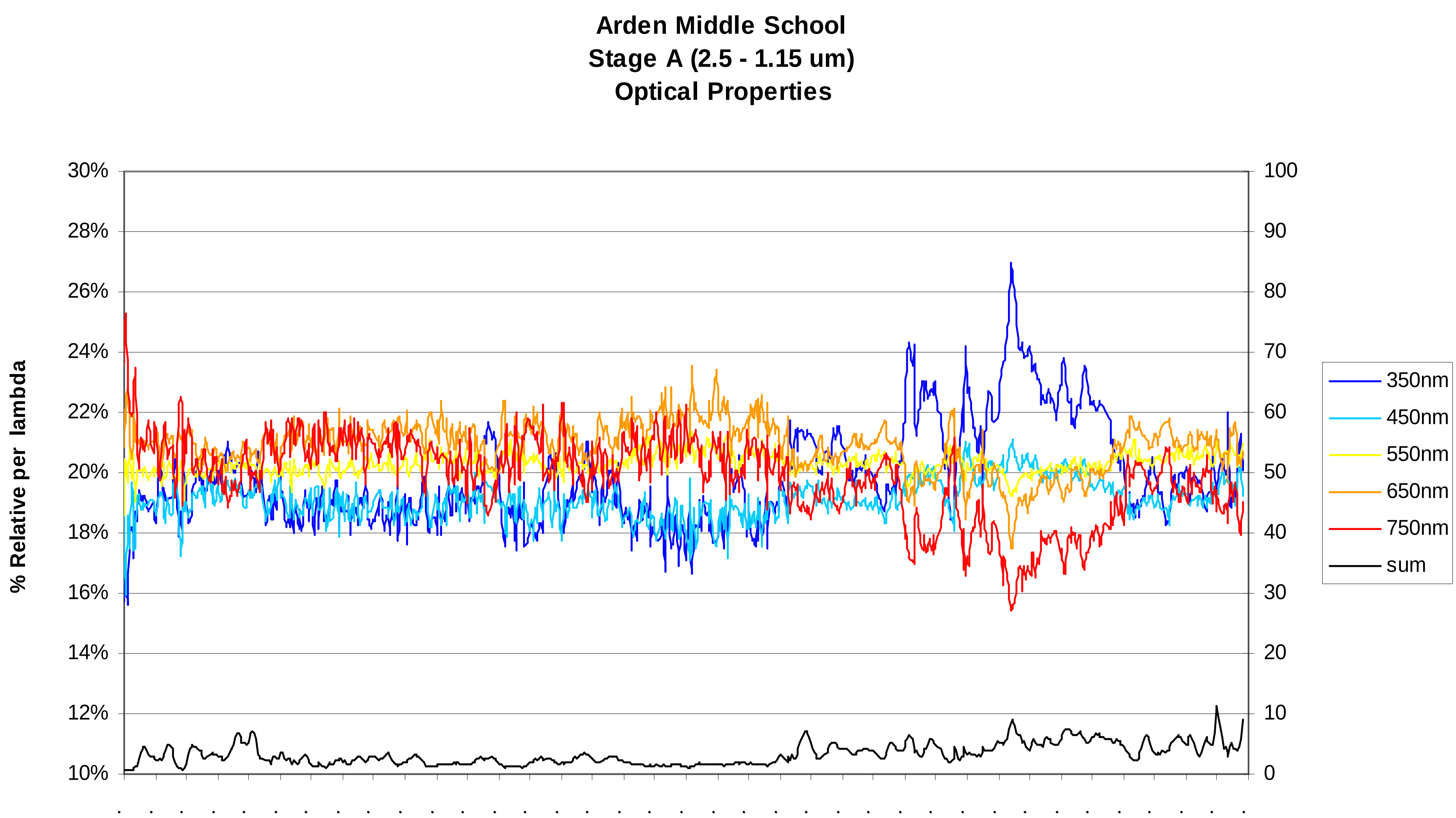

"Droplet" Mode Aerosol Mass
1.15 > Dp > 0.75 microns
Crocker Art
ARB 13th & T
Sacramento River
Micrograms/m3
0
5
10
15
20
25
29
30
31
1
2
3
4
5
6
7
8
9
January, 2003


Very Fine Mode Aerosol Mass
0.26 > Dp > 0.09 microns
Crocker Art
ARB 13th & T
Sacramento River
Micrograms/m3
0
5
10
15
20
25
29
30
31
1
2
3
4
5
6
7
8
9
January, 2003

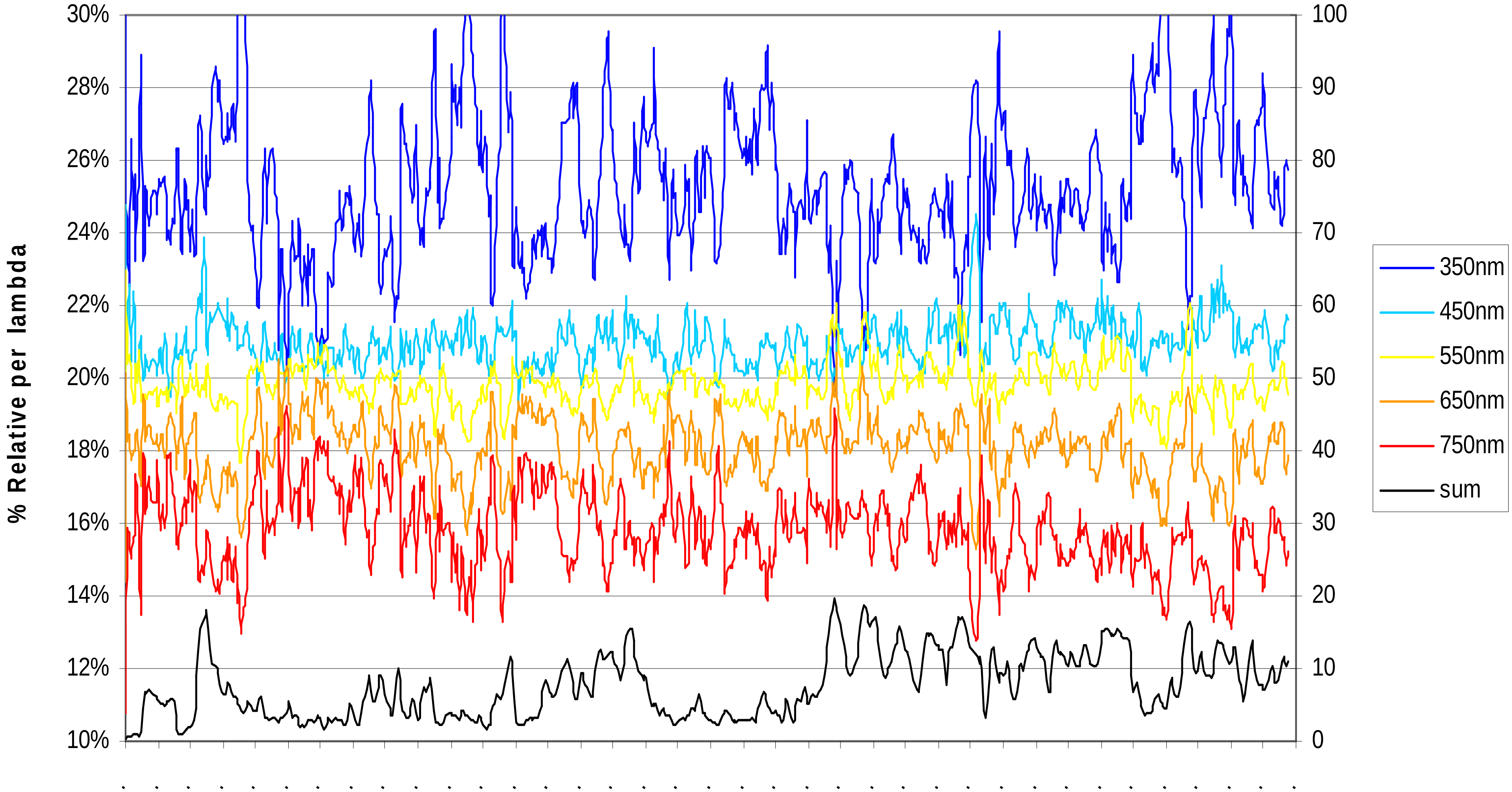


ALASET HETF Sacramento I-5 Transect Study
DELTA DRUM very fine particles (0.26 > Dp > 0.09microns) , S-XRF analysis
Possible tracers of diesel exhaust
Sulfur
Zinc x 10
Phosphorus x 10
Nanograms/m3
70
60
50
40
30
20
10
0
12 14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13 15
13 15 17 19 21 23 25 27 29 31 2 4 6 8 10 12 14 16
December, 2002
January, 2003

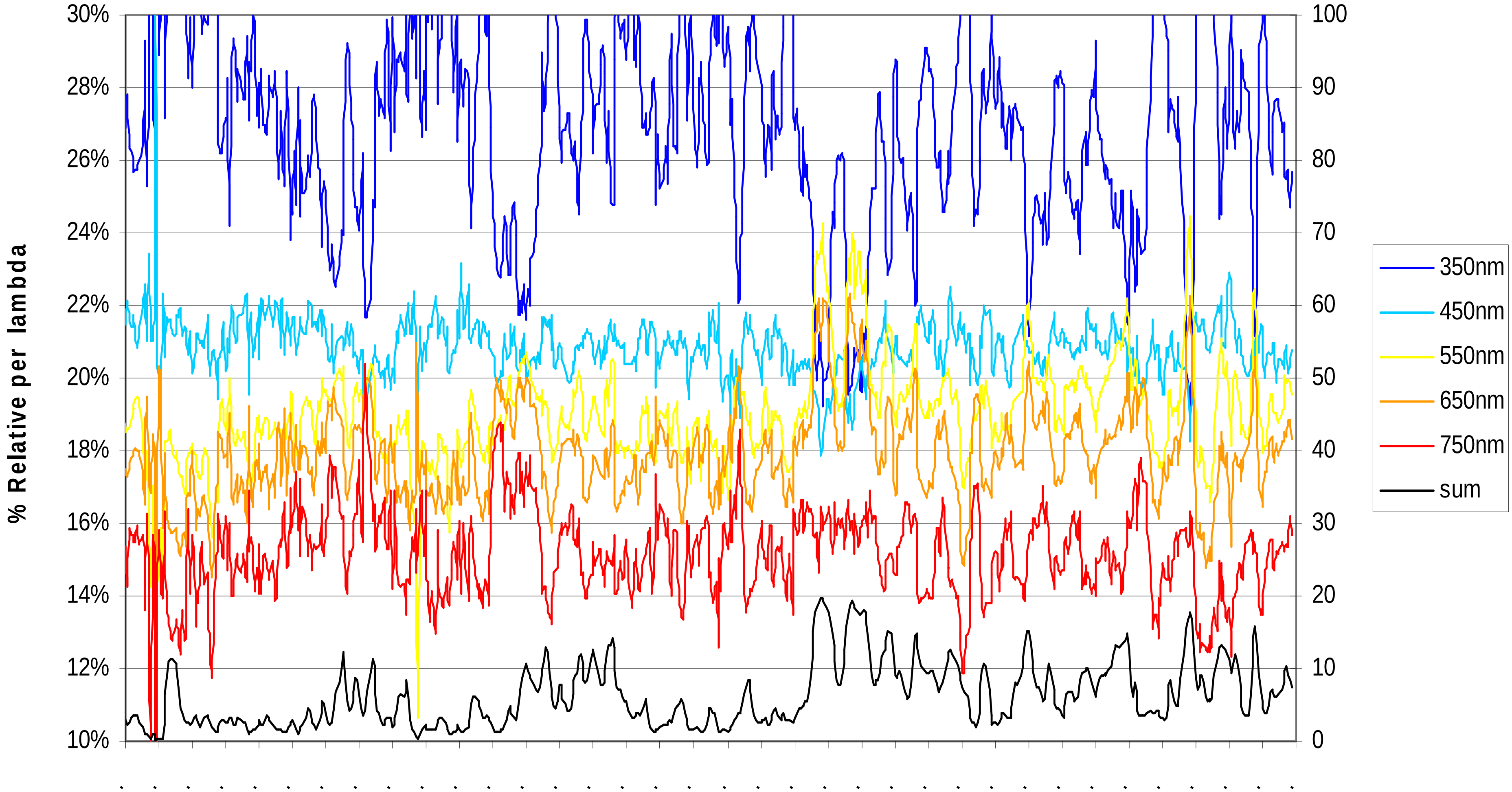

ALA/SET HETF Sac/I-5 Transect Study
2.5 to 1.15 microns, UC Davis DELTA Group DRUM Impactors , S-XRF Analysis
Sulfur
Chlorine
Potassium
Calcium
Nanograms/m3
500
400
300
200
100
0
Sea salt aerosols
14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13 15
13 15 17 19 21 23 25 27 29 31 2 4 6 8 10 12 14
December, 2002
January, 2003
1.15 to 0.34 microns, UC Davis DELTA Group DRUM Impactors , S-XRF Analysis
Sulfur
Chlorine
Potassium
Calcium
Nanograms/m3
2000
1500
1000
500
0
Biomass smoke on a south wind
14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13 15
13 15 17 19 21 23 25 27 29 31 2 4 6 8 10 12 14
December, 2002
January, 2003
0.34 to circa 0.1 microns, UC Davis DELTA Group DRUM Impactors , S-XRF Analysis
Sulfur
Chlorine
Potassium
Calcium
Nanograms/m3
400
300
200
100
0
14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13 15
13 15 17 19 21 23 25 27 29 31 2 4 6 8 10 12 14
December, 2002
January, 2003


Arden Middle School
Stage A (2.5 - 1.15 um)
Optical Properties
% Relative per lambda
30%
28%
26%
24%
22%
20%
18%
16%
14%
12%
10%
100
90
80
70
60
50
40
30
20
10
0
350nm
450nm
550nm
650nm
750nm
sum

Arden Middle School
Stage B (1.15-.34 um)
Optical Properties

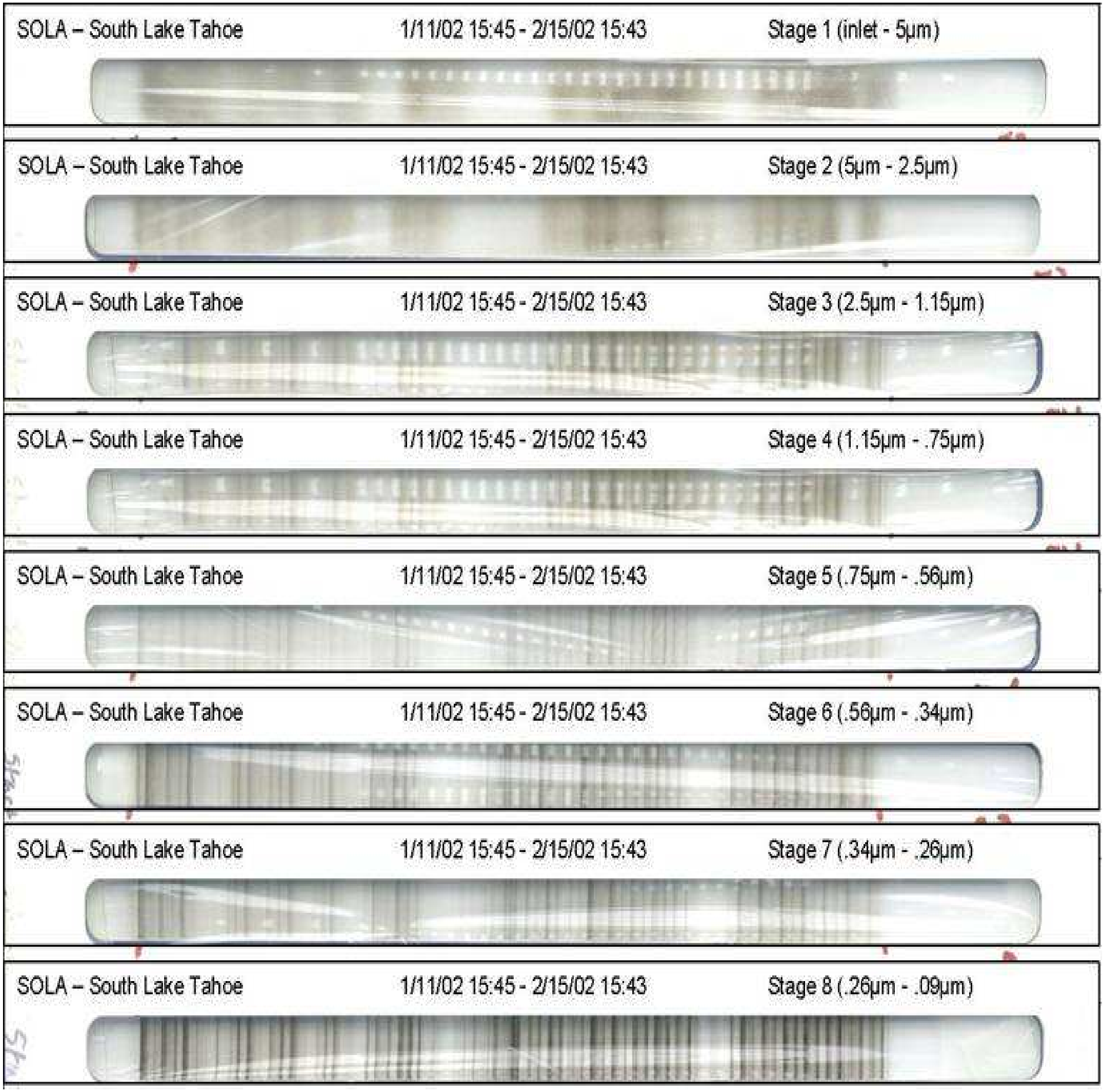


Arden Middle School
Stage C (.34-.09 um)
Optical Properties

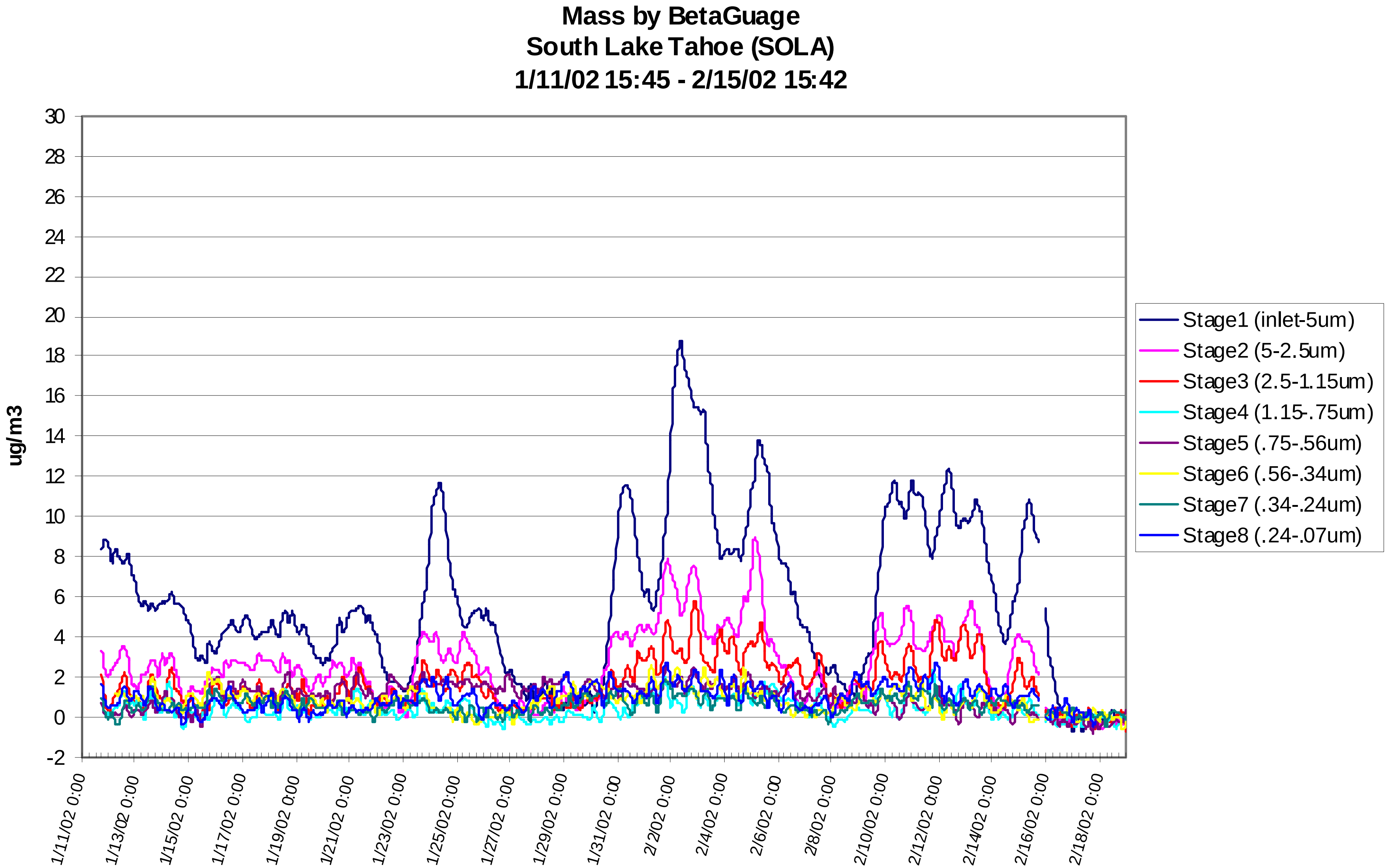


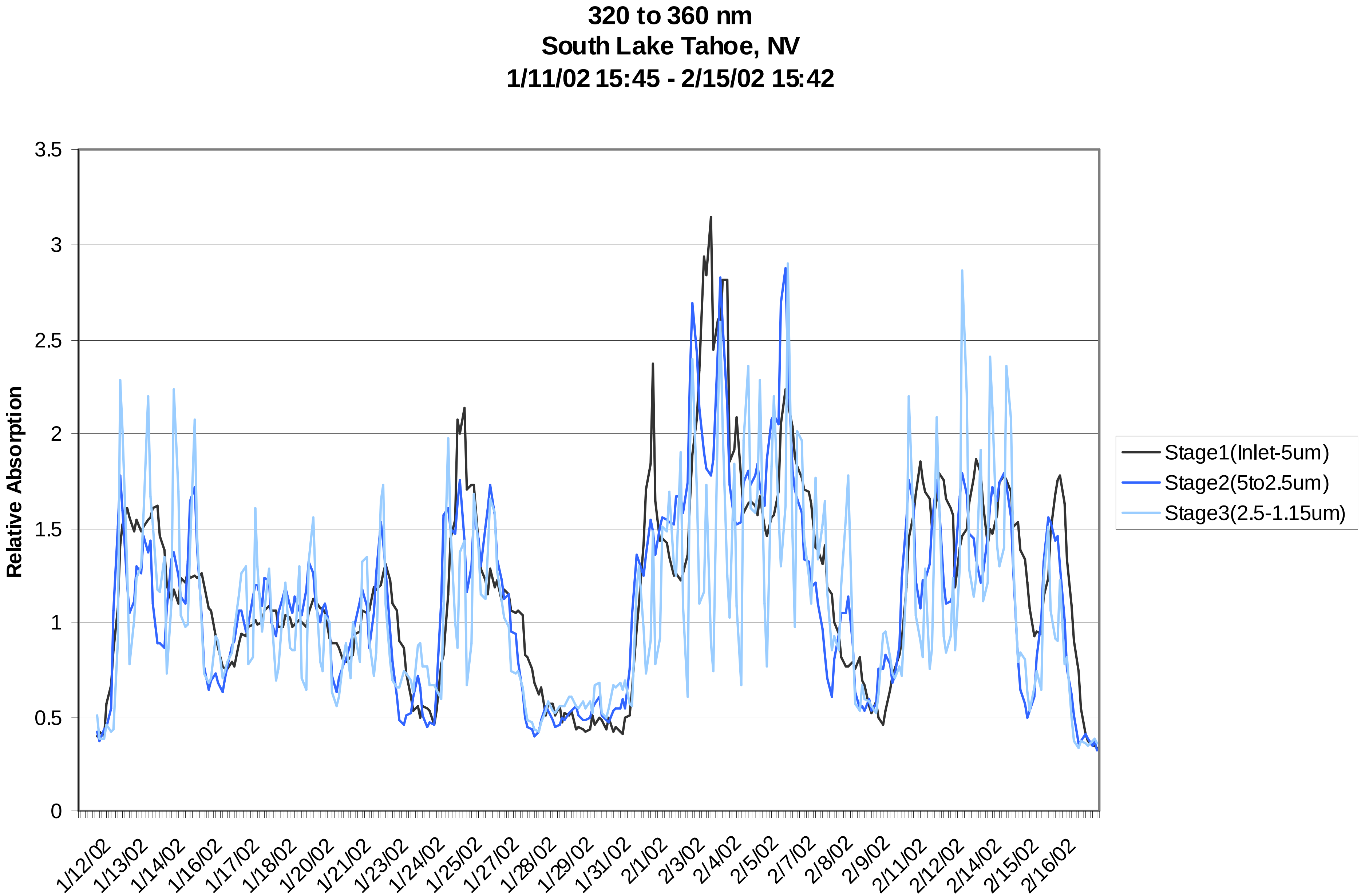
Example #2 – Diesel/smoking car impacts on visibility at Lake Tahoe

- Long term (1989-present) monitoring by IMPROVE filters protocols by TRPA for haze analysis at South Lake Tahoe
- Result:
  - Gasses are always local, except for ozone
  - Aerosols, in summer roughly ½ local, ½ transported into the basin
  - Aerosols, in winter, overwhelmingly local, derived largely from
    - residential wood smoke and
    - highway derived, road sanding and exhaust
- TRPA can regulate wood smoke, but not vehicles

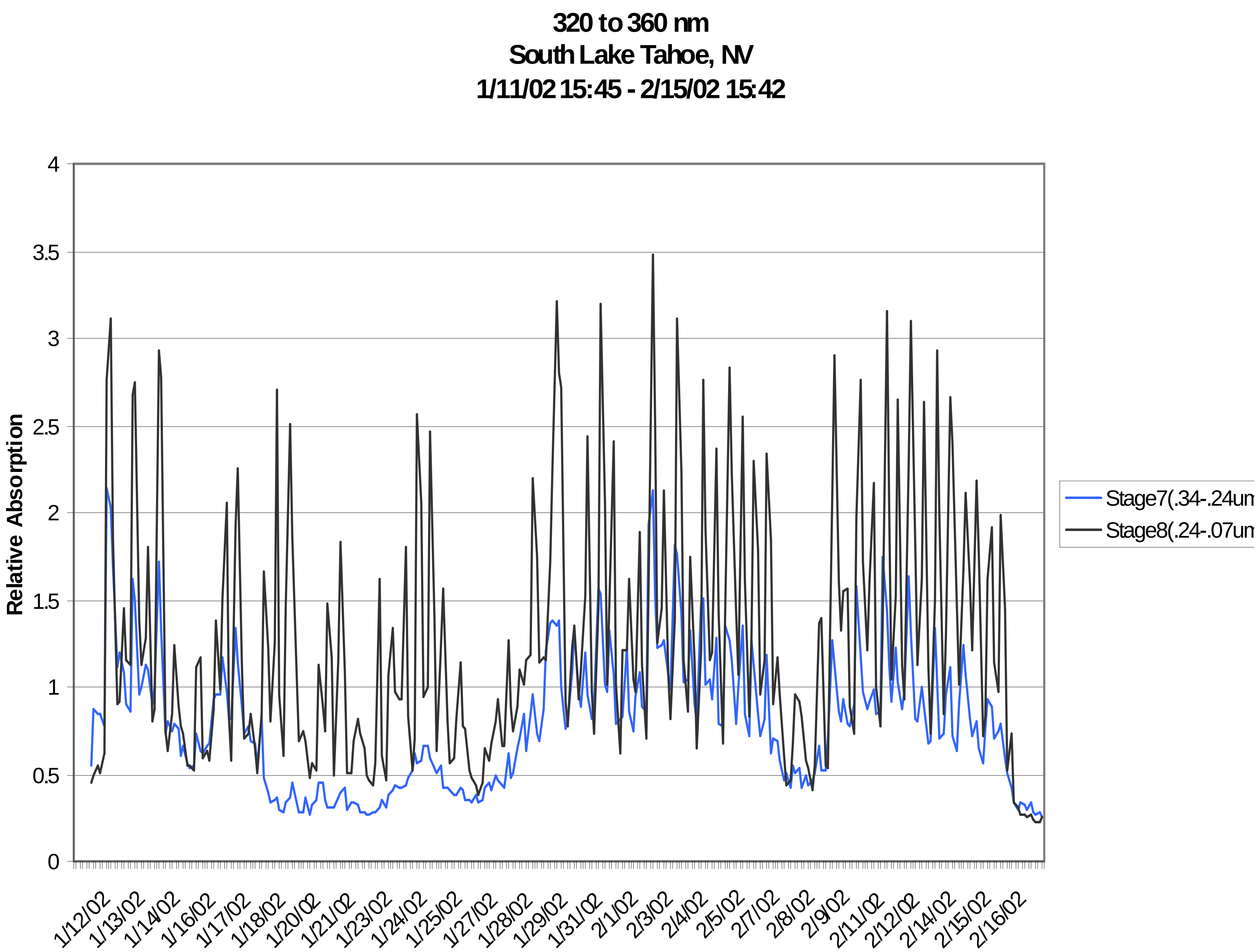


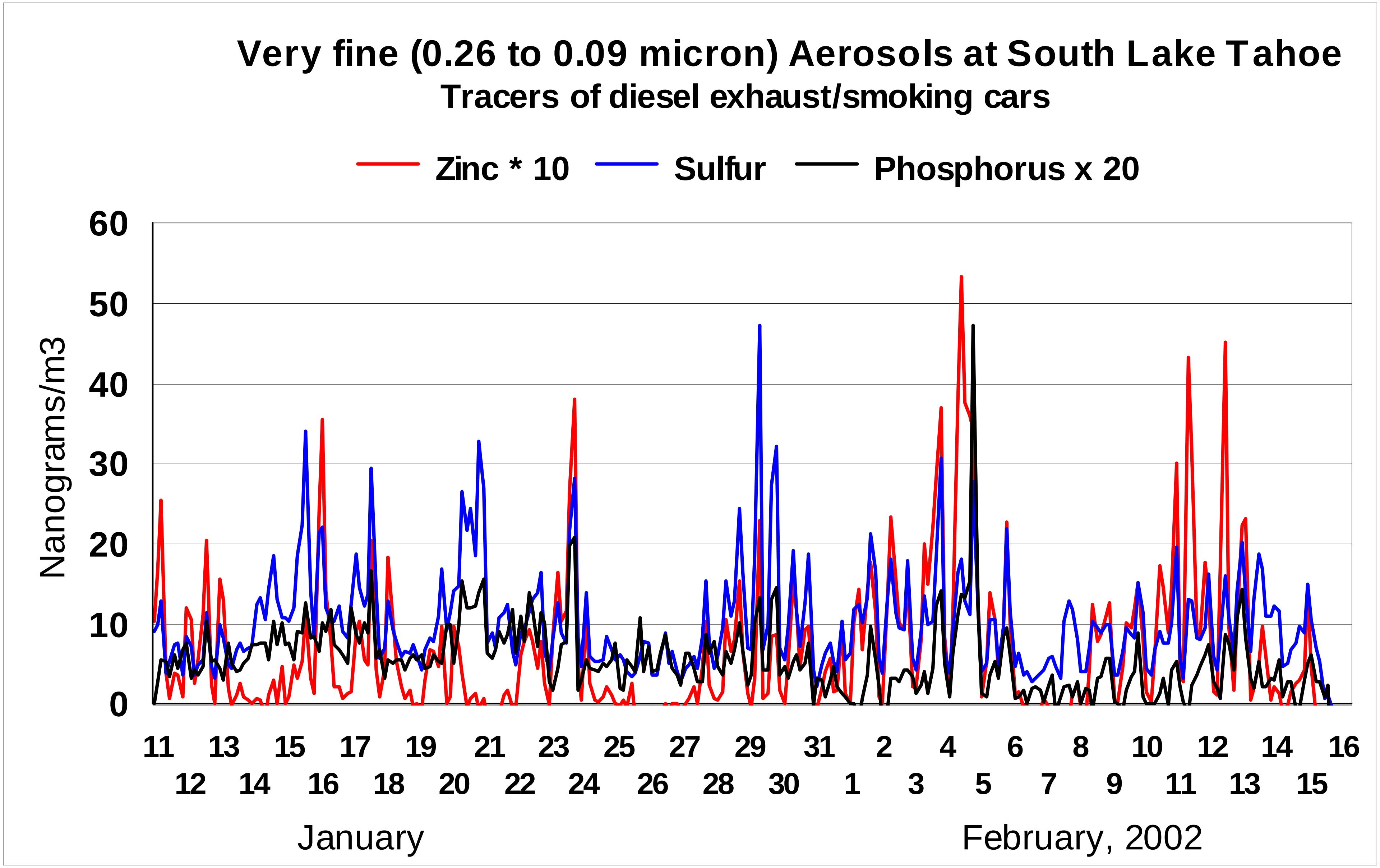
SOLA – South Lake Tahoe 1/11/02 15:45 - 2/15/02 15:43 Stage 1 (inlet - 5µm)
SOLA – South Lake Tahoe 1/11/02 15:45 - 2/15/02 15:43 Stage 2 (5µm - 2.5µm)
SOLA – South Lake Tahoe 1/11/02 15:45 - 2/15/02 15:43 Stage 3 (2.5µm - 1.15µm)
SOLA – South Lake Tahoe 1/11/02 15:45 - 2/15/02 15:43 Stage 4 (1.15µm - .75µm)
SOLA – South Lake Tahoe 1/11/02 15:45 - 2/15/02 15:43 Stage 5 (.75µm - .56µm)
SOLA – South Lake Tahoe 1/11/02 15:45 - 2/15/02 15:43 Stage 6 (.56µm - .34µm)
SOLA – South Lake Tahoe 1/11/02 15:45 - 2/15/02 15:43 Stage 7 (.34µm - .26µm)
SOLA – South Lake Tahoe 1/11/02 15:45 - 2/15/02 15:43 Stage 8 (.26µm - .09µm)


Mass by BetaGuage
South Lake Tahoe (SOLA)
1/11/02 15:45 - 2/15/02 15:42
ug/m3
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
-2
1/11/02 0:00
1/13/02 0:00
1/15/02 0:00
1/17/02 0:00
1/19/02 0:00
1/21/02 0:00
1/23/02 0:00
1/25/02 0:00
1/27/02 0:00
1/29/02 0:00
1/31/02 0:00
2/2/02 0:00
2/4/02 0:00
2/6/02 0:00
2/8/02 0:00
2/10/02 0:00
2/12/02 0:00
2/14/02 0:00
2/16/02 0:00
2/18/02 0:00
Stage1 (inlet-5um)
Stage2 (5-2.5um)
Stage3 (2.5-1.15um)
Stage4 (1.15-.75um)
Stage5 (.75-.56um)
Stage6 (.56-.34um)
Stage7 (.34-.24um)
Stage8 (.24-.07um)

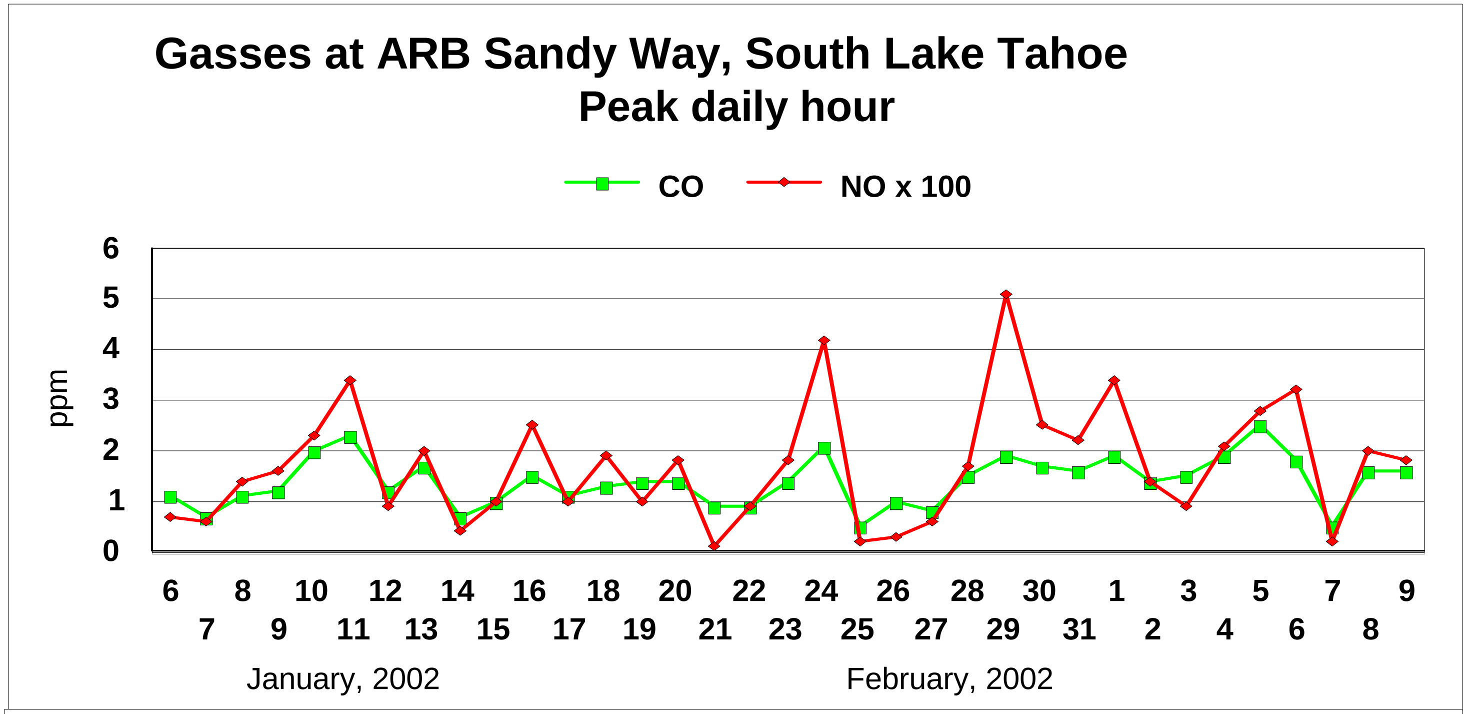


320 to 360 nm
South Lake Tahoe, NV
1/11/02 15:45 - 2/15/02 15:42
Relative Absorption
3.5
3
2.5
2
1.5
1
0.5
0
1/12/02
1/13/02
1/14/02
1/16/02
1/17/02
1/18/02
1/20/02
1/21/02
1/23/02
1/24/02
1/25/02
1/27/02
1/28/02
1/29/02
1/31/02
2/1/02
2/3/02
2/4/02
2/5/02
2/7/02
2/8/02
2/9/02
2/11/02
2/12/02
2/14/02
2/15/02
2/16/02
Stage1(Inlet-5um)
Stage2(5to2.5um)
Stage3(2.5-1.15um)

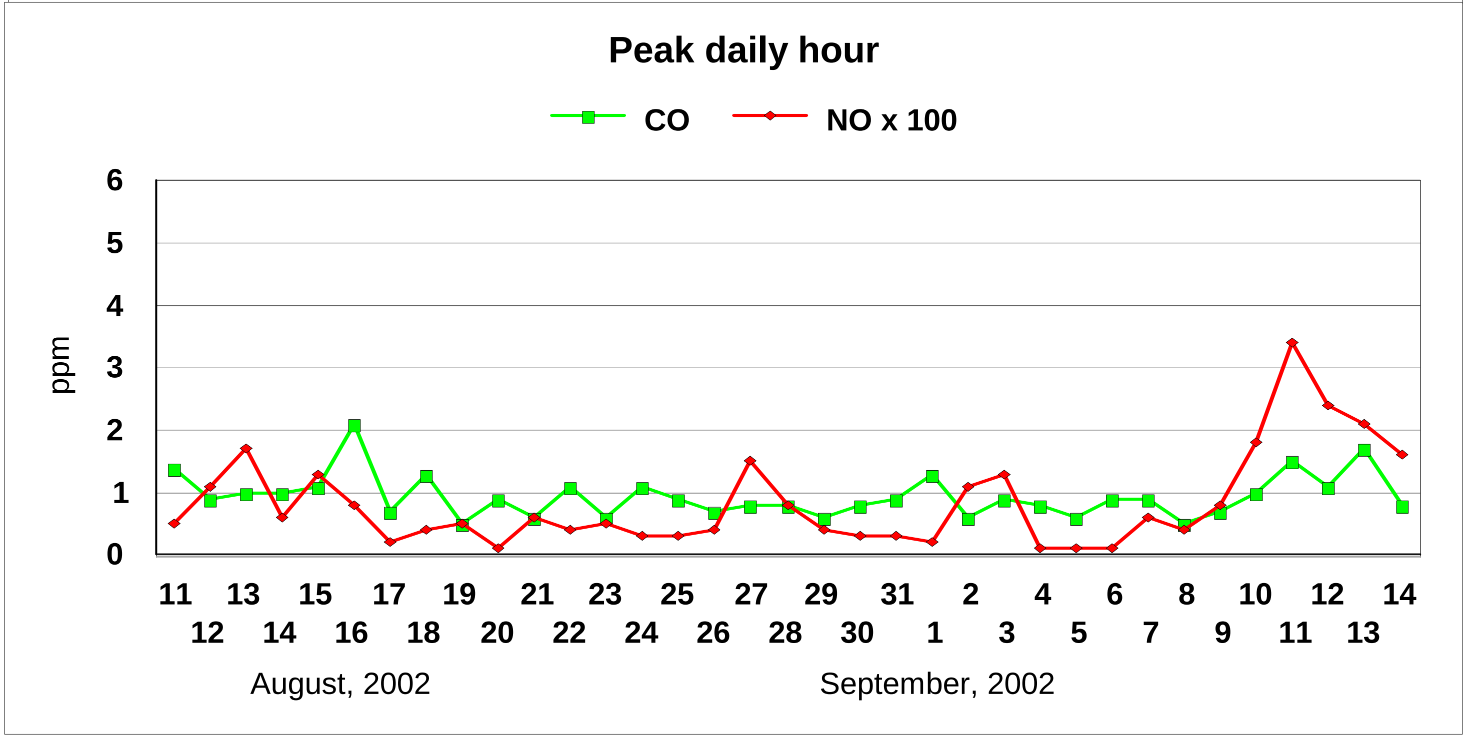

320 to 360 nm
South Lake Tahoe, NV
1/11/02 15:45 - 2/15/02 15:42
Relative Absorption
0
0.5
1
1.5
2
2.5
3
3.5
4
1/12/02
1/13/02
1/14/02
1/16/02
1/17/02
1/18/02
1/20/02
1/21/02
1/23/02
1/24/02
1/25/02
1/27/02
1/28/02
1/29/02
1/31/02
2/1/02
2/3/02
2/4/02
2/5/02
2/7/02
2/8/02
2/9/02
2/11/02
2/12/02
2/14/02
2/15/02
2/16/02
Stage7(.34-.24um
Stage8(.24-.07um



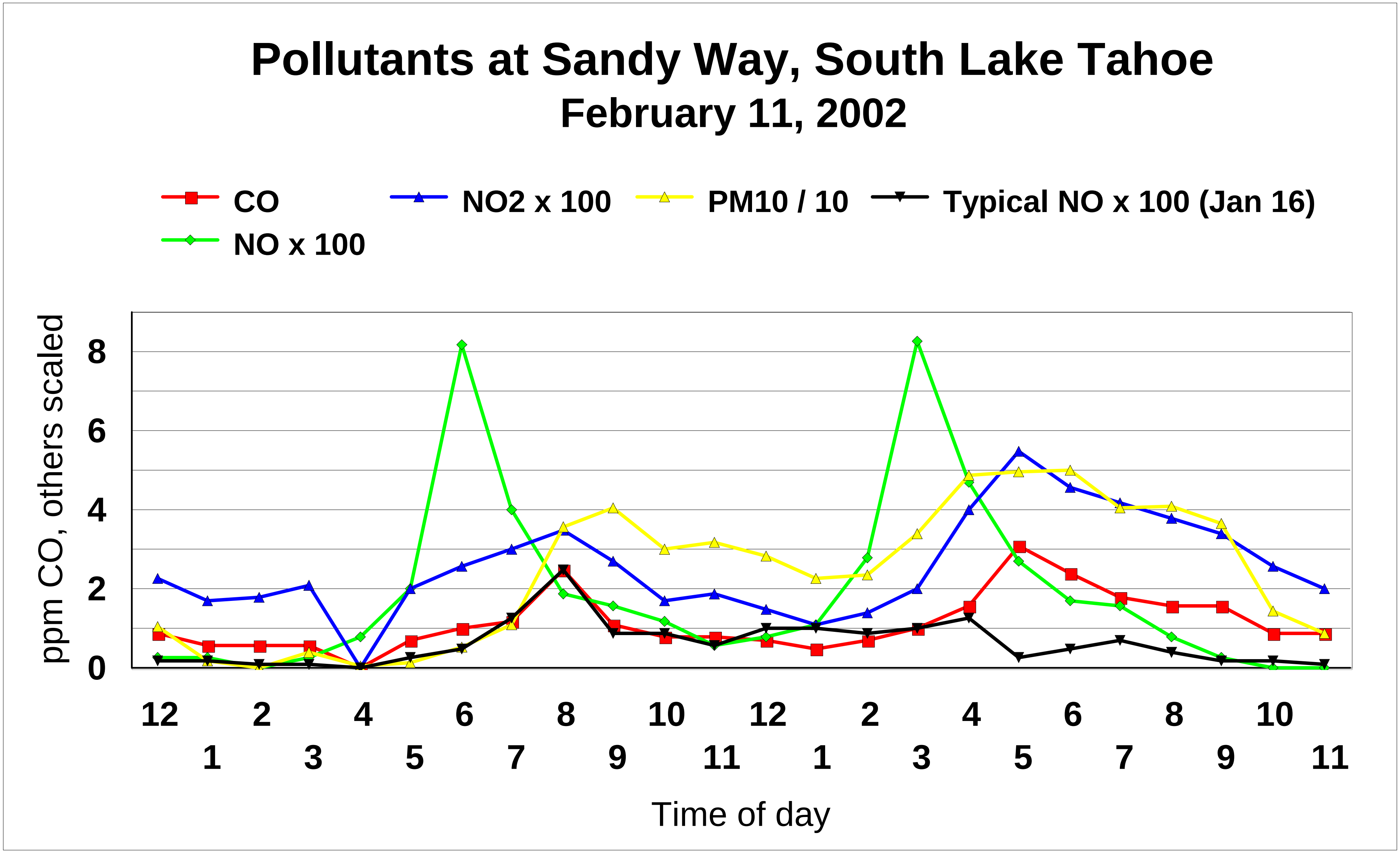
Very fine (0.26 to 0.09 micron) Aerosols at South Lake Tahoe
Tracers of diesel exhaust/smoking cars
Zinc * 10
Sulfur
Phosphorus x 20
Nanograms/m3
60
50
40
30
20
10
0
11 13 15 17 19 21 23 25 27 29 31 2 4 6 8 10 12 14 16
12 14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13 15
January
February, 2002



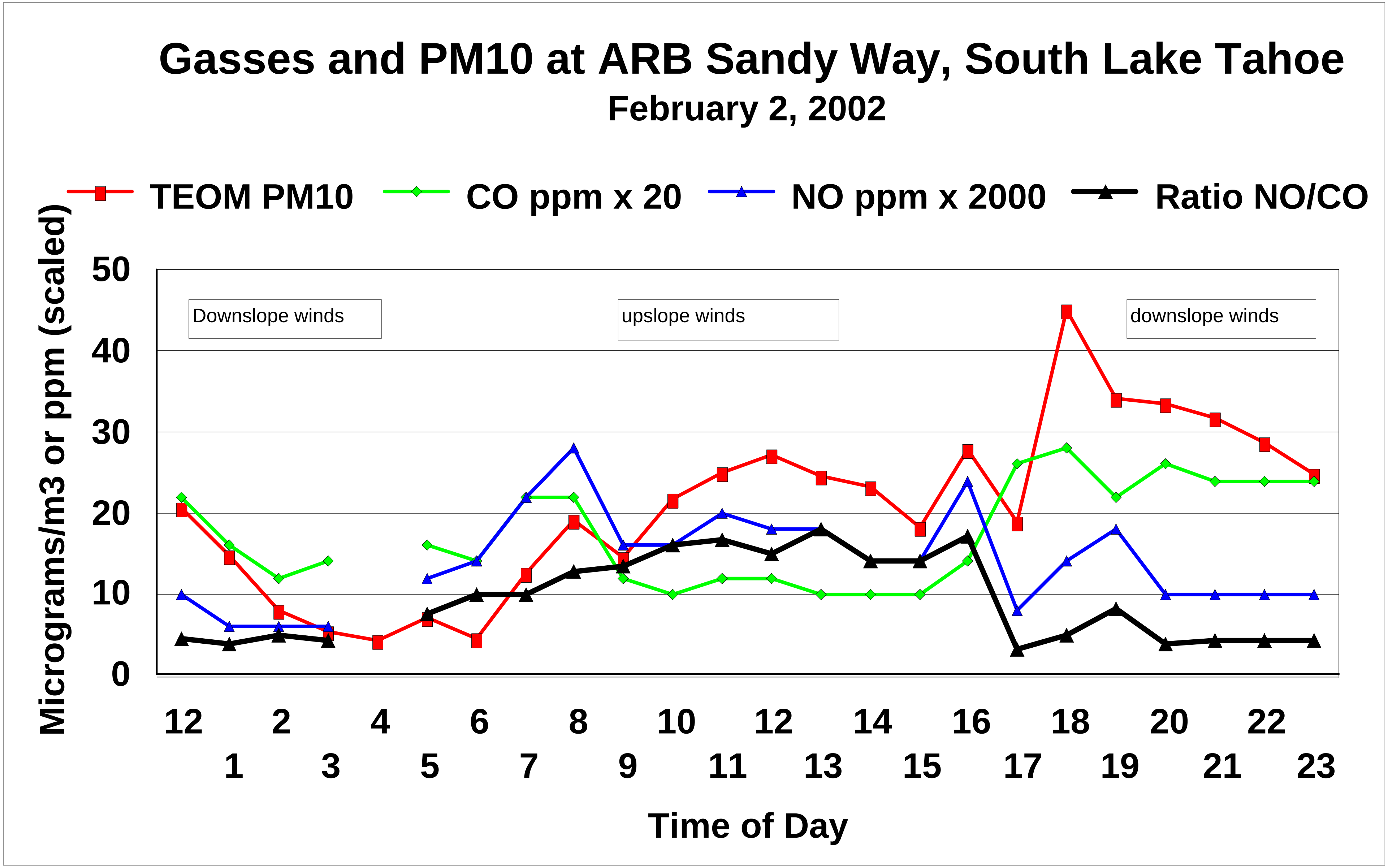
Gasses at ARB Sandy Way, South Lake Tahoe
Peak daily hour
CO
NO x 100
ppm
6
5
4
3
2
1
0
6 8 10 12 14 16 18 20 22 24 26 28 30 1 3 5 7 9
7 9 11 13 15 17 19 21 23 25 27 29 31 2 4 6 8
January, 2002
February, 2002

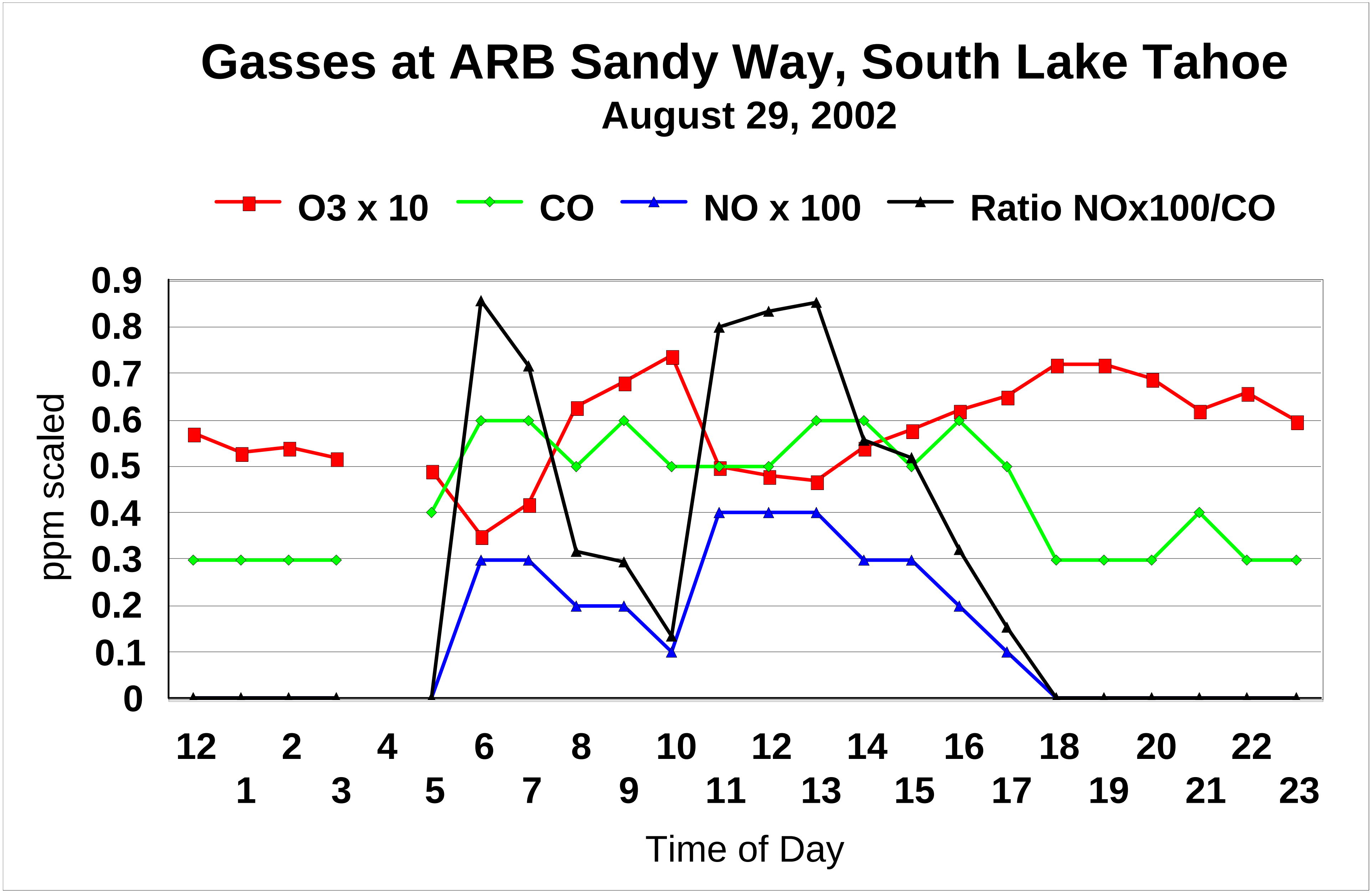


Peak daily hour
CO
NO x 100
ppm
6
5
4
3
2
1
0
11 13 15 17 19 21 23 25 27 29 31 2 4 6 8 10 12 14
12 14 16 18 20 22 24 26 28 30 1 3 5 7 9 11 13
August, 2002
September, 2002

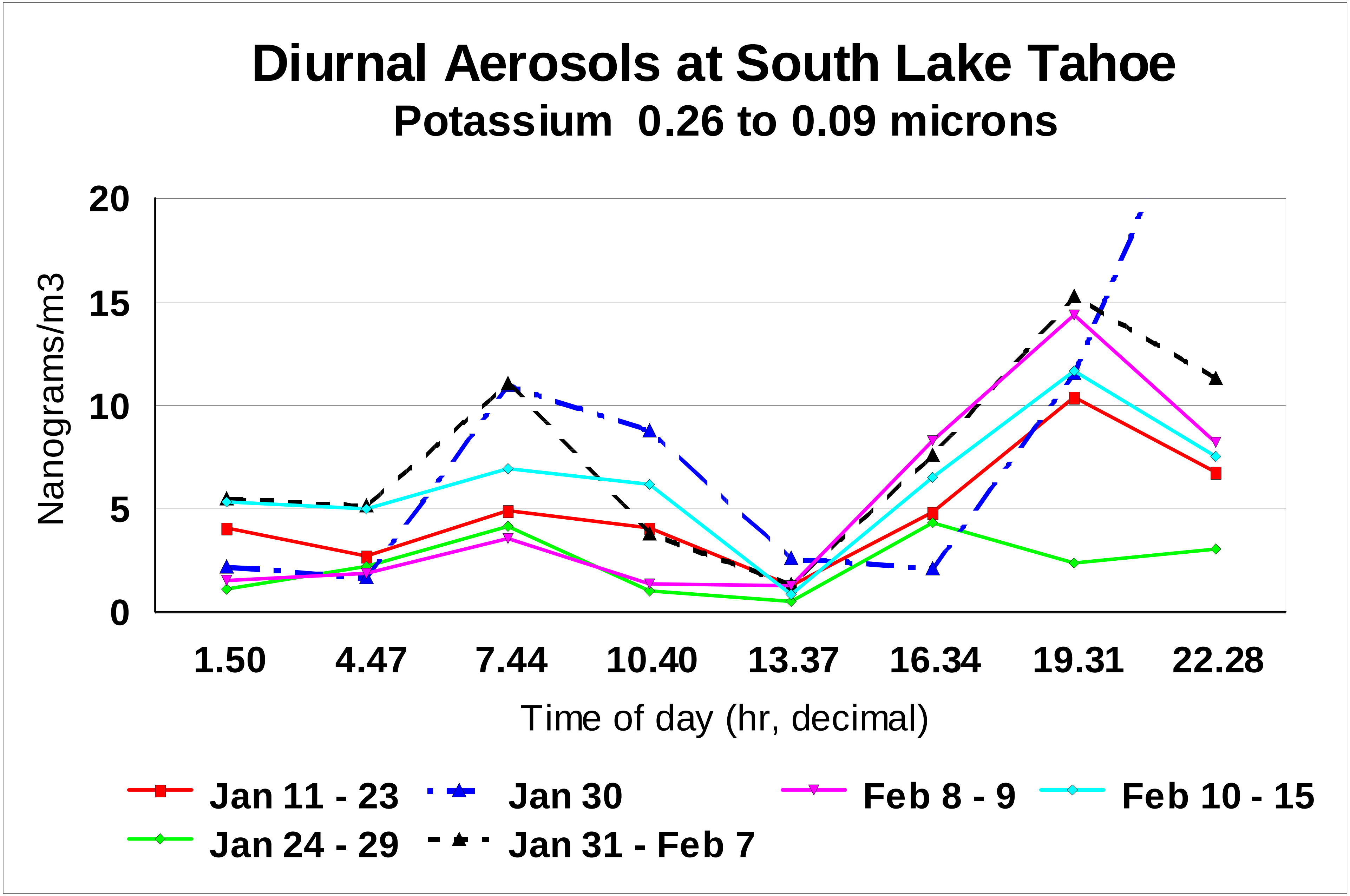


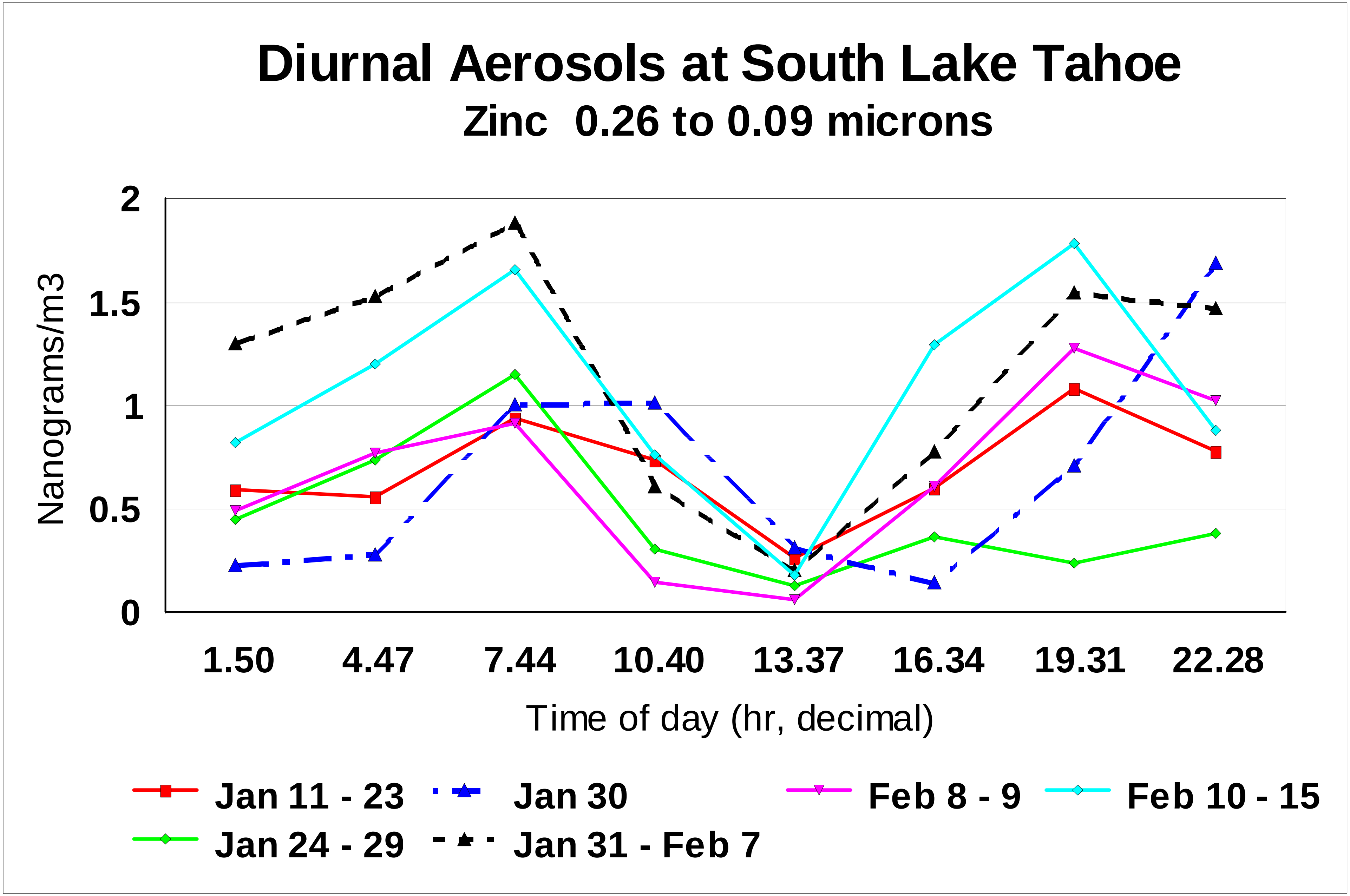
Pollutants at Sandy Way, South Lake Tahoe
February 11, 2002
CO
NO2 x 100
PM10 / 10
Typical NO x 100 (Jan 16)
NO x 100
ppm CO, others scaled
0
2
4
6
8
12
1
2
3
4
5
6
7
8
9
10
11
12
1
2
3
4
5
6
7
8
9
10
11
Time of day


Gasses and PM10 at ARB Sandy Way, South Lake Tahoe
February 2, 2002
TEOM PM10
CO ppm x 20
NO ppm x 2000
Ratio NO/CO
Micrograms/m3 or ppm (scaled)
50
40
30
20
10
0
Downslope winds
upslope winds
downslope winds
12
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Time of Day

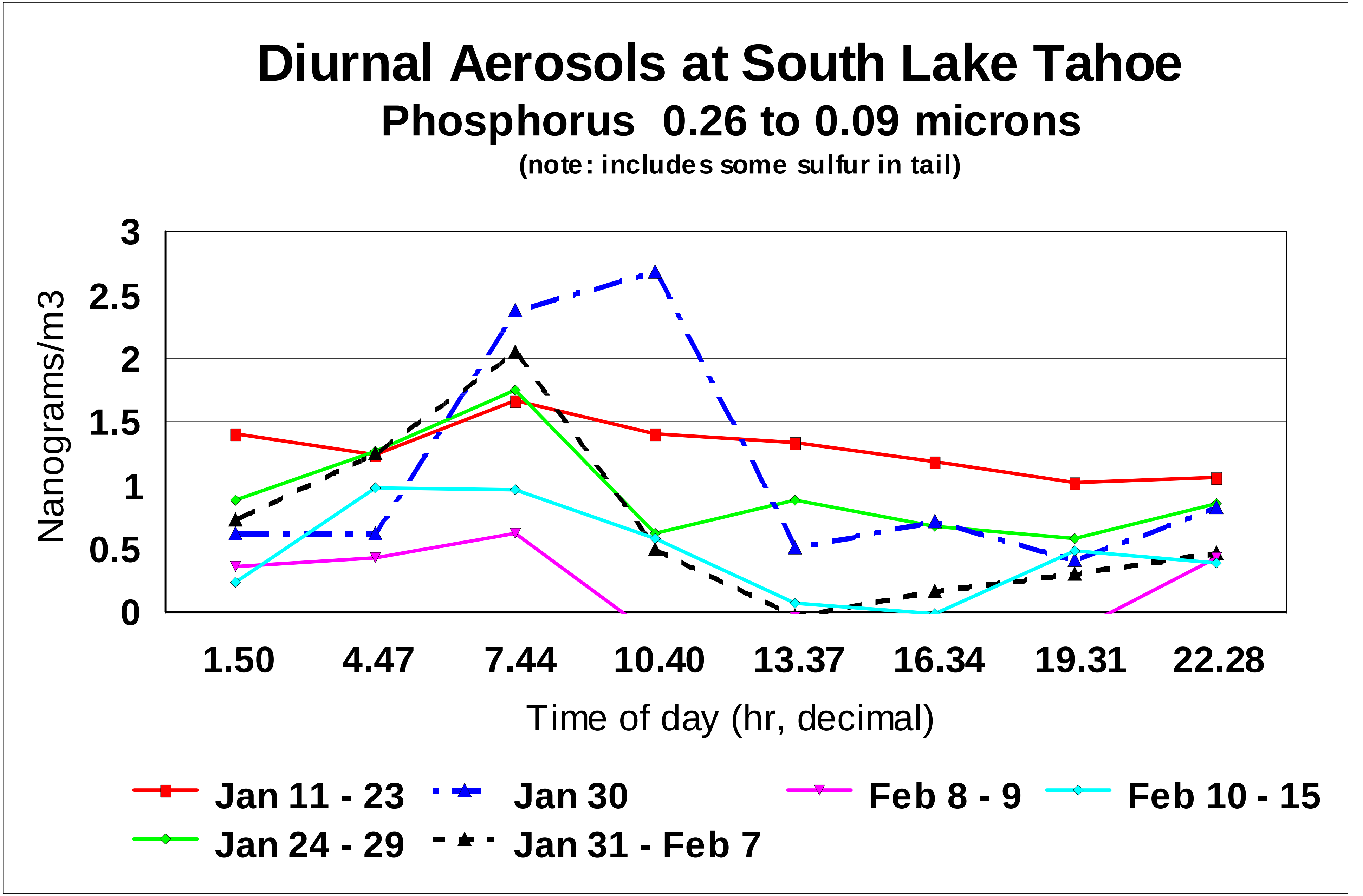


Gasses at ARB Sandy Way, South Lake Tahoe
August 29, 2002
O3 x 10
CO
NO x 100
Ratio NOx100/CO
ppm scaled
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time of Day


Diurnal Aerosols at South Lake Tahoe
Potassium 0.26 to 0.09 microns
Nanograms/m3
0
5
10
15
20
1.50
4.47
7.44
10.40
13.37
16.34
19.31
22.28
Time of day (hr, decimal)
Jan 11 - 23
Jan 30
Feb 8 - 9
Feb 10 - 15
Jan 24 - 29
Jan 31 - Feb 7



Diurnal Aerosols at South Lake Tahoe
Zinc 0.26 to 0.09 microns
Nanograms/m3
2
1.5
1
0.5
0
1.50
4.47
7.44
10.40
13.37
16.34
19.31
22.28
Time of day (hr, decimal)
Jan 11 - 23
Jan 30
Feb 8 - 9
Feb 10 - 15
Jan 24 - 29
Jan 31 - Feb 7


Diurnal Aerosols at South Lake Tahoe
Phosphorus 0.26 to 0.09 microns
(note: includes some sulfur in tail)
Nanograms/m3
3
2.5
2
1.5
1
0.5
0
1.50
4.47
7.44
10.40
13.37
16.34
19.31
22.28
Time of day (hr, decimal)
Jan 11 - 23
Jan 30
Feb 8 - 9
Feb 10 - 15
Jan 24 - 29
Jan 31 - Feb 7

Conclusions

- There will never be another automotive tracer like lead (unless we provide one)
- The similarity of smoking car and diesel exhaust will continue to be a problem (but do we care?)
- Multiple techniques will be required for a statistically sound identification of diesel exhaust in the ambient atmosphere
  - Particle size, color, behavior with temperature and oxidants, elemental composition, chemical composition,… are potential tools (but can we afford them?).
- Current best: EC in sizes < 0.25 µm