PM_{10} "Hot Spot" Emissions from California Roads

A report to Caltrans from the Air Quality Group,

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Summary

PM_{10} aerosols, meteorology, and traffic flow were measured during daylight hours in July 1994 at three sites. The first was at Florin Road west of Stockton Boulevard, a site with free flowing, low speed traffic averaging 40 mph. On July 7, 1994 from 9:00 a.m. to 5:30 p.m. 16,677 vehicles passed the samplers. The second site was the intersection of Florin Road and Stockton Boulevard where 39,081 vehicles, controlled by traffic lights, passed the samplers. This site was sampled simultaneously with the Florin Road site. The third site was Interstate 80 west of Davis; 74,481 vehicles passed at high speed (70 mph) during air sampling. Sampling at the Interstate 80 site was cumulative over a six day period to sample only during favorable wind.

We compared the PM_{10} background levels to downwind concentrations and calculated vehicle emission rates in grams/vehicle kilometer traveled (VKT). Florin Road appeared more polluting than I-80 despite having only ¼ the vehicles of I-80. Traffic on Florin Road added 7.3 $\mu g/m^3$ to the 68 $\mu g/m^3$ background level (using gravimetric mass measurements) during the 8 hr 20 minutes of sampling The intersection of Florin Road and Stockton Boulevard added about 83 $\mu g/m^3$ to the 68 $\mu g/m^3$ background. The emission rate at Florin/Stockton was 1.30 g/VKT; at Florin Road it was approximately 0.034 g/VKT. We are concerned about the gravimetric mass measurements at Florin and Stockton, though. The sum of measured elemental concentrations, along with the associated unmeasured elements, usually accounts for nearly all the measured mass. At Florin and Stockton, however, this reconstructed mass only accounted for 40-80% of the measured mass. Interstate 80 was less significant for PM_{10}, with the highway adding only 5.2 $\mu g/m^3$ to the 50 $\mu g/m^3$ background. The resulting emission rate of 0.02 g/VKT is lower than expected by predictions from models using current emission factors. At Interstate 80, the reconstructed mass accounted for nearly 100% of the measured mass.

The Interstate 80 PM_{10} results obtained here are similar to values measured across Los Angeles area freeways in 1973, when corrected for the removal of lead from gasoline. The intersection results are compared to a recent intersection study in the City of Davis, which showed less impact on the surrounding area than Florin-Stockton.

A clear signature of elemental carbon, as measured by light absorption on the filters, was observed across Interstate 80, roughly doubling the background elemental carbon present. There was little change in elemental carbon across Florin Road, but the Florin Road and Stockton Boulevard intersection transect displayed about four times the enhancement as Interstate 80 on a per-vehicle basis. Elemental carbon impact in the Davis study was insignificant. Elemental carbon is normally dominated by diesel exhaust, but there is some contribution from older cars. We also calculated the emission rates of the elemental components of PM_{10} across Interstate 80, Florin Road, and the Florin Road Stockton Boulevard intersection. These

emission rates were generally comparable to those measured in the Van Nuys tunnel during the Southern California Air Quality Study in 1987.

Recommendations

The emission rate calculated by applying the "sliding box" model to the measured upwind and downwind concentrations on Interstate 80 is a factor of 3-15 lower than the rates predicted by a model such as PART 5 that uses the AP-42 fugitive dust emissions equations for paved roads. The silt loading used in our calculations is half the average of U.S. cities reported in AP-42. Although the silt loading used was measured on Interstate 80 in Utah, only about 5% of high ADT paved roads listed in AP-42 had a lower silt loading. Recognizing that the emission factor in Table 9 does not account for the direct vehicular tailpipe, brake and tire emissions, whereas the actual measured concentrations reflect these additional sources as well as re-entrained dust, the AP-42 overestimate of re-entrained dust from the roadway is even greater.

Because measurement of silt loadings on California freeways is not practical for safety reasons, PART 5 will greatly overestimate freeway emissions if recommended values of silt loading from AP-42 are used. Therefore, the default values of silt loading to be used in California need to be reexamined.

The increment of PM_{10} ambient concentrations added by Interstate 80 is so low relative to the 24-hour federal or state standards that it is extremely unlikely that PM_{10} "hotspots" will be associated with projects that improve level of service on freeways. We recommend that PM_{10} modeling not be required for such projects.

The Florin-Stockton intersection was a preliminary study to test the experimental protocol and was intended to be repeated at a later date. Based on the data obtained from that intersection, however, it is conceivable that a PM_{10} "hotspot" leading to an exceedance of the state standard could occur. It is unlikely that an exceedance of the 24-hour federal standard could occur during the summer months when there are diurnal shifts in wind direction. We recommend that the experiment be repeated at that intersection in both the summer and winter (poor ventilation) seasons. The experiments should include measurement of the silt loading on the street to determine if the PART5 model (based on AP-42) will provide reasonable re-entrained dust estimates. Furthermore, efforts to identify the unexplained mass (the difference between the gravimetric and the reconstructed mass) should be a goal of the study. It may be that semi-volatile and non-volatile organics are associated with the direct particulate emissions at that location.

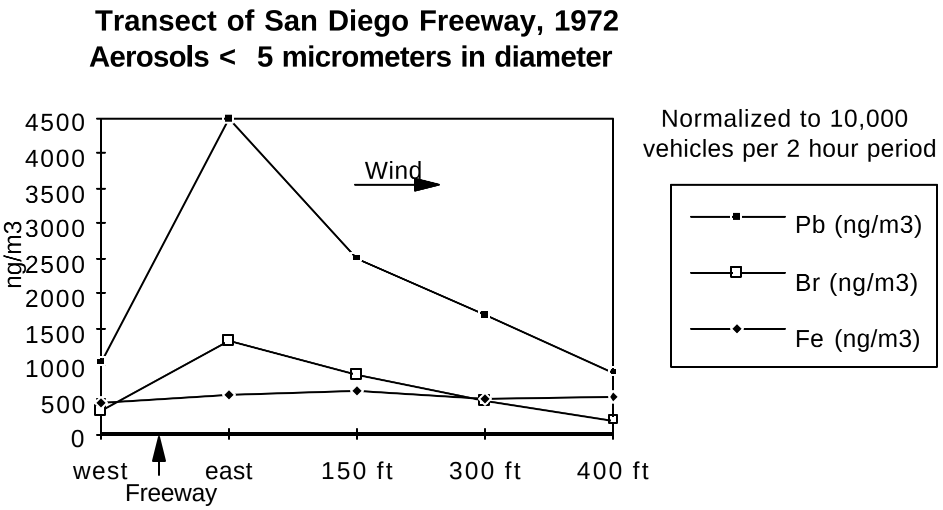
Introduction

Caltrans has been required to evaluate the effect of roadway projects on local PM_{10} concentrations, especially with regard to the potental for PM_{10} "hot spots". This has focused attention on the lack of information on PM_{10} emissions from California roadways. Few emission rate studies carried out in the past twenty years collected PM_{10} data, and fewer still attempted correlation of PM_{10} aerosols with traffic in real systems. Most studies were not adequate for air quality planning for PM_{10} in California. Currently, information derived by the US EPA from studies in the mid western United States forms the basis for air quality modeling in every state. However, the US EPA's "AP-42" emission factors were derived in conditions very different from those in California. The use of these emission factors in current air quality models may be inadequate for predicting downwind PM_{10} levels.

Previous studies

The most detailed previous study of aerosols by size and composition was sponsored by the ARB and Caltrans in 1972-1974. Figure 1 shows profiles of fine particles across the San Diego freeway measured during that study. Clearly, the influence of the freeway can be easily separated from upwind sources by this sampling method. Table 1 gives the results for lead. Many other materials were also measured, and these were compared directly with calculated emission rates of all automotive expendables (fuel byproducts, tire wear, roadway erosion, re-suspended soils...). The emissions were modeled using a "sliding box" model, compared with observed emissions, and the results published. Table 2 reproduces these results of the San Diego freeway study (3).

Figure 1. Pb, Br, and Fe Concentrations Across a Transect of the San Diego Freeway in 1972(3).



As may be seen from the results at site 3, the modeled or calculated values and the measured values correlate very well at the freeway edge. Downwind of the freeway, the correlation is not perfect between modeled and measured values, but remains quite close.

Table 1 indicates the values derived from the box model closely match the observed values for lead, so we may assume the model is viable for other elements as well. Lead was an excellent tracer element for freeway emissions in 1972-74 since its presence was almost entirely due to combustion of leaded fuels. Currently, no tracer comparable to lead is available for freeways since most other elemental concentrations are confounded by emissions from non-freeway sources. Verifications of the box model, at the current time, would be difficult. However, the comparison of modeled and actual lead emissions demonstrates the box model may be utilized with confidence to estimate emissions in current studies.

In 1974, we did not have the analytical tools necessary to resolve mass and all elemental components from the filters. However, we can now use a "reconstructed mass" approach to approximate the unmeasured mass values (11). This approximation has been used in the national IMPROVE (Interagency Monitoring of Protected Visual Environments) monitoring program, with U.S. EPA support. However, the lack of organic measurements in the 1974 studies increases the uncertainty in the approximation. Using measurements of organics from the current study, we have set reasonable limits on the organic values for the 1974 data, improving our confidence in the reconstructed mass calculation.

Table 1. Traffic derived lead levels versus sampling site(4). Concentrations are for particles less than 5 μm effective aerodynamic diameter normalized to vehicle flow of 5000 vehicles/hr. Winds have mean values of about 3 m/sec. Distance in meters is from the freeway median (3).

site, date	Wind	Pb (μg/m^{3}) 27 meters	Pb (μg/m^{3}) 40 meters	Pb (μg/m^{3}) 100 meters	Pb (μg/m^{3}) 160 meters
Site 1, 6/72 (cut section)	parallel	4.9	.85	0.30	
Site 2, 6/72 (cut section)	transverse	4.5	1.7	0.26	
Site 3, 8/72 (at grade)	transverse	**4.0**	**3.1**	**1.40**	**0.35**
site 3, 6/72 Modeled	transverse	**4.0**	**3.4**	**1.40**	**0.41**
Site 4, 6/72 (fill section)	transverse	6.0	2.7	2.2	
Site 4, 8/72 (fill section)	transverse	3.6	2.0	4.0	3.5
site 4, average	transverse	4.8	2.3	3.1	

Table 2. Particle Production Rates by Size, Source, and Major Elements(3)

	All Elements	Total Al and above	Size Range >5m D_{eff}	 <5m D_{eff}
Gasoline	339 mg/mile			
Pb		60 mg/mile	12 mg/mile	48 mg/mile
Br		22 mg/mile	2 mg/mile	20 mg/mile
S		15 mg/mile	<1 mg/mile	15 mg/mile
Cl		10 mg/mile	2 mg/mile	8 mg/mile
Motor Oil	4.3 mg/mile*			
Zn		0.2 mg/mile		
Exhaust Train	10 mg/mile			
Fe		10 mg/mile	8 mg/mile	2 mg/mile
Tires	110 mg/mile			
Zn		1.6 mg/mile	1.2 mg/mile	0.4 mg/mile
Road Bed	66 mg/mile			
Si		12 mg/mile	11 mg/mile	1.0 mg/mile
Ca		7 mg/mile	6.2 mg/mile	0.8 mg/mile
Al		4.6 mg/mile	0.9 mg/mile	0.2 mg/mile
Fe		1.8 mg/mile	1.6 mg/mile	0.2 mg/mile

Table 3 shows the results of this approximation, based upon the impactor cut-points used in the 1974 studies and interpolation of AP-42 estimates.

Table 3. Measured versus modeled emission rates for the 1974 freeway studies

	1974 measured values UCD/ARB/Caltrans	1974 modeled values AP 42
Coarse particles, Dp > 5 microns Reconstruced Mass	0.044 g/VKT	0.21 g/VKT
Fine particles, Dp < 5 microns Reconstructed Mass	0.062 g/VKT	0.175 g/VKT

Similar emission factors were obtained from tests at the General Motors proving grounds in 1978 (5), as shown in Table 4. This test utilized a box model similar to the one used in the current 1994 Caltrans study to derive emissions. However, direct comparisons with other samplers are difficult as the samplers used probably accepted particles above PM_{10}. Note also that California has sharply reduced sulfur in gasoline, so that this component is nearly absent from aerosols generated by vehicle exhaust.

Table 4. Effective generation rates per automobile for three GM test runs and corresponding values from the 1972 Los Angeles study

Date	Sulfur mg/km	Calcium mg/km	Iron mg/km
Oct 1, 1975	9.7	7.0	3.0
Oct 2, 1975	12.0	8.0	3.7
Oct 3, 1975	8.7	6.1	2.1
Mean	10.1 ± 1.7	7.0 ± 0.9	2.9 ± 0.8
Los Angeles summer 1972	0.3	4.5	7.1

(From Courtney, et al., March 1978)

The effective generation rates listed in Table 4 were derived from filter samples of particulate matter upwind and downwind of a road, and from wind speed and direction, mixing height over the road (box height), and traffic counts.

Objectives

The primary objective of this study was to measure the emission factors from paved roads at potential "hot spots" of PM_{10} emissions. In this study, PM_{10} was measured upwind and downwind from roads and a simple box model was used to derive approximate emission factors. This study was contracted to the Air Quality Group at UC Davis to obtain a review of the existing literature on PM_{10} and California roadways, to make a limited number of new measurements to establish actual PM_{10} values near various roadways, and to estimate emission factors. Data collected under normal traffic regimes were directly compared with the predictions of AP-42 and models based upon these emission factors. This provides an indication of the applicability of the AP-42 emission factors in California.

Measurements were made during dry, hot conditions with moderate winds in July 1994. These conditions were expected to maximize the generation of resuspended dusts from dry soils. At the time of the study, no rainfall had occurred for over two months at any of the sites. This study obtained meteorological and PM_{10} measurements, with elemental concentrations and estimates of organics and elemental carbon. The analyses provide a preliminary database for apportioning PM_{10} mass associated with the roadway to the sources (re-suspended soils, soot, tire wear) in a mass-consistent manner. This study should be treated as a pilot study to determine where additional efforts should be focused.

Methodology and quality assurance

Mass Balance of a Source using the "Sliding Box" Model

Mass balance techniques in air pollution attribution studies are based upon an analysis of the mass flux through a closed system that, internally, can be considered uniform or well mixed over some integrating period. Some good examples are the tunnel studies of Pierson, et al. (1991) and Ingalls, et al. (1989), and analyzed further by Pierson (1993). In the Van Nuys tunnel during the Southern California Air Quality Study (SCAQS), the physical barrier of the tunnel walls defined the box. Air flow within this volume was tested via SF_6 tracers, and the amount and type of traffic in the tunnel was monitored.

The same type of test can be performed without a tunnel, using a "box" defined by meteorological mixing dimensions instead of physical tunnel walls. The advantage of this technique is that it can be done on any road, and in realistic conditions of road surface unobtainable in tunnels.

The "sliding box" model was used extensively in early studies of aerosols from Los Angeles freeways, as line source diffusion models in use then were theoretically and experimentally inadequate to evaluate freeway sources. First, since the freeways were of large lateral extent, they required the application of several line sources to predict concentrations at the downwind edge. The sources themselves were spatially separated on the freeway, with dust sources at each edge, diesel sources primarily in the outer lanes, and mostly automobile traffic in the inner lanes. Second, the local wind velocities caused by the passage of vehicles were an order of magnitude greater than the meteorological winds. Each vehicle left a turbulent wake that was quickly transported into the adjacent lane, with chaotic effects that were impossible to model. Thus, the assumptions of the "line" source model were violated in near-freeway conditions. Finally, in light wind conditions, heat input from vehicles modified the heat balance and, hence, Pasquill stability estimates. From a modeling perspective, it was easy to add this excess heat to a volume or "box" source, but it gave unrealistic values (i.e., infinite temperature) when applied to a line source. This excess heat flow was neglected in EPA models current in 1974, resulting in a large overestimate of near-freeway sulfate concentrations in certain terrain and wind conditions. Many models still do not properly handle this heat factor.

Since it was imperative to get correct values at the edge of the freeway, and since a parallel Caltrans study was measuring the height of the turbulence zones (top of the box), we applied the "sliding box" model to arrive at freeway-edge conditions.

The conditions required for application of the box model are that winds must be sufficiently stable that the limits of the box and the flux of air can be measured quantitatively. This generally requires well-defined air flows in simple terrain. If the "box" is then allowed to slide laterally across the road at the speed of the wind, then one has a "sliding box" model that allows mass balance to be calculated in much the same way as in the tunnel studies. In the 1974 studies, the sampling systems were placed upwind and downwind of the freeways, extending several hundred meters downwind, and meteorological parameters were recorded (wind velocity, direction, temperature, sky cover, etc.). Several thousand samples were collected in the 1973-1974 studies in six different roadway configurations (Cahill and Feeney, 1973; Feeney et al, 1975). Figure 1 shows an example of the data collected during the 1974 studies. (Feeney et al., 1975.)

At the edge of the freeway, beyond the lateral turbulence of the vehicular wakes (estimated to be about the same dimension as the height of the turbulence or the top of the box, h_b), one can use a line source diffusion model to predict lateral transport. At that point, the box model output was used as input to standard line source diffusion model (with particulate settling) to estimate the concentration profile as a function of distance downwind of the freeway (Feeney and Cahill, 1973; Dunn, 1974; Feeney et al, 1975). It should be noted that the "sliding box" estimates worked well in all configurations to deliver freeway-edge concentrations, but the diffusion model worked well only in ideal terrain and meteorology. In complex terrain such as cut-section or raised berm freeways, it resulted in errors of up to an order of magnitude (Feeney et al., 1975).

Hence, the "sliding box" mass balance method provided an independent verification of the line source models in the limit of high local turbulent source mixing, without requiring knowledge of the atmospheric stability. The dispersion further downwind does, however, demand knowledge of such factors. It should be noted that the tunnel studies of Pierson, et al. (1991) and Ingalls, et al. (1989), and additional analysis by Pierson (1993) also provided independent estimates of gaseous emission rates in real roadway conditions, and showed roadway emission rates of CO and HC far above the laboratory-derived emission rates used in all current models.

Theory

The ambient concentration of pollutants downwind of the highway source is given as:

$$C_p = M_p/V_b$$

where M_p is the mass of pollutants (grams) emitted and V_b is the volume of the box (cubic meters) into which they are emitted. Generally, for particles, the units of C_p are expressed as micrograms/m^3 to match standard usage in the measurement of particulate matter in the ambient atmosphere, while the units for gasses are in parts per million by volume.

The mass of pollutants emitted is given by the mass emission rate (normally mg/km) times the number of vehicles times the distant traveled. If we use an emission rate in mg/km, then,

$$M_p = E_v \times N \times L_b$$

where E_v is the emission rate in mg/km, N is the number of vehicles (sorted by type) within the box, and L_b is the length of the box.

The volume of the box is given by

$$V_b = h_b \times w_b \times L_b$$

where L_b is the length of the box, w_b is the width of the mixed zone, and h_b is the height of the mixed zone.

It is important to realize that the velocities associated with vehicular wakes are generally very high in rural freeway conditions, as the partial vacuum created behind the vehicle results in local wind speeds roughly equaling the vehicle's speed. Karman vortices have been observed in nighttime smoke tests to extend well behind the vehicle, gradually becoming wider and higher as time passes. In real roadway situations, however, growth of the mixed zone is almost immediately interrupted by the next vehicle or by vehicles in adjacent lanes, thus repeating the process every few seconds. The result is a chaotic but well-mixed volume whose dimensions are hard to calculate. The mixed volume depends on many parameters. These include traffic volume, mix and velocity, local terrain features such as bridges, retaining walls, and roadway configuration relative to the adjacent terrain.

Estimation of box height

In 1974, the California Department of Transportation commissioned a study of vehicular wakes by AeroVironment, Inc., using smoke releases on an unused runway at night. From these studies, the height of the mixed layer was found to be roughly twice the mean height of the predominant vehicle in the traffic mix. For California freeways, the mixed layer height averaged about 3.5 meters. Hence, for h_b we will use a value of 3.5 meters, with an estimated lower limit of 2.5 meters but an upper limit that might reach 4.5 meters when many trucks are present.

This value of h_b assumes that there is no plume rise other than that associated with turbulent eddies. However, in the 1974 work on the Los Angeles freeways, we observed air flow patterns and pollutant concentrations that were consistent with a buoyant plume. Calculation of the vehicular waste heat gave a temperature rise of 1.4^{o}F/minute on the Santa Monica Freeway, for a typical traffic volume of 250,000 vehicles/day (Feeney et al., 1973). The net upward movement of the entire air mass must be vectorially added to the lateral movement of the air mass (the "sliding" of the box) to obtain the correct volume of the box at the edge of the roadway. In most conditions, this buoyant lift factor is quite small. Nevertheless, the use of vertical profiles downwind of the roadway is recommended when traffic volumes are high and lateral transport is weak.

Estimation of box width

The width of the box is set by the width of the freeway, w_f, plus a lateral extension due to turbulent wakes. This was measured by numerous observations of near Los Angeles freeways in the 1974 study. For this study, we chose to increase the width of the freeway by the height of the turbulence zone, h_b. Thus, the box width is

$$w_b = w_f + 2h_b$$

This correction is small for realistic conditions, typically amounting to about 10%.

From this analysis, it can be seen that the uncertainty in the height of the box dominates the uncertainty in the volume. In the section on validation, we will compare the concentrations calculated by the model to the observed values near roadways. This comparison will be made for conditions in which the emission rates are well known. We can then check our calculation of box volume, which will in turn better define the uncertainties in emission rates for which the source terms are poorly known.

Estimation of the replacement time

The final factor that must be considered is the time it takes for the air to "slide" laterally across the roadway, bringing the upwind air mass onto the roadway and the roadway air mass off the roadway and over the air samplers. This requires measurement of the wind speed at approximately the middle of the box, i.e., at height $h_b/2$. There must be a well-defined upwind-downwind direction, reasonably stable wind velocities, and a well-defined vertical profile of wind velocity. In our work, we limit sampling to periods when wind velocities fall between a lower limit of 1 m/s and an upper limit of about 5 m/s, and wind directions that vary no more than about ± 20° from the mean wind direction. The replacement time of the air mass is:

$$t_r = w_b / v_w \sin(\theta_w)$$

where v_w in the mean wind speed and θ_w is the angle of the mean wind with the roadway. Typically, replacement times are about 20 to 30 seconds for the conditions optimal for use of the sliding box model on California roadways.

Estimation of number of vehicles

The number of vehicles in the box can now be found from:

$$N = N_o \text{ (veh/hr)} \times t_r \text{ (hr)}$$

where N_o is the traffic rate in vehicles/hr, and t_r is the replacement time of the air in the box.

Estimation of emission rates

After making the appropriate substitutions, the final form of the emission rate equation from the "sliding box" model becomes:

$$C_p = (E_v \times N_o \times t_r \times L_v) / (h_b \times w_b \times L_v)$$

Note that the length of the box, L_v , cancels out. Also, since $t_r = w_b / v_w \sin(\theta)$, the width of the box, w_b, drops from the final form of the equation. The final form, when rearranged to solve for the emission rate, then becomes: (Courtney et al, 1978)

$$E_v = 3.6 \times v_n \times h_b \times C_p \times \sin(\theta) / N_o$$

where E_v is the emission rate in g/VKT,
v_n is the wind velocity in m/s,
h_b is the height of the box in meters,
C_p is the pollutant concentration in μg/m^3,
N_o is the number of vehicles/hr,
θ is the angle of the wind with the roadway, and
3.6 converts the units to g/VKT.

Validation of the "sliding box" model

The emission rate for fine lead particles was not available to us when the field measurements were made in 1972, but was later established by Hababi (1973) and Ter Haar et al. (1972). Their published rates were used for the emission estimates of the "sliding box" model of Cahill and Feeney (1973).

The "sliding box" estimates worked very well in all roadway and meteorological conditions, with an observed value for fine lead particles of 4.6 +/- 0.8 micrograms/m^3 for 5,000 v/hr, versus model predictions of 4.0 micrograms/m^3.

Table 1 also shows the downwind profile of particle concentrations from the line source diffusion model of Dunn, 1974. The agreement for the at-grade profile of Site 3 (8/72) is excellent, 4.0 μg/m^3 at the edge of the freeway, and is still in good agreement (0.41 μg/m^3 vs. measured 0.35 μg/m^3) at 160 meters downwind. The model and observations differ by as much as a factor of 10 at other sites and configurations. The very low model values in both the cut sections (Site 1, the Santa Monica Freeway, and Site 2, the Harbor Freeway) were later traced to the effect of traffic heating of the air in a confined system.

The same model was applied to highways in the Lake Tahoe basin (Cahill et al., 1978) and in a set of well-controlled tests sponsored by the USEPA at the General Motors Proving Grounds (Courtney et al., 1978). In the latter tests, cars were run on a test track with catalytic converters and fuel containing a known fraction of sulfur. Table 4 (from Courtney et al., 1978) gives the results of these tests, and compares them to the Los Angeles Freeway studies (Cahill and Feeney, 1973).

The test results for sulfur emission rates varied strongly from car to car, by almost a factor of 4, and as a function of the length of time the car had been operation (Cadle et al.,1977). This was despite the fact that all cars were new General Motors cars and used identical gasoline with a sulfur content close to the pre-1974 California value. Nevertheless. despite some differences in the conditions in which the data were taken, the results were reasonably similar. Probably the best study used SF_6 as a measure of air volume, and measured sulfate emission rates of 23 +/- 4 mg/km per vehicle (Cadel et al 1977). The results of the "sliding box" model gave of 30 +/- 5 mg/km (Courtney et al, 1978) , while the third ambient test, a downwind measurement, gave 17 mg/km. (Wilson et al, 1977). Please note, however, that sulfur in present California gasoline is reduced by about a factor of 10 below the 1974 values, so these results are not typical of present California highways. As far as we are aware, California is the only state with sulfur-reduced gasoline, which also leads to other emission changes due to the longer life of exhaust train components than in the rest of the US.

This ability to match emission rates in field conditions gives confidence for those many parameters in which no emission factors are available. The "sliding box" model is thus a simple and reliable method to extend "mass balance" techniques to high-speed open roadway situations. Theoretically, it should also be valid for smaller roads, especially since some of the spatial and temperature effects of freeways are less important in less traveled streets. The method does not need the detailed road-surface condition information required by the EPA, such as vacuuming dust off the roadway surface which is almost inconceivably difficult for a roadway such as I-80. Finally, the "sliding box" model requires less detailed meteorological information than other models, allowing use in complex situations for which diffusion modeling is difficult and uncertain. For these reasons, it was chosen as the model for the preliminary CalTrans tests in summer, 1974.

Sampling locations

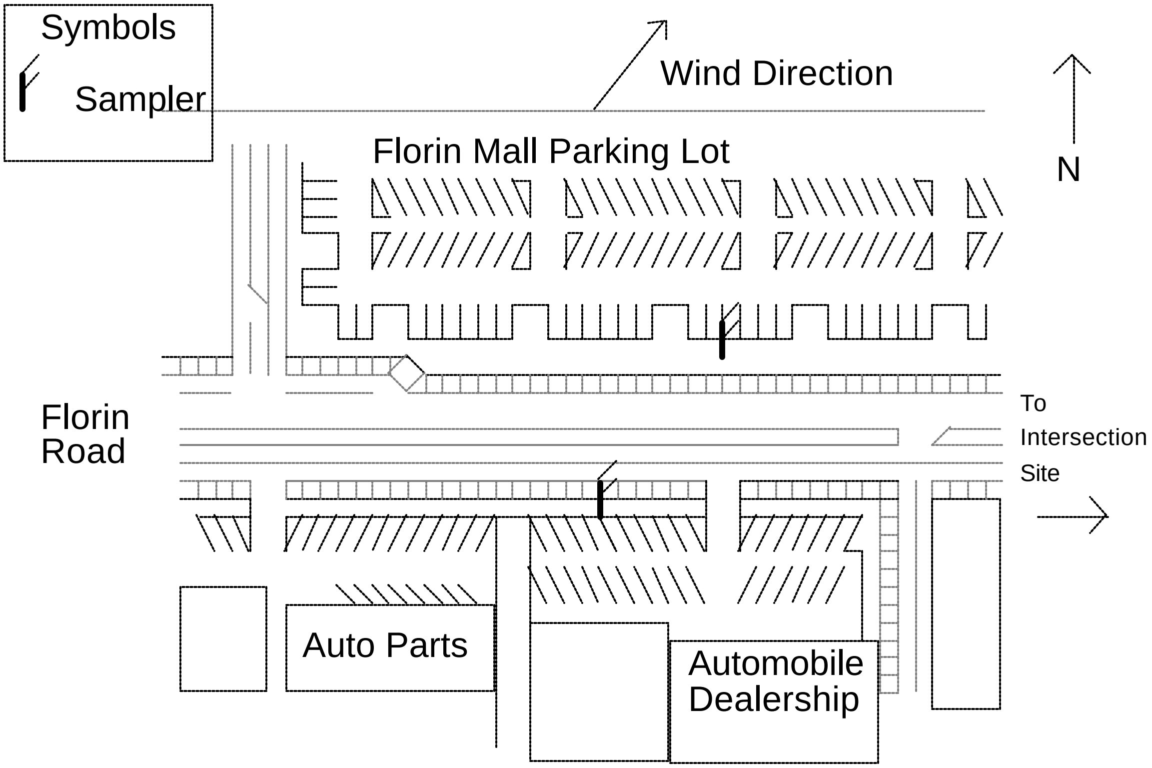
The first study was conducted along Florin Road, an arterial street in Sacramento, several hundred meters west of the intersection of Stockton Boulevard and Florin Road. Simultaneous sampling was conducted at the intersection of Florin Road and Stockton Boulevard to characterize stop and go traffic.

The Florin road site utilized four measurements, two upwind and two downwind of the road. The upwind tower was at a car dealership south of the road and was sited four meters from the curb. The downwind tower was at the Florin Mall parking lot, north of the road, and was located three meters from the curb (Figure 2). The samplers were placed at two and four meters above the road surface on the two towers.

Sampling at the intersection of Stockton Boulevard and Florin Road involved two measurements, one upwind and one downwind (Figure 3). The upwind site was in the parking lot of a tire store on the southwest corner of the intersection. The downwind site was on the northeast corner of the intersection in the parking lot of a fast food restaurant that had gone out of business. Both sites were located three meters from the curb of the right turn lanes.

The second study was conducted across Interstate 80 two miles west of Highway 113. The sites were accessed by taking the Kidwell Road exit. Both sites were near the ends of the roads running parallel to Interstate 80 east of the Kidwell road exit. The upwind site was at the end of Sparling Lane, south of Interstate 80, while the downwind site was at the end of Olmo Road (Figure 4).

Figure 2. Sampling site at Florin Road



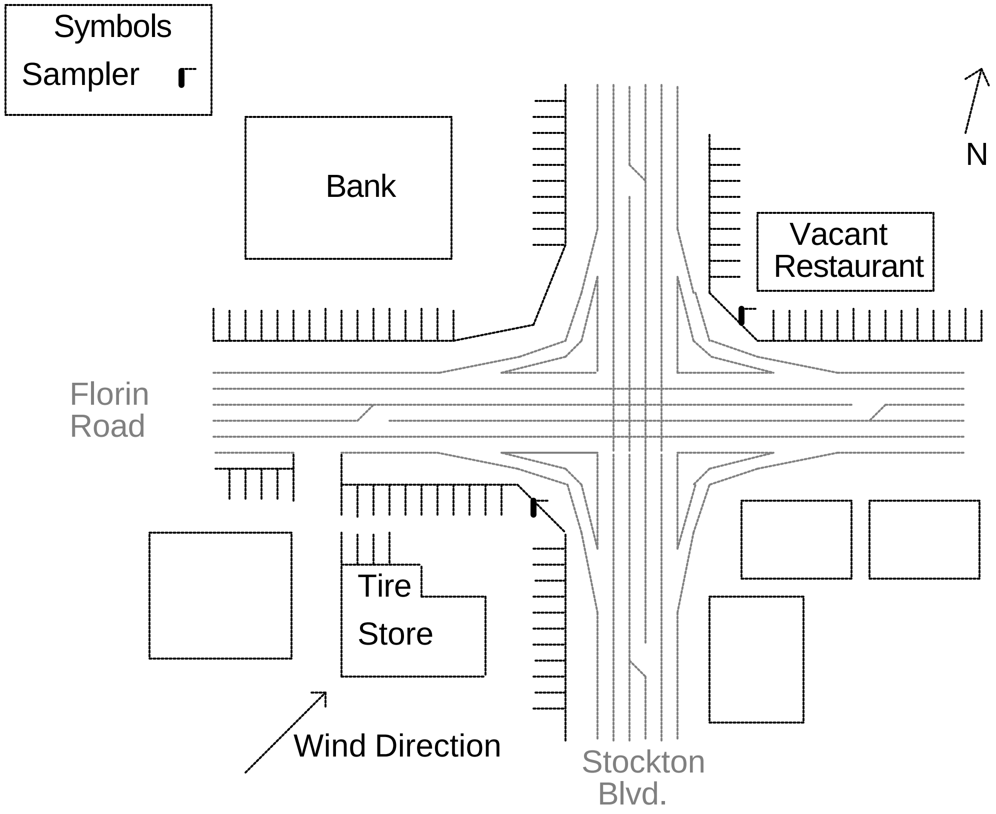
The upwind site was a ten meter tower located 35 meters from the solid white line defining the freeway's south edge. The tower, instrumented at two, four and eight meters, was set up in an unused field that had been disked a week earlier to eliminate weeds.

The first downwind site, Downwind 1, was located seventeen meters north of the solid white line defining the freeway's north edge. The site was a single two meter tower placed at the fence bounding the freeway.

The second downwind site, Downwind 2, was located thirty-five meters from the solid white line defining the freeway's north edge. The ten meter tower, instrumented at two, four and eight meters, was set up in a field where, two weeks earlier, a drilling team had put in a test well. There was some fugitive dust generated north of this tower, but none between the tower and the freeway.

The third downwind site, Downwind 3, was located seventy meters from the solid white line defining the freeway's north edge. The site was a single two meter tower placed in an area downwind of a few potential sources of fugitive dust. We did not sample during periods when the winds were strong enough to blow dust from the surface.

Figure 3. Sampling site at the intersection of Stockton Boulevard and Florin Road

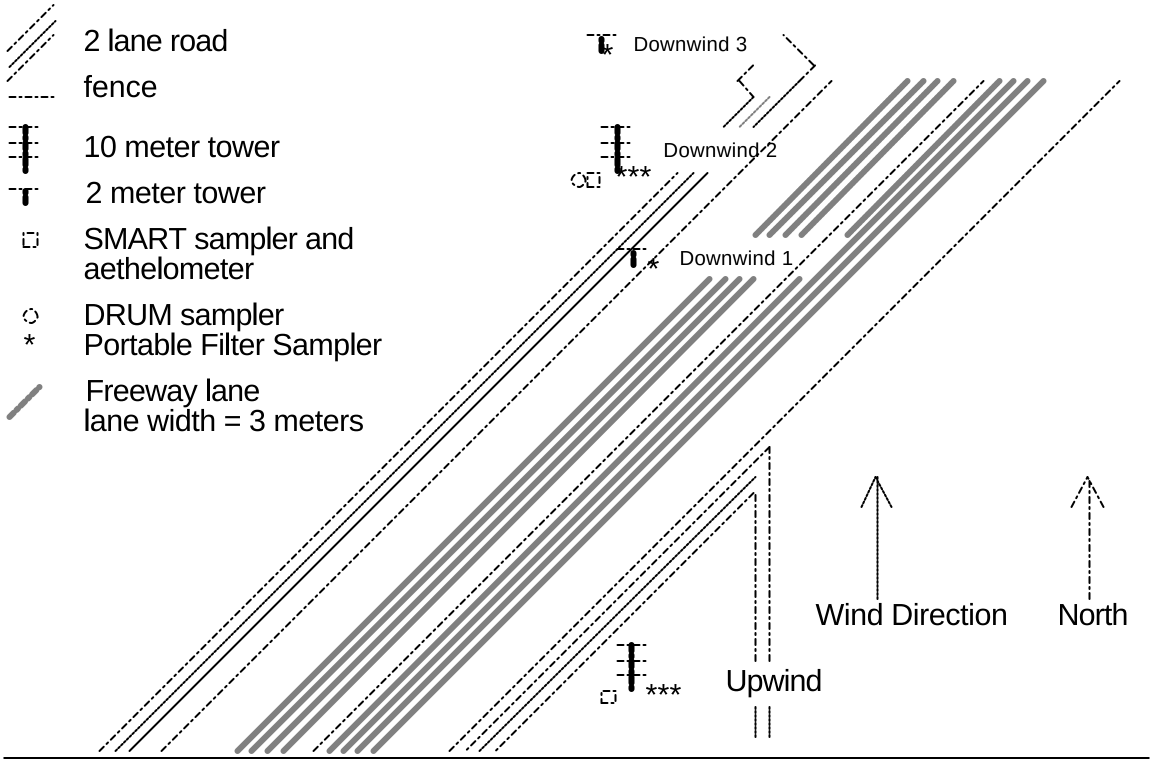


Meteorology

In the first study, wind speed and direction were measured at the downwind site on Florin Road at two meters and four meters from the surface. The sampling period was from 9:40 a.m. to 6:00 p.m. on July 7, 1994. This period was selected because it represented normal business hours, and it was expected to be a period of fairly stable wind direction. Moreover, twenty-four hour sampling at that site presented security risks with the available personnel and resources. Unfortunately, the wind was not as stable as desired, but was adequate for a rough calculation of emission factors in this area.

During the Interstate 80 study, meteorological data were collected at two meters, four meters, and eight meters from the surface. The data were collected continuously for the first two days, until a transformer failure caused an equipment malfunction. No meteorological data were collected at the upwind site from July 16 through 18 due to the damaged equipment. Once the equipment was repaired, data collection resumed, though the wind speed channels continued malfunctioning for unknown reasons. Data on wind direction and speed were also measured at a two meter height at the second downwind site so we were able to determine whether sampling criteria were being met.

Figure 4. I-80 study site



Data from local meteorological stations were obtained from the National Weather Service (NWS) and UC Davis, and compared to measured data for quality assurance. The collected data closely matched the NWS and Davis data, so gaps in the collected data set were filled with these data. The NWS sites utilized included a site at the Forest Service Tree Farm in South Davis and a downtown Sacramento site. The Davis data were collected in an experimental field approximately one mile north of Interstate 80 and one mile east of Highway 113.

Traffic flow data

At the Florin Road and Stockton Boulevard site, traffic data were collected each hour by recording the number and type of vehicles passing the sampler in a ten minute period. This was multiplied by six to approximate hourly average traffic levels.

During the Interstate 80 study on July 15 through July 21, traffic data were recorded on videotape for ten minutes of every hour during sampling periods. The vehicles were counted and average hourly traffic counts were calculated. These were compared to data collected by Caltrans during similar time periods in June 1994 for quality assurance.

Data on traffic flows and meteorology are included in Appendix A.

Sample collection

We used the National Park Service IMPROVE (Interagency Monitoring of Protected Visual Environments) protocols (12) to analyze our samples for mass, optical absorption, hydrogen, and the elements from Na to Pb in the periodic table. Although we did not have access to IMPROVE samplers for this study, we used IMPROVE filters and protocols whenever possible.

PM_{10} mass

PM_{10} aerosols were collected using portable filter samplers (PFS). These samplers, designed at UC Davis, run at 2.7 liters per minute and are battery powered to allow their use in remote areas or areas without readily accessible power. Samples were collected on 25 mm Teflon filters and were processed for mass, absorption coefficient (b_{abs}), and elemental composition using standard NPS/IMPROVE protocols(12).

Gravimetric analysis of samples requires that the collected or differential mass be determined through two weighings. Teflon filters were assigned a unique identification, pre-weighed, post-weighed, analyzed and archived. The two weighing operations were identical and referred to as PRE and POST. Laboratory and field controls were utilized to determine mass artifact in the same manner. The measurements were made on a Cahn-28 micro-electrobalance having a precision of ± 2μg.

Field blanks were sent out to each sampling site. Field blanks followed the complete analysis path of a normal sample, except no air was pulled through the filter. Their purpose was to quantify the effect of transport and storage on filter mass.

Aerosol Composition

The Teflon filters were non-destructively analyzed for all elements from sodium to uranium by Particle Induced X-ray Emission (PIXE) and X-ray Fluorescence (XRF). The two methods are similar, differing primarily in the range of elements that provides the best sensitivity.

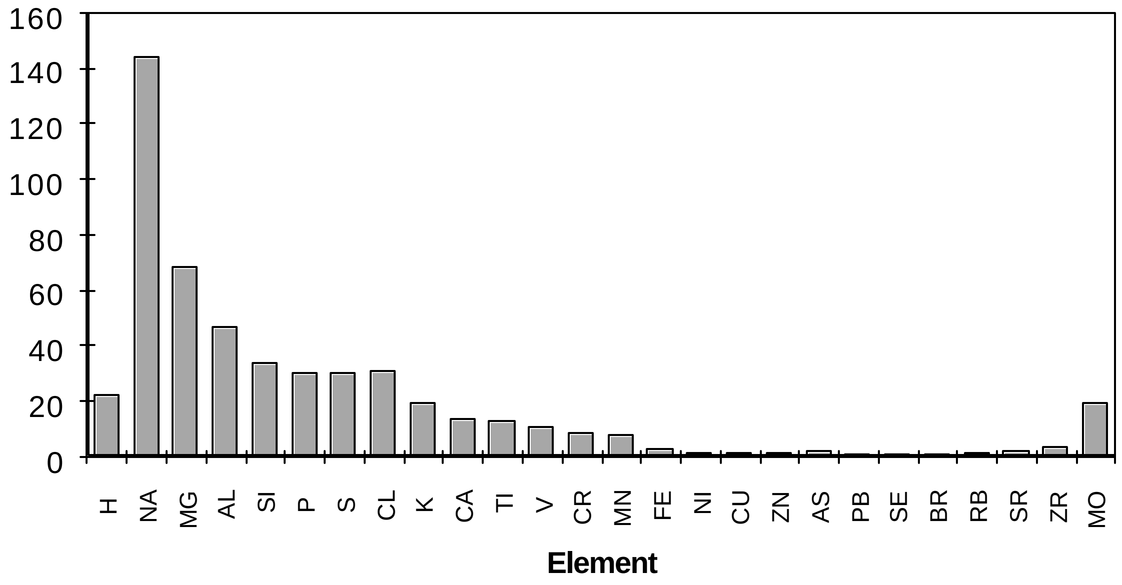
In the Air Quality Group they are used together to provide high sensitivity for elemental composition while minimizing analysis time and expense.

The protocol for the normal UCD analysis is to use PIXE for the lighter elements (below Fe) and for overall normalization, and XRF for the elements Fe to Pb. The samples are first analyzed by XRF (x-ray florescence) to acquire concentrations for the elements Fe to Pb. Next, the filters are analyzed with the PIXE/PESA system for H and Na to Pb. In both XRF and PIXE, energy is used to excite the aerosol deposit causing it to emit x-rays. The XRF system uses molybdenum x-rays to excite the deposit while PIXE uses high energy (4.5 MeV) protons. The energies of the emitted x-rays are element specific, and the number of x-rays of a particular energy provides a measurement of the amount of that element in the deposit. Comparisons of concentrations derived for elements analyzed in both systems is part of the quality assurance protocol.

The PESA method was developed by the Air Quality Group in 1984 to determine the hydrogen content of the NPS network samples. The method is simple, sensitive, and accurate (as well as adding almost no additional cost). By placing a proton detector at a 30° forward angle, the same proton beam used for PIXE is able to measure the concentration of hydrogen with minimum detectable limits similar to those for PIXE, approximately 10 ng/m^3. Since Teflon filters contain very low concentrations of hydrogen, the measured value is due solely to the hydrogen in the collected aerosol. This hydrogen is correlated with organics, sulfates, and nitrates, depending on the ambient conditions. In the western United States, the correlations are generally good.

The minimum detectable limits (mdl) for the complete elemental analysis (XRF, PIXE, and PESA) are shown in Figure 5. The values for Fe and above are from XRF. H is from PESA, and Na through Mn are from PIXE. The mdl's for Ni to Sr are all below 0.1 ng/m^3, with As and Se at 0.3 ng/m^3.

Figure 5: Minimum Detectable Limits (ng/m^3) for elemental analysis of Caltrans PM-10 samples



Using the elemental concentrations provided by the analysis we can reconstruct soil, organics, smoke, elemental carbon, and marine components of the aerosol with a reasonable degree of certainty. Other components, such as debris from tire wear, brake linings, decaying car bodies, diesel trucks, etc., may be reconstructed if these sources provide distinctive elements, or ratios of elements, to use as tracers.

Elemental Carbon

Integrated plate method

Optical Absorption is measured using our LIPM (Laser Integrating Plate Method), system, which takes pre- and post-sample measurements of the optical transmission of each filter. From our measurements of transmission, we can determine b_{abs}, the coefficient of absorption for each sample. From the coefficient of absorption, we can estimate the amount of light absorbing, or elemental, carbon in the sample.

To convert the coefficient of absorption (b_{abs}) to concentration of light-absorbing carbon, the coefficient must be divided by the absorption efficiency of the particles. A factor of 10 m^2/g is recommended on the basis of measurements of elemental carbon particles, primarily diesel emissions. Thus, a b_{abs} coefficient in 10^{-8} m^{-1} is numerically equal to an elemental or light-absorbing carbon concentration in ng/m^3. Comparisons between the integrating plate system and an integrating sphere system verify that the LIPM system accurately determines the absorption for the filter. However, because of shielding by other particles, this is less than the atmospheric coefficient. An empirical equation has been derived which corrects for the shielding effect using the areal density of all particles on the filter. The reported b_{abs} and the precision include this correction factor. Collocated samplers with differing collection areas verify that the expression is reasonable.

Aethelometer

Two aethelometers were used in the I-80 study to measure the concentrations of black carbon (elemental carbon from combustion processes) in the atmosphere. One sampler was sited upwind of Interstate 80 and was collocated with the two-meter meteorological and PM_{10} samplers. The other sampler was downwind of Interstate 80 at the Downwind 2 site and was collocated with the two-meter meteorological and PM_{10} samplers. The aethelometers allow real time, high resolution measurements of soot, which are not possible with the long-term averaging of our filter samplers.

Both aethelometers were run whenever PM_{10} sampling occurred. Unfortunately, the upwind sampler developed a malfunction that damaged all but one of the days of data. It is possible that the elevated temperature at the site was part of the reason for the malfunction, though unstable power may also have played a role. On the day when both aethelometers were functional, the lowest thirty percent of the measurements at the downwind site closely approximated the upwind values. The upwind background concentrations were reconstructed from the downwind measurements using this relationship. For the remaining four days of sampling, the lowest thirty percent of the downwind values is assumed to represent the background (upwind) level.

Further studies of aethelometer data and its correlation with b_{abs} numbers are currently underway.

Results

I-80 west of Davis, July 14-21, 1994

The PM_{10} mass and b_{abs} data collected on Interstate 80 are shown in Figure 6. Figure 6 suggests there is little impact on PM_{10} downwind of the freeway except for the 2m height on the tower at the downwind site. Field personnel observed dust emissions from the unpaved shoulder of the frontage road by passing cars, so this data point may be suspect. However, the b_{abs} values, representing elemental carbon, were high at this sampler, suggesting the influence of freeway vehicles on concentrations. Because of these conflicting results, we have calculated the emission factors from Interstate 80 using two different methods.

For Method 1, we noted that the b_{abs} values at the near downwind site were similar to the downwind site, suggesting that both the near downwind and the downwind site were similarly affected by the freeway. At the far downwind site, 70 meters from the freeway, the measured b_{abs} concentrations approached the upwind values. Sulfur, chlorine, calcium, chromium, zinc, and bromine also had concentration profiles resembling the b_{abs} profile. Based on this analysis, the measurements from the 2m height at the near downwind and the downwind sites were averaged to obtain the freeway addition to the upwind values.

For Method 2, we noted that the 2m downwind site may have been unduly influenced by occasional traffic on the frontage road. The soil components at this sampler were, in fact, higher than at the near downwind site. We averaged the 2m and 4m upwind measurements to obtain an average upwind concentration, then averaged the near downwind measurement (2m) and the 2m and 4m downwind measurements to obtain an average downwind concentration.

Table 5 shows the upwind and downwind concentrations, as plotted in Figure 6, for PM_{10} and b_{abs} at Interstate 80. The estimate of mass gain due to I-80 by either Method 1 or Method 2 is 5.3 $\mu g/m^3$; about 10% of the ~50 $\mu g/m^3$ upwind or background PM_{10} mass. The b_{abs} gain is about 33×10^{-6} m^{-1} by Method 1 or 31×10^{-6} m^{-1} by Method 2, nearly double the background b_{abs} measured at the upwind site.

Figure 6. **Mass concentration and optical absorption for PM_{10} samples collected on a transect across Interstate 80.**

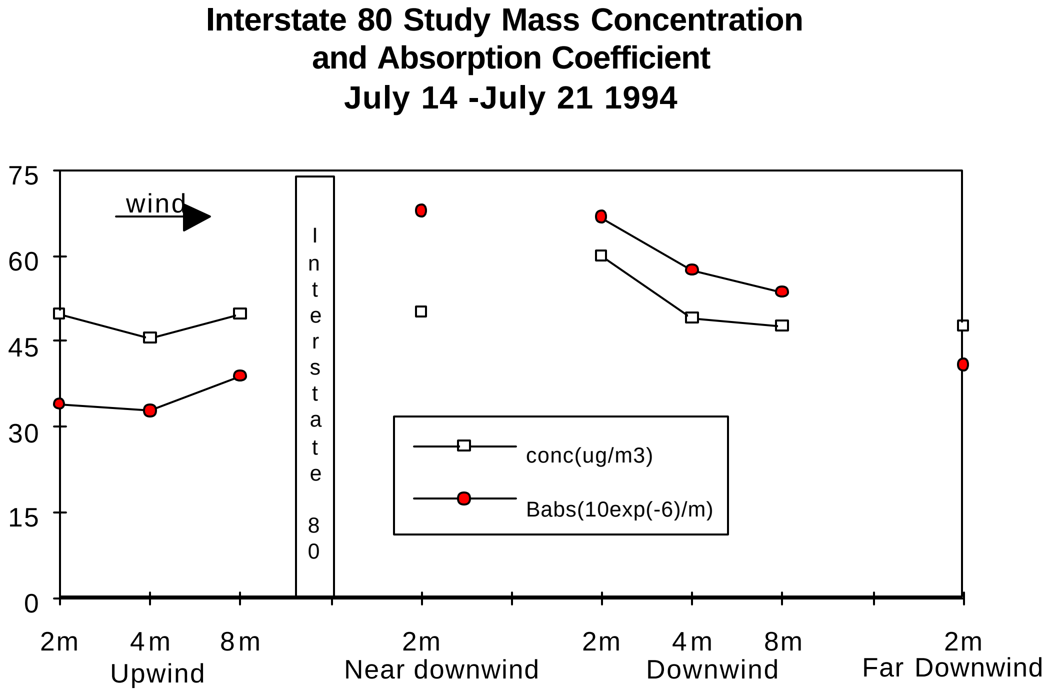


Table 5. **Average Mass and b_{abs} data from Interstate 80 study, July 1994**

	Average PM_{10} Mass (µg/m3)	b_{abs} (10^{-6} m^{-1})
Upwind 2m	49.7	33.9
Upwind 4m	45.6	32.7
Upwind 8m	49.6	38.8
Near downwind	50.1	67.6
Downwind 2m	59.8	66.6
Downwind 4m	49.0	57.4
Downwind 8m	47.6	53.5
Far downwind	47.7	40.8

Florin Road and the Florin/Stockton intersection, July 1994

The site at Florin Road was chosen to represent a surface street with free-flowing traffic. Unfortunately, the PM_{10} measurements at this site were inconclusive. At the 2m height, there was a decrease in mass from upwind to downwind; there was an increase at the 4m height. The average of the two heights gave an increase in mass across the road. At the 4m height, and by averaging the two heights, there was a greater mass difference between upwind and downwind samples at Florin Road than at the I-80 site. This was also the case at the intersection of Florin Road and Stockton Boulevard.

The mass measurements at Florin Road and at the intersection are questionable. Normally, we can reconstruct 70-90% of the measured mass by adjusting the measured elemental concentrations to account for oxides and other unmeasured chemical compounds. At Interstate 80, the reconstructed mass, when multiplied by 1.33, represented all of the measured mass. At the Florin and Stockton sites, however, this procedure accounted for only 40-80% of the measured mass. We have reweighed the filters and reanalyzed them for elemental components, with the same results as originally obtained. This indicates there is either a systematic error in the mass measurements, or there is an unmeasured component to the PM_{10} at the Florin Road and Stockton Boulevard sites. We will present both the gravimetric mass results and the reconstructed mass results in our analysis.

The difference in gravimetric mass concentrations across Florin Road was approximately 7.4 $\mu g/m^3$ (by averaging the 2m and 4m heights). This is significantly greater than that seen at I-80, especially since I-80 had twice the traffic flow (5,000 vehicles per hour) as Florin Road (2,700 vehicles per hour) during this 8 hr test. The reconstructed mass gave an increase of 4.3 $\mu g/m^3$.

The gravimetric mass measured diagonally across the intersection of Florin Road and Stockton Boulevard showed a mass increase of 82.7 $\mu g/m^3$. The reconstructed mass increase at this location was 16.5 $\mu g/m^3$. This intersection was chosen, like the Florin Road site, for lack of obstructing buildings close to the intersection as well as for high traffic volume with accelerations and decelerations. Approximately 39,091 vehicles passed through this intersection in 8 hours and 20 minutes of sampling on July 7, 1994.

Optical absorption/elemental carbon

The optical absorption measured from the filters is shown in Table 6 for I-80 and in Table 7 for the arterial streets. Optical absorption measured from the filters shows a clear enhancement across I-80, with elemental carbon almost doubling across the highway (Figure 6). In addition, the filters downwind of the freeway had a black color, as opposed to the brown color upwind of the freeway that is characteristic of soils and biomass burning.

Compositional analysis

The compositional analysis of these samples is shown in Table 6 for I-80 and in Table 7 for the arterial streets. These tables also restate some of the mass data with slightly different averaging conditions to match the compositional data.

Table 6. I-80 study aerosol composition and comparisons

Site	PM-10 components-derived species (ug/m3)							PM-10 ratio	Trace elements (ng/m3)	
	PM-10 mass gravimetric	PM-10 mass reconstructed	sulfates (NH4)2SO4	Organics	Soils	Other	Soot	reconstructed /gravimetric	Cu	Zn
Method 1										
Upwind	49.7	50.8	2.3	10.9	22.6	1.6	0.9	1.02	0.002	0.013
Downwind	54.9	57.9	2.7	10.4	24.9	1.8	4.0	1.05	0.005	0.020
Difference	5.22	7.18	0.37	-0.51	2.30	0.19	3.1	0.03	0.003	0.007
Uncertainty	1.5	1								
% difference	10%	14%	16%	-5%	10%	12%	335%		142%	57%
Method 2										
Upwind	47.7	50.8	2.3	10.9	22.6	1.6	0.9	1.07	0.002	0.013
Downwind	53.0	55.2	2.7	10.1	23.4	1.7	3.8	1.04	0.005	0.019
Difference	5.30	4.48	0.39	-0.86	0.85	0.10	2.9	-0.02	0.003	0.006
Uncertainty	1.5	1								
% difference	11%	9%	17%	-8%	4%	6%	317%		137%	46%
All heights										
All Upwind	48.3	50.9	2.4	10.1	23.3	0.8	1.0	1.05	0.002	0.010
All Downwind	50.8	51.9	2.6	9.6	22.0	0.8	3.3	1.02	0.006	0.017
Difference	2.53	0.96	0.16	-0.56	-1.29	0.04	2.3	-0.03	0.004	0.007
Uncertainty	2.2	1								
% difference	5%	2%	7%	-6%	-6%	5%	247%		193%	74%

The I-80 results in Table 6 show slight enhancement of PM_{10} mass due to the freeway. They also show a doubling of optical absorption. This measurement is correlated to elemental carbon and is used as a tracer of diesel exhaust and oil burning vehicles. From Table 6, zinc, a tracer of tire wear, and copper also show substantial enhancement across the freeway. The mass contributions of both are small, and consistent with the very small mass gain across I-80. In summary, the impact of Interstate-80 on PM-10 was low, no more than 5% ± 4% of the existing background aerosol.

Table 7 shows the compositional analysis for Florin Road, and the intersection of Florin Road and Stockton Boulevard. Again, Florin Road showed only modest influence over any parameter, with the largest impact being soil. On the other hand, the intersection had significant impacts for gravimetric mass, reconstructed mass, soot, organic matter, copper and zinc. These last four are clearly tied to vehicular "tail pipe" emissions.

Emission Rates

Table 8 shows the emission rates for PM_{10} and its elemental components. For comparison, the rates measured at the Van Nuys Tunnel (Ingalls, et al., 1989) during the Southern California Air Quality Study in 1987 and at the Tuscarora Tunnel in 1977 (Pierson and

Brachaczek, 1983) are also shown. The PM$_{10}$ emission rate was approximately 0.02 g/VKT on Interstate 80, and was 0.26-1.29 g/VKT at Florin Road and Stockton Boulevard, depending on whether the reconstructed mass or gravimetric mass is used.

Table 7. Sacramento arterial streets study aerosol composition and comparisons.

Site		PM-10 components-derived species (ug/m3)						PM-10 Ratio	Trace elements (ng/m3)	
	PM-10 mass gravimetric	PM-10 mass reconstructed	sulfates (NH4)2SO4	Organics	Soils	Other	Soot	reconstruced /gravimetric	Cu	Zn
Florin Road										
2m height only										
Upwind	67.7	47.3	3.6	13.4	13.7	1.3	2.1	0.70	10.5	55.0
Downwind	75.0	51.4	3.8	12.1	18.0	1.4	2.2	0.69	19.6	60.8
Difference	7.3	4.1	0.1	-1.3	4.3	0.1	0.1	0.57	9.1	5.8
Uncertainty	4.3	2.1								
% difference	11%	9%	4%	-10%	31%	5%	4%		86%	10%
Florin/Stockton										
2m & 4m average										
Upwind	68.1	41.9	3.2	11.7	13.8	0.8	1.4	0.62	10.4	26.9
Downwind	150.8	58.4	3.6	17.0	14.4	0.9	7.4	0.39	30.8	71.8
Difference	82.7	16.5	0.4	5.3	0.6	0.1	6.0	0.20	20.5	44.9
Uncertainty	5.0	2.1								
% difference	121%	39%	13%	46%	4%	10%	442%		197%	167%

The elemental components do not compare exactly with the Van Nuys or Tuscarora Tunnels, nor do the two tunnels compare exactly with each other. The Tuscarora Tunnel study was conducted in 1977, and the particle size upper limit varied from 5.5 µm to ~40 µm. The fuel in use in 1977 contained much more sulfur and lead, as can be seen in the emission rates of these elements.

The EPA-recommended method to calculate emission rates from paved roads is given in AP-42, "Compilation of Air Pollutant Emission Factors." AP-42 is currently undergoing revision, and a new emission factor equation for paved roads will be recommended. We have calculated PM$_{10}$ emission rates using both the old equation and the new equation. The old equation for PM$_{10}$ from urban paved roads is:

$$E = 2.28 \times (sL/0.5)^{0.8}$$

where sL is the silt loading in g/m^2 on the road surface. The new AP-42 equation is:

$$E = 4.6 \times (sL/2)^{0.65} \times (W/3)^{1.5}$$

where sL is the silt loading and W is the average vehicle weight in Tons.

AP-42 recommends measuring the silt loading at the site of interest, as they vary by site and time of year. If it is not possible to measure the silt loading, AP-42 recommends estimating it from tables of measured values. We examined the tables and selected a range of measured values from roadways with characteristics closely matching Interstate 80 and the Florin/Stockton area during summer months. For I-80, we used silt loadings of 0.011-0.034 g/m^2, as measured on I-80 in Utah in April, 1990. This is on the low end of the range given in AP-42 for high ADT roads. For Florin Road and Stockton Boulevard, we used silt loadings of 0.9-3.8 g/m^2. For the new equation, we used average vehicle weight of 1.5-2.5 Tons to bracket the emission rates.

Table 8. Measured Emission Rates in mg/VKT for Interstate 80, Florin Road, and the Florin Road/Stockton Boulevard Intersection.

Species	I-80 Method 1	I-80 Method 2	Florin	Florin/ Stockton	Van Nuys Tunnel	Tuscarora Tunnel
Reconstructed Mass	25	24	19	259		
Gravimetric Mass	18	18	34	1,295		
Ammonium Sulfate	1.3	1.2	0.62	4.7		
Soil	8.0	1.4	19.7	6.4		
Soot	10.6	10.4	0.40	66.1		
H	-0.05	0.04	-0.41	4.56		
NA	0.33	0.41	0.95	1.36		
MG	0.32	-0.09	-0.12	1.49	0.31	1.68
AL	0.56	-0.02	1.37	1.42	0.85	1.43
SI	1.65	-0.13	3.03	-1.10	2.49	2.49
P	0.00	0.00	0.00	0.00	0.11	0.24
S	0.31	0.29	0.15	1.15	0.41	3.92
CL	0.14	0.13	-0.23	-0.52	0.11	0.40
K	0.14	0.00	0.21	-0.68	0.37	0.30
CA	0.79	0.56	0.32	0.82	0.99	1.99
TI	0.05	0.00	0.23	0.23	0.14	0.23
V	0.04	0.02	-0.08	0.21		
CR	0.06	0.02	0.03	0.76		0.01
MN	0.02	0.01	0.00	0.26	0.07	0.11
FE	0.51	0.36	0.00	1.74	3.39	0.93
NI	0.00	0.00	-0.01	0.00		
CU	0.01	0.01	0.04	0.23	0.33	0.07
ZN	0.03	0.03	0.03	0.50	0.30	0.22
AS	0.00	0.00	0.00	0.00		
PB	0.01	0.01	0.02	0.01	<3.66	12.31

Table 9 shows the calculated emission factors using AP-42 and the estimates of silt loading and vehicle weight discussed above. For comparison, the measured emission rates are also shown. At the Florin/Stockton site, the emission rates calculated by AP-42 (new equation) agree within a factor of four with the measured gravimetric results, but are higher than the reconstructed mass emission rates by one to two orders of magnitude. On Interstate 80, the AP-42 rates are also higher, but only by approximately an order of magnitude.

Table 9. Emission Rates Calculated Using AP-42 Emission Factor Equations and Estimated Silt Loading

Interstate 80 (Measured 18-25 mg/VKT)				
Weight (Tons)	1.5	1.5	2.5	2.5
Silt Loading (g/m2)	0.011	0.034	0.011	0.034
Old Equation (mg/VKT)	108	265	108	265
New Equation (mg/VKT)	55	115	119	248
Florin /Stockton (Measured 260-1300 mg/VKT)				
Weight (Tons)	1.5	1.5	2.5	2.5
Silt Loading (g/m2)	0.9	3.8	0.9	3.8
Old Equation (mg/VKT)	3649	11550	3649	11550
New Equation (mg/VKT)	968	2468	2082	5311

Discussion

Measured versus modeled values

Why do the measured emission factors fall so far below AP-42? We think that the reasons lie in the way the AP-42 results were obtained and the way high speed California highways operate.

The AP-42 values were based on sample collection near midwestern US roadways (although many new measurements have been made in Montana). Most of these sites are subject to a variety of conditions foreign to California, especially the sanding and de-icing of roadways, including the use of road salt. The sand is ground down and often builds up at the road edges, with periodic wetting and/or mobilization onto the road by rainfall. The salt attacks car structures, resulting in erosion of car bodies. Finally, average vehicle speeds near most sites were low, allowing source material to be retained near the paved surface.

California freeways generally are not sanded or salted. With drainage provisions and central crowns, water rarely runs over the road surface during the winter rains. For much of the year, no rain falls at all. The high freeway speeds and presence of trucks sweep the freeways with hurricane-velocity winds several times each minute. The roadway itself is slightly greasy to the touch, with very low surface silt loading. Thus, the only re-suspended soils can come from the roadways' margins, which are usually paved well away from the traffic flow. The major soil sources are located well away from the traffic lanes, allowing them to stabilize, often with vegetation. Finally, the strict California emission tests and inspections aid in reducing particles from the vehicles themselves. Other factors may be operating as well, e.g. less rapid deterioration of the exhaust system, but these results of California tests, from 1973 through 1994, indicate that freeways are not a major source of PM_{10} particles.

At the Florin-Stockton area, some of the factors above do not apply. There are paved curbs and no peripheral vegetation. This allows soils to be trapped near the roadway. The traffic is generally low speed, with a much smaller number of large trucks; thus vehicular winds are reduced. Control of surface water is less certain, and irrigation water occasionally becomes involved with road-edge soils. At the intersection, stop-and-go traffic implies rapid acceleration of cars and ejection through the tailpipe of combustion materials and corrosive products from the exhaust train. Thus, the intersection, and to some extent the arterial streets between intersections, are sources of primary and resuspended PM_{10}.

Additional data from the City of Davis studies

PM_{10} transects were measured across Davis from fields west of the city into the downtown area as part of a study with the City of Davis and the UC Davis Atmospheric Sciences 124 class and laboratory. The results are shown in Table 10. The results of December 23, 1993, are especially interesting, since there was very heavy traffic near the sampling site at Third and F Street (all stop-and-go) during the entire sampling period. Traffic estimates were roughly 18,000 vehicles in the 24 hour period. The sampling site was 120 feet from the Davis intersection, downwind during the heaviest traffic periods. Other streets with almost equal traffic were close in all directions. Winds were light and a strong inversion was present each night.

Table 10. Aerosol composition for the City of Davis study, winter 1993

Sampling location	PM10 mass	Sulfates (NH4)2SO4	Organics	Soils	BABS	CU	ZN
Evapotranspiration site (West of Highway 113 in agricultural area)	44.37	2.63	19.86	0.91	3.99	0.00	0.01
Mann Laboratory sign, UCD	50.80	3.17	18.24	1.14	4.44	0.00	0.01
Central Park near market pavilion	46.16	3.26	22.82	1.32	5.00	0.00	0.01
Police Station flag pole (3rd & F)	45.21	3.18	22.06	1.35	4.88	0.00	0.01
Chestnut Park backstop	45.28	3.45	22.95	1.52	4.36	0.00	0.01

Despite all these factors, PM_{10} was enhanced little, if at all, at this intersection. Thus, the downtown Davis study shows that vehicles do not play a large role in PM_{10} concentrations. It must be noted that speed limits in central Davis are 25 mph, so that re-entrainment may also be diminished in comparison to the Stockton-Florin site, and that large trucks are not prevalent in the area.

Implications

The data collected in this study imply that the freeway site with smoothly-flowing traffic does not significantly increase downwind PM_{10} concentrations. Because there was little surface material on the freeway, little fugitive dust was generated from the Interstate 80 site examined. The percentage increase of tailpipe emissions was high, but the actual amount of increased tailpipe PM_{10} concentrations was low. The increased ambient concentrations observed from the Interstate 80 study are so low relative to the 24-hour federal or state standards that it is extremely unlikely that PM_{10} "hotspots" will be associated with projects that improve level of service on freeways. We expect, however, that congested freeways with stop-and-go traffic would generate higher levels of tailpipe PM_{10} emissions.

The Florin Road site generated more fugitive dust than the freeway, probably due to higher levels of surface material on the roads. It also generated more tailpipe emissions, especially at the intersection. It is conceivable that a PM-10 "hotspot" leading to an exceedance of the State standard could occur at the intersection, though it is unlikely that an exceedance of the 24-hour federal standard would occur during the summer months when there are diurnal shifts in wind direction.

The Florin-Stockton intersection was a preliminary study to test the experimental protocol and was intended to be repeated at a later date. We recommend that the experiment be repeated in both the summer and winter (poor ventilation) seasons. The experiments should include measurement of the silt loading on the street to determine if the PART5 model (based on AP-42) will provide reasonable re-entrained dust estimates. Furthermore, efforts to identify the unexplained mass (the difference between the gravimetric and reconstructed mass) should be a goal of the study. It may be that semi-volatile and non-volatile organics are associated with the direct particulate emissions at that location.

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Appendix B "Effect of Roadbed Configuration on Traffic Derived Aerosols", P.J. Feeney, T.A. Cahill, R.G. Flocchini, R.A. Eldred, D.J. Shadoan, and T. Dunn, (*J. Air Pollution Control Association*) 25, 1145-1147 (1975).

Appendix A Data on Traffic Flow and Meteorology, July, 1994

Stockton Boulevard and Florin Road Traffic Flow

Average hourly traffic counts, July 7, 1994

	9:00 AM	10:00 AM	11:00 AM	12:00 PM	1:00 PM	2:00 PM	3:00 PM	4:00 PM	5:00 PM
Florin Road	1890	2262	2460	2598	2394	2334	2604	3048	2814
Stockton Boulevard				1968	1920	1710	1854	1782	1884

Total traffic during sampling

Florin Road	22404
Stockton Boulevard	16677

Interstate 80 Study Traffic Flow

Average traffic during sampling periods

	7/15/94	7/16/94	7/19/94	7/20/94	7/21/94
westbound	10388	7161	5378	8922	5373
eastbound	10563	7362	5082	9135	5117

Total traffic during sampling

westbound	37222
eastbound	37259

Stockton Boulevard and Florin Road Mean Wind Speed and Direction

Date	7/7/94
Sampling time	8:00 to 18:40
Mean wind speed	3.2 mph
Mean wind direction	216 degrees

Interstate 80 Mean Wind Speed and Direction

Date	7/15/94	7/16/94	7/19/94	7/20/94	7/21/94
Sampling time	11:03 to 14:53	10:54 to 12:59	12:50 to 14:50	12:46 to 16:05	12:10 to 14:10
Mean wind speed	4.5mph	2.6mph	4 mph	4.2 mph	5 mph
Mean wind direction	148 degrees	166 degrees	182 degrees	141 degrees	178 degrees
Mean Temperature	91 degrees	83 degrees	86 degrees	85 degrees	81 degrees

Appendix B

Effect of Roadbed Configuration on Traffic Derived Aerosols

P. J. Feeney, T. A. Cahill, R. G. Flocchini
R. A. Eldred, D. J. Shadoan, and T. Dunn
University of California, Davis

Aerosols present upwind and downwind of freeways in the Los Angeles Basin were collected in five particle size ranges by Lundgren impactors with after filters and analyzed for elemental content by ion-excited x-ray emission. The contribution of freeway traffic to total airborne particulate load was obtained by subtracting the local background, measured by an upwind sampler, from the values obtained by downwind samplers on a size by size, element by element basis. This contribution correlated reasonably well with estimates derived from automotive and roadbed expendable rates. Traffic-derived aerosols, normalized to vehicular flow, were considerably lower in mass downwind of depressed roadbed configurations than either at grade or raised configurations. A line source model, combined with literature values for emitted lead, produced good agreement with results obtained in the at grade configuration.

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The contributions of traffic to particulate matter in near roadway locations assume considerable importance in situations involving large numbers of vehicles. In order to examine this problem, the California Air Resources Board initiated a study through the University of California, Davis, of particulate matter in near roadway areas.[1] The two main thrusts involved the correlation of particulate matter with automotive and roadbed expendables, and the examination of particulate dispersal patterns as a function of weather, traffic and roadbed configurations.

Particulate matter was collected using up to 6 Lundgren rotary drum impactors with after filters.* Particles were separated into effective diameters ($\rho = 1$) of ~100 to 17 μm, 17 to 5 μm, 5 to 2 μm, 2 to 0.6 μm, and 0.6 to 0.1 μm, and collected respectively on 4 paraffin-coated mylar strips, and a Whatman 41 after filter. Collection efficiency was verified by comparisons with Hi-volume and filter sampling, while particle sizing was established by uranine dye studies, studies of bounce-off versus paraffin coating, and scanning electron microscope pictures of the first four stages. Losses of particles below 17 μm were established as being less than 15%.

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* Purchased from Environmental Research Corporation, St. Paul, MN

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Appendix B

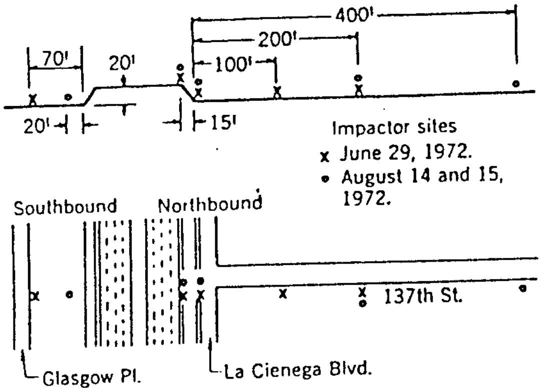

Figure 1. Site number 4 (SD). San Diego Freeway near 137th Street. 6/29/72 and 8/14–15/72.

Samplers were placed in arrays at locations along the instrumented "42 mi freeway loop" in the Los Angeles basin, generally at sites selected by the California Division of Highways in its ongoing study of freeways. Sites were selected to illustrate major roadbed configurations and alignments with prevailing summer winds. The sites, configurations, and approximate wind alignments were as follows: Site 1, Santa Monica Freeway at 4th Street, a 10 meter cut section with parallel winds; Site 2, Harbor Freeway at 146th Street, a 10 m cut section with transverse winds; Site 3, San Diego Freeway near the Harbor Freeway intersection, an at grade freeway with transverse winds; Site 4, (Figure 1) San Diego Freeway at 137th Street, a 5 m fill section freeway with transverse winds. Neighborhoods were residential with largely single family residences, including mature trees, for Sites 1, 2, and 4, while Site 3 was mostly an open field. Samplers were located 1 m above the ground, as far from obstructions as possible, and faced into the prevailing wind. This orientation, checked every 30 min, provided quasi-isokinetic sampling at wind velocities between 1 and 2 m/sec. Samplers were located upwind of the freeway and at locations downwind from close to the roadbed to ~160 m from the median strip. Sampling took place during nine 24 hr days between March and August, 1972; Site 1, 3/22 → 3/24 and 6/27; Site 2, 6/28; Site 3, 8/16 → 8/17; Site 4, 6/29 and 8/14 → 8/15. Weather data were obtained from local sources, the Division of Highways on freeway stations, and hand held velocity and direction instrumentation. Traffic flow and velocity data were supplied by the Division of Highways, while traffic mix (and occasional flow) counts were made by staff personnel. Traffic flows of up to 17,000 vehicles/hr were encountered, while daily averages of 200,000 to 250,000 vehicles were common. Truck traffic was a small percentage at almost all times.

All samples were processed at Davis by being separated into 2 hr segments and analyzed for all elements heavier than sodium by ion-excited x-ray analysis (IXA).[2-5] Detectable limits for the stages were around 10 nanograms/m^3 of air for most elements, but cadmium region elements and rare earths were much worse, ranging in the hundreds of nanograms/m^3 of air, as were results from the filters. Due to the choice of filter material (Whatman 41) and analytical technique (x-rays), elements lighter than potassium were not available from the after filters. About 6000 analyses were made during this program, including some x-ray fluorescence and ESCA measurements, the latter done at the Lawrence Berkeley Laboratory (T. Novakov). Accuracy of the method was established through use of 36 gravimetrically measured elemental standards. It was verified by 8 interlaboratory and intermethod comparisons, including 10 hi-vol samples taken on fiberglass at Site 3 during our sampling regime and analyzed for lead by atomic absorption in the Division of Highways' laboratories and by IXA at Davis.[1]

The contribution of traffic to particulate matter was obtained by subtracting upwind values from downwind values, element by element, size by size, during each 2 hr period when upwind and downwind had a clear meaning, or when calm periods enormously enhanced the traffic's dominance over the relatively low background values at the sites near the ocean (3 and 4) (Table I).

Particulate matter seen near the roadways correlated reasonably well with elemental content and use rates of expendables associated with traffic (fuel, tires, roadbed wear, and exhaust train erosion providing most of the particulate mass).[6] Some fine sulfur particulates were seen in association with traffic, which were tentatively identified as originating in gasoline, or, possibly motor oil combustion. The most unambiguous traffic tracer proved to be, as expected, lead in correlation with bromine, mostly in the $<5\ \mu m$ size range. The Br/Pb ratio was 0.33 ± 0.03, close to the value for PbBrCl of 0.355.

The second part of the program, involving an investigation of dispersal patterns from highways, was accomplished by examining the levels of lead and bromine downwind of highway sections. Several 2 hr periods were identified during which the wind had a mean velocity greater than 1 m/sec and was aligned either transverse to or parallel to the highway alignment within ±45°. Lead and bromine values from locations up to 160 m from the highway median were collected, normalized to traffic flow, and separated into two size ranges, $< 5\ \mu m$ or $>5\ \mu m$. An example of one of the 2 hr plots is shown in Figure 2. Upwind values were then subtracted, and all data collected within a given 2 day sampling period that met the meteorological conditions were averaged together. These data are displayed in Table II for the size fraction below 5 μm. While error flags are not included in the table, analyses of variability within a given sampling period for each 2 hr increment indicate a standard error of about ±20% in the result.

Table I. Relative elemental composition of freeway associated particulates.

	$D_p < 5\mu m$ (80%)	$D_p > 5\mu m$ (20%)	Weighted average
Al	N.A.	0.29	N.A.
Si	N.A.	1.32	N.A.
P	N.A.	<0.006	N.A.
S	N.A.	<0.016	N.A.
Cl	N.A.	0.11	N.A.
K	0.004	0.019	0.007
Ca	0.03	0.48	0.12
Fe	0.05	0.76	0.19
Cu	0.003	0.014	0.005
Zn	0.013	0.08	0.024
Br	0.33	0.19	0.30
Pb	1.000	1.000	1.00

N.A. – No quantitative data available due to the choice of filter substrate. Observed amounts of these elements were in all cases minor.