MEASUREMENTS OF PM_{10} AND $PM_{2.5}$ EMISSION FACTORS FROM PAVED ROADS IN CALIFORNIA

Final Report
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1001 I Street
Sacramento, CA 95812

Prepared by:

Dennis R. Fitz
Center for Environmental Research and Technology
College of Engineering
University of California
Riverside, CA 92521
(909) 781-5781
(909) 781-5790 fax

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DISCLAIMER

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We wish to thank the many staff members of CE-CERT who contributed this study. These include Kurt Bumiller, John Collins, Matthew Smith, and Charles Bufalino.

ABSTRACT

The emission factors of PM_{10} and $PM_{2.5}$ (particulate matter less than 10 and 2.5 μm aerodynamic diameter, respectively) for vehicles operated on paved roads in California were characterized by a three-way approach. The primary PM measurement device was a Thermo Systems Inc. DustTrak, a fast-response instrument based on light scattering. These instruments were calibrated against PM concentrations determined from filter collection followed by mass weighing.

The first approach was a long-term upwind-downwind program measuring PM concentrations on both sides of an arterial road. Despite collecting two months of data and focusing only on periods when the wind was perpendicular to the roadway, the downwind PM_{10} concentrations were only slightly greater, on the average, than those upwind. No attempt was made to measure $PM_{2.5}$ concentrations since the concentration difference would be expected to be even smaller. Likewise, further analysis of the data and application of dispersion models would not likely produce emission factors with high confidence levels.

In the second approach, we measured PM concentrations directly in a vehicle's wake using an instrumented vehicle with a trailer. Although the measurements were somewhat erratic, the concentration differences between the front and rear of the vehicle were generally significant. Emission factors were calculated assuming that the vehicle swept out a volume based on the frontal area of the vehicle and that the PM measurements in the "plume" behind the vehicle were representative of the mean concentrations within the wake. Measurements were made on all types of road types. There was not a great amount of difference in emission rates between local, collector, arterial and freeway roads. The rates ranged from 0.064 g/VKT (0.000230 lbs./VMT) for a collector road to 0.129 g/VKT (0.000465 lbs./VMT) for an arterial road. These are on the low end of measurements that have previously been made based on the less precise upwind-downwind approach and significantly lower than the AP-42 factors based on default silt loadings. By comparison, the ARB uses emission factors ranging from 0.000574 lbs./VMT to 0.003479 lbs./VMT. The real-time measurements allowed determination of emission factors as a function of the vehicle's speed. These relationships were similar to those reported using a DustTrak sampling within the wheel well of a vehicle.

The final approach determined the effect of trackout, an upset condition where soil was directly deposited on the road's surface. While these conditions caused a temporary rise in PM_{10} concentrations, the rise was not greatly different than that due to the roadway without trackout applied. While no attempt was made to quantify emission factors caused by this upset condition, the results of this study allowed a number of recommendations that would aid quantification in future studies.

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GLOSSARY

AP-42 .... U.S. EPA guidance document for emission inventory development

ARB or CARB .... California Air Resources Board

Ave……………………………Avenue

Avg……………………………Average

Blvd. .... Boulevard

CE-CERT .... College of Engineering-Center for Environmental Research and Technology, University of California, Riverside

DAS .... Data acquisition system

DT……………………………..DustTrak

L .... Liter

$\mu g/m^3$ .... Micrograms per meter cubed

mph…………………………….Miles per hour

n………………………………..Sample size

OD .... Outside diameter

RH .... Relative humidity

RSD .... Relative standard deviation

SD……………………………..Standard Deviation

SEM…………………………...Standard Error of the Mean

TMP…………………………..Temperature

VKT.. Vehicle kilometers traveled

VMT .... Vehicle miles traveled

VWS…………………………..Vertical wind speed

WD .... Wind direction

WS.. Wind speed

EXECUTIVE SUMMARY

There is a great deal of uncertainty in measuring particulate emissions from fugitive sources such as paved roads. Since urban areas have a great many miles of paved roads compared with other sources, small changes in the emission factors used for inventory development will have a major effect on the proportion of PM in an emission inventory due to these roads.

Currently emission inventories are based on an emission factor equation developed from upwind-downwind measurements, with silt loading of the road being the primary variable. AP-42, the U.S. Environmental Protection Agency (EPA) guidance document for emission inventory development, recommends using the following equation for PM emission factors:

$$E = k(sL/2)^{0.65} (W/3)^{1.5} \text{ g/VKT} \quad (1)$$

where:

E = PM emission factor in the units shown
k = A constant dependant on the aerodynamic size range of PM (1.8 for $PM_{2.5}$; 4.6 for PM_{10})
sL = Road surface silt loading of material smaller than 75 μm in g/m^2
W = mean vehicle weight in tons
VKT = vehicle kilometers traveled

Silt loadings can either be measured on the roadways, or default loadings given in AP-42 can be used. The AP-42 document states that traffic rapidly develops equilibrium silt loading and that new deposits are needed for continued PM production. Therefore, it is difficult to understand the dependency between the silt loading and the PM emission rate.

In many cases the PM inventory from sources of geological origin appear to give much higher concentrations of this material (often a factor of two) than ambient concentration measurements. A number of studies to measure emission rates have been conducted after those used to develop the AP-42 equation to evaluate this seemingly contradictory equation. The results from these studies have shown that the factors calculated from Equation (1) tend to be higher that that measured. In all studies of urban roads the measured concentration differential of PM between upwind and downwind have been very close to the measurement uncertainty. This was less of a problem for the measurements used to develop Equation (1) since most of the roads used were industrial haul roads with PM emissions generally much higher than public roads due to the rate of deposition from the industrial operations. It is not clear whether these industrial roads were suitable surrogates for most public roads.

The objective of this study was to develop a more accurate method of determining the emission rate of particulate matter (PM) from paved roads. Three different techniques were evaluated:

- Upwind-downwind PM measurements using real-time particle sensors.

- Mounting real-time particle sensors on a vehicle to measure PM concentrations immediately in front of and behind a vehicle.

- Evaluating PM emission rates from trackout of crustal material from unpaved to paved areas using a combination of the two above methods.

The real-time PM sensor was a Thermo Systems Inc. DustTrak, a fast-response instrument based on light scattering. The sensor is equipped with impactors to select either a $PM_{2.5}$ or PM_{10} fraction of aerosol. These instruments were calibrated against PM concentrations determined from filter collection followed by mass weighing.

The first approach used was a long-term upwind-downwind program measuring PM concentrations on both sides of an arterial road. Despite collecting two months of data and focusing only on periods when the wind was perpendicular to the roadway, the downwind PM_{10} concentrations were only slightly greater, on the average, than those upwind. No attempt was made to measure $PM_{2.5}$ concentrations since the concentration difference would be expected to be even smaller. Likewise, further analysis of the data and application of dispersion models was likely to produce emission factors with low confidence levels.

In the second approach, the concentration differences between the front and rear of the vehicle were generally significant. Emission factors were calculated assuming that the vehicle swept out a volume based on the frontal area of the vehicle and that the PM measurements in the "plume" behind the vehicle were representative of the mean concentrations within the wake. Measurements were made on all types of road types. There was not a great amount of difference in emission rates between local, collector, arterial and freeway roads. The rates ranged from 0.064 g/VKT (0.000230 lbs./VMT) for a collector to 0.129 g/VKT (0.000465 lbs./VMT) for an arterial road. These are on the low end of measurements that have previously been made based on the less precise upwind-downwind approach and significantly lower than the AP-42 factors based on default silt loadings. By comparison, the ARB uses emission factors ranging from 0.000574 lbs./VMT to 0.003479 lbs./VMT. The real-time measurements allowed determining emission factors as a function of the vehicle's speed. These relationships were similar to those reported using a DustTrak sampling within the wheel well of a vehicle.

The final approach determined the effect of trackout, an upset condition where soil was directly deposited on the road's surface. While these conditions caused a temporary rise in PM_{10} concentrations, the rise was not greatly different from that due to the roadway without trackout applied. While no attempt was made to quantify emission factors caused by this upset condition, the results of this study allowed a number of recommendations that would aid quantification in future studies.

This study has shown that an instrumented vehicle is a viable approach to measuring PM emissions from roads. There are several major advantages:

- The effort required to outfit a vehicle and conduct measurements is small compared to the amount of data obtained.

- Results are available immediately rather than days later as is the case of filter samples that are weighed.

- Entire roads may be surveyed in minutes compared with days of sampling at a single point on a road.

- The difficulty of safely determining silt loading is avoided.

- The concentration differential is much higher than upwind-downwind sampling since the sampling point is immediately behind the source. This results in less measurement uncertainty.

We have shown that the PM_{10} emitted from the paved roads that we tested were significantly lower than those calculated from the AP-42 equation even when measured silt loadings from southern California were used. The result is that paved roads would be responsible for a much smaller fraction of the PM_{10} inventory. The importance of the other sources should therefore be addresses so that cost-effective control technologies can be recommended. A much broader application of this approach could be conducted at modest cost. This would allow a more accurate and robust estimation of the amount of PM_{10} due to paved roads in an entire air basin and the faction of the total amount of geologic PM_{10} for which they may be responsible.

Some additional improvements in the technique are recommended prior to initiating larger-scale measurements. This would involve the development of a useful feedback mechanism to control the flow of the isokinetic sampling probe and the installation of a high-resolution GPS to track the vehicle's movement directly with logging of the measured PM concentration.

1.0 INTRODUCTION AND OBJECTIVES

1.1 Background

Many areas in the State of California consistently exceed both the State and Federal PM_{10} air quality standards, and they are expected to exceed the new $PM_{2.5}$ standards. To formulate effective mitigation approaches, the sources of the PM must be accurately known. Receptor modeling has shown that PM_{10} of geologic origin is often a significant contributor to the concentrations in areas that are in non-attainment (Chow et al., 1992). A significant portion of this geologic material has been estimated to originate from paved roads (Zimmer et al., 1992; Gaffney, 1995). A number of studies have been conducted to determine the contribution of paved roads to measured concentrations of PM_{10} (Venkatram and Fitz, 1998; Ashbaugh et al., 1996; Harding Lawson, 1996; Kantamaneni et al., 1996; Claiborn et al., 1995; U.S. EPA, 1993; Zimmer et al., 1992; Cowherd and Englehart, 1984). These studies used upwind-downwind sampling by filtration to determine the net mass emission due to the roadway.

The studies conducted by Cowherd and co-workers primarily in the Midwest resulted in an empirical expression relating the PM emission rate with the silt loading of the road. This expression was incorporated into the EPA document AP-42 for predicting emission rates and has been widely used all over the country to estimate the fraction of PM_{10} originating from roads:

$$E = k(sL/2)^{0.65} (W/3)^{1.5} \text{ g/VKT} \qquad (1)$$

where:

E = PM emission factor in the units shown
k = A constant dependant on the aerodynamic size range of PM (1.8 for $PM_{2.5}$; 4.6 for PM_{10})
sL = Road surface silt loading of material smaller than 75μm in g/m^2
W = mean vehicle weight in tons
VKT = vehicle kilometer traveled

Equation (1) is an empirical equation derived by measuring the total flux across roadways using a PM_{10} monitoring array and based solely on surface silt loading. The AP-42 states that the sL reaches an equilibrium value without the addition of fresh material. If equilibrium is attained, then the emission rate should go to zero, although this is not what the equation predicts. Therefore, it is difficult to understand how this equation could be universally applicable unless the material is continuously replaced, a phenomenon which for most public roads is not likely.

If the silt loading were decreased by sweeping, PM_{10} emissions would be expected to decrease proportionately. The EPA has estimated that a thorough sweeping program could reduce the emissions from paved roads by approximately one-third (Duncan, 1984). In a study conducted in Reno, NV, however, no relationship was observed between sweeping streets and ambient PM_{10} concentrations (Chow et al., 1990). This lack of relationship could be caused by the emissions created during the sweeping process canceling out the expected benefits. We have recently quantified the emission rates of regenerative sweepers similar to those used in the Reno study and found them to be insignificant compared with the silt removed (Fitz, 1998). Another explanation is that the silt loading is rapidly replaced after sweeping to an equilibrium level dependent on factors such as vehicle speed and density. A third explanation is that the Reno study was not sufficiently sensitive to detect a change.

We previously conducted a study to measure and model the PM_{10} emissions from paved roads in southern California (Venkatram and Fitz, 1998). Emissions were quantified by making filter-based PM_{10} measurement upwind and downwind of several types of paved roads. In most instances, the differences in concentrations were very close or at the measured precision of the measurement method. This resulted in a large amount of error when calculating the emission factors from a modeling approach. Silt measurements were made concurrently for a number of the tests. There was no correlation between silt loading and the estimated emission factors. Silt loadings were generally lower than those suggested as defaults in AP-42. This is not unexpected since many of the roads in southern California do not have a significant source of crustal material to create emissions. The silt loadings are likely to rapidly equilibrate at a low level due to the effective "vacuuming" from the vehicle's wake or motion of the tire. Nicholson and Branson (1990) observed this rapid attainment of equilibrium when particles tagged with a fluorescent dye were deposited on a road and monitored.

As an extension of this program, we performed measurements before and after sweeping the streets (Fitz, 1998). Even on a street that is not routinely swept, there was no significant change in either the PM_{10} emission factor or in the silt loading of the active traffic lane.

Because emissions from a fugitive source cannot be measured directly, they must be inferred This is usually achieved by one of the following methods:

- By estimating the flux of material through a horizontal plane downwind of the source (Cowherd and Englehart, 1984) or

- By fitting a dispersion model to measurements of concentrations and winds (Dyck and Stukel, 1976; McCaldin and Heidel, 1978) made at locations downwind of the source; the emission rate is essentially the parameter that results from this analysis.

In principle, the calculation of horizontal flux can be an accurate method if the sampling density is sufficiently high. In practice, this density is difficult to achieve. The approach also requires measurements of low winds close to the ground where the highest concentrations occur. This is also difficult to do experimentally. To calculate emission factors it is often necessary to make assumptions about the behavior of the concentrations and wind velocities near the ground. For example, Cowherd and Englehart (1984) assumed that the flux at the ground was equal to that at 1m. The validity of this assumption has not been justified. The robustness of the flux measurement depends on good coverage of several downwind locations using profilers. Most studies to date have used only one profiler.

The second method of inferring emissions involves fitting a dispersion model to a small set of concentration measurements. The accuracy of the method depends upon information on wind speed, release height, and vertical plume spread, and a physically realistic dispersion model applicable to surface releases. Some of these parameters must be estimated for emissions due to vehicles. To avoid the problem of the wind speed being zero at the surface, a release height is can be chosen at which the velocity is specified. Independent measurements of emission factors are needed to estimate the uncertainty of this technique.

1.2 Objectives

The primary objective of this project was to make more accurate estimates of $PM_{2.5}$ and PM_{10} emission factors from paved roads. The data collected should allow more accurate estimates than those possible using the AP-42 approach. Specifically, we:

- Characterized $PM_{2.5}$ and PM_{10} emissions from roadways using real-time upwind-downwind measurements.
- Estimated the PM emission rates from an individual vehicle over a wide range of parameters and for various types of roadways.
- Evaluated PM emission characteristics from trackout of crustal material from unpaved to paved areas.

2.0 APPROACH

There were two major differences in our approach compared with previous studies of PM emissions from paved roads. First, we used real-time measurement methods based on optical scattering. While these instruments do not directly measure mass concentration and the response is dependent on the particle-size distribution, their measurements have been found to be highly correlated with those of filter collection/mass determination (White et al., 1994). These instruments are generally more sensitive than mass-based methods and allow for immediate feedback to guide experimental procedures. The instrument we used was the DustTrak model 8520 Aerosol Monitor manufactured by TSI Incorporated (Shoreview, MN). This instrument is battery operated and has a resolution of 1 $\mu g/m^3$ with a time constant of 1 second. It has interchangeable nozzles for either $PM_{2.5}$ or PM_{10} measurements.

The second major difference is that we made measurements directly behind moving vehicles and characterized the emissions under a wide variety of driving conditions. This approach has several advantages. First, the concentrations are expected to be much higher when nearer to the source since the PM would disperse in the process of reaching the a position far enough from the roadway to safely collect a sample. Our observations of vehicles traveling on unpaved roads showed that the plume does not appreciably disperse for several car lengths. In previous studies, others and we have estimated the lower limit emission factor of 0.1g VKT (vehicle kilometer traveled) on high-speed, high-traffic-count paved roads. Using this emission factor, the plume from the wake would have a concentration of 25 $\mu g/m^3$. Given this low plume concentration, ambient background, and subsequent dispersion, it is understandable why downwind PM measurements are typically only several $\mu g/m^3$ higher than upwind.

The second advantage to real time sampling is that dispersion modeling was not needed since the monitoring was done before any significant dispersion occurred. We characterized the PM distribution within the wake of the vehicle and used these data to determine the emission rate in g/VKT by dividing the PM concentration by the wake area. Combining the real-time measurements on a moving vehicle also gave the advantage of being able to rapidly collect data over a wide variety of vehicle operating parameters and road types.

2.1 Upwind-Downwind Real-Time PM Measurements

The purpose of this component of the research was to use the real-time measurements from the DustTrak monitors to measure downwind concentrations of particulate matter from traffic on a moderately traveled two-lane road. The real-time measurements were compared with filter-based measurements. Complete meteorological data were also collected during the sampling period to determine appropriate data analysis intervals**.**

Site Selection

The logistics of finding appropriate upwind and downwind monitoring site was complicated by the need of security and power in addition to an appropriate perpendicular alignment with the prevailing wind. Therefore, we chose to locate our sites on University land. The long-term monitoring program was established on both sides of Iowa Avenue, a two lane arterial roadway

13m wide and located between University Avenue and Martin Luther King Boulevard, an area of UCR property west of the main campus.

Iowa Avenue is a north-south street that travels through the UCR Agricultural Operations area. These are orange groves (tree are 4-6 m high) that are enclosed with cyclone fencing for security. Iowa Avenue has no defined curb; on the east there is a 4.3 m soil buffer between the road and the fence, and on the west there is a 2.5 m buffer. The normal wind pattern is from west to east. The 24-hour traffic count between University Avenue and Martin Luther King Boulevard was reported to be 10,891 in 1997 with a predicted increase of 2% per year (Riverside City Traffic Engineering Division, Riverside, CA). The estimated 24-hour traffic at the time of the project was estimated to be 11,557.

Lead-acid storage batteries were use to power the DustTraks and data logging equipment while generators were located on both sides of the road to deliver power to the pumps used for gravimetric sampling.

PM Measurements

- **Real-Time Measurements**

Previous upwind-downwind filter based measurements made in southern California were not sufficiently precise to accurately determine PM_{10} emission factors. This is likely due to roads in this region being generally cleaner than those used, primarily in the Midwest, to develop the AP-42 model. The use of real-time optical analyzers rather than collecting and weighing filters offered a number of advantages. Unlike the integrated measurements of a filter, the real-time measurements should allow the "puff" of the emission to be measured, resulting in a greater signal for a given noise. This approach was used by Moosmüller et al. (1998) with integrating nephelometers to characterize emissions from unpaved road shoulders. At the same time of the "puff" we could determine the wind speed and direction and determine when the upwind measurement was in the same air mass as the downwind measurement.

Another benefit of the real-time measurement approach also allowed for long-term monitoring with little operator intervention. A DustTrak model 8520 (TSI Inc., Shoreview, MN) was chosen as the real-time monitoring instrument. We have previously used this instrument to measure emissions from street sweepers. It has also been used to measure PM concentrations in the wheel wells of moving vehicles (Kuhns et al., 2001). Inlets for both PM_{10} and $PM_{2.5}$ were used as provided by the manufacturer.

- **Filter Based Measurements**

We calibrated the optically based real-time measurements with mass determinations from filter collection at both the downwind and upwind sites. This was necessary since the response of these instruments is dependent on the size distribution of the particulate matter being measured. For PM_{10} a Graseby-Andersen model 246B (Smyrna, GA) inlet was used, but modified so that the inlet attaches directly to a 47mm filter holder. For $PM_{2.5}$ a Sensidyne (Clearwater, FL) model 240 cyclone inlet was attached directly to a closed face 47mm filter holder. Gelman Teflo 2.0μm filters (Pall Corp., Ann Arbor, MI) were used for both samplers. A Cahn model 35-C microbalance (Analytical Technology, Inc., Boston, MA) was used to determine the mass of the filters before and after sampling to within ±1µg. All filters were equilibrated to 15°C and 50% RH for 24 hours prior to weighing.

Three DustTraks were collocated with the inlets for the filter samples in two configurations. In both configurations there was collocated sampling at the downwind measurement location. In configuration 1 sampling was done at both the 2.6 and 11 m elevation and for configuration 2 all sampling was done at 2.6 m above the ground.

Meteorological Monitors and Data Acquisition

Three-component wind speed measurement devices (Gill Propeller Anemometer, Model 27106 and Wind Monitor-AQ, model 05305-5, R. M. Young Co., Traverse City, MI) were located at two elevations (4 and 11 m). Relative humidity and temperature (Temperature and Relative Humidity Probe, model HMP45C, Campbell Scientific, Inc., Logan, UT) and total solar radiation (Net Radiometer, model REBS Q*7.1, Radiation and Energy Balance Systems, Inc., Seattle, WA) were also measured. A Campbell CR10X data logger (Campbell Scientific, Inc., Logan, UT) was used to collect data. Most data was collected as 15 minute averages while some was collected as 2-second averages for use in analyzing “puffs.”

Monitoring Locations

Figure 2-1 is a layout drawing of the sampling arrangement. DustTrak and filter sampler inlets were placed 2.5 m from the road on the upwind (west) side and 8.2 m from the road on the downwind side. Two DustTraks were collocated on the downwind side. All inlets were set at a height of 2.6 m above ground level. The DustTraks were kept in a metal box (61 cm wide x 122 cm long x 61 cm high) with the ¼ inch OD tubing run to the sampling point. We later found that the DustTrak repose was sensitive to temperature so we cut 6.4 cm holes in the sides of the box and covered it with a reflective aluminum (Everbrite by Alcoa Aluminum) sheet with dimensions of 1.2 x 1.8 m. A 10cm air gap was maintained between the box and the reflective cover for added insulation from solar heating. Meteorological sensors for wind speed, wind direction, vertical speed, and temperature were mounted on a downwind tower at two heights, 4 and 11 m above the ground. A net radiometer was installed at 0.8 m above the soil. A combined relative humidity /temperature sensor was installed at the upwind site 2.6 meters above the ground.

Site Operations and Data Capture

The site was operated during two periods: July 17, 2000, to November 16, 2000, and January 9, 2001, to February 6, 2001. The first period was to assess PM concentration differences due to the road, while the second was set up to perform the trackout experiments. Site checks were performed every other day on the average during the first period. During these checks the physical integrity of the site was confirmed, the data were downloaded, and batteries were recharged. Zero and flow checks were performed monthly on the average. All three DustTraks were set up for collocated sampling for a total of 15 days during the first period. A total of eight sets of collocated filter sampling episodes were conducted to compare the response of the DustTraks with mass measurements. These sampling periods ranged from 2.5 to 9.6 hours.

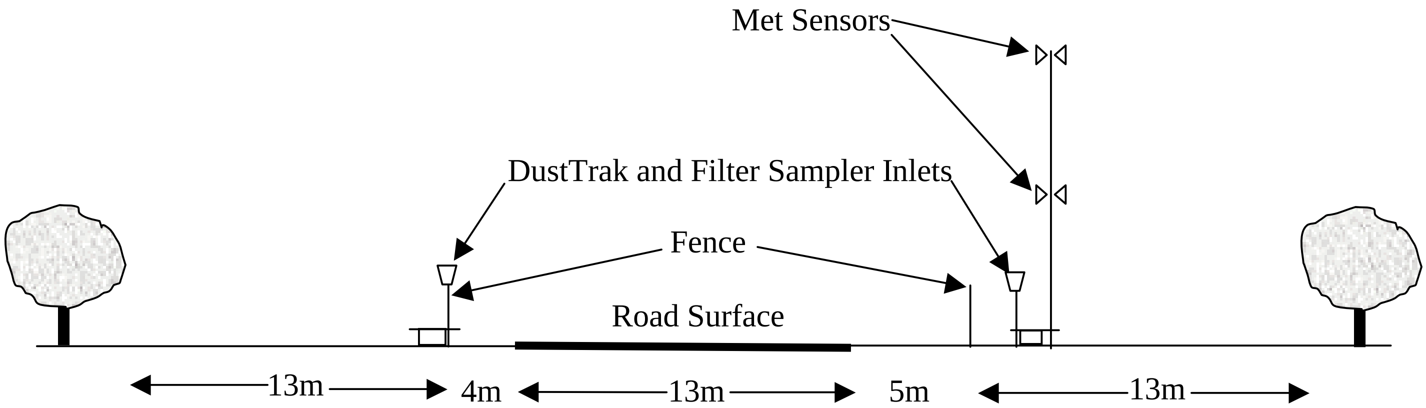

Figure 2-1. Layout diagram of the long-term PM measurements on Iowa Avenue, facing north.

During the second period the site was operated with all three DustTraks collocated except for periods when trackout experiments were being conducted. The equipment was checked for proper operation before the trackout experiments. Zero response and sample flow were checked before and after performing each trackout experiment.

The collocated data from the entire fixed site sample period were compiled and all data were normalized to DustTrak 1 (s/n 21955) before they were analyzed.

2.2 On-Vehicle Real-Time PM Emission Measurements

This task was broken into three phases. The first involved the design and construction of an isokinetic sampling probe, the second was characterization of the PM distribution in a vehicle's wake, and the third was the measurement of PM emission rates on a variety of roads and driving conditions.

- **Isokinetic Sampling Inlet**

Collecting particulate samples from a vehicle moving at speeds of 0 mph to 60 mph required designing an inlet that would provide, as much as possible, isokinetic sampling at all speeds. Figure 2-2 shows the design of the inlet, and Figure 2-3 is a photograph of the device. A vacuum pump is used to maintain the bulk air speed at the inlet equal to the speed of the air going past the inlet. To slow the flow to the sample flow rate of the DustTrak without creating a virtual impactor, excess air is pulled through a hollow, cylindrical filter. The flow to the vacuum pump is adjusted at speed to produce a reading of zero pressure on the gauge. When the pressure equals zero, there is no pressure drop from the probe inlet to the tubing that leads to the DustTrak. This condition creates a no-pressure-drop inlet; therefore, the sampled airstream has the same energy as the ambient airstream. The output of the pressure transducers were recorded on a Campbell CR10X data logger.

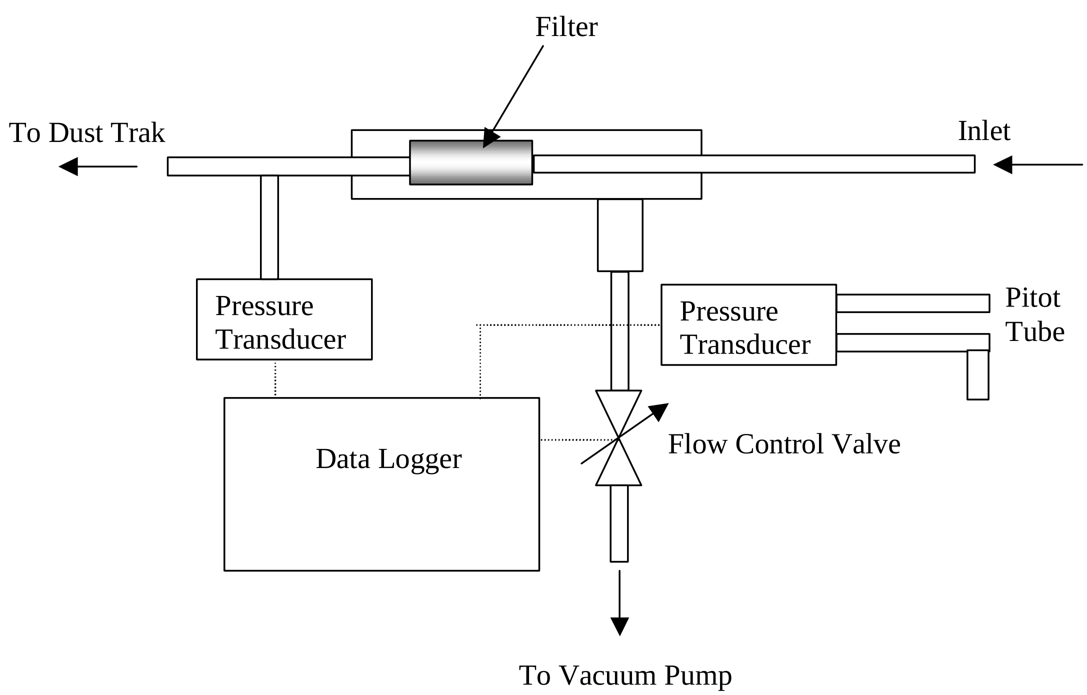

Figure 2-2. Schematic diagram of the isokinetic sampling probe.

A. Isokinetic sample tube

B. Blow-out of isokinetic sample tube

Figure 2-3. Photograph of the isokinetic sampling inlet.

- **Characterization of the Vehicle Wake and Sampling Point Optimization**

To determine where in the vehicle wake to collect samples, the PM concentrations in the vehicle wake must be characterized. To do this, it was necessary to measure PM concentrations at many locations behind a moving vehicle under controlled conditions. A rectangular frame (2 m wide and 2 m high) was constructed on a small trailer to hold sampling inlets at any position within the frame. A small trailer was used to hold sampling inlets at various locations behind the vehicle. The DustTraks, inlet pumps, and data logger were mounted in plastic boxes strapped to the rear of the trailer.

Metal impregnated ¼ inch OD plastic tubing (Bev-A-Line XX tubing, Thermoplastic Processes, Inc., Warren, NJ) was used to transport sample from the isokinetic sampling probe to the DustTrak. The metal impregnation of the tubing reduced static charges on the tubing for greater particle penetration. In addition, the shortest possible lengths of tubing were used. The trailer, frame, and associate components were designed to minimize the aerodynamic influence of the trailer with respect to the vehicle's wake. The trailer was equipped with a 6 m adjustable tongue to vary the distance of the sampling array from 1.4 to 5.9 m behind the tow vehicle. Figure 2-4 shows a photograph of the trailer; the tow vehicle is out of the picture to the left. The DustTraks were attached to the bed of the trailer (left foreground). Three of the plastic boxes contain DC vacuum pumps for the inlet; the fourth one housed the data logger. All the isokinetic sampling probes are located on the left side of the sampling bar. Figure 2-5 is a close-up photograph of these probes.

Figure 2-4. Photo of the trailer used to mount the isokinetic sampling probes and the DustTrak PM sensors.

Figure 2-5. Close-up photograph of the isokinetic sampling probes.

A number of locations to perform the tests on closed paved courses were investigated but rejected due to cost, insurance requirements, or insufficient length to reach 60 mph for any sustained period. We did the initial wake characterization on unpaved roads near Riverside. This resulted in high DustTrak responses, but the high dust loadings required factory cleaning of the optics. In addition, higher speeds were difficult to obtain or maintain. We then searched for and found a little used publicly accessible paved road to conduct the testing. This was Seminole Drive in Cabazon, an infrequently traveled 1.5 mile long road that runs parallel to Interstate 10. We were able to sample at several speeds between 20 and 60 mph. In addition, the surface was quite weathered and contained sufficient loading of fine debris that addition of a surrogate particle source was not necessary to obtain adequate DustTrak responses.

As shown in figure 2-6, PM_{10} measurements were made at several positions 4.3 meters behind the rear bumper using three DustTraks to determine the wake PM concentration characteristics. The reference sampling position was on the vehicle centerline 0.78 meters above the ground. The other two positions were located either 1.98 or 2.59 m from the ground, with one on the centerline and the other 1.22 m from the centerline. Due to safety concerns we did not extend probes further than 1.23 m from the centerline.

Based on the initial screening on unpaved roads, the reference probe should be located in a high PM_{10} concentration area. The elevation 1.98 m above the ground is near the vehicle's roofline height. As observed on the unpaved roads, this is the approximate height of the visual plume. The 1.22 m from the centerline places the probe slightly (0.1m) past the maximum width of the vehicle and therefore near the dust plume's visually observed lateral boundary. These test positions should therefore outline the PM wake of the vehicle. Table 2-1 summarizes the probe positions and speeds used for the various tests that were conducted. All data was collected as 2-second averages.

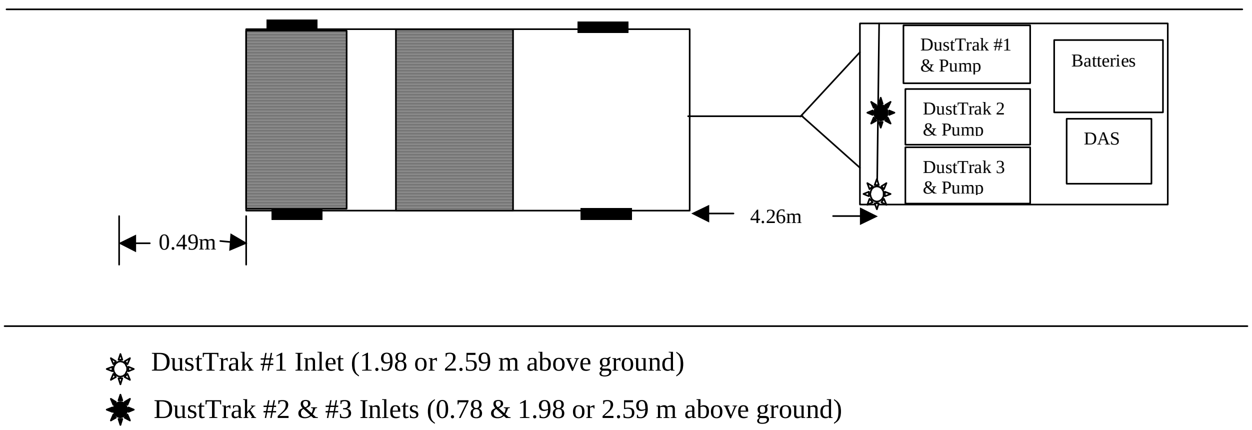

Figure 2-6. Schematic diagram of the sampling configuration for vehicle wake PM characterization.

Table 2-1. Vehicle wake characterization sample test matrix inlet locations.

Speed (mph)	Sample location on trailer* (meters)				Site
		X	Y	Z	
20, 30, 40, 50	DT#1	4.25	1.98	1.23	Riverside, unpaved
	DT#2	4.25	0.78	0.0	
	DT#3	4.25	1.98	0.0	
20, 25, 30	DT#1	4.25	1.98	1.23	Cabazon
	DT #2	4.25	0.78	0.0	
	DT#3	4.25	1.98	0.0	
30, 40, 50, 60	DT#1	4.25	1.98	1.23	Cabazon
	DT#2	4.25	0.78	0.0	
	DT#1	4.25	1.98	0.0	
20, 30, 40, 50, 60	DT#1	4.25	1.98	1.23	Cabazon
	DT#2	4.25	0.78	0.0	
	DT#3	4.25	1.98	0.0	
20, 30, 40, 50, 60	DT#1	4.25	2.59	1.23	Cabazon
	DT#2	4.25	0.78	0.0	
	DT#3	4.25	2.59	0.0	

*X distance from rear of vehicle, Y distance from ground, Z distance from centerline

- **Field Measurements**

Field measurements were conducted using a Chevrolet Suburban towing the test trailer. Two sampling probes were place on the trailer: Position 1: 0.76 m from the ground and 4.25 m from the rear of the vehicle. Position 2: 2.59 m from the ground and 4.25 m from the rear of the vehicle. Both sampling ports were on the centerline of the vehicle. The front sampling port (reference) was centered 0.43 m in front of the hood of the vehicle and 1.07 meters from the ground. A Campbell CR10X data logger was used to collect all data at intervals of two seconds.

After several rounds of initial testing on various roads and speeds in the Riverside area, we settled on a test routes that contained segments of arterial, collector, and local roads. As we later found out, the DustTrak required approximately 30 seconds of integration to produce stable and accurate data (see section 3-1). Figure 3-12 shows this route. Separate tests were conducted on Interstate 215 to gather data on high speed, limited access freeways. Notes were taken coinciding with the data logger time to describe the segment tested, the speed, and any unusual circumstances. On each road and for each PM nozzle (10μm and 2.5μm) the tests were repeated twice.

We also attempted evaluate the use of the test vehicle to sample the dust plume produced by other vehicles. This was done on the freeway under light traffic conditions to minimize the interference from other vehicles. We drove next to and in front of a heavy-duty truck and then dropped back and to the rear of the vehicle. This test was done using PM_{10} inlets for only one test vehicle and roadway type.

At the end of each day the three DustTraks were collocated using one inlet or the other. To help minimize measurement noise and other factors the collocated data from the entire sample period were compiled and used to normalized DustTrak measurements. The method for performing the normalization is fully described under the Results and Discussion sections.

2.3 Trackout PM Emission Measurements

Trackout experiments were performed at the fixed site used for long-term upwind-downwind measurements (Iowa Avenue). A weighed amount of native soil (6.8 kg) passed through a 1/8 inch mesh screen and applied on the roadway to simulate drop-off. While the traffic was stopped, this soil was applied to the entire upwind lane (southbound lane) of the roadway from the double centerline to the road edge over a length of 23 m centered on the location of the PM inlets. A Scotts fertilizer spreader was used to make the application. The beginning and ending time of application was noted, the average time for application was eight minutes. Figure 2-7 shows the experimental layout.

On days when multiple runs were performed the time interval between test runs was adjusted to account for the rate of emission decline. A minimum interval of three hours between test runs was allowed even though the PM change appeared to have dispersed within 15 minutes after application. At the end of each day the three DustTraks were collocated.

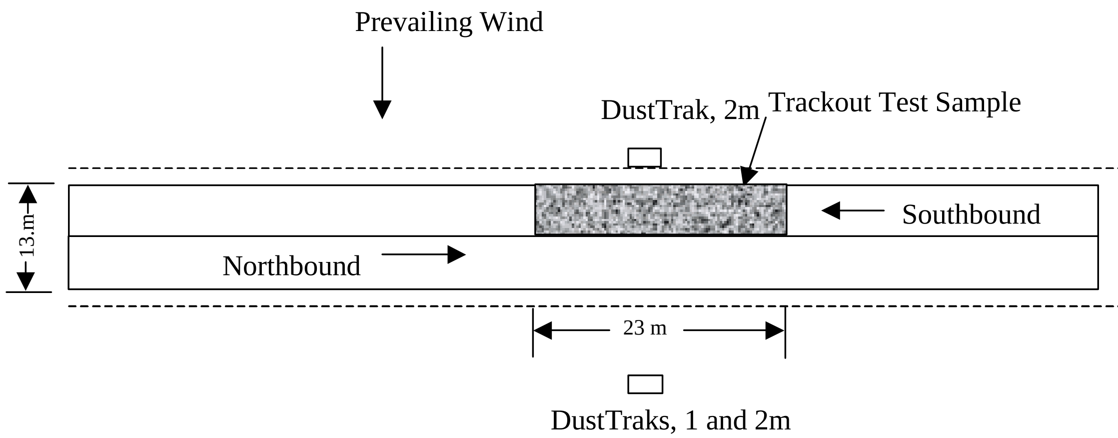

Figure 2-7. Layout to determine the PM_{10} emission effect of trackout.

2.4 Data Management Overview

Source data received for this project includes written logbook and data sheet entries, data logger text files, analytical laboratory results, and reduced data sets. All data from the data logger were converted to Excel spreadsheets. All data were check for outliers and flagged accordingly or removed from the data set. This full data set is to be submitted to the ARB on a CD-ROM along with this final report. The list below identifies data sources.

Meteorology: WS, WD, TMP, RH, Net Radiation
DustTrak $PM_{2.5}$ and PM_{10}
Weighed filter samples
Campbell data logger files

A typical data record for the on-vehicle real time PM emission measurement contains the following fields:

- Date and time (hh:mm:ss)
- DustTrak 1 concentration (mg/m^3)
- DustTrak 2 concentration (mg/m^3)
- DustTrak 3 concentration (mg/m^3)
- Pressure Isokinetic tube 1 (psi)
- Pressure Isokinetic tube 2 (psi)
- Pressure Isokinetic tube 3 (psi)
- Pito (mph)
- Comment

A typical data record for the stationary site and trackout measurements contains the following fields:

- Date and time (hh:mm:ss)
- DustTrak 1 concentration (mg/m^3)
- DustTrak 2 concentration (mg/m^3)
- DustTrak 3 concentration (mg/m^3)
- Downwind TMP @ 11 m (^oC)
- Downwind WD @ 11 m (degrees)
- Downwind WD @ 4 m (degrees)
- Downwind TMP @ 4 m (^oC)
- Downwind WS @ 11 m (m/s)
- Downwind WS @ 4 m (m/s)
- Downwind VWS @ 11 m (m/s)
- Downwind VWS @ 4 m (m/s)
- Downwind Net radiation (watts/m^3)
- Downwind Sigma W @ 11 m
- Downwind Sigma W @ 4 m
- Downwind Sigma Theta @ 11 m
- Downwind Sigma Theta @ 4 m
- Upwind TMP @ 2.6 m (^oC)
- Upwind RH @ 2.6 m (%)

3.0 RESULTS AND DISCUSSION

3.1 Data Quality

Before describing the experimental results we include this section to describe the overall quality of data that the DustTraks provide and some of the corrective action that we undertook to improve the data quality.

- **DustTrak Averaging Time**

The DustTrak updates at one hertz. We originally compared collocated sampling using data collected and stored at 2-second intervals. Figure 3-1 is typical example of the 2-second data collected from two collocated DustTraks. The correlation coefficients were always much less than 0.5. With this data we could not ascertain whether the DustTraks were even measuring the same phenomenon, let alone whether they were equivalent. When the data are compared as 60-second running averages as shown in Figure 3-2, the correlation coefficients are quite acceptable. It was discovered that approximately 30-second averaging times were necessary for the DustTraks to provide equivalent data.

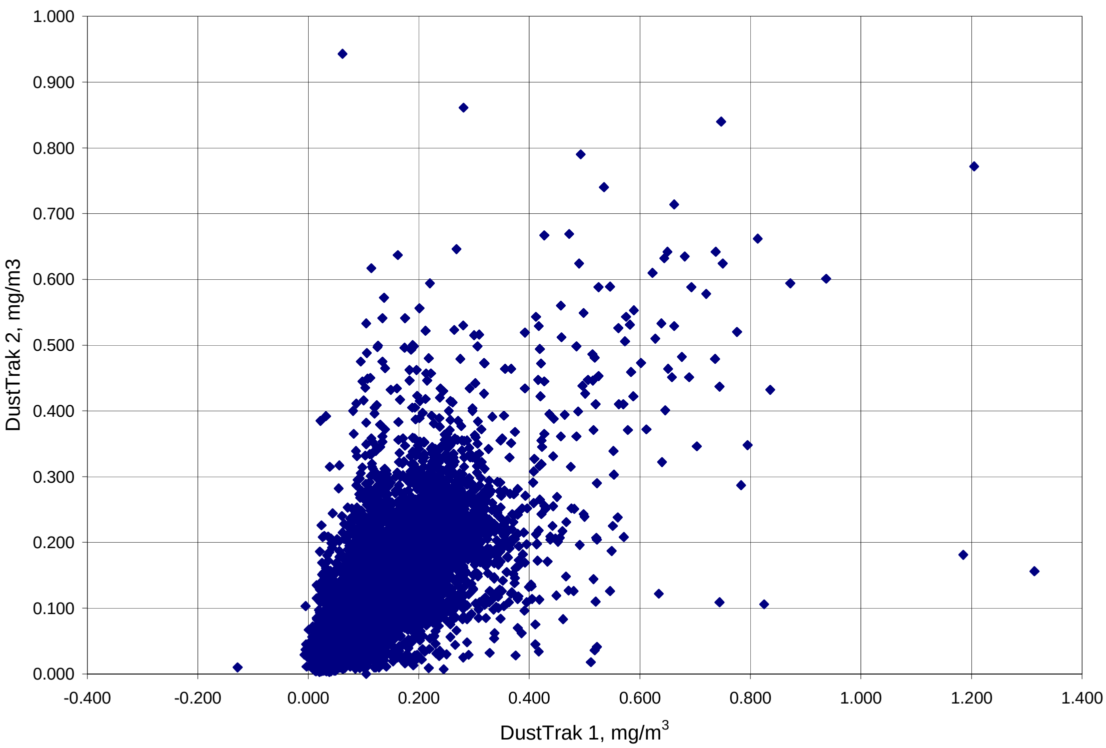

Figure 3-1. Comparison of two collocated DustTraks using 2-second PM_{10} data.

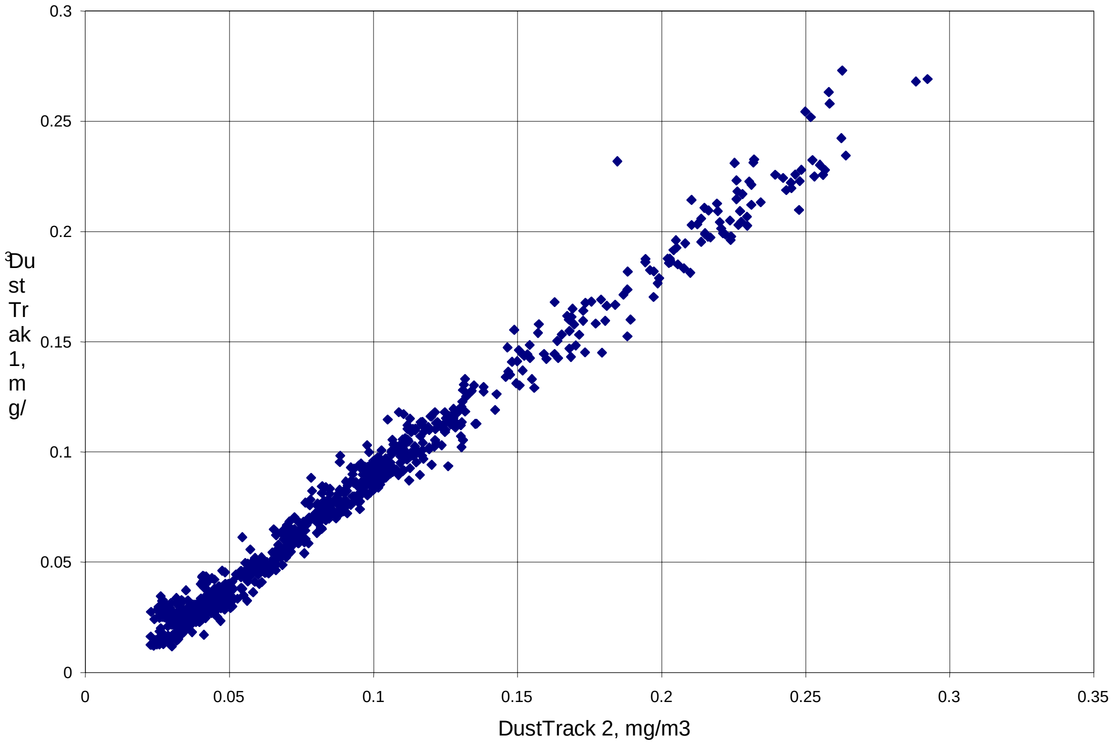

Figure 3-2 Comparison of two collocated DustTraks using 60-second PM_{10} data.

We could not use DustTrak measurement durations of much less than 30 seconds. This had a profound effect on the experimental approach for aspects of this study. For the upwind-downwind measurement study we could not quantitatively measure "puffs" of PM (the net upscale readings – downwind less upwind values – of the DustTraks) since such "puffs" were expected to last only a few seconds as a car passed the test area. Only averaged values of 30 seconds or more could be compared. The result was a loss of some of the measurement sensitivity expected from using instruments that could capture individual "puffs" of concentrations significantly higher than the background. When DustTraks were used to measure PM concentrations behind a moving vehicle it was necessary to maintain a speed for approximately 30 seconds to be able to calculate a net difference between the DustTrak's responses. This made the testing much more difficult to perform.

- **Uncertainty**

To calculate measurement uncertainty we calculated the relative standard deviation (RSD) of the difference between the PM_{10} measured by the collocated samplers. We calculated the mean and standard deviation of the percent absolute difference between the three samplers in all combinations 2-1, 3-1, and 3-2. The standard deviation was divided by the mean, and the average RSD was calculated. Since the data collection for each segment of this project was separated by significant time periods we calculated a RSD for each testing regimen, including: 1) vehicle plume characterization, 2) on board vehicle PM measurements, and 3) stationary site and trackout emission measurements.

For onboard measurements two-second data were collected. To reduce measurement noise, a six second running mean was calculated followed by one-minute averages. The calculated RSD for the vehicle plume characterization component was 0.79%. For the other on-board vehicle PM measurements the calculated RSD was 7.10%. In this case, two extreme outliers were removed from the sample of 7,984 one-minute averages of 2 second collocated samples used in the calculation. Finally, the RSD was 2.17% for the stationary site and trackout emission measurements (averaging time of 15 minutes). These RSDs, which are good for any ambient air measurement, were used to estimate measurement uncertainty for data reported from these studies.

- **Evaluation of PM Losses in the Sampling Line**

It was necessary to use sampling lines ranging in length from 1 to 3 m to change positions during the on-board wake characterization and for protection from the elements and security for long-term stationary monitoring. To evaluate losses of particles within the sampling lines, three DustTraks equipped with PM_{10} inlets were collocated and sampled ambient air for two hours, alternating 10 minutes without tubing and 10 minutes with tubing (1.70 m). Data were collected as 30-second averages. The data are summarized in Table 3-1. Based on the means, the tubing caused a loss of PM ranging from 21 to 29 percent depending on which DustTrak was evaluated.

Table 3-1. Mean DustTrak PM_{10} response on ambient air with and without Bev-A-Line tubing.

Mean DustTrak 1 (mg/m^3) w/o tubing	Mean DustTrak 1 (mg/m^3) w/ tubing	Difference DT 1 (w/o - w)	% Difference DT 1 (w/o - w)	SD of Difference
0.269	0.213	0.056	20.8%	0.117
Mean DustTrak 2 (mg/m^3) w/o tubing	Mean DustTrak 2 (mg/m^3) w/ tubing	Difference DT 2 (w/o - w)	% Difference DT 2 (w/o - w)	SD of Difference
0.359	0.272	0.087	24.2%	0.132
Mean DustTrak 3 (mg/m^3) w/o tubing	Mean DustTrak 3 (mg/m^3) w/ tubing	Difference DT 3 (w/o - w)	% Difference DT 3 (w/o - w)	SD of Difference
0.253	0.179	0.074	29.3%	0.110

In addition, the data sets for each DustTrak were compared with and without the tubing using the Wilcoxan (Mendenhall, 1971) non-parametric ranking test. For all three DustTraks the data sets were shown to not be equivalent. The loss of PM due to the tubing, therefore, is significant, but could be corrected. For these studies we did not use the correction since we were either comparing relative responses or calibrated the DustTraks directly using these sampling lines against filter-based mass measurements of PM.

- **Comparison of DustTrak with Filter Sample PM Measurements**

Figure 3-3 shows the results of comparing the filter and DustTrak PM_{10} data during periods of collocation. Since these data will be used for all future comparisons between DustTraks on a mass basis, it was necessary to normalize their responses. This was using the following equations from the collocated sampling:

DustTrak #2 normalized = (DustTrak #2 raw) 0.93 +0.009) (R^2 = 0.945)
DustTrak #3 normalized = (DustTrak #3 raw) 0.96 +0.008) (R^2 = 0.975)

The DustTrak values are the means of the 30-second data during the period in which the filter samplers were operating. The data are somewhat scattered, especially at the lower concentrations where there is more uncertainty in both of the methods. Since the PM_{10} correlation is relatively good, the regression equation for DustTrak #1 will be used to correct all data (since DustTrak #2 and #3 were all normalized to #1 via collocated sampling) to give concentrations directly comparable with the filter measurements of mass concentration.

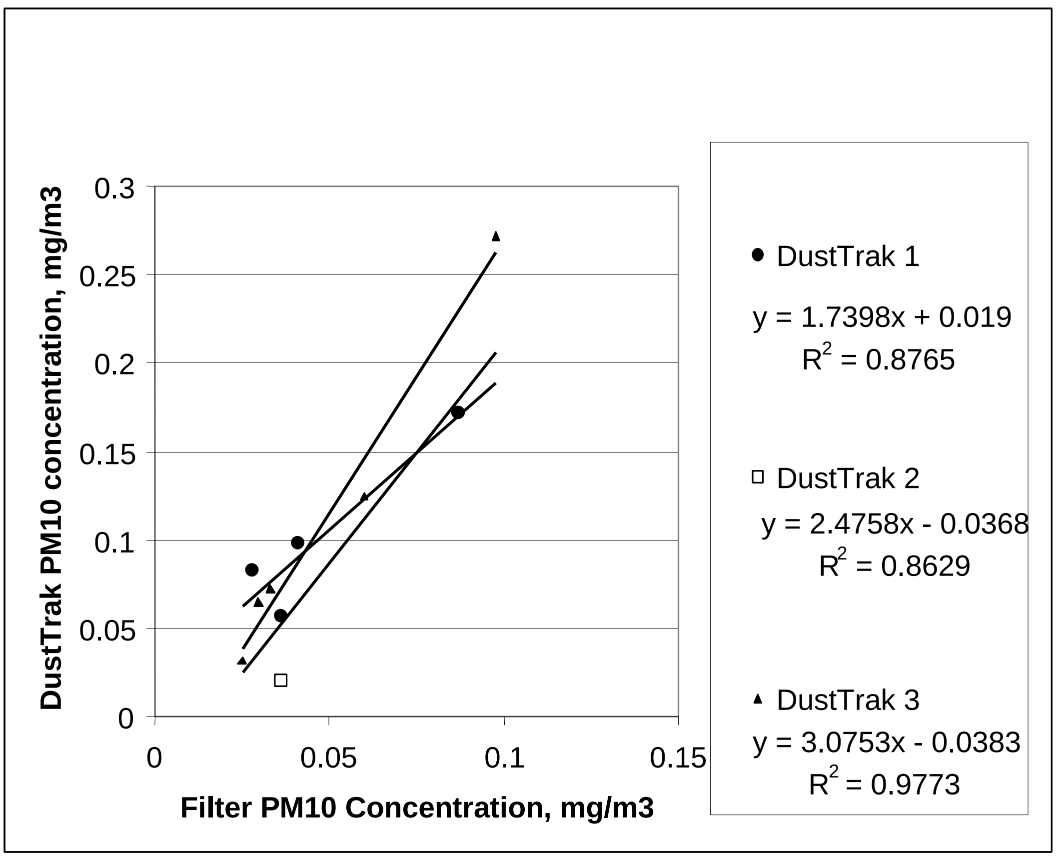

Figure 3-3. Comparison of filter and DustTrak PM_{10} data while collocated.

- DustTrak Temperature Response Study

The DustTraks were located in a metal box with the data logger. The temperature within the data logger was recorded, as was the ambient temperature (in a shielded thermocouple holder). After setup we observed that the temperature appeared to affect the output of the DustTrak, being most noticeable while performing a zero response test with filtered ambient air. Figure 3-4 shows a typical time series plot of the DustTrak output while sampling particle-free air and temperature recorded by the nearby data logger. The peak temperature in the box was over 45°C. It appears that the responses of both DustTraks #2 and #3 did a step change increase just over 40°C. Also note that the response of DustTrak #1 is relatively flat, indicating a potential malfunction. The temperature sensitivity was also recently confirmed by Ramachandran et al. (2000).

Figure 3-5 shows a typical time series plot of the “box” temperature and the ambient temperature before we ventilated the box and added a reflective cover. During the daytime the temperature in the box is much higher, up to 20°C, than ambient. During hot weather the temperature rise may be high enough to risk instrument failure. Figure 3-6 shows a typical day after these temperature mitigation steps were taken. The “box” temperature is a few degrees lower until late afternoon when it becomes a few degrees higher. Figure 3-7 shows a time series of the DustTraks’ response to particle-free air and temperature after ventilating the box and having the instruments sent back to the manufacturer for repairs and maintenance. It was reported that the optical system was “very dirty.” The DustTraks now responded similarly to changes in temperature. For a 20°C temperature change, the DustTrak response to particle-free air changes approximately 0.03 mg/m^3.

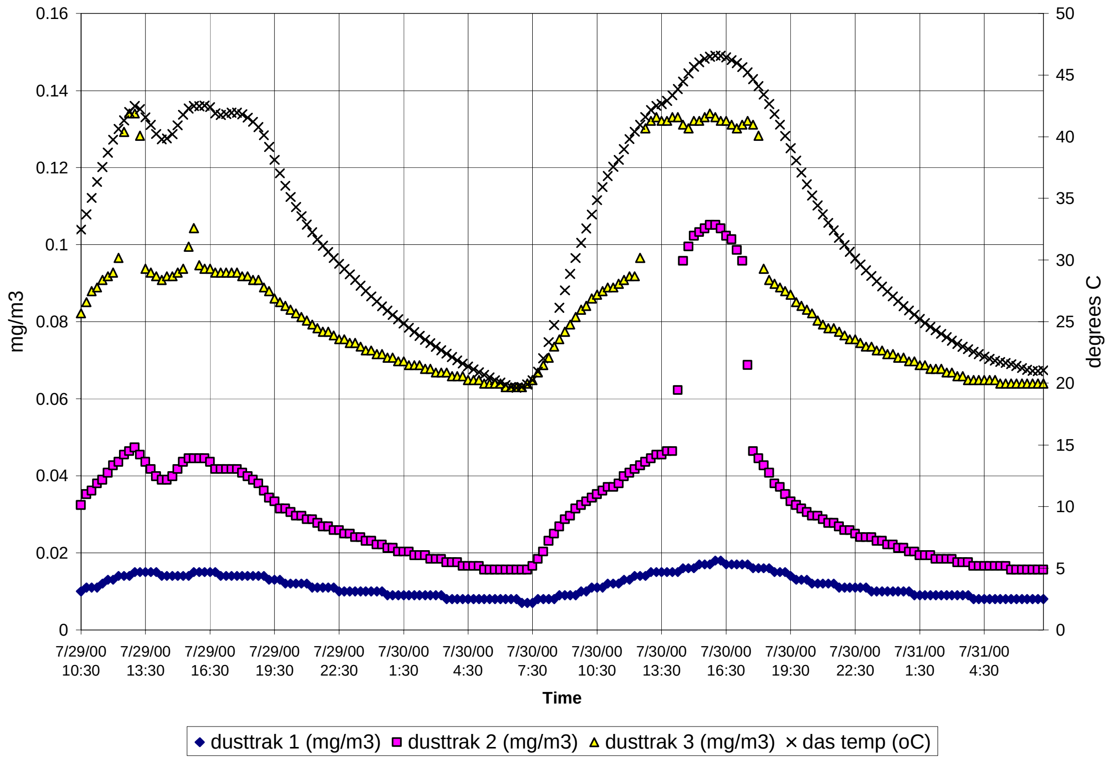

Figure 3-4. Time series showing the DustTraks's response with temperature while sampling particle-free air.

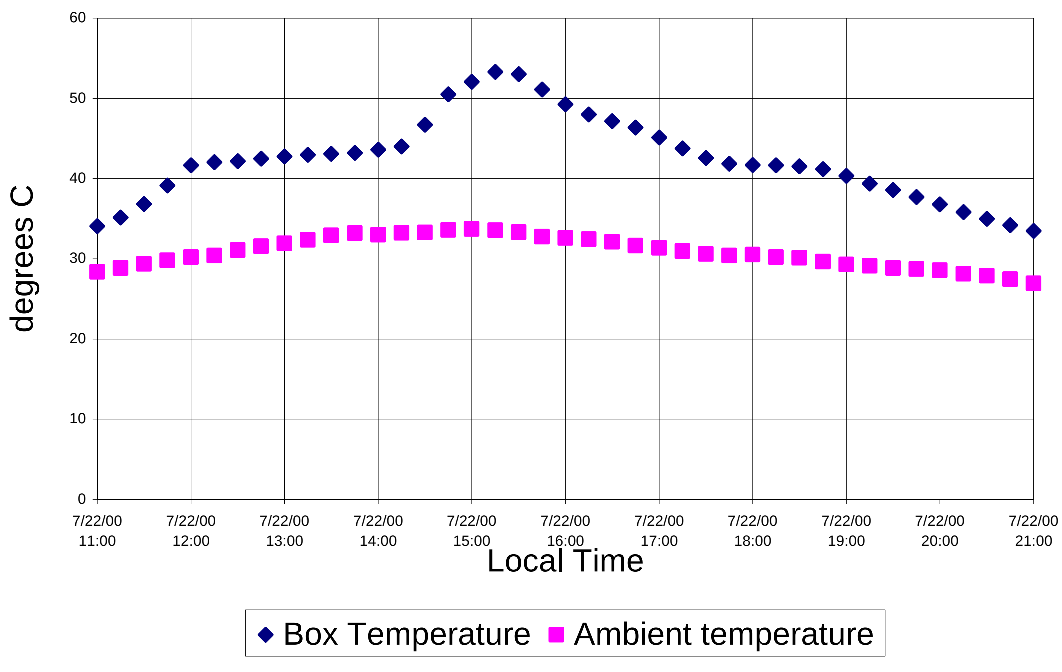

Figure 3-5. Comparison of ambient and temperature in the sampler "box" before adding ventilation and a reflective cover.

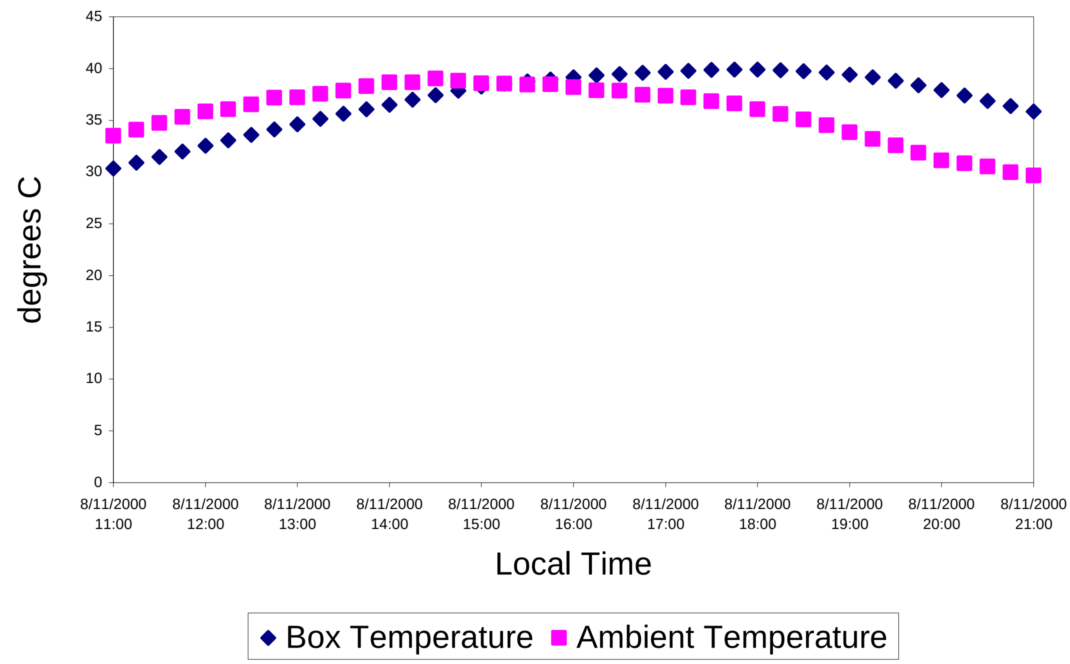

Figure 3-6. Comparison of ambient and temperature in the sampler “box” after adding ventilation and a reflective cover.

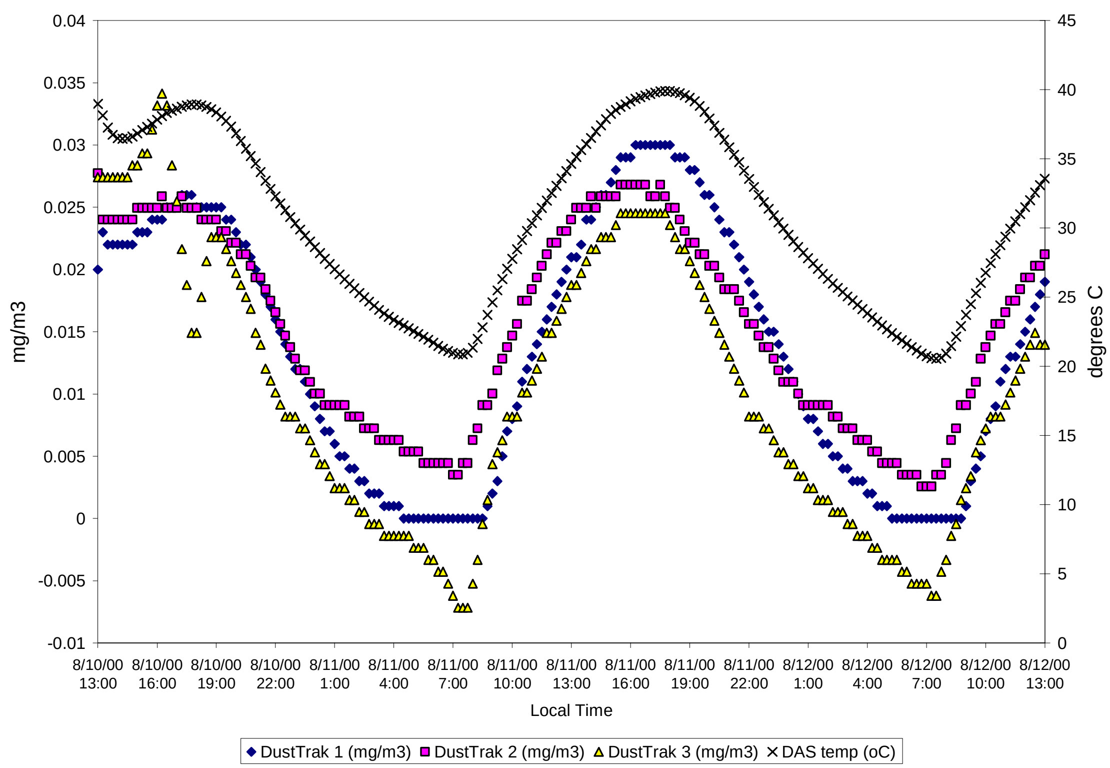

Figure 3-7. Time series showing the response of DustTraks with temperature while sampling particle-free air after repairs and adding ventilation.

3.2 Upwind-Downwind Real-Time PM Measurements

The upwind-downwind measurement program was conducted over five months to evaluate the ability of the DustTraks to measure concentrations differences across a roadway compared with filter-based methods. Only PM_{10} inlets were used since this size range offered the greatest signal for PM originating from the roadway compared to the background. For data analysis we selected only a block each day when the wind speed was within ±16° of 255° and with a wind speed of 1.0 m/s. Days with blocks of time less than three hours were excluded. This was done to insure that the wind flow pattern was established and that the wind was not shifting direction. There were 51 days in which the data met these criteria. The upwind-downwind real-time measurements the three DustTraks were collocated for fifteen periods during the course of the 51 day measurement interval. The collocated data from DustTraks #2 and #3 were regressed against DustTrak #1 to normalize the data. The least squares regressions resulted in the following equations:

DustTrak #2 Normalized Concentration = 0.93(response) + 0.009 (R^2 = 0.945)

DustTrak #3 Normalized Concentration = 096 (response) + 0.008 (R^2 = 0.975)

The 2-second data set was also transformed into 15-minute data for comparison purposes.

Many thousands of data points were collected, but it is most useful to review the overall averages to evaluate the contribution of the paved road to PM_{10} concentrations. Appendix Table A-3 contains the full data set with the average, standard deviation, number of 30-second segments, and standard error of the mean of the upwind and downwind concentration, and the concentration difference for each favorable day. Table 3-2 shows PM_{10} concentrations and the average difference in concentration between upwind and downwind samplers for the entire 51 days for which data were compared. Two collocated DustTraks were used downwind, and the average of these was used to calculate the difference from the upwind measurements. The downwind PM_{10} is, on the average, lower than the upwind by 0.009 mg/m^3 (subtracting the averaged data directly leads to a difference of 0.006). The standard deviation is, however, nearly three time the mean difference. We conclude that overall we cannot detect any PM_{10} differences from one side of the roadway to the other within the experimental uncertainty.

Table 3-2. Upwind and downwind concentrations, standard deviations, and standard error of the mean, and concentration difference on Iowa Avenue for 51 days.

	Upwind Concentration (mg/m^3)	Downwind Concentration (mg/m^3)	Concentration Downwind-Upwind (mg/m^3)
avg	0.106	0.100	-0.009
sd	0.090	0.073	0.024
n	51	51	51
sem	0.013	0.010	0.003

Figure 3-8 presents a different way of looking at the data. This figure is a composite of the 15-minute PM_{10} difference data during the day for the entire 51-day data set. This figure is notable in that the differential peaks around 1:30 pm on the average. While the DustTraks have a temperature dependence, this dependence should be canceled out by taking the difference between measurements. It is possible that there was not a cancellation and that the downwind instruments may have been heated proportionately higher than the upwind during early afternoon. Composite time series plots (Figures A-11 through A-4 in the Appendix) did not indicate a correlation between the net PM_{10} concentrations and wind speed, wind direction, ambient temperature, or relative humidity.

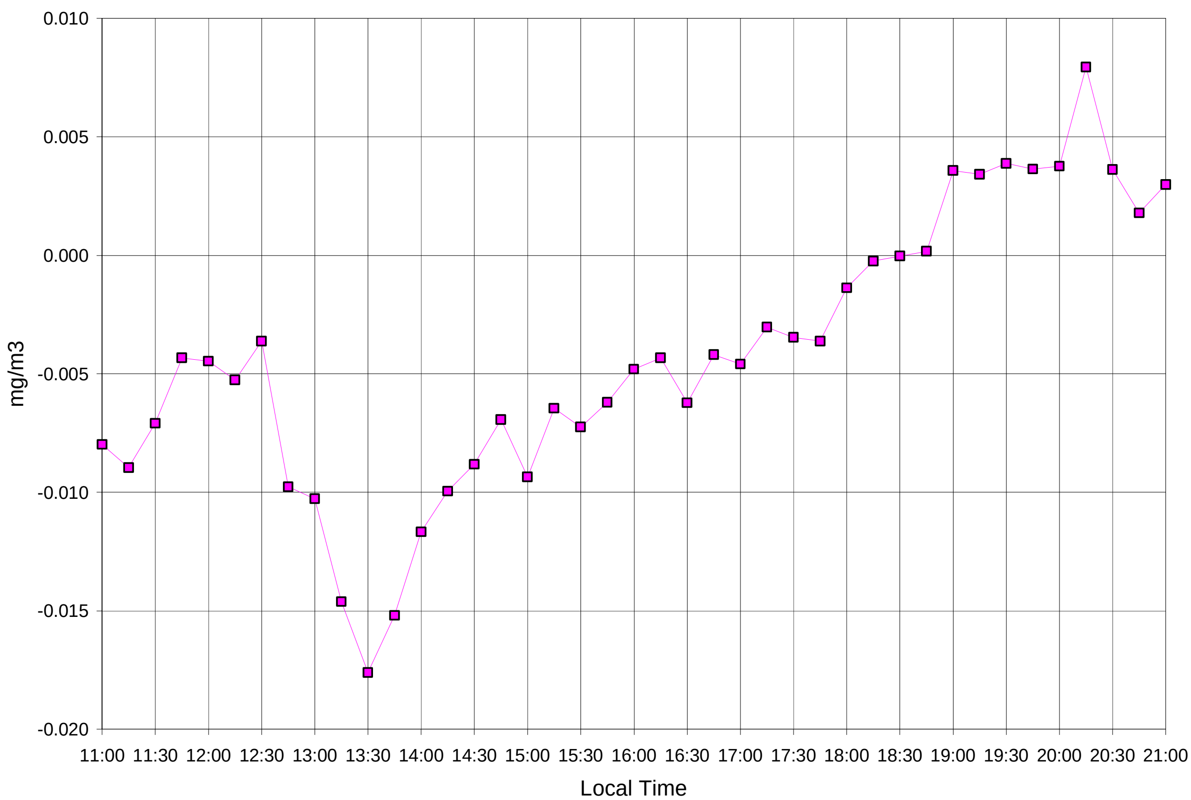

Figure 3-8. 51-day composite time series of PM_{10} concentration difference (average downwind–upwind).

Figure 3-9 is a further analysis of temperature and its effect on the DustTraks' relative response. In this time series the temperature difference of the data logger in the upwind instrument box (the data logger and DustTraks were located in close proximity) is subtracted from the temperature in the downwind data logger is plotted against time as a composite plot for the entire 51 days. From 11:00 to 18:15 hours the temperature of the upwind data logger was higher than the downwind data logger. Since DustTraks respond to particle-free air directly with temperature, it is likely that the upwind DustTrak would have a higher response, given equal PM concentration, than the downwind DustTrak. This is reflected in Figure 3-8 by the negative concentration difference until 18:30 hours. After 18:15 hours the temperature of the downwind DustTrak is consistently higher than the temperature in the one upwind. In Figure 3-8 we see that after 18:30 the concentration difference is consistently positive. We conclude that the DustTrak temperature differences have a large effect on the upwind-downwind PM measurements using the DustTrak. Thus the DustTrak measurements are not useful for the low concentration differences in PM from upwind to downwind.

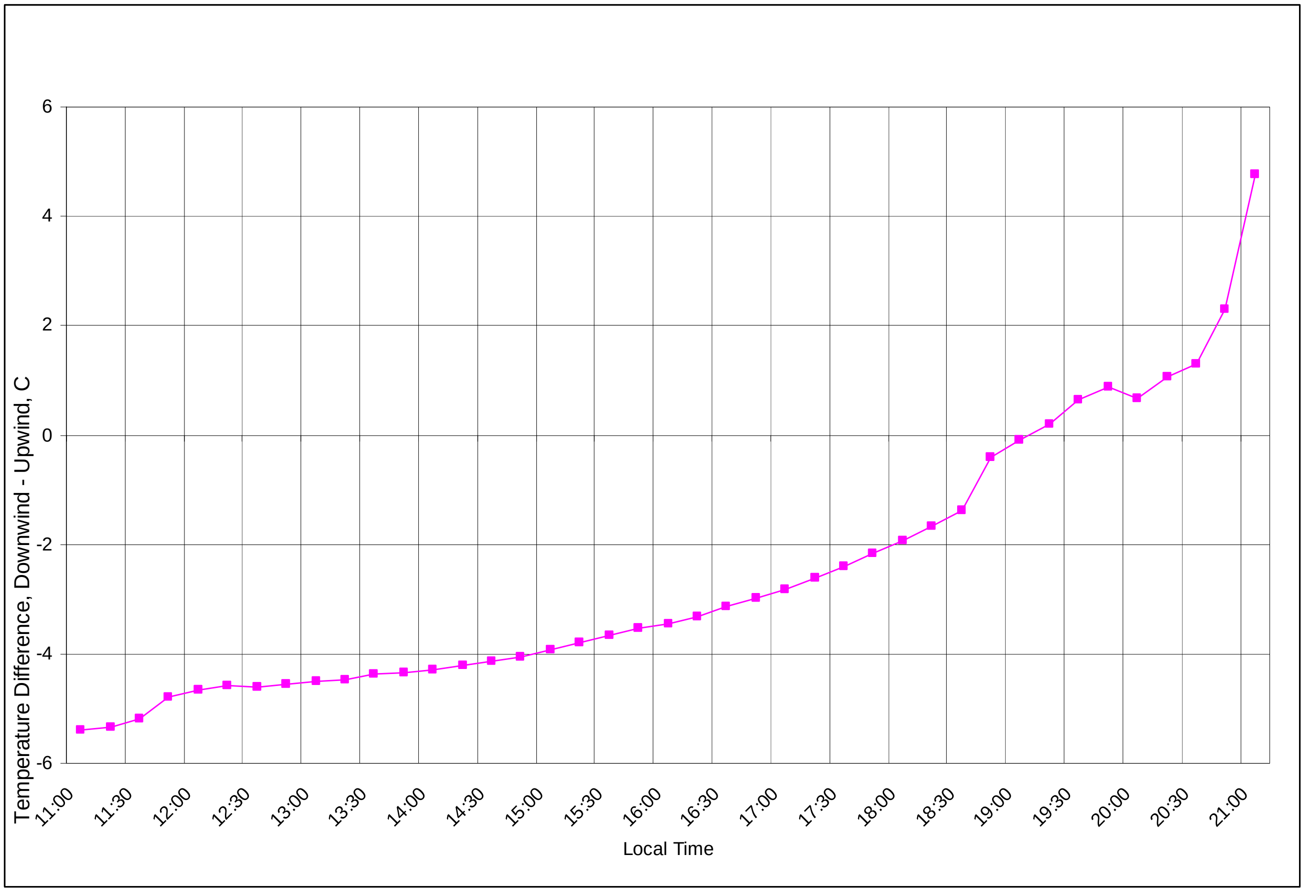

Figure 3-9. 51-day composite time series of temperature of the downwind data logger (DAS) less the temperature of the upwind data logger (DAS).

3.3 On-Vehicle Real-Time PM Emission Measurements

In our original design, the bypass flow of the isokinetic sampling probe was to be controlled by the data logger as it monitored the speed using a pitot tube. The pressure differential of the pitot tube, measured with a transducer, was found to be highly variable, most likely due the effect of the wind. Since zero pressure drop relative to static pressure would be an indicator of sampling isokineticity we attempted to use this parameter to control the bypass flow. This pressure differential, while not as noisy as the pitot tube, was too noisy to be a reference in controlling the bypass flow as the bypass flow would continually overshoot the desired flow. Our solution was to determine the flow required to achieve zero pressure drop at the DustTrak inlet at any given speed. The flow was then adjusted to the anticipated speed used for monitoring and the pressure differential was continually recorded by the data logger.

- Wake Characterization

With the sampling matrix presented in Table 2-1 we determined:

- The precision of the measurement (with all three DustTraks sampling from the same point).
- The homogeneity of the PM within the vehicle's wake with respect to the vehicle's speed.
- The vertical and horizontal extent of the plume as a function of vehicle speed and cross wind.
- The optimum sampling position.

The three DustTraks were collocated on several days during the characterization of the vehicle wake. Identical lengths of the anti-static tubing was used from each sampling point to the DustTraks' inlet. Collocated data from DustTrak #2 and #3 were plotted against DustTrak #1, and least-squares regression analyses were performed. To improve the comparability, data from DustTraks #2 and #3 were normalized to #1 using the following regression equations:

DustTrak #2 normalized = 0.1.13(DustTrak #2 raw) –0.005 ($R^2 = 0.926$)

DustTrak #3 normalized = 0.93 (DustTrak #3 raw) + 0.13 ($R^2 = 0.920$)

For actual testing the length of the tubing varied with the location of the inlet on the matrix (1.70, 2.29, or 2.74 m). The tubing was manually interfaced to the DustTrak to obtain sequential samples at each test point. Losses of PM were not corrected for.

The data are summarized in Figures 3-10 and 3-11. The average concentration, standard deviation, number of runs, and standard error of the mean for each speed tested are shown for each DustTrak in Table A-1 in the Appendix. DustTrak #2 was chosen as the reference, and Table A-1 also shows the average difference of DustTrak #1 and DustTrak #2, and of DustTrak #3 and DustTrak #2.

The PM_{10} concentration of the plume clearly drops as the sampling point is raised from the top of the tow vehicle to 2 feet above it. The concentration also drops rapidly when sampling just beyond the edge of the 2 m wide tow vehicle (1.2 m from the centerline). These data confirm that the plume is confined primarily within the frontal area of the tow vehicle and that a sampling position in the geometric center of the tow vehicle frontal area is an appropriate sampling point. We therefore chose two sampling locations in the rear of the vehicle: 1) a reference probe centered 0.78 m from the ground and 2) a probe centered 2.59 m from the ground.

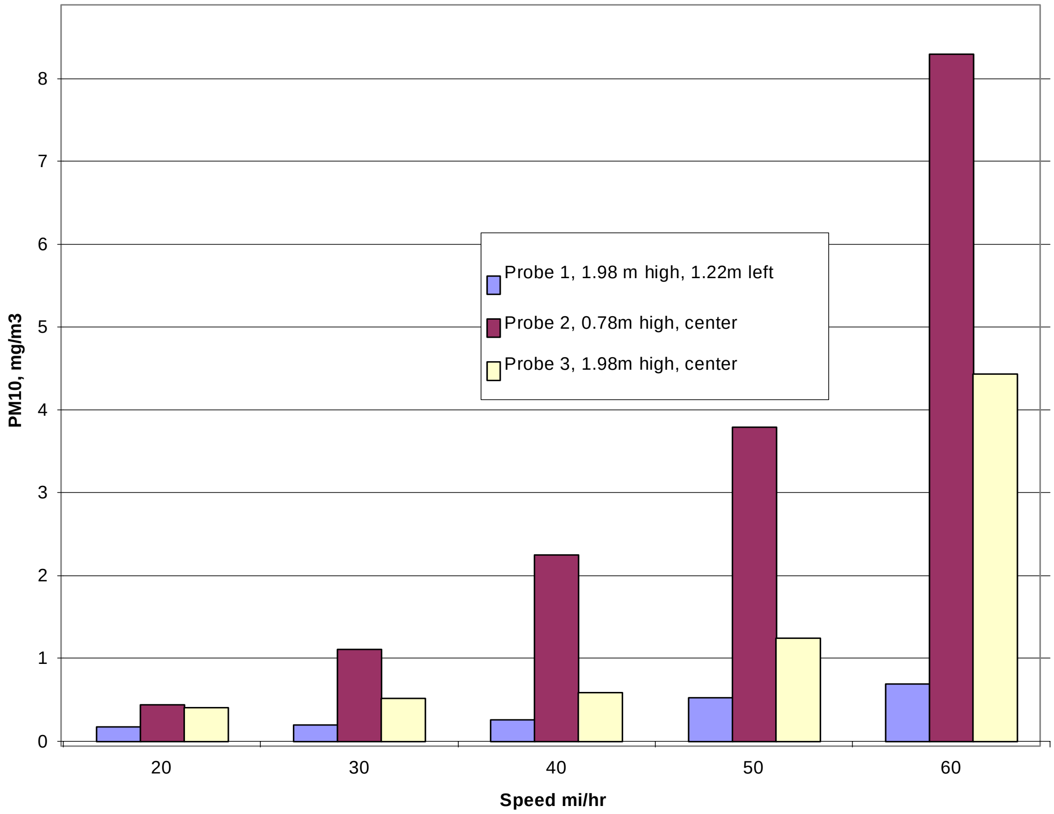

Figure 3-10. PM_{10} concentration while towing the test trailer at various speeds with two of the isokinetic sampling probes located 78 inches (1.98 m) above the ground.

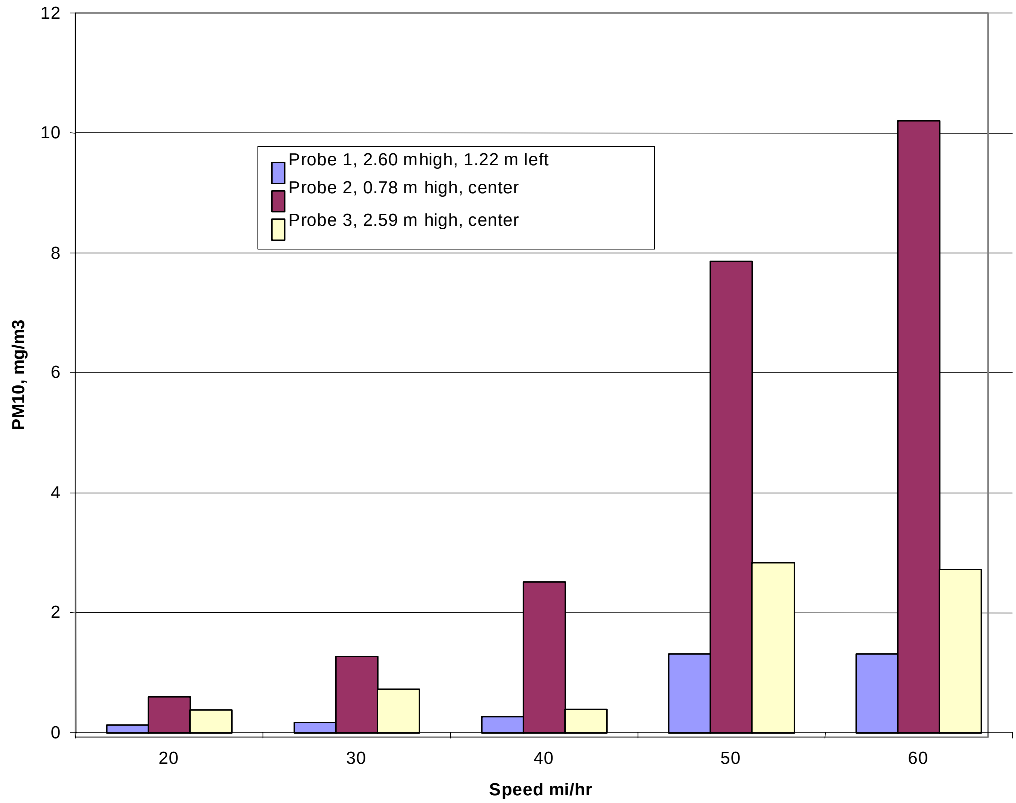

Figure 3-11. PM_{10} concentrations while towing the test trailer at various speeds with two of the isokinetic sampling probes located 102 inches (2.59 m) above the ground.

- **On-Vehicle Real-Time Emission Measurements**

Segments of roadways were driven at several different speeds as safety and road conditions permitted. For surface streets, segment was defined as the total time and distance traveled between stops (stop sign, stoplight, or sharp turn). For freeways the segments were the distance from entering to exiting the freeway. The roadways driven were defined as the following:

> Freeways: Four or more lanes with a car count of at least 150,000 cars per day.
>
> Arterial: Three, four, or more lanes with a car count of 10,000 to 150,000 cars per day.
>
> Collector: Two lanes with a car count of 5 00 to 10,000 cars per day.
>
> Local: Two lanes with a car count of 500 or fewer cars per day.

Figure 3-12 is a map showing all the segments reported. Each segment is identified by a number that refers to a location described in Table 3-3.

Figure 3-12. Road segments used to measure PM emissions.

Table 3-3. Identification of road segments.

ID #	Roadway name and location	Direction	Roadway type
1	La Cadena Ave. between Rancho Ave and La Loma Ave	North and South	Arterial
2	Columbia Ave. between CE-CERT and Iowa Ave.	North and South	Collector
3	Hidden Springs Ave	North and South	Local
4	60 Freeway between Pigeon Pass Rd. and Perris Blvd.	East and West	Freeway
5	60 Freeway between Pigeon Pass Rd. and Perris Blvd.	East and West	Freeway
6	Mountain View Dr.	East and West	Local
7	91 freeway from Columbia to Van Buren	South	Freeway
8	91 Freeway between Van Buren Blvd. and Madison	North and South	Freeway
9	Van Buren Blvd between Dufferin Ave. and Mockingbird Canyon	North and South	Arterial
10	Van Buren Blvd between Dufferin Ave. and Mockingbird Canyon	North and South	Arterial
11	Dufferin Ave between Stewart St. and Van Buren Blvd.	East and West	Local
12	215 Freeway from Blaine	East	Freeway
13	Heacock St between Ironwood and Sunnymead Blvd	North and South	Collector
14	Ironwood Ave. between Heacock St. and Perris Blvd.	East and West	Collector
15	Perris Blvd. between Ironwood Ave. and Sunnymead Blvd.	North and South	Collector
16	Sunnymead Blvd. between Heacock St. and Perris Blvd.	East and West	Collector
17	60 Freeway E from Perris Blvd to 215 N, To 10 W, exit Sierra	East, North, West	Freeway
18	Main St. between Columbia Ave. and Riverside Ave.	North	Arterial
19	Riverside Ave. between Agua Mansa Rd. and Garner Rd.	North and South	Arterial
20	Slover Ave. between Riverside Ave. and Cedar Ave.	East and West	Collector
21	Jurupa Ave between Willow Ave. and Cedar Ave.	East and West	Arterial
22	Cedar Ave/Rubidoux Blvd. between 11th St. and Avalon St.	North and South	Arterial
23	Central Ave. between Watkins Ave. and Canyon Crest	North and South	Arterial
24	Alessandro Blvd. between Sycamore Canyon Blvd. and Mission Grove Pkwy.	East and West	Arterial
25	Sycamore Cyn. Blvd. between Alessandro Blvd and Eastridge Ave.	North and South	Arterial
26	Market St. between Rubidoux Ave and 24th St.	North and South	Arterial
27	60 Freeway between Market St and Spruce St.	South	Freeway

Table 3-4 shows the number of segments of various types for which we report data. Thirty-second averages were taken within each segment. DustTrak #1 is the reference, mounted in front of the vehicle, DustTrak #2 is on the trailer at the centerline 0.78m from the ground, and DustTrak #3 is in a similar location except 2.59 m above the ground.

The collocated data from the entire sample period were compiled and the data were normalized to DustTrak #1 to improve the comparability. This was done by regressing DustTraks #2 and #3 against DustTrak #1 using the following equations:

DustTrak #2 normalized = 0.86(DustTrak #2 raw) –0.001 ($R^2 = 0.967$)

DustTrak #3 normalized = 0.94 (DustTrak #3 raw) + 0.013 ($R^2 = 0.986$)

Table 3-4. Number of segments for which PM emission measurements were made.

Roadway Type	PM sampled	20 MPH	25 MPH	30 MPH	35 MPH	40 MPH	45 MPH	50 MPH	55 MPH	57 MPH	60 MPH
Freeway Roadway	10					1		1	12	2	
Freeway Roadway	2.5				1				7	1	
Arterial Roadway	10					4	44	3	4		
Arterial Roadway	2.5					2	27		5		
Collector Roadway	10						22				
Collector Roadway	2.5						17				
Local Roadway	10				15						
Local Roadway	2.5				15						
Decomposed Roadway	10	4		6		6		6			6
Decomposed Roadway	2.5										
Unpaved Roadway	10	3	1	4		2		2			
Unpaved Roadway	2.5										

Table 3-5 has segment averages and emission factors for each roadway type driven for PM_{10} and $PM_{2.5}$ as well as segment averages when we followed a semi-truck on the freeway. Table A-2 in the Appendix shows the entire data set, with means, standard deviations, number of 30-second averages, and standard error of the mean for each DustTrak on each road type for each speed traveled. The table also presents the difference of DustTrak 2 from DustTrak 1, and DustTrak 3 from DustTrak1. An emission factor was calculated for each segment and is also shown in this table.

To calculate emission factors we assumed that a wake of the dimensions of the vehicle's frontal area was swept out and that the PM emissions remained within this volume until the point of measurement. We further assumed that the mean of the two PM measurements behind the vehicle (one located at 0.76 m and the other at 2.59 m above the road surface was representative of the concentration within the plume created by the wake). The emission rate was therefore calculated by multiplying the frontal area by the concentration. This results in units of mg/m, which was then converted to mg/km by multiplying by 1000.

Table 3-5. Average PM emission rates for various road types.

DustTrak #1[a] (mg/m^3)	DustTrak #2[b] (mg/m^3)	DustTrak #3[b] (mg/m^3)	Difference DustTrak #2-#1 (mg/m^3)	Difference DustTrak #3-#1 (mg/m^3)	Road type	DustTrak #2-#1 emission factor[d] (mg/km)	DustTrak #3-#1 emission factor[d] (mg/km)	PM
0.019	0.040	0.040	0.021	0.021	Local	68.7 +/- 4.9	68.0 +/- 4.8	10
0.044	0.057	0.053	0.013	0.009	Collector	43.2 +/- 3.1	30.7 +/- 2.2	10
0.059	0.088	0.073	0.030	0.015	Arterial	98.4 +/- 7.0	48.6 +/- 3.5	10
0.056	0.089	0.061	0.033	0.005	Freeway	79.3 +/- 5.6	14.9 +/- 1.1	10
0.072	0.105	0.081	0.032	0.008	Before truck	106.8 +/-12.2	27.1 +/- 1.9	10
0.093	0.102	0.085	0.009	-0.008	Behind truck	29.7 +/- 3.3	-28.0 +/- 2.0	10
0.180	0.044	0.053	-0.136	-0.127	Passing truck	176.1 +/- 51.2	-448.0 +/- 31.8	10
0.019	0.015	0.028	-0.003	0.009	Front of truck	93.0 +/- 1.3	-11.2 +/- 0.8	10
0.012	0.031	0.032	0.019	0.020	Local	61.1 +/- 4.3	64.9 +/- 4.6	2.5
0.074	0.084	0.079	0.010	0.005	Collector	31.7 +/- 2.3	15.4 +/- 1.1	2.5
0.048	0.058	0.058	0.013	0.011	Arterial	41.5+/- 3.0	35.7 +/- 2.5	2.5
0.026	0.035	0.038	0.009	0.013	Freeway	29.4 +/- 2.1	41.3 +/- 2.9	2.5

a) DustTrak #1 in front 1.07 m from ground, 0.42 m from vehicle, centered
b) DustTrak #2 on trailer 0.76 m from ground, 4.26 m from vehicle, centered
c) DustTrak #3 on trailer 1.35 m from ground, 4.26 m from vehicle, centered
d) Emission factor = (PM concentration difference, mg/m^3)*(frontal area, $3.30m^2$)*$1000mkm^{-1}$

The data in Table 3-5 show that there are measurable PM_{10} emissions in the wake of the test vehicle. Local roadways, traversed at moderate speeds of 35 mph, had a mean difference of 0.21 mg/m^3 between the front and the two levels sampled in the rear of the test vehicle. Both rear elevations showed similar concentration differences. We calculated an average emission factor of 68 mg/km for these roads. Based on our collocated DustTrak and filter-based measurements, multiplying this value by 1.74 would convert the DustTrak response to mass filter measurements and yield 118 mg/km.

Collector roads were traveled at an average speed of 45 mph. The average concentration difference was 0.013 mg/m^3 at the 0.76 m elevation and 0.009 mg/m^3 at the 1.35 m sampling position. At the greater speed the plume may have higher concentration near the ground. The average PM_{10} emission rate was 64 mg/km on a corrected mass basis (i.e., DustTrak values multiplied by 1.74 to obtain corrected mass). Both the arterial and freeway was traveled at an average speed of 50 to 55 mph. The average concentration difference for the arterial roadway at the 0.76 m position was much higher, 0.030 mg/m^3, than the higher position or the local or collector roads. The average emission rate on the corrected mass basis was 129 mg/km. The emission rates from the freeway driving was between arterial and collector roads but the much lower emission from the measurements at 1.35 m indicate that even more of the plume remains lower to the ground. The average corrected mass basis emission rate was 82 mg/kg.

Table 3-6 compares the emission factors from this study with others expressing the results in grams per vehicle kilometer travels (VKT) and pounds per vehicle mile traveled (VMT). The data indicate that the low end of the emission factors are similar to the other studies, but we did not find the spread observed by these other studies. The values are also lower than the default values calculated by AP-42 using silt loadings. Unlike the other studies that measured emission rates from concentration differences, it is possible that the roads we evaluated had low amounts of PM-generating material being deposited on them. The other studies also did not report negative concentration differences (i.e., downwind concentrations lower than upwind) since such results cannot be modeled. Their values would then be skewed high, particularly when making measurements near the detection limit.

Table 3-6. Comparison of PM_{10} emission factors reported by other sources.

Study	**Road Type**	**Emission Factor (g/VKT)**	**Emission Factor (lbs/VMT)**
This Study	Freeway-local	0.06 – 0.13	0.00022-0.00047
Venkatram and Fitz, 1998	Freeway-local	0.1-0.3	0.00036-0.0011
Cahill et al., 1995	Intersection	<0.3	<0.001
Claiborn et al., 1995	Freeway-local	0.5 to 34	0.0018-0.12
Harding and Lawson, 1996	Freeway-local	0.03 to 180	0.00011-0.65
AP-42 Default[a]	Arterial-local	0.08-0.53	0.00030-0.0019
ARB Default	Arterial-local	0.10-0.61	0.00036-0.0022

a: From silt loadings measured in southern California, assuming 2 ton vehicles

The concentration differences we observed were generally higher, as expected than what we saw for upwind-downwind measurements. Since the concentration differences are higher and a much greater amount of roadway was sampled compared with upwind-downwind or silt measurements conducted at a single or several sites, we feel that this technique is able to measure PM emissions from vehicles with greater accuracy than previous determinations. This conclusion recognizes that we are assuming that the frontal area of the vehicle represents the volume of the plume behind the vehicle and that the concentrations within the plume are uniform. While these are significant assumptions, the assumptions and uncertainties of the other methods are likely to be as great or greater.

The data for $PM_{2.5}$ are in general agreement with those from PM_{10} sampling but lower in magnitude. Only a limited number of filter samples were collected for $PM_{2.5}$, and, therefore, we do not have a regression equation to adjust the values to a mass basis.

Only one test was performed passing a semi trailer-tractor. During the “Behind truck” segment, we were following approximately 20 feet behind it. This experiment showed highly variable concentration measurements and it is unlikely that the data would be useful even on a qualitative basis. In addition, while passing the trailer became somewhat unstable in the truck's wake. This experiment was not repeated due to safety concerns and the questionable usefulness of the data.

All types of roadways developed higher concentrations at the 0.76 m sampling position than at the 1.35 m sampling position for PM_{10}. Collector and arterial roadways produced higher concentrations at the 0.76 m sampling position and local and freeway roadways.

3.4 Trackout PM Emission Measurements

The data collected from the entire fixed site sample period were compiled, and the PM concentrations were normalized to DustTrak #1 before they were analyzed. (See section 3.2 for the regression equations used.) Figures 3-13 and 3-14 show time series plots of DustTrak measurements (30-second averaging time) for the trackout periods for $PM_{2.5}$ and PM_{10}, respectively. In these figures the upwind concentration is subtracted from the mean of the two downwind concentrations (2 and 11 m above the ground). These time series show that there is a small rise in the PM concentration differences between upwind and downwind locations during and immediately after application of the trackout material. This supports the observation that during application wakes from traffic in the southbound lane aerosolized the trackout material immediately after application. The concentration differences observed are not much larger, however, that the differences without the trackout material applied. This makes quantification difficult, although the results can be used to calculate an upper limit to the effect of trackout on the concentration. Due to 30 second averaging time required by the DustTrak to produce useful data, it was not feasible to measure the emission rate using the instrumented van as originally proposed. At 50 mph this would require a deposit over a quarter mile in length.

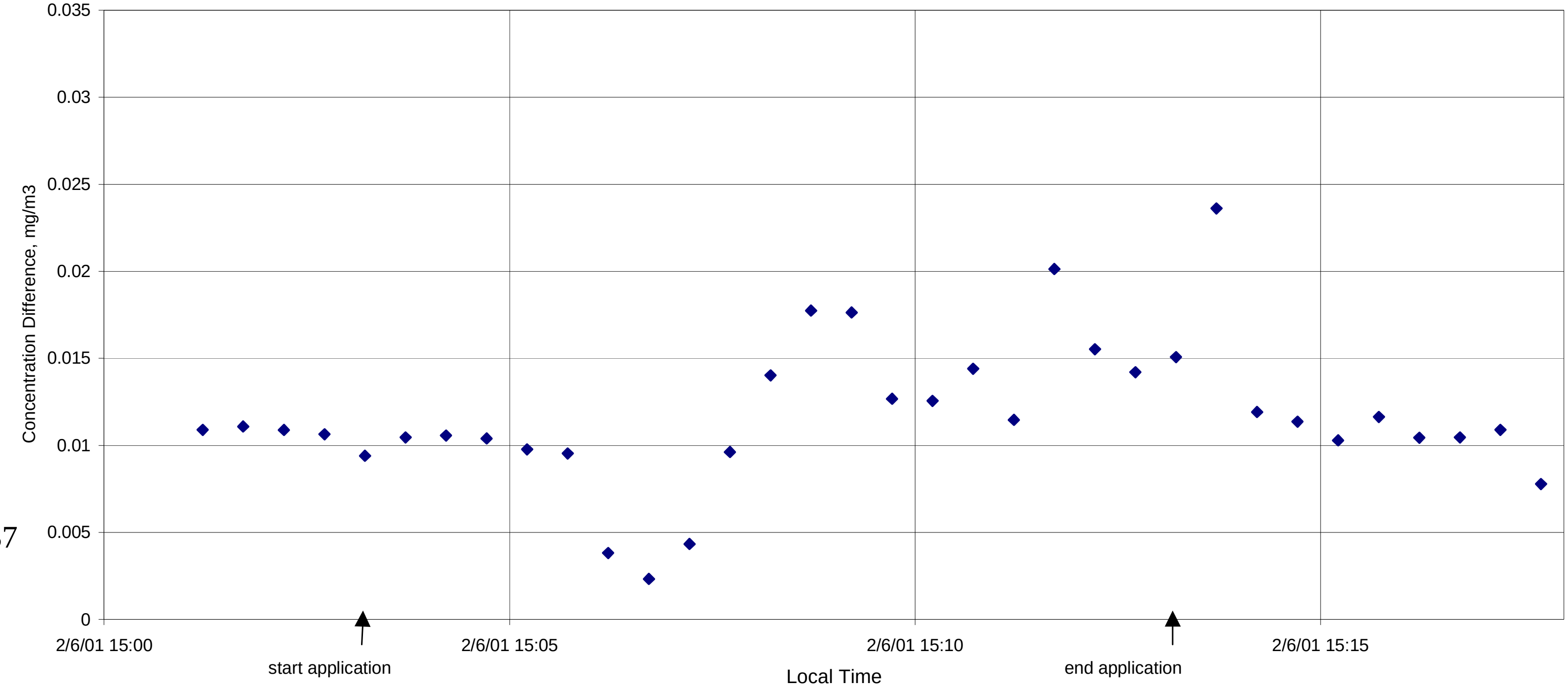

Figure 3-13. Time series plot of the difference in $PM_{2.5}$ concentrations between upwind and downwind DustTrak samplers.

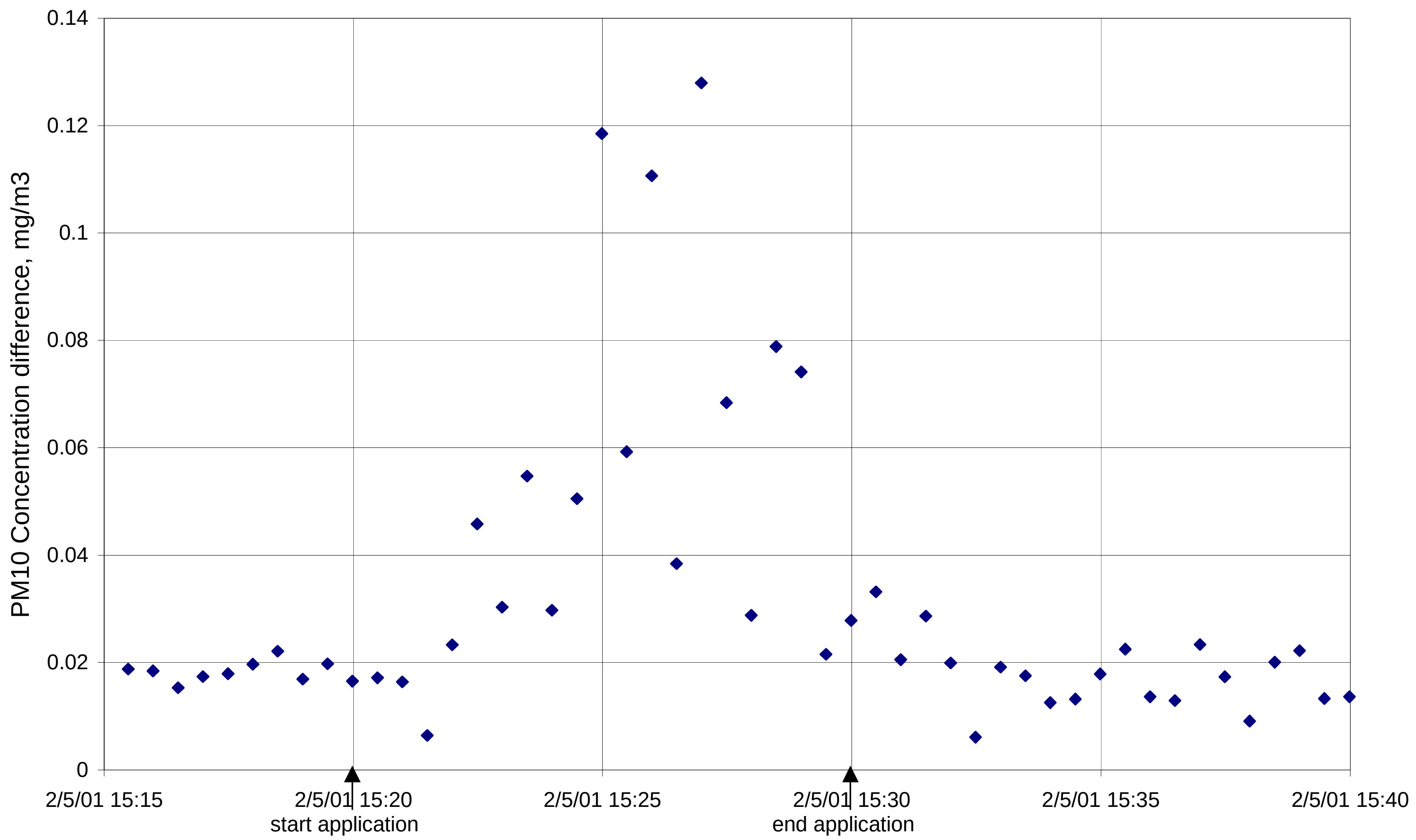

Figure 3-14. Time series plot of the difference in PM_{10} concentrations between upwind and downwind DustTrak samplers.

4.0 CONCLUSIONS

- **Upwind-Downwind Measurement**

We conducted measurements over several months and probably collected more data points than have ever been done in measuring the concentration differences across a roadway. The data showed that the difference between upwind and downwind PM concentrations was small compared with the background concentrations on the arterial road that was used. Compounding the problem was the sensitivity of the DustTraks response to temperature. This approach, for typical paved roads in California, is not useful in measuring PM emission rates.

- **On-Vehicle Measurements**

Real-time measurements in front of and behind a vehicle were found to be a useful method to characterize PM_{10} emission rates from paved roads. The emission rates ranged from 64 to 124 mg/km and are in general agreement, but on the low side, of those previously reported. By contrast, the current ARB emission factors range from 130 to 830 mg/kg using the AP-42 methodology with California-specific silt loading values. The emission rates did not vary a great amount from local roads with a few hundred cars per day to freeways with over 40,000 cars per day per lane of traffic. Unlike the upwind-downwind approach, a significant concentration differential was measured. The emission rate could also be calculated without applying modeling techniques that are also likely to have high uncertainty. Therefore, we feel that this approach is more accurate than the upwind-downwind approaches used in the past and also allows the testing of much longer sections of roadway with relatively little effort.

While the isokinetic sampler was successfully used, we were unable to construct a feedback loop to control the bypass flow. The reason was that the pitot tube was not a useful indicator of speed due to the interference from the wind, which caused rapid pressure fluctuations. These pressure fluctuations caused the bypass flow to continually overshoot the desired zero differential pressure set-point, resulting in a highly oscillating behavior. This would cause the inlet to alternately sample above and below the desired isokinetic flow rate. Adjusting the flow manually for a desired speed allowed us to sample much closer to isokinetic conditions.

- **Trackout Measurements**

The trackout experiments only provided some qualitative information of the PM_{10} emission rates from this source. The material was removed from the road by vehicle traffic within a few minutes after application. Although we could not quantify this rapid removal, the DustTraks showed an immediate response to the application of the material.

5.0 RECOMMENDATIONS

- **Upwind-Downwind Measurements**

Upwind-downwind measurements using DustTraks do not appear to be a useful approach to measuring emission rates from paved roads due to the DustTrak's limited resolution and significant temperature sensitivity. If these instruments are used for these studies they should be used on roads with higher PM emissions and the instruments maintained in very well ventilated shelters to maintain equal temperature as much as possible.

- **On-Vehicle Measurements**

The on-vehicle measurement approach could possibly be improved if the isokinetic sampling probe were automatically adjusted to compensate for vehicle speed. This would allow for more accurate data collection and minimize the need to constantly adjust the pumping speed manually for each change in vehicle segment speed. To achieve this goal a location for the static pressure probe is needed that will not change rapidly due to outside influences such as wind.

The mapping of the PM_{10} concentrations behind the plume was a labor-intensive exercise for which additional testing would be worthwhile. A GPS would be a very useful addition to log location, direction and speed. A device to stamp flags on the data logger with respect to driving conditions would also be useful. Measurements should focus on PM_{10} rather than $PM_{2.5}$ since this would produce a higher signal compared to the background noise. This is necessary since the concentration differences are low compared to the background and the instrumental sensitivity.

- **Trackout Measurements**

Trackout measurements should be made using a road that has at least two lanes in the same direction. This would allow us to safely stop traffic to apply the trackout material. A larger amount of material, perhaps an order a magnitude in loading, should be applied to increase the measurement sensitivity. Since trackout often involves construction equipment with mud caked on the wheels and body, the effect of either applying the material wet or to a wetted surface should be investigated. This would also greatly reduce the entrainment by nearby vehicles during application. Quantifying the effect of trackout material is difficult because entrainment and immediate dispersion is caused by the vehicle's wake with an influence from the prevailing wind. A line source would be the most appropriate condition to estimate the response and this would require a much longer application on the roadway, perhaps several hundred meters due to the affect of the vehicle's wake.

6.0 FUTURE RESEARCH NEEDS

Additional measurements are needed using the on-board real time measurement approach following the recommendations in the previous section. To meet the objective of determining the contribution of paved roads to the PM_{10} inventory the focus should be on driving on as many typical roads as possible rather than trying to determine the emission characteristics of each road at several speeds. While less comprehensive, this approach will yield measurements that will be extremely useful in developing effective policies to mitigate PM concentrations in urban areas.

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Appendix

Table A-1. Vehicle characterization test matrix results: average concentration, standard deviation, number of runs, and standard error of the mean of each sampler and their difference for each roadway and vehicle speed**.**

Location	Date		Estimated Speed (mph)	DustTrak 1 (mg/m^3)	DustTrak 2 (mg/m^3)	DustTrak 3 (mg/m^3)	Difference DT1 - DT2 (mg/m^3)	Difference DT3 - DT2 (mg/m^3)
Cabazon (decomposed roadway)**	05/17/00	avg	30	0.192	0.200	0.122	-0.008	-0.078
		sd		0.088	0.116	0.058	0.109	0.084
		n		19	19	19	19	19
		sem		0.020	0.027	0.013	0.025	0.019
		avg	40	0.442	0.429	0.319	0.013	-0.110
		sd		0.200	0.127	0.128	0.193	0.105
		n		12	12	12	12	12
		sem		0.058	0.037	0.037	0.056	0.030
		avg	50	0.928	0.928	0.630	0.000	-0.298
		sd		0.496	0.371	0.261	0.495	0.369
		n		10	10	10	10	10
		sem		0.157	0.117	0.082	0.157	0.117
		avg	60	1.226	1.297	0.941	-0.071	-0.356
		sd		0.585	0.750	0.482	0.583	0.397
		n		4	4	4	4	4
		sem		0.613	0.649	0.471	-0.036	-0.178
Cabazon (dirt road)**	05/19/00							
		avg	20	3.958	5.621	3.355	-1.663	-2.266
		sd		2.230	2.829	1.950	0.947	1.047
		n		3	3	3	3	3
		sem		1.288	1.633	1.126	0.547	0.604
		avg	25	13.571	14.047	16.742	-1.266	1.709
		sd		13.777	13.243	17.580	2.299	5.654
		n		4	4	4	4	4
		sem		6.888	6.621	8.790	1.150	2.827
		avg	30	14.707	15.583	17.206	-0.876	1.624
		sd		14.122	14.982	18.191	3.725	5.280
		n		4	4	4	4	4
		sem		7.061	7.491	9.096	1.862	2.640
UCR Moreno Field Station (dirt road)**	05/22/00							
		avg	20	0.688	1.356	0.855	-0.668	-0.500
		sd		0.588	2.186	0.875	2.028	1.881
		n		8	8	8	8	8
		sem		0.208	0.773	0.309	0.717	0.665

		avg	30	3.895	3.545	3.181	0.350	-0.364
		sd		3.606	3.486	3.084	0.777	1.137
		n		5	5	5	5	5
		sem		1.613	1.559	1.379	0.348	0.509
		avg	40	9.464	8.895	7.623	0.569	-1.272
		sd		8.746	8.265	7.800	3.709	3.840
		n		6	6	6	6	6
		sem		3.571	3.374	3.184	1.514	1.568
		avg	50	7.083	9.273	5.478	-2.189	-3.795
		sd		2.784	6.986	1.688	4.201	5.298
		n		2	2	2	2	2
		sem		1.969	4.940	1.193	2.971	3.746
Cabazon (decomposed roadway)*	05/26/00							
		avg	20	0.062	0.260	0.190	-0.198	-0.070
		sd		0.014	0.236	0.131	0.234	0.188
		n		27	27	27	27	27
		sem		0.003	0.045	0.025	0.045	0.036
		avg	30	0.090	0.560	0.399	-0.470	-0.160
		sd		0.111	0.774	0.553	0.770	0.769
		n		17	17	17	17	17
		sem		0.027	0.188	0.134	0.187	0.186
		avg	40	0.135	1.071	0.201	-0.937	-0.871
		sd		0.267	0.907	0.069	0.883	0.902
		n		13.000	13.000	13.000	13.000	13.000
		sem		0.074	0.251	0.019	0.245	0.250
		avg	50	0.649	3.978	1.548	-3.329	-2.431
		sd		0.549	1.793	1.555	1.768	1.718
		n		10	10	10	10	10
		sem		0.174	0.567	0.492	0.559	0.543
		avg	60	0.941	5.619	2.035	-4.679	-3.585
		sd		0.410	3.786	1.606	3.427	2.854
		n		8	8	8	8	8
		sem		0.145	1.338	0.568	1.212	1.009
Cabazon (decomposed roadway)**	05/26/00							
		avg	20	0.084	0.182	0.205	-0.098	0.023
		sd		0.084	0.182	0.205	-0.098	0.023
		n		25	25	25	25	25
		sem		0.017	0.036	0.041	-0.020	0.005
		avg	30	0.088	0.328	0.241	-0.240	-0.087
		sd		0.004	0.102	0.009	0.102	0.099
		n		8	8	8	8	8
		sem		0.002	0.036	0.003	0.036	0.035
		avg	40	0.135	0.739	0.307	-0.605	-0.433
		sd		0.080	0.324	0.048	0.335	0.305
		n		13	13	13	13	13
		sem		0.022	0.090	0.013	0.093	0.085
		avg	50	0.255	1.651	0.632	-1.397	-1.019
		sd		0.244	0.697	0.326	0.689	0.744
		n		10	10	10	10	10

		sem		0.077	0.221	0.103	0.218	0.235
		avg	60	0.345	3.516	2.020	-3.171	-1.496
		sd		0.134	1.278	1.541	1.193	2.209
		n		7	7	7	7	7
		sem		0.051	0.483	0.583	0.451	0.835

* DT2 & DT3 2.59 m from ground
** DT2 & DT3 1.98 m from ground

Table A-2. Concentration average, standard deviation, number of 30-second averages, standard error of the mean, differences, and emission factor of each sampler for each roadway and vehicle speed traveled.

	DustTrak 1 (mg/m3)	DustTrak 2 (mg/m3)	DustTrak 3 (mg/m3)	DustTrak 2-1 (mg/m3)	DustTrak 3-1 (mg/m3)	Road type	DustTrak 2-1 Emission factor (mg/Km)	DustTrak 3-1 Emission factor (mg/Km)
PM10 35mph						Local		
avg	0.027	0.053	0.050	0.026	0.023	Local	85.2 +/- 6.1	75.7 +/- 5.4
sd	0.007	0.010	0.010	0.005	0.006	Local		
n	20	20	20	20	20	Local		
sem	0.002	0.002	0.002	0.001	0.001	Local		
PM10 35mph						Local		
avg	0.013	0.033	0.036	0.020	0.023	Local	65.2 +/- 4.6	76.9 +/- 5.5
sd	0.003	0.006	0.004	0.006	0.003	Local		
n	32	32	32	32	32	Local		
sem	0.001	0.001	0.001	0.001	0.001	Local		
PM10 45mph						Collector		
avg	0.013	0.004	0.024	-0.009	0.011	Collector	-30.3 +/- 2.2	36.4 +/- 2.6
sd	0.007	0.007	0.006	0.005	0.005	Collector		
n	38	38	38	38	38	Collector		
sem	0.001	0.001	0.001	0.001	0.001	Collector		
PM10 45mph						Collector		
avg	0.049	0.060	0.049	0.011	0.000	Collector	35.9 +/- 2.6	0.1 +/- 0.0
sd	0.003	0.006	0.007	0.005	0.005	Collector		
n	25	25	25	25	25	Collector		
sem	0.001	0.001	0.001	0.001	0.001	Collector		
PM10 45mph						Collector		
avg	0.064	0.082	0.073	0.018	0.009	Collector	60.8 +/- 4.3	31.27 +/- 2.22
sd	0.009	0.019	0.034	0.015	0.033	Collector		
n	31	31	31	31	31	Collector		
sem	0.002	0.003	0.006	0.003	0.006	Collector		
PM10 50mph						Arterial		
avg	0.038	0.065	0.054	0.026	0.016	Arterial	87.1 +/- 6.2	53.6 +/- 3.8
sd	0.003	0.011	0.006	0.009	0.004	Arterial		
n	4	4	4	4	4	Arterial		
sem	0.001	0.006	0.003	0.004	0.002	Arterial		
PM10 55mph						Arterial		
avg	0.013	0.034	0.032	0.021	0.020	Arterial	70.6 +/- 5.0	64.7 +/- 4.6
sd	0.014	0.021	0.013	0.013	0.012	Arterial		

n	13	13	13	13	13	Arterial		
sem	0.004	0.006	0.004	0.004	0.003	Arterial		
PM10 40mph						Arterial		
avg	0.113	0.148	0.132	0.035	0.020	Arterial	115.1+/- 8.2	65.1 +/- 4.6
sd	0.071	0.083	0.066	0.018	0.013	Arterial		
n	16	16	16	16	16	Arterial		
sem	0.018	0.021	0.017	0.005	0.003	Arterial		
PM10 45mph						Arterial		
avg	0.035	0.046	0.039	0.012	0.004	Arterial	40.3 +/- 2.9	14.8 +/- 1.1
sd	0.010	0.017	0.010	0.014	0.009	Arterial		
n	60	60	60	60	60	Arterial		
sem	0.001	0.002	0.001	0.002	0.001	Arterial		
PM10 45mph						Arterial		
avg	0.090	0.142	0.092	0.059	0.013	Arterial	195.1 +/- 13.9	43.1 +/- 3.1
sd	0.091	0.097	0.099	0.094	0.078	Arterial		
n	87	87	87	87	87	Arterial		
sem	0.010	0.010	0.011	0.010	0.008	Arterial		
PM10 55mph						Freeway		
avg	0.042	0.065	0.049	0.022	0.007	Freeway	72.8 +/- 5.2	23.2+/- 1.7
sd	0.020	0.028	0.017	0.012	0.005	Freeway		
n	40	40	40	40	40	Freeway		
sem	0.003	0.004	0.003	0.002	0.001	Freeway		
PM10 57mph						Freeway		
avg	0.020	0.024	0.032	0.004	0.012	Freeway	14.5 +/- 1.0	40.0 +/- 2.8
sd	0.003	0.006	0.003	0.006	0.002	Freeway		
n	13	13	13	13	13	Freeway		
sem	0.001	0.002	0.001	0.002	0.001	Freeway		
PM10 55mph						Freeway		
avg	0.079	0.136	0.081	0.057	0.001	Freeway	186.6 +/- 13.3	4.0 +/- 0.3
sd	0.025	0.128	0.022	0.127	0.006	Freeway		
n	53	53	53	53	53	Freeway		
sem	0.003	0.018	0.003	0.017	0.001	Freeway		
PM10 55mph						Freeway		
avg	0.072	0.105	0.081	0.032	0.008	Freeway	106.8 +/- 7.6	27.1 +/- 1.9
sd	0.005	0.006	0.004	0.001	0.001	Freeway		
n	2	2	2	2	2	Freeway		
sem	0.003	0.004	0.003	0.001	0.001	Freeway		
PM10 50mph						Freeway		
avg	0.078	0.102	0.078	0.024	-0.001	Freeway	79.456 +/- 5.64	-2.044 +/- 0.15
sd	0.015	0.015	0.012	0.003	0.003	Freeway		
n	3	3	3	3	3	Freeway		

sem	0.009	0.009	0.007	0.002	0.002	Freeway		
PM10 50mph						Freeway		
avg	0.072	0.105	0.081	0.032	0.008	Before truck	106.8 +/- 7.6	27.1 +/- 1.9
sd	0.005	0.006	0.004	0.001	0.001	Before truck		
n	2	2	2	2	2	Before truck		
sem	0.003	0.004	0.003	0.001	0.001	Before truck		
PM10 40mph						Freeway		
avg	0.093	0.102	0.085	0.009	-0.008	Behind truck	29.7 +/- 2.1	-28.0 +/- 2.0
sd	0.017	0.015	0.011	0.009	0.007	Behind truck		
n	6	6	6	6	6	Behind truck		
sem	0.007	0.006	0.004	0.004	0.003	Behind truck		
PM10 55mph						Freeway		
avg	0.180	0.044	0.053	-0.136	-0.127	Passing truck	-448.0 +/- 31.8	-418.2 +/- 29.7
sd	0.274	0.022	0.020	0.274	0.267	Passing truck		
n	4	4	4	4	4	Passing truck		
sem	0.137	0.011	0.010	0.137	0.134	Passing truck		
PM10 55mph						Freeway		
avg	0.019	0.015	0.028	-0.003	0.009	Front of truck	-11.2 +/- 0.8	31.0 +/- 2.2
sd	0.003	0.006	0.004	0.003	0.001	Front of truck		
n	2	2	2	2	2	Front of truck		
sem	0.002	0.004	0.003	0.002	0.000	Front of truck		
PM2.5 35mph						Local		
avg	0.013	0.030	0.031	0.016	0.018	Local	54.2 +/- 3.9	58.1 +/- 4.1
sd	0.003	0.004	0.002	0.002	0.002	Local		
n	15	15	15	15	15	Local		
sem	0.001	0.001	0.001	0.001	0.000	Local		
avg	0.010	0.025	0.030	0.015	0.020	Local	49.8 +/- 3.5	65.0+/- 4.6
sd	0.001	0.001	0.001	0.001	0.001	Local		
n	9	9	9	9	9	Local		
sem	0.000	0.000	0.000	0.000	0.000	Local		
PM2.5 35mph						Local		
avg	0.011	0.026	0.031	0.016	0.021	Local	51.3 +/- 3.6	67.8 +/- 4.8
sd	0.001	0.001	0.001	0.001	0.001	Local		
n	20	20	20	20	20	Local		
sem	0.000	0.000	0.000	0.000	0.000	Local		

PM2.5 0mph						Collector		
avg	0.180	0.193	0.183	0.013	0.002	Collector	42.812 +/- 3.04	8.018 +/- 0.57
sd	0.006	0.005	0.003	0.002	0.004	Collector		
n	3	3	3	3	3	Collector		
sem	0.004	0.003	0.002	0.001	0.002	Collector		
PM2.5 20mph						Collector		
avg	0.181	0.201	0.191	0.021	0.010	Collector	67.783 +/- 4.81	33.706 +/- 2.39
sd	0.030	0.026	0.028	0.008	0.006	Collector		
n	10	10	10	10	10	Collector		
sem	0.010	0.008	0.009	0.003	0.002	Collector		
avg	0.018	0.021	0.029	0.003	0.010	Collector	8.736 +/- 0.62	34.426 +/- 2.44
sd	0.006	0.011	0.006	0.006	0.001	Collector		
n	40	40	40	40	40	Collector		
sem	0.001	0.002	0.001	0.001	0.000	Collector		
PM2.5 0mph						Collector		
avg	0.034	0.043	0.044	0.009	0.010	Collector	30.716 +/- 2.18	33.875 +/- 2.14
sd	0.007	0.012	0.007	0.006	0.005	Collector		
n	40	40	40	40	40	Collector		
sem	0.001	0.002	0.001	0.001	0.001	Collector		
PM2.5 0mph						Collector		
avg	0.030	0.037	0.032	0.007	0.002	Collector	23.473 +/- 1.67	5.593 +/- 0.40
sd	0.007	0.007	0.006	0.002	0.002	Collector		
n	5	5	5	5	5	Collector		
sem	0.003	0.003	0.003	0.001	0.001	Collector		
PM2.5 45mph						Collector		
avg	0.032	0.040	0.034	0.008	0.002	Collector	27.278 +/- 1.94	5.951 +/- 0.42
sd	0.005	0.006	0.005	0.001	0.001	Collector		
n	24	24	24	24	24	Collector		
sem	0.001	0.001	0.001	0.000	0.000	Collector		
PM2.5 0mph						Collector		
avg	0.060	0.067	0.059	0.007	-0.001	Collector	23.194 +/- 1.65	-2.709 +/- 0.19
sd	0.006	0.008	0.005	0.003	0.002	Collector		
n	19	19	19	19	19	Collector		
sem	0.001	0.002	0.001	0.001	0.000	Collector		
PM2.5 45mph						Collector		
avg	0.059	0.068	0.060	0.009	0.001	Collector	29.3 +/- 2.1	4.3 +/- 0.3
sd	0.004	0.004	0.003	0.001	0.001	Collector		

n	16	16	16	16	16	Collector		
sem	0.001	0.001	0.001	0.000	0.000	Collector		
PM2.5 50mph						Arterial		
avg	0.011	0.023	0.025	0.012	0.014	Arterial	38.9 +/- 2.8	47.6 +/- 3.4
sd	0.005	0.007	0.005	0.002	0.001	Arterial		
n	4	4	4	4	4	Arterial		
sem	0.002	0.003	0.002	0.001	0.001	Arterial		
PM2.5 55mph						Arterial		
avg	0.004	0.014	0.023	0.010	0.019	Arterial	32.198 +/- 2.29	61.740 +/- 4.38
sd	0.007	0.009	0.007	0.003	0.003	Arterial		
n	11	11	11	11	11	Arterial		
sem	0.002	0.003	0.002	0.001	0.001	Arterial		
PM2.5 0mph						Arterial		
avg	0.011	0.013	0.024	0.003	0.014	Arterial	9.057 +/- 0.64	44.985 +/- 3.19
sd	0.004	0.006	0.005	0.004	0.002	Arterial		
n	16	16	16	16	16	Arterial		
sem	0.001	0.002	0.001	0.001	0.001	Arterial		
PM2.5 0mph						Arterial		
avg	0.150	0.162	0.157	0.012	0.007	Arterial	38.7 +/- 2.8	24.2 +/- 1.7
sd	0.064	0.066	0.059	0.003	0.005	Arterial		
n	7	7	7	7	7	Arterial		
sem	0.024	0.025	0.022	0.001	0.002	Arterial		
PM2.5 40mph						Arterial		
avg	0.142	0.154	0.148	0.011	0.006	Arterial	37.451 +/- 2.66	18.564 +/- 1.32
sd	0.053	0.056	0.047	0.004	0.006	Arterial		
n	18	18	18	18	18	Arterial		
sem	0.012	0.013	0.011	0.001	0.001	Arterial		
PM2.5 0mph						Arterial		
avg	0.030	0.036	0.038	0.014	0.012	Arterial	46.427 +/- 3.30	39.667 +/- 2.82
sd	0.011	0.018	0.017	0.015	0.020	Arterial		
n	30	30	30	30	30	Arterial		
sem	0.002	0.003	0.003	0.003	0.004	Arterial		
PM2.5 45mph						Arterial		
avg	0.026	0.021	0.029	0.013	0.012	Arterial	42.4 +/- 3.0	39.5 +/- 2.8
sd	0.002	0.014	0.005	0.016	0.012	Arterial		
n	40	40	40	40	40	Arterial		
sem	0.000	0.002	0.001	0.002	0.002	Arterial		
PM2.5 0mph						Arterial		
avg	0.053	0.074	0.056	0.021	0.003	Arterial	68.5 +/- 4.9	8.3 +/- 0.6
sd	0.012	0.016	0.012	0.009	0.007	Arterial		
n	27	27	27	27	27	Arterial		

sem	0.002	0.003	0.002	0.002	0.001	Arterial		
PM2.5 45mph						Arterial		
avg	0.059	0.079	0.060	0.021	0.002	Arterial	68.808 +/- 4.89	7.647 +/- 0.54
sd	0.036	0.041	0.028	0.008	0.014	Arterial		
n	53	53	53	53	53	Arterial		
sem	0.005	0.006	0.004	0.001	0.002	Arterial		
PM2.5 0mph						Freeway		
avg	0.018	0.029	0.029	0.012	0.011	Freeway	38.324 +/- 2.72	37.664 +/- 2.67
sd	0.009	0.012	0.008	0.003	0.001	Freeway		
n	13	13	13	13	13	Freeway		
sem1	0.002	0.003	0.002	0.001	0.000	Freeway		
PM2.5 55mph						Freeway		
avg	0.004	0.014	0.023	0.010	0.019	Freeway	32.198 +/- 2.29	61.740 4.38
sd	0.007	0.009	0.007	0.003	0.003	Freeway		
n	11	11	11	11	11	Freeway		
sem	0.002	0.003	0.002	0.001	0.001	Freeway		
PM2.5 35mph						Freeway		
avg	0.019	0.024	0.034	0.005	0.015	Freeway	15.697 +/- 1.11	48.686 +/- 3.46
sd	0.004	0.004	0.003	0.001	0.001	Freeway		
n	4	4	4	4	4	Freeway		
sem	0.002	0.002	0.002	0.000	0.000736	Freeway		
PM2.5 57mph						Freeway		
avg	0.018	0.021	0.032	0.004	0.015	Freeway	12.533 +/- 0.89	48.955 +/- 3.48
sd	0.004	0.004	0.004	0.002	0.002	Freeway		
n	7	7	7	7	7	Freeway		
sem	0.002	0.001	0.001	0.001	0.001	Freeway		
PM2.5 55mph						Freeway		
avg	0.071	0.085	0.074	0.015	0.003	Freeway	48.037 +/- 3.14	9.506 +/- 0.67
sd	0.020	0.024	0.017	0.004	0.003	Freeway		
n	30	30	30	30	30	Freeway		
sem	0.004	0.004	0.003	0.001	0.001	Freeway		

Table A-3. The date, average concentration, standard deviation, number of 15-minute intervals, and standard error of the mean of the upwind downwind, and difference for each day for the stationary site.

Date		Average Upwind Conc. (mg/m^3)	Average Downwind Conc. (mg/m^3)	Conc. Difference (mg/m^3)
8/15/00	avg	0.106	0.105	0.001
	sd	0.039	0.035	0.010
	n	30	30	30
	sem	0.007	0.006	0.002
8/18/00	avg	0.053	0.055	-0.002
	sd	0.021	0.022	0.004
	n	35	35	35
	sem	0.004	0.004	0.001
9/19/00	avg	0.069	0.071	-0.002
	sd	0.029	0.028	0.007
	n	37	37	36
	sem	0.005	0.005	0.001
8/20/00	avg	0.080	0.081	-0.001
	sd	0.040	0.039	0.005
	n	36	36	36
	sem	0.007	0.006	0.001
8/21/00	avg	0.076	0.081	-0.006
	sd	0.015	0.014	0.007
	n	37	37	37
	sem	0.002	0.002	0.001
8/22/00	avg	0.138	0.132	0.005
	sd	0.056	0.044	0.014
	n	39	39	39
	sem	0.009	0.007	0.002
8/23/00	avg	0.136	0.129	0.007
	sd	0.058	0.045	0.016
	n	41	41	41
	sem	0.009	0.007	0.002
8/24/2000	avg	0.219	0.205	0.014
	sd	0.092	0.081	0.019
	n	22	22	22
	sem	0.020	0.017	0.004
8/25/00	avg	0.141	0.137	0.003
	sd	0.051	0.038	0.015
	n	40	40	40
	sem	0.008	0.006	0.002
8/26/00	avg	0.103	0.101	0.002
	sd	0.039	0.035	0.006
	n	41	41	41
	sem	0.006	0.006	0.001

8/27/00	avg	0.112	0.108	0.003
	sd	0.017	0.016	0.003
	n	34	34	34
	sem	0.130	0.126	0.053
8/28/00	avg	0.126	0.124	0.002
	sd	0.041	0.040	0.004
	n	41	41	41
	sem	0.006	0.006	0.001
8/31/00	avg	0.042	0.039	0.003
	sd	0.012	0.011	0.002
	n	18	18	18
	sem	0.003	0.003	0.000
9/1/00	avg	0.037	0.031	0.006
	sd	0.008	0.007	0.002
	n	21	21	21
	sem	0.002	0.002	0.000
9/16/00	avg	0.106	0.094	0.012
	sd	0.047	0.034	0.016
	n	25	25	25
	sem	0.009	0.007	0.003
9/17/00	avg	0.136	0.115	0.021
	sd	0.001	0.001	0.002
	n	33	33	33
	sem	0.000	0.000	0.000
9/19/00	avg	0.190	0.156	0.034
	sd	0.063	0.040	0.025
	n	29	29	29
	sem	0.012	0.007	0.005
9/20/00	avg	0.216	0.168	0.047
	sd	0.087	0.059	0.028
	n	37	37	37
	sem	0.014	0.010	0.005
9/21/00	avg	0.080	0.069	0.011
	sd	0.021	0.019	0.003
	n	37	37	37
	sem	0.003	0.003	0.000
9/24/00	avg	0.060	0.078	0.079
	sd	0.022	0.012	0.012
	n	29	29	29
	sem	0.004	0.002	0.002
9/25/00	avg	0.031	0.042	-0.011
	sd	0.031	0.033	0.007
	n	33	33	33
	sem	0.005	0.006	0.001
9/29/00	avg	0.188	0.184	0.005
	sd	0.070	0.053	0.021
	n	28	28	28
	sem	0.013	0.010	0.004
9/30/00	avg	0.245	0.221	0.024

	sd	0.069	0.050	0.02
	n	33	33	33
	sem	0.012	0.009	0.003
10/1/00	avg	0.292	0.264	0.029
	sd	0.064	0.062	0.012
	n	31	31	31
	sem	0.012	0.011	0.002
10/2/00	avg	0.159	0.158	0.001
	sd	0.046	0.032	0.017
	n	26	26	26
	sem	0.009	0.006	0.003
10/3/00	avg	0.167	0.158	0.009
	sd	0.093	0.073	0.022
	n	38	38	38
	sem	0.015	0.012	0.004
10/4/00	avg	0.050	0.062	-0.012
	sd	0.009	0.009	0.003
	n	34	34	34
	sem	0.001	0.001	0.000
10/5/00	avg	0.138	0.142	-0.004
	sd	0.042	0.040	0.004
	n	33	33	33
	sem	0.007	0.007	0.001
10/6/00	avg	0.131	0.141	-0.01
	sd	0.015	0.014	0.005
	n	34	34	34
	sem	0.003	0.002	0.001
10/7/00	avg	0.145	0.149	-0.004
	sd	0.017	0.018	0.003
	n	34	34	34
	sem	0.003	0.003	0.001
10/8/00	avg	0.243	0.213	0.031
	sd	0.043	0.027	0.018
	n	20	20	20
	sem	0.010	0.006	0.004
10/9/00	avg	0.271	0.234	0.037
	sd	0.044	0.030	0.016
	n	25	25	25
	sem	0.009	0.006	0.003
10/11/00	avg	0.016	0.022	-0.006
	sd	0.003	0.004	0.003
	n	10	10	10
	sem	0.001	0.001	0.001
10/12/00	avg	0.019	0.020	-0.002
	sd	0.013	0.012	0.002
	n	33	33	33
	sem	0.002	0.002	0.000
10/13/00	avg	0.056	0.051	0.005
	sd	0.021	0.019	0.004

	n	30	30	30
	sem	0.004	0.003	0.001
10/14/00	avg	0.052	0.044	0.008
	sd	0.034	0.032	0.004
	n	29	29	29
	sem	0.006	0.006	0.001
10/15/00	avg	0.084	0.074	0.01
	sd	0.016	0.015	0.004
	n	31	31	31
	sem	0.003	0.003	0.001
10/17/00	avg	0.045	0.038	0.007
	sd	0.030	0.028	0.008
	n	21	21	21
	sem	0.007	0.006	0.002
10/19/00	avg	0.273	0.196	0.077
	sd	0.031	0.018	0.015
	n	32	32	32
	sem	0.005	0.003	0.003
10/20/00	avg	0.379	0.294	0.085
	sd	0.065	0.062	0.017
	n	26	26	26
	sem	0.013	0.012	0.003
10/21/00	avg	0.042	0.062	0.041
	sd	0.018	0.023	0.018
	n	14	14	14
	sem	0.005	0.006	0.005
11/4/00	avg	0.000	0.005	-0.005
	sd	0.008	0.007	0.002
	n	30	30	30
	sem	0.001	0.001	0.000
11/5/00	avg	0.033	0.039	-0.006
	sd	0.009	0.008	0.003
	n	29	29	29
	sem	0.002	0.001	0.001
11/6/00	avg	0.084	0.092	-0.009
	sd	0.013	0.015	0.018
	n	26	26	26
	sem	0.003	0.003	0.004
11/7/00	avg	-0.009	0.000	-0.008
	sd	0.002	0.002	0.002
	n	35	35	35
	sem	0.000	0.000	0.000
11/8/00	avg	-0.001	0.010	-0.011
	sd	0.009	0.005	0.007
	n	30	30	30
	sem	0.002	0.001	0.001
11/10/00	avg	-0.017	-0.002	-0.014
	sd	0.004	0.002	0.005
	n	35	35	35

	sem	0.001	0.000	0.001
11/11/00	avg	-0.013	0.000	-0.013
	sd	0.009	0.005	0.007
	n	34	34	34
	sem	0.002	0.001	0.001
11/13/00	avg	0.003	0.012	-0.009
	sd	0.009	0.006	0.003
	n	15	15	15
	sem	0.002	0.002	0.001
11/14/00	avg	0.034	0.047	-0.013
	sd	0.009	0.012	0.01
	n	17	17	17
	sem	0.002	0.003	0.002
11/15/00	avg	0.028	0.055	-0.027
	sd	0.037	0.024	0.034
	n	29	29	29
	sem	0.007	0.004	0.006

Figure A-1. Composite time series of concentration difference and wind direction for 51-day period.

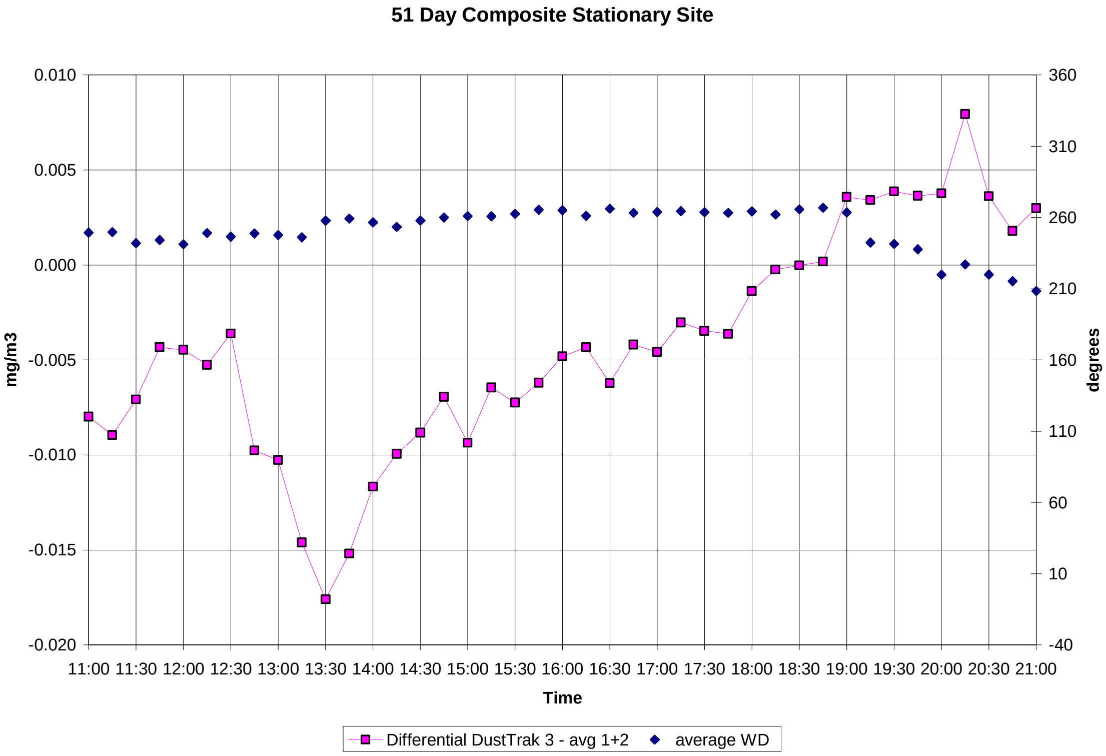

Figure A-2. Composite time series of concentration difference and wind speed for 51-day period.

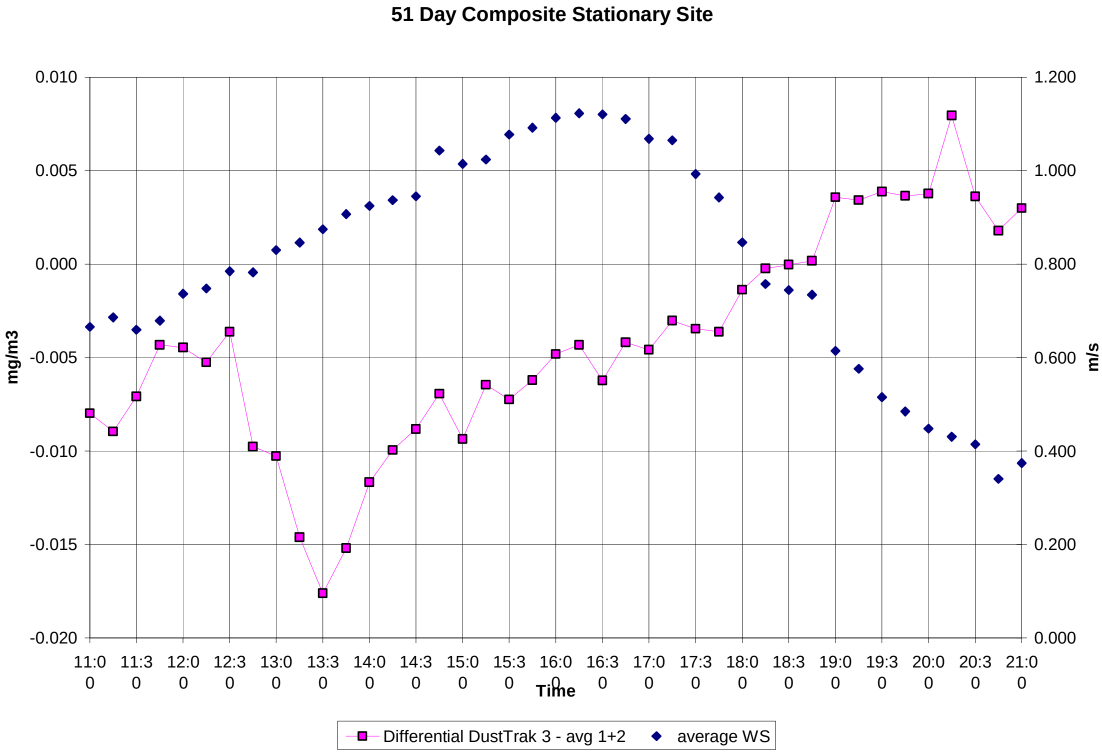

Figure A-3. Composite time series of concentration difference and % relative humidity for 51-day period.

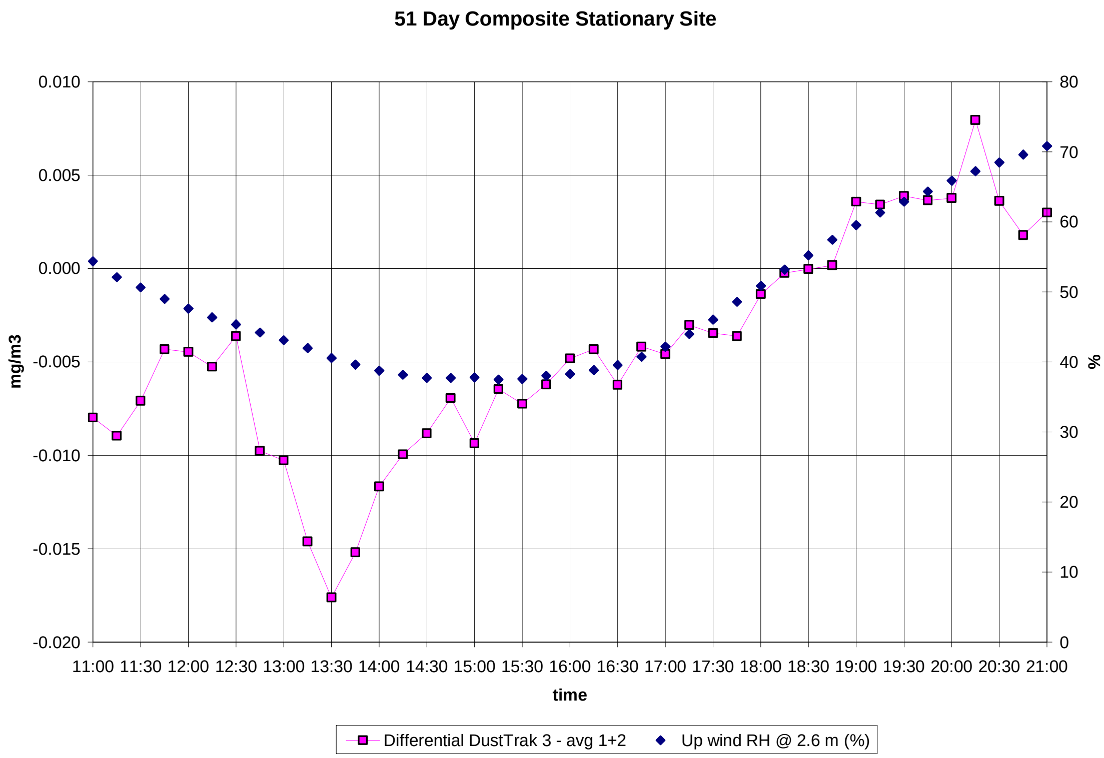

Figure A-4. Composite time series of concentration difference and temperature for 51-day period.