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Particulate Matter from Roadways

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U.S. Department of Transportation
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Paved roads constitute a major category of PM-10 and PM-2.5 emissions in urban areas. Paved roadway resuspension processes emit antiskid materials, abraded pavement particles, rubber tire fragments, and dirt that is tracked from unpaved areas. In the Denver area, exceedances of the PM-10 standard in late winter and early spring are related to residual road sand loadings from wintertime antiskid controls. This report presents the results of research, sponsored by the Colorado Department of Transportation, to (a) determine the relationships between the paved roadway surface dust characteristics and fine particle emissions, and (b) evaluate emission control measures that reduce road surface silt loadings (either by preventive or mitigative means).

Several types of field studies were used in performing this research. The Correlation Studies entailed simultaneous paved road plume profiling and road surface material sampling at three test sites in the Denver metropolitan area. The composition of collected airborne and surface samples were analyzed by chemical and microscopical analysis. The upwind/downwind airborne particulate matter samples that were selected for analysis included PM-10 and PM-2.5, while the road surface samples included the resuspended PM-10 and PM-2.5 from MRI's Dustiness Test Chamber. The Correlation Studies demonstrated that emission control effectiveness for the paved road resuspension processes can be evaluated in terms of reductions of roadway surface material loadings. Additional composite surface sampling of Denver arterial roadways compared the effects of winter sanding and alternative chemical deicers on surface loadings

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Preface

This report describes the results of work performed by Midwest Research Institute (MRI) and AlphaTRAC (subcontractor) under Contract No. 96H4401073 with the Colorado Department of Transportation. The report was prepared by Dr. Chatten Cowherd, Project Leader, with assistance from Dr. Greg Muleski and Mr. Gary Garman of MRI. Other MRI technical staff who contributed to the project included Ms. Mary Ann Grelinger, Mr. Michael Raile, and Mr. Andrew Page. The AlphaTRAC project staff included Mr. Michael McCarter (Project Leader for AlphaTRAC) and Mr. Reed Hodgin.

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Introduction

Dust reentrained from paved roads by vehicle traffic is considered to be a significant contributor to particulate air quality problems in several Colorado locations designated as PM-10 nonattainment areas. The State of Colorado is conducting technical studies designed to produce a better understanding of the relationship between reentrained road dust and PM-10 air quality. This report presents test results from a 3-year study of paved road emissions sponsored by the Colorado Department of Transportation (CDOT). The final year of the study ends on June 30, 1998. This study was divided into three tasks, as follows:

1. Task 1—Identify the size, chemical make-up, and dynamics of reentrained dust from roads.
2. Task 2—Develop standardized silt loading procedures, and
3. Task 3—Identify cost-effective particulate matter control strategies.

While the process of paved road dust entrainment is very complex in nature, data collected as early as 1975 indicate a significant relationship between resuspendable dust loading on the pavement surface and traffic-generated fine particle emissions. This is clearly supported by field observations of visible dust plumes from roads with heavy surface loadings. Such loadings often occur at mud/dirt "trackout" points around construction sites and in areas where fine antiskid abrasives accumulate after winter storm events.

It should be noted that most prior studies have found that non-dust components of particulate emissions (e.g., vehicle exhaust) from paved roads constitute a minor fraction of the PM-10 emissions, except for high speed roads. Also, recognizing that the dirt from track-on and vehicle underbody release tends to be ubiquitous, chemical composition of road surface material has been a relatively unsatisfactory indicator of uniqueness for paved road dust.

The subject study was directed to providing answers to the following critical questions:

1. What are the sources of dust on paved roads (in Colorado)?
2. What is the relationship between surface dust loading and PM-10 emissions?
3. How should the standardized surface loading measurement procedure be designed to best reflect the relationship in (2)?

4. What are the size and composition of paved road dust emissions?

5. How cost-effective are available and new emission control measures that reduce surface loading (either by preventive or mitigative means)?

Dynamics of Reentrained Dust From Roads

The particle size distribution of the exposed soil or surface material determines its susceptibility to mechanical entrainment by vehicle traffic. The upper size limit for particles that can become "suspended" (i.e., having a drift potential exceeding about 100 m when released from a ground-level source) has been estimated at about 75 µm in aerodynamic diameter. Conveniently, 75 µm in physical diameter is also the smallest particle size for which size analysis by dry sieving is practical. Below that particle size, wet sieving as a recommended method enhances particle disaggregation so that the texture of the material may be substantially modified in comparison with its "in place" condition. Particles passing a 200-mesh screen (74 µm opening) on dry sieving are termed "silt" by highway officials. Note that for fugitive dust particles, the physical diameter and aerodynamic diameter are roughly equivalent because of the offsetting effects of higher density and irregular shape.

In a series of predictive emission factor equations for fugitive dust sources, as published by USEPA, the silt content of an exposed dust-producing material has been used as a representative predictor of fine particle emissions. This applies not only to Total Suspended Particulate Matter (TSP, with a particle size cutpoint of approximately 30 µm in aerodynamic diameter) but also to the fine fraction components (PM-10 and PM-2.5).

Previous testing has shown that typically an "equilibrium silt loading" exists for a given road based on its traffic volume (ADT). Under this condition, the rate of emissions balances the rate of deposition. If the silt loading is higher than the equilibrium, because of the short-term addition of surface material (e.g., from antiskid material application), the emissions will be temporarily elevated, so that the rate of emission exceeds the rate of deposition. The emissions will decay to the equilibrium value as the equilibrium loading is approached. On the other hand, if the silt loading is temporarily decreased by surface cleaning (e.g., road sweeping), the decreased emissions will gradually increase to the equilibrium value, as the silt loading returns to the equilibrium value.

The equilibrium silt loading has been found to be inversely correlated with the average daily traffic (ADT) count. This inverse relationship in Equation 2 is consistent with the fact that roadways designed for high-volume traffic flow also tend to convey traffic at high speed (so that volume and speed are directly correlated). In addition to the self-cleaning effect of high-speed traffic, such roads provide less opportunity for track-on from unpaved areas, because of the buffering effect of paved feeder roads.

As roadways become cleaner, the resuspended dust component of the particulate emissions may lose its dominance over emissions from vehicle exhaust, from tire and brake wear, and from direct sloughing of particles from vehicle underbodies (tires, wheel wells, etc.). Therefore for such roads, silt loading may lose its effectiveness as a predictor of traffic-related particulate emissions from paved roadways.

Fugitive dust particle sizing is especially difficult because the fine particles are irregular in shape and tend to be attached to other particles. As a result of USEPA-sponsored collaborative tests of paved road dust "exposure profiling" and associated particle sizing,[5] high-volume *in situ* inertial particle sizing (cascade impaction with cyclonic preseparation) has continued as the method used for more than 15 years in support of the particle size data published in AP-42. Nevertheless, in spite of the steps taken to minimize the effects of particle bounce, residual particle bounce problems associated with the method continue to create uncertainty in particle sizing results, especially for PM-2.5.

Correlation Studies: Test Methods

"Correlation Studies" were performed in the Denver area, to examine what relationship exists between road surface loading and roadway emissions (on either a mass per VMT or a mass per road mile per hour basis). These studies combined roadway surface sampling with near-source air quality (4- to 6-hr periods) upwind and downwind of the roadway source with emphasis on investigating the air quality effects of winter storm events at Denver test sites. Specifically, the period of enhanced paved road particulate emissions subsequent to drying of the sanded road surface was of greatest interest.

Test Sites—Year 1

Two road sites were selected for testing during Year 1:

- I-225 south of I-70: high volume, high speed traffic.
- One-way facilities adjacent to Botanical Gardens: high volume, low speed traffic

These sites were selected primarily on the basis of road facility type (traffic volume and speed) with a center city representation.

After a given storm event, testing was performed on consecutive days (up to 6 hr sampling duration per day) after the road surface dried at the specific site identified for the test series. To the extent possible, each of the emission tests was performed during periods following snowfall, after the test road surface had dried. In most cases, sand application was ordered, because the relatively light snow conditions characteristic of the 1996 winter did not trigger routine sand application.

It should be noted that, as a general rule, a test had to be initiated by no later than 11:00 a.m. to provide sufficient time for collecting adequate sample mass prior to evening disorganization of winds and to avoid interfering with the evening rush hours. Therefore, if the given test road dried in the early afternoon, for example, it was necessary to postpone testing until the next day.

Test Site—Year 2

Because of the problems of achieving adequate testing efficiency at the first two sites during the winter of 1996 (which yielded a total of six complete profiling tests), it was decided to take two steps in redesigning the remainder of the Correlation Studies.

1. Move to a new "core" sampling site in an area with full wind exposure and other conditions that would expedite plume profiling, and
2. Combine (a) the testing of "artificial" sanding and wetting, during periods of moderate weather (autumn), with (b) the testing of significant wintertime storm events.

The main purpose of these changes was to increase the efficiency of profiling data collection and to increase PM-10 and PM-2.5 sample masses above the 1 mg adequacy threshold for chemical determination of elemental abundances. A test location on Kipling just east of the Denver Federal Center was selected as the Core Site.

It was recognized that the pre-winter sand applications would be removed from the test road more quickly by traffic in comparison with the sand removal rate from freshly dried roads after a winter snow/ice event. This effect would result primarily from more rapid evaporation of residual moisture films in the prewinter testing and unavailability of trapped sand in packed snow/ice strips between lanes and along the edges of the road. However, it was believed that the primary result would be simply to "speed up" the removal process from the three to four days that it would consume in the winter to a period of about one or two days in the autumn. Furthermore, the results of the autumn studies could be transferred to the wintertime based on a comparison of the silt loading decay curves for the two periods.

During Year 2, plume profiling (and associated surface sampling) was performed at the Core Site, as follows:

Test Series	Test Period
4 pre-winter baseline emission tests	mid-October 1996
7 pre-storm correlation tests (with sand application)	late October/early November 1996
8 post-storm correlation tests	February and March 1997

The pre-winter baseline emission levels were needed to establish the emission impacts of anti-skid materials, so that credits could be assigned to emission reductions resulting from (a) reduced sand application, (b) more effective removal of residual sand, or (c) use of chemical deicers with, or in place of, sand. (Alternatively, the pre-winter baseline emission levels could be projected from the pre-winter baseline silt loadings.)

Emission Testing Procedures

The source-directed field sampling conducted in this study employed an "exposure profiling" approach to characterize near-source particulate mass concentrations and particle size distributions by height.

Exposure Profiling

The "exposure profiling" technique is based on the profiling concept used in conventional (stack) testing. The passage of airborne pollutant immediately downwind of the source is measured directly by means of simultaneous, multipoint sampling over the effective cross section of the open dust source plume. This technique, which uses a mass flux measurement scheme similar to USEPA Method 5 for stack testing, does not require an indirect emission rate calculation through the application of a generalized atmospheric dispersion model. Further details of the exposure profiling method can be found in earlier technical reports, such as the 1986 USEPA collaborative study.[5]

For measurement of particulate emissions from the paved test roads, a three- to four-point vertical array of high-volume cyclone samplers was positioned approximately 5 m downwind from the edge of the road. The Sierra Model 230CP cyclone preseparator exhibits an effective 50% cutoff diameter (D_{50}) of approximately 10 µm when operated at a constant flow rate of 40 cfm (68 m^3/hr). The downwind distance of 5 m is far enough that sampling interferences due to traffic-generated turbulence are minimal, but close enough to the source that the vertical plume extent can be adequately characterized with a maximum sampling height of about 7 m.

Deployment for Year 1

The equipment deployment scheme for Year 1 made use of a variety of sampling instruments. The principal downwind plume reference height was 2 m. A reference PM-10 high-volume sampler (Wedding inlet) provided PM-10 samples for analysis of particle morphology.

For particle sizing, high-volume air samplers equipped with cyclone preseparators and parallel-slot, three-stage cascade impactors were used. This equipment is consistent with that used to develop the particle size multipliers that accompany the AP-42 predictive emissions factor equations for paved roads. The Sierra Model 230CP cyclone preseparator exhibits an effective 50% cutoff diameter (D_{50}) of approximately 15 µm (µm) in aerodynamic diameter when operated at a constant flow rate of 20 cfm (34 m^3/hr). The corresponding 50% cutoff aerodynamic diameters of the three-stage Sierra Model 233 cascade impactor are 10.2 µm, 4.2 µm, and 2.1 µm. The backup filter provides a PM-2.1 sample, with much larger sample mass than the fine fraction filters from the dichotomous samplers discussed below. The PM-2.1 sample was to be used for analysis of particle morphology.

The other set of particle-sizing samplers consisted of Sierra Anderson Model 245 dichotomous samplers with cut points of 10 µm and 2.5 µm. These samplers were operated in pairs at both the upwind and downwind locations. Within each set of paired dichotomous samplers, one was operated with Teflon filters and the other with quartz fiber filters. These sampling media were required for the chemical analyses that are described later.

Throughout each test, wind speed was monitored by "wind odometers" mounted at three downwind heights. The vertical wind speed profile was determined using data from these sensors, assuming a logarithmic distribution. Horizontal wind direction was also monitored at a single height using an R. M. Young wind monitor. The cyclone sampling intakes were adjusted for proper directional orientation based on the approximate average wind direction measured during consecutive observation periods.

Deployment for Year 2

The air sampling matrix for Year 1 was carried over to Year 2, which was initiated with the fall 1996 test period at the Core Site. However, because shifting winds limited the run time on most test days, most filters were exposed on more than one test day in the hope of achieving sample masses that would be sufficient for chemical characterization. The exception was the profiling cyclones, for which filters were changed after every test.

It should be noted that a minimum of 10% field blanks were collected for quality control (QC) purposes. This procedure involved handling at least one filter in every 10 in an identical manner as the others to determine systematic weight changes. These changes were then used to mathematically correct the net weight gain determined from gravimetric analysis of the filter samples. During field blank collection, filters were loaded into samplers and then recovered without operating the samplers.

Surface Sample Collection and Analysis

In conjunction with the emission tests, samples of the dust on the road surface were obtained. These samples were needed to characterize the test roads in terms of dust loading, texture, chemical composition, and particle morphology. The refined procedures developed as part of the silt loading method validation were used to collect and analyze paved road surface samples for determination of texture and loading.

Where practical, road surface sampling focused on the segment of the particular road being tested. For each test, a composite sample of at least three or four component surface areas was accumulated. Each component area had a width that matched an active travel lane and a length dimension that was based on the observed surface loading in comparison with the requirement for sufficient sample mass.

The MRI dustiness test chamber was used to suspend the road surface material for collection as PM-10 and PM-2.5 samples. The test chamber is a bench-scale device that generates and samples airborne particulate resulting from the dropping of bulk material (27 L) over a 25 cm distance to the floor of the chamber. In its standard configuration, air is drawn at 8.3 L/min through an open-faced 47 mm diameter filter at the top of the chamber for a period of 10 min beginning with the start of the 30 sec pouring period. For this series of tests, the chamber was modified from its standard configuration to incorporate a MiniVOL sampler with a PM-10 or a PM-2.5 inlet mounted in an inverted position.

In the case of the broom sweeper the removal efficiency for total loading was much higher than the efficiency for silt loading. In contrast, the vacuum sweeper exhibited nearly the same removal efficiency for total loading and silt loading. Because of the fractional power dependence of PM-10 emissions in silt loading, the corresponding PM-10 control efficiencies were correspondingly lower.

Source Activity Monitoring

Vehicle-related parameters were obtained using a combination of manual and automated counting techniques. Periodic manual traffic observation was used to acquire traffic volume data and to obtain traffic mix information. In addition, CDOT provided daily cycles of traffic volume for the Core Site on Kipling adjacent to the Denver Federal Center.

Chemical and Morphological Analysis

The four "best" tests from this phase of the project were selected for "correlation analysis," beyond the normal requirements for sample mass determination by gravimetry. Selection of these reward tests was based on occurrence of favorable conditions of the wind and the road surface.

For each of the four tests selected for correlation analysis, the following analyses (chemistry and particle morphology) was performed in late 1997:

- X-ray Fluorescence (37 elements)
- Ion Chromatography: chloride, nitrate and sulfate
- Thermal/Optical Reflectance: elemental and organic carbon
- Polarized Light Microscopy: silicate minerals, rubber tire fragments, and elemental carbon

Study Findings

Surface/Ambient Correlations

The Year 1 testing provided initial data on the mass concentrations/loadings and particle size distributions of in-place road surface material and airborne emissions at the two test sites after winter storm events. It also yielded emission factors that could be compared with USEPA's predictive model. The measured emissions were generally higher than the AP-42 predictions but well within the predictive accuracy of the emission factor equation. However, the measured emission factors correlated strongly with silt loading.

Lack of favorable wind conditions after winter storm events, which created significant problems in meeting the acceptance criteria for testing, limited the amount of testing that could be accomplished, especially at the site adjacent to the Denver Botanical Gardens. The testing at the I-225 site showed that the impact of wintertime sand application on high-speed high-volume roads with limited access is short-lived. Once the road surface dries, the residual sand is quickly thrown from the active road surface except in confined locations around ramps. This finding is significant in concluding that the air quality impact of such roadways appears to be relatively insignificant.

The Year 1 experience also demonstrated the need for selecting an additional test site with the more favorable wind exposure to accomplish more efficient field data acquisition for the remainder of Correlation Studies. Kipling Street just east of the Denver Federal Center was selected as the Core Site.

After measurement of the pre-winter baseline silt loading (Series 1) at the core site, the main test series (Series 2) was directed to studying the emissions resulting from sand application under simulated high-impact wintertime conditions of the road surface. At the beginning of a test day, the sand was applied and then immediately wetted. When the road surface had dried, the emission sampling began. Each test included both a full plume (exposure) profiling and a surface loading characterization.

As expected, in the absence of the "holding capacity" of snow and ice cover, the sand was thrown from the road much more rapidly than would occur during a significant wintertime snow event. This appeared to account for higher ratios of predicted to observed PM-10 emissions, due to the lack of opportunity for the silt to grind into finer components.

During this test series, a number of profiling samples were composited, to provide sample masses that were adequate for reliable chemical analysis. Compositing was done mostly for upwind samples and low-volume downwind samples.

The samples collected during this period were combined with those collected earlier in determining chemical and microscopical fingerprints of road surface and airborne particulate matter. Along with the mass concentration/loading and particle size data, this information would help establish the relationship between the road surface condition and the air quality impact over the winter storm cycle.

Percentage of Road Dust in PM-10 Emissions

Traffic generated paved road emissions consist of four components: vehicle exhaust, tire and brake wear, sloughing of underbody deposits, and suspended road dust. Of these components, only vehicle exhaust resides primarily in the fine fraction (PM-2.5) of PM-10. Background PM-10 on a "neighborhood" scale in a populated area surrounding an arterial roadway consists of roughly equal coarse and fine fractions.

The test data suggest that for clean arterial roadways, PM-10 emissions from the roadway also have coarse and fine fractions that are roughly equal. In other words, the vehicle exhaust emissions are approximately equal to the contributions from the other road emission components.

However, for the 24-hr period following a winter snow/road sanding event (i.e., just after the roadway has dried), the data indicate that the 24-hr average silt loading on an arterial roadway is in the range of 3 to 10 times higher than the winter baseline silt loading. For example in February 1997, the silt loading at the Core Site on Kipling was consistently about 0.25 g/m^2 until the day after a sanding event, when it increased to about 0.70 g/m^2 On the other hand in the winter of 1996, the silt loading on I-225 immediately after a sanding event (0.184 g/m^2) dropped to 0.0127 g/m^2 over the following two days.

Consistent with the PM-10 emission factor equation for paved roadways, the PM-10 emissions during a period with a 5-fold increase in silt loading, will increase by a factor of about 3 (above the baseline emission rate). Because virtually all of these increased emissions are in the form of road dust, the percentage of the total PM-10 emissions from road traffic that consist of road dust increases from about 50% to as much as 80% or 90% during the "high impact" 24-hr period following road sanding.

Prior tests of emissions from unpaved roadways and from heavily loaded paved roadways indicate that as little as about 10% of the PM-10 road dust emissions reside in the fine fraction (PM-2.5). Thus, for dry paved roadways that have been recently sanded, with more than 80% of the emissions in the form of road dust, the ratio of PM-2.5 to PM-10 in the road emissions may be as low as 10 to 15%. As the roadway returns to its baseline ("clean") condition for the season, the ratio of PM-2.5 to PM-10 emissions increases to roughly 50%.

The results of chemical analysis show that silicon is the most abundant element in both the PM-10 source emissions and the resuspended PM-10 components of associated road dust samples. This element is related to the composition of road sand used in Denver for wintertime antiskid control. Chlorine was also found to be an abundant element when the sand/salt mixture was applied to dry roads (artificial sanding).

Organic carbon is also abundant in the PM-10 emission samples but much less so in the resuspended road dust. The microscopical analysis results show that organic carbon can be associated mostly with tire wear particles. The relative absence of organic carbon in the resuspended PM-10 component of the road dust substantiates other recent findings that tire particles are directly emitted, rather than resuspended, from the road surface. Substantial amounts of nitrate and sulfate are also present in the upwind and downwind PM-10 samples but not in the resuspended road dust.

The roadway PM-2.5 impact also exhibits an abundance of silicon, chlorine (after artificial sanding), and organic carbon. Once again, these can be associated with the application of the salt/sand mixture and with the emissions of tire particles. The resuspended road dust PM-2.5 samples show a large silicon component but negligible organic carbon. As expected, soot (elemental carbon from unburned fuel) constitutes a larger fractional component in PM-2.5 than in PM-10.

Emission Control Effectiveness

In an effort to reduce the air quality impacts of wintertime sanding, various portions of the Denver Metropolitan Area have committed to reductions in sand application and to street sweeping programs to remove residual sand, as required to meet the goals of transportation conformity. The base year for determining the reductions is 1989. Sanding reductions for individual subareas, to be achieved by the year 2000, range from about 30% to as much as 75 %. Statistics on Denver area sand application already show substantial reductions in sand application over the past few years. The 1994-1995 application rate typically represents a reduction of at least 30% in comparison with the period around 1990. Also within the 6-county area, alternative deicers are being tested in many localities.

Understanding the relationship between road surface dust loading and PM-10 (or PM-2.5) emissions is critical to the evaluation of the effectiveness of (a) reduced sand application, (b) residual sand removal, and (c) chemical deicers in improving air quality. This requires an analysis of temporal cycles in surface loading around winter storm events. These cycles must be determined for each control measure, separately and in combination.

Reduced sand application has an immediate, and predictable, effect-or-reduced PM-10 emissions. This applies not only to the period of greatest air quality impact, when the road surface has dried immediately after a winter storm event, but also to the wintertime baseline condition. Less preferable as a control method is sweeping to mitigate the effects of road sanding. Year 2 testing of broom and vacuum sweeping effectiveness showed PM-10 control efficiencies of 60 to 70%, but these values were enhanced by the unrealistically high silt loading that was applied to a dry road for test purposes.

Answers to Key Questions

Q. *What are the sources of dust on paved roads in Colorado?*

A. The dust on paved roads in Colorado is dominated by mineral silicates. Winter sanding of paved roads increases the silt loading by up to two orders of magnitude (above the winter baseline value) when the road dries following a winter storm. Trackout of soil from areas adjacent to roadways also increases in the winter because of higher soil moisture levels. The contribution of road wear particles to the silt loading is also enhanced during the winter because of freeze/thaw cycles.

Q. *What is the relationship between surface dust loading and PM-10 emissions?*

A. The test data from this study strongly support the predictive emission factor equation for paved roads as published by USEPA. This equation contains silt loading as a "correction parameter" raised to the 0.65 power.

Q. *How should standardized surface loading measurement procedures be designed to best reflect the relationship discussed in the second question?*

A. The silt loading measurement procedures published by USEPA were refined in this study based on information gathered in the laboratory and field validation phases. The new sampling procedure is provided as Appendix A to this report.

Q. *What are the size and composition of paved road emissions?*

A. Most of the wintertime PM-10 emissions consist of mineral silicates from road sanding. Directly emitted tire particles generally constitute the next largest portions of paved road dust emissions. This is followed by elemental carbon from unburned fuel. Under high surface dust loadings, the PM-10 emissions from paved roads have a relatively small PM-2.5 component, ranging from about 10 to 20%.

Q. *How cost effective are available and new emission control measures that reduce surface loading (either by preventive or mitigative measures).*

A. Preventive methods are always more cost effective than mitigative (clean-up) methods. Reduction in the use of antiskid abrasives (sand) causes a direct, readily quantifiable reduction in PM-10 emissions. Street sweeping of residual sand, although relatively ineffective in reducing silt loading, has a more substantial benefit by reducing the reservoirs of sand accumulation in the gutters and other infrequently traveled areas. These reservoirs tend to feed grindable materials into the traveled portion of the roadway over long periods of time. Specific costs of silt loading (and emissions) control measures, which vary with geographic location, should be based on actual control application experience in the Denver area.

Section 1
Introduction

Dust reentrained from paved roads by vehicle traffic is considered to be a significant contributor to particulate air quality problems in seven Colorado locations designated as PM-10 nonattainment areas. The State of Colorado is conducting technical studies designed to produce a better understanding of the relationship between reentrained road dust and PM-10 air quality. This report reviews progress on a 3-year study of paved road emissions sponsored by the Colorado Department of Transportation (CDOT). This study is divided into three tasks, as follows:

1. Task 1—Identify the size, chemical make-up, and dynamics of reentrained dust from roads.
2. Task 2—Develop standardized silt loading[1] procedures, and
3. Task 3—Identify cost-effective particulate matter control strategies.

While the process of paved road dust entrainment is very complex in nature, data collected by MRI as early as 1975 (Cowherd et al., 1977) indicate a significant relationship between resuspendable dust loading on the pavement surface and traffic-generated fine particle emissions. This is clearly supported by field observations that visible dust plumes are observable only on roads with heavy surface loadings. Such loadings often occur at mud/dirt "trackout" points around construction sites and in areas where fine antiskid materials accumulate after winter storm events.

It should be noted that most prior studies have found that non-dust components of particulate emissions (e.g., vehicle exhaust) from paved roads constitute a minor fraction of the PM-10 emissions. Also, recognizing that the dirt from track-on and vehicle underbody release tends to be ubiquitous, chemical composition of road surface material has been a relatively unsatisfactory indicator of uniqueness for paved road dust.

The subject study is directed to providing answers to the following critical questions:

1. What are the sources of dust on paved roads (in Colorado)?
2. What is the relationship between surface dust loading and PM-10 emissions?
3. How should the standardized surface loading measurement procedure be designed to best reflect the relationship in (2)?

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[1] Silt loading refers to the size fraction of the dust loading on the paved road surface that passes a 200-mesh screen (75-μm opening); it is measured in units of grams per square meter of road surface area.

4. What are the size and composition of paved road dust emissions?

5. How cost-effective are available and new emission control measures that reduce surface loading (either by preventive or mitigative means)?

The remainder of this report is organized as follows: Section 2 provides technical background information. Section 3 presents the results of the Silt Loading Validation Study. Section 4 describes the test methods used in the Correlation Studies. Section 5 presents the results of the Correlation Studies conducted at the Core Site on Kipling in the fall of 1996 and winter of 1997. Section 6 describes the particle analyses for chemical and microscopical characteristics. Section 8 summarizes the findings of the study. Finally, Section 9 lists the references.

The appendices to this report contain supporting information. Appendix A presents the sampling procedure for road surface silt loading that was developed in this study. Appendix B provides the field and laboratory data from the correlation studies, and Appendix C presents an example calculation from the Exposure Profiling method.

Additional supporting data are available in the Supplement to the Final Report. It contains data from the chemical and microscopical analyses that were performed as part of this study. It also contains data from the road surface sample collection and analysis activity for determination of silt loadings.

Section 2
Background

This section presents background information for each of the three study tasks.

2.1 Size, Chemical Make-up, and Dynamics of Reentrained Dust from Roads

The particle size distribution of the exposed soil or surface material determines its susceptibility to mechanical entrainment by vehicle traffic. The upper size limit for particles that can become "suspended" (i.e., having a drift potential exceeding about 100 m when released from a ground-level source) has been estimated at about 75 µm in aerodynamic diameter (Cowherd et al., 1974). Conveniently, 75 µm in physical diameter is also the smallest particle size for which size analysis by dry sieving is practical (ASTM, 1984). Below that particle size, wet sieving as a recommended method enhances particle disaggregation so that the texture of the material may be substantially modified in comparison with its "in place" condition. Particles passing a 200-mesh screen (74 µm opening) on dry sieving are termed "silt" by highway officials. Note that for fugitive dust particles, the physical diameter, and aerodynamic diameter are roughly equivalent because of the offsetting effects of higher density and irregular shape.

Throughout Chapter 13 of the Emission Factor Handbook (AP-42) published by USEPA (1995), the silt content of an exposed dust-producing material has been used as a representative predictor of fine particle emissions. This applies not only to Total Suspended Particulate Matter (TSP, with a particle size cutpoint of approximately 30 µm in aerodynamic diameter) but also to the fine fraction components (PM-10, PM-2.5, and PM-1.0).

The AP-42 predictive emission factor equation for paved roads is as follows:

$$E = k\ (sL/2)^{0.65}\ (W/3)^{1.5} \tag{1}$$

where: E = particulate emission factor
k = base emission factor for particle size range and units of interest (see below)
sL = road surface silt loading (grams per square meter) (g/m^2)
W = average weight (tons) of the vehicles traveling the road.

This equation uses silt loading and average vehicle weight as predictors of the emission potential of a paved road surface.

It is important to note that Equation 1 calls for the average weight of all vehicles traveling the road. For example, if 99% of traffic on the road are 2-ton cars/trucks while the remaining 1% consists of 20-ton trucks, then the mean weight "W" is 2.2 tons. More specifically, Equation 1 is not intended to be used to calculate a separate emission factor for each vehicle weight class. Instead, only one emission factor should be calculated to represent the "fleet" average weight of all vehicles traveling the road. The particle size multiplier (k) above varies with aerodynamic size range as follows:

Particle Size Multipliers for Paved Road Equation

	Multiplier k[b]		
Size range[a]	g/VKT	g/VMT	lb/VMT
PM-2.5	2.1	3.3	0.0073
PM-10	4.6	7.3	0.016
PM-15	5.5	9.0	0.020
PM-30[c]	24	38	0.082

[a] Refers to airborne particulate matter (PM-x) with an aerodynamic diameter equal to or less than x micrometers.

[b] Units shown are grams per vehicle kilometer traveled (g/VKT), grams per vehicle mile traveled (g/VMT), and pounds per vehicle mile traveled (lb/VMT).

[c] PM-30 is sometimes termed "suspendable particulate" (SP) and is often used as a surrogate for TSP.

To determine particulate emissions for a specific particle size range, use the appropriate value of k above.

Previous testing has shown that typically an "equilibrium silt loading" exists for a given road based on its traffic volume (ADT). Under this condition, the rate of emissions balances the rate of deposition. If the silt loading is higher than the equilibrium, because of the short-term addition of surface material (e.g., from antiskid material application), the emissions will be temporarily elevated, so that the rate of emission exceeds the rate of deposition. The emissions will decay to the equilibrium value as the equilibrium loading is approached. On the other hand, if the silt loading is temporarily decreased by surface cleaning (e.g., road sweeping), the decreased emissions will gradually increase to the equilibrium value, as the silt loading returns to the equilibrium value.

The equilibrium silt loading has been found to be inversely correlated with the average daily traffic (ADT) count (Cowherd and Englehart, 1984), as follows:

$$sL = 21.3/(V^{0.41}) \qquad (2)$$

where: sL = surface silt loading (g/m^2)
V = average daily traffic volume (vehicles/d)

The inverse relationship in Equation 2 is consistent with the fact that roadways designed for high-volume traffic flow also tend to convey traffic at high speed (so that volume and speed are directly correlated). In addition to the self-cleaning effect of high-speed traffic, such roads provide less opportunity for track-on from unpaved areas, because of the buffering effect of feeder roads.

As noted in the Introduction, most prior studies have found that non-dust components of particulate emissions (e.g., vehicle exhaust) from paved roads constitute only a minor fraction of the PM-10 emissions. Also, recognizing that the dirt from track-on and vehicle underbody release tends to be ubiquitous, chemical composition of road surface material has been a relatively unsatisfactory indicator of uniqueness for paved road dust.

Of course, as roadways become cleaner, the resuspended dust component of the particulate emissions may lose its dominance over emissions from vehicle exhaust, from tire and brake wear, and from direct sloughing of particles from vehicle underbodies (tires, wheel wells, etc.). Therefore for such roads, silt loading may lose its effectiveness as a predictor of traffic-related particulate emissions from paved roadways.

The functional form(s) of the relationship between fine particle emissions and silt loading can be better defined by increasing the availability of reliable test results based on sound study designs and test methods. Temporal and spatial variations in silt loading (and emissions) make this assessment more difficult and require a larger database of emission tests.

Reliable emission factors for paved road dust (or any other sources) entail two critical requirements:

1. Availability of **accurate emission rates** from test roads (before and after control application).

2. **Representative test sites and conditions** relative to the paved road population of interest.

Of course, more data points alone cannot improve the reliability of emission factors. Any data gathered to augment the basis for emission factor development must be both accurate and representative to be useful.

Fugitive dust particle sizing is especially difficult because the fine particles are irregular in shape and tend to be attached to other particles. As a result of USEPA-sponsored collaborative tests of paved road dust "exposure profiling" and associated particle sizing (Pyle and McCain, 1986), high-volume in situ inertial particle sizing (cascade impaction with cyclonic preseparation) has continued as the method used for more than 15 years in support of the particle size data published in AP-42. Nevertheless, in spite of the steps taken to minimize the effects of particle bounce, residual particle bounce problems associated with the method continue to create uncertainty in particle sizing results, especially in the finer fractions of PM-10.

2.2 Standardized Silt Loading Procedures

Although a standard method exists for collecting and analyzing silt loadings on paved roads, it has never been collaboratively tested. This method was developed by MRI and is published in USEPA's *Compilation of Air Pollutant Emission Factors* (AP-42), Appendices C1 and C2. MRI has studied the use of different vacuum devices for collecting surface samples, and has found the natural variations in silt loading to be significantly greater than the variations created by using different vacuum devices. The greatest uncertainty in the method comes from the somewhat subjective judgment as to the line of demarcation between traveled and untraveled (e.g., curbed) portions of a paved road. Typically there is a sharp increase in loading on the untraveled portion.

The need for standardized procedures to collect and analyze paved road surface loadings is clear. As one example, consider that in a 1989 study of Denver roads, PEI Associates found a very strong correlation (significant well beyond the 1% level) between silt loading and measured emission factors for both "baseline" and sanded roadways (PEI Associates, 1989). On the other hand, no such relationship was found when RTP Environmental Associates used the same sampling plan in a 1990 study (RTP Environmental Associates, 1990). However, the 1990 road surface samples underwent *wet sieving* rather than the dry sieving procedure routinely used in fugitive dust studies. Results from the two types of sieving are not comparable. When the 1989 and 1990 databases were combined, the correlation disappeared, not unexpectedly. This led to a different approach to paved road emission factor development for the Denver area, as described above.

The question is often raised as to why resuspended PM-10 is not used in place of silt as a predictor of fine particle emissions. This would require that the surface sample be resuspended as the basis for determining its PM-10 component. The complex equipment and procedures for laboratory resuspension and PM-10 collection are available only in a few laboratory facilities nationwide. In addition, such methods are not standardized and have never been subjected to collaborative testing. Conversely, standard sieving to determine the dry silt fraction of a collected road surface sample can be performed by almost any testing laboratory. Finally and most importantly, the silt loading has been shown to be effective as a predictor for PM-10 emissions as well as total particulate emissions; this seems to reflect the existence of a consistent particle size distribution in the silt formed by fracturing processes.

MRI has long advocated both the development of standardized sampling/analysis methods as well as greater emphasis on quality assurance (QA) guidelines for paved road surface loading measurement. Our past studies (e.g., MRI, 1991) have found that *total loading* (i.e., total mass of loading, without regard to particle size) can vary between different vacuum cleaners and even different persons operating the same cleaner. *Silt loading*, on the other hand, has been found to be far less dependent. In addition, recognizing that surface loading can vary substantially along a road, the use of "embedded" collocated samples, as described in Section 3, is effective in smoothing out these variations.

2.3 Cost-Effective Particulate Matter Control Strategies

Methods for controlling dust emissions from paved roads focus on reduction of suspendable surface material. Preventive methods of control (i.e., those that reduce sources of elevated surface loadings) are generally much more cost effective than mitigative methods of control (i.e., those that entail removal of materials that constitute the elevated surface loading). The use of silt loading as a predictor of dust emission potential provides a direct, quantifiable measure of the effectiveness of the control.

Periodically applied control measures begin to decay in effectiveness almost immediately after implementation. Consequently, a single-valued control efficiency is usually not adequate to describe the performance of an periodic control.

In order to quantify the performance of a specific period control, two measures of control efficiency are required. The first is "instantaneous" control and is defined by

$$c(t) = \left(1 - \frac{e_c(t)}{e_u}\right) \times 100\% \qquad (3)$$

where: $c(t)$ = instantaneous control efficiency (%)
$e_c(t)$= instantaneous emission factor for the controlled source
e_u = uncontrolled emission factor
t = time after control application

The other important measure of periodic control performance is average efficiency, defined as

$$C(T) = \frac{1}{T}\int_{0}^{T} c(t)\,dt \qquad (4)$$

where: $C(T)$ = average control efficiency during the period ending at time T after application (%)
$c(t)$ = instantaneous control efficiency at time t after application (%)
T = time period over which the average control efficiency is referenced

The average control efficiency values are needed to estimate the emission reductions due to periodic applications.

The data on effectiveness of paved road dust controls are very limited and need to be expanded (Cowherd, et al., 1988). This reflects the challenges of fugitive dust emission measurement for tests of controlled road sections, because reduced silt loadings require that sampling times be lengthened. Moreover, control application parameters and ensuing traffic conditions need to be quantified just as carefully as the emission rate.

The MRI/AlphaTRAC approach to cost-effectiveness analysis is presented in the Technical Information Document that MRI prepared for USEPA in 1992 (USEPA, 1992). Cost effectiveness is simply the ratio of the annualized cost of the emissions control to the amount of emissions reduction achieved. Mathematically, cost effectiveness is defined by:

$$C* = \frac{C_a}{\Delta R} \qquad (5)$$

where: $C*$ = cost-effectiveness, \$/mass of emissions reduction
C_a = annualized cost of the control measure, \$/year
ΔR = reduction (mass/year) in annual emissions

This general methodology is equally applicable to different controls that achieve equivalent emissions reduction on a single source and to measures that achieve varied reductions over multiple sources.

The most common basis for comparison of alternative control system is that of annualized cost. The annualized cost of a fugitive emission control system includes operating costs such as labor, materials, utilities, and maintenance items as well as the annualized cost of the capital equipment. The annualization of capital costs is a classical engineering economics problem, the solution of which takes into account the fact that money has time value. These annualized costs are dependent on the interest rate paid on borrowed money or collectable by the plant as interest (if available capital is used), the useful life of the equipment, and the depreciation rates of the equipment.

Mathematically the annualized costs of control equipment can be calculated from:

$$C_a = CRF(C_p) + C_o + 0.5\, C_o \qquad (6)$$

where: C_a = annualized costs of control equipment, \$/year
CRF = Capital Recovery Factor, 1/year
C_p = installed capital costs, \$
C_o = direct operating costs, \$/year
0.5 = overhead factor

Capital costs for purchase and installation include freight, sales tax, and interest on borrowed money. The operation and maintenance costs reflect increasing frequency of repair as the equipment ages along with increased costs due to inflation for parts, energy, and labor. On the other hand, costs recovered by claiming tax credits or deductions are considered as income.

Section 3
Silt Loading Method Validation

This section describes the laboratory and field phases of the silt loading method validation. The laboratory validation was performed at MRI's main facility in Kansas City during May of 1996 (Year 1), and the field validation was performed at a Denver test site in September of 1996 (Year 2).

3.1 Laboratory Validation [Year 1]

This section describes a laboratory study that was performed to determine the efficiency of vacuuming as a technique for recovery of known amounts of silt loading (g/m^2) from flat surfaces. The dust characteristics, surface loadings, surface texture, and vacuuming devices were selected to represent ranges of field conditions encountered in performing paved road silt loading measurements according to the methodology promulgated by USEPA in AP-42. Although methods for collection and analysis of surface particulate samples from paved roads already exist in Appendix C-1 and C-2 of AP-42, these methods have never been fully investigated for quantitated uncertainty.[2]

Study Objectives

The purpose of this laboratory study was to characterize the performance of the vacuuming method for collection and analysis of surface materials as the basis for determining silt loading (g/m^2) on paved road travel lanes. Specifically, this study was directed to quantify total mass loading recovery associated with different vacuum devices, surface loadings, particle size distributions and surface textures.

The following parameters were varied in these experiments.

1. Surface roughness (3 test surfaces)
2. Size distribution of surface material (2 test dusts)
3. Level of surface loading (3 test loadings)
4. Type of vacuum devices (2 test devices)

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[2] A limited study was performed for USEPA by MRI in 1991 (MRI, 1991).

The tests were designed to examine the following **potential sources of inaccuracy** in silt loading measurement:

1. Incomplete pick-up of surface material
2. Line losses between pick-up head and collection bag
3. Fine particle penetration of collection bag
4. Losses during removal of sample from collection bag
5. Losses during sieving of sample.

Equipment Configuration and Test Materials

Paved road surfaces were simulated by 4 ft by 8 ft panels that lay flat on the floor and were mounted in external frameworks of 2" by 6"s ribbed with 2" by 4"s. A tempered masonite panel represented the limiting case of a smooth surface, and a coated fiberboard panel provided a rough textured surface. The rough texture was applied to the fiberboard panel using a masonry/basement paint containing Portland cement and silica (a waterproofing and sealing paint containing soya alkyd resin and mineral spirits from Wel-Cote Manufacturing Company). A third surface was a smooth metal surface used to determine vacuum bag penetration losses.

Simulated paved road surface loadings were prepared using two test materials. These test materials were blended from mixtures of a fine grade of Ottawa Foundry Sands (U.S. Silica sand F-70 and standardized Arizona coarse road dust—see size distributions in Figure 2). Two proportions of Arizona road dust to sand (0.1:1 and 0.46:1) were used to create test materials having 10% silt and 30% silt contents, respectively. A salt shaker was used to dispense pre-weighed material for different surface loadings on the 4 ft by 8 ft surface, excluding 2.5"-wide strips along the edges.

Two vacuum cleaners were used to collect the deposited material from the wood panels into tared bags for gravimetric analysis. The first device was a Dayton portable vacuum; the second vacuum was a Tornado model used by MRI on most previous road vacuuming tests. Standard vacuum bags supplied with each device were utilized. Both devices were equipped with backup foam filters.

Test Parameters

The test parameters that were characterized are listed below.

Surface texture

A. Smooth masonite 4 ft by 8 ft panel

B. Fiberboard 4 ft by 8 ft panel coated with masonry paint applied with roller; panel is dried and well-vacuumed before onset of testing

Silt content of surface material

Two test dusts were created from the U.S. Silica F-70 fine sand and Arizona SAE coarse test dust using proportions specified above.

A. Test dust with 10% silt content

B. Test dust with 30% silt content

Surface loading

A. Test dust with 10% silt content applied at 10 g/m^2 (heavy loading)

B. Test dust with 30% silt content applied at 2 g/m^2 (medium loading)

C. Test dust with 30% silt content applied at 100-200 g/m^2 (very heavy loading)

Vacuum cleaner

A. Dayton vacuum cleaner (portable handheld bench Model 2Z437F)

B. Tornado vacuum cleaner (Model Super 100)

Test Protocols

Two test protocols were utilized. Test Protocol I involved multiple vacuumings of a 4' x 8' surface area to collect sufficient mass for weighing. The steps involved in Test Protocol I are described below.

1. Condition surface to be tested. Surface will be conditioning by applying equal portions of U.S. Silica F-10 fine sand and Arizona SAE coarse road dust to panel surface using a soft bristle brush.

2. Thoroughly vacuum the panel after conditioning. Use bag that will not be weighed.

3. Start actual test procedure by placing new, tared bag and backup filter on vacuum cleaner.

4. Calculate number of tests required to obtain sufficient bag sample from desired loading. Based on tare weights of the bags, the Dayton bag requires a minimum 80 g of sample; the Tornado bag requires a minimum of 180 g of sample.

5. Prepare sample containers of U.S. Silica F-10 fine sand and Arizona SAE coarse road dust. Determine and record weights of each container.

6. From each container, weigh appropriate amounts of two selected test materials into a salt shaker for selected loading of panel. Swirl test material in shaker until visibly well mixed.

7. Sprinkle test dust onto panel surface, taking care to distribute evenly up to 2.5" of the edges/side frames.

8. Vacuum the panel according to method utilized in field sampling for the selected vacuum model.

9. Repeat steps 4 through 6 until sufficient sample has been collected.

10. Remove vacuum bag and backup filter and weigh immediately on Sartorius electronic balance; store bag and filter in separate plastic bags for later audit weighing. Examine and document appearance of backup filter as an indicator of pass-through of dust through vacuum bag.

11. Determine and record final weights of each container, as a check on the total amount of test material weighed into the salt shaker and deposited on the panel.

12. Record test data and provide comments on any test deviations in laboratory notebook or on data form, especially noting variations in test conditions or vacuuming operation, e.g., "forward/back motion estimated to cover each area twice."

13. Place new tared bag on vacuum cleaner; physically agitate vacuum to loosen any trapped material. Remove bag, weigh, and store appropriately for audit weighs.

Test Protocol II was conducted on a smooth metal surface to characterize vacuum performance and bag collection efficiency. Steps are presented below for the tests of vacuuming total sample mass within an approximate 1 min test duration.

1. Start actual test procedure by placing new, tared bag and backup filter on vacuum cleaner.

2. For Dayton vacuum, apply 80 g of test dust in pile on clean metal surface; for Tornado vacuum, apply 180 g of test dust to surface.

3. Vacuum all material from metal surface, observing and documenting auditory changes in motor speed due to overloading (clogging) of bag and total time to remove all material from surface.

4. Remove vacuum bag and backup filter and weigh immediately on Sartorius electronic balance; store bag and backup filter in separate plastic bags for later audit weighing.

5. Record test data and provide comments on test in laboratory notebook or on data form.

Samples of each of the three test materials were collected for later particle size analysis. Photographs were taken to document the test equipment setup.

Test Matrix

The test matrix is shown in Table 1. Except for the lowest loading, which required vacuuming of the test panel in more than 30 increments, each test was replicated to determine test precision. Following each test, the tared vacuum bag and backup filter were removed and final weighed. A second test bag collected any materials that could be shaken loose from the vacuum after sampling. Additional untared bags were utilized for clean-up and throwaway purposes after surface conditioning. In the bag penetration tests, known amounts of dust were added directly into the vacuum device inlet, so that no pickup or line losses were involved.

Vacuum collection efficiency was characterized by comparing bag and backup filter sample masses to the amount of test dust applied to the surface (or injected directly into the vacuum inlet).

As shown in Table 1, the surface recovery percentages were close to 100% in all cases. They averaged about 99% for the smooth test surfaces. The first series of test of recovery from the rough surface (runs 4, 5, and 6) showed slightly more than 100%; this is believed to be the result of small quantities of poorly bound silica in the masonry/basement paint. This effect disappeared in later runs where recoveries dropped to as low as 97%. The bag penetration tests showed about 99% recovery of the injected materials.

The surface recovery experiments were designed to examine the impacts associated with the first two sources of potential inaccuracy: pick-up and line losses. The bag penetration tests were directed to the third source of inaccuracy. Examination of actual data from recent paved road studies were used to assess the final two potential sources of inaccuracy: losses during sample removal from the collection bag and during sieving.

Table 1. Results of Laboratory Vacuuming Tests

Test No.	Vacuum	Surface	Silt content (%)	Surface loading (gm^2)	Bag recovery (%)
1	Dayton	Smooth—masonite	10	10	99.4
2	Dayton	Smooth—masonite	10	10	99.2
3	Dayton	Smooth—masonite	10	10	98.8
7	Dayton	Smooth—masonite	30	2	99.4
12	Tornado	Smooth—masonite	10	10	98.9
13	Tornado	Smooth—masonite	10	10	99.0
8	Dayton	Smooth—steel	30	> 100	98.4
9	Dayton	Smooth—steel	30	> 100	99.1
4	Dayton	Rough—masonry paint	10	10	102.5
5	Dayton	Rough—masonry paint	10	10	106.3
6	Dayton	Rough—masonry paint	10	10	103.6
14	Tornado	Rough—masonry paint	10	10	100.0
15	Tornado	Rough—masonry paint	10	10	97.0
18	Dayton	Rough—masonry paint	30	2	97.6
10	Dayton	Bag penetration test	30	100	100.0
11	Dayton	Bag penetration test	30	100	99.6
16	Tornado	Bag penetration test	30	200	98.9
17	Tornado	Bag penetration test	30	200	98.7

Significant amounts of actual data on losses during bag dissection and sieving are available from two prior MRI studies of contributors to elevated surface loadings on paved roads: antiskid materials and trackout from construction sites. In the study of the air quality impacts of antiskid materials (Kinsey, 1995), 68 samples were collected; the average loss of sample during bag dissection and sieving was 1.4% with a range of 0.1% to 4.1%. In the study of the air quality impacts of trackout from construction sites (Raile, 1996), 165 samples were collected; the average loss of sample was 1.0% with a range of 0.5% to 6.3%.

The errors in the method associated with incomplete recovery of surface material are small in comparison to the spatial (and temporal) variations in silt loadings on paved roadways. In the study cited earlier (MRI, 1991), the lowest percent differences in "colocated" samples obtained from two roads in the Kansas City area ranged from 10% to

22% when the "stick-broom" was used. When the heavy-duty vacuum cleaner was used, the percent difference in colocated samples increased substantially (43-69%), due in large part to the lack of sample mass in comparison to the bag weight.

3.2 Field Validation [Year 2]

This section presents the results of the field validation tests in September of 1996 to determine the interlaboratory reproducibility of silt loading measurements at paved road and parking lot test sites in the Denver metropolitan area.

The paved road surface sampling was performed independently by MRI and AlphaTRAC personnel, following the procedure that was included as an appendix to our final report for Year 1. Both laboratories used the Tornado Model Super 100 vacuum cleaner. This model was also used (along with the Dayton Model 2Z437F) in the laboratory study of silt collection efficiency, also described in the Year 1 report.

A total of five paved surface areas were sampled:

- Two segments of Kipling near the location of the Core Site for the Correlation studies
- Ohio Street near Fenton
- Two areas of the parking lot on the east side of Kipling and adjacent to the Core Site

At each location, alternating (colocated) strips of equal area were identified for sampling by AlphaTRAC and MRI. The strips were marked with colored string. The overall size of each sampling area, within which the strips were imbedded, reflected the visually estimated loading on the paved surface. For example, because Kipling itself showed little evidence of surface loading, a very large area was sampled to provide adequate sample mass.

The two laboratories functioned independently in collecting the samples. The laboratories started sample collection at opposite ends of the set of colocated strips. The persons collecting the samples did not talk to one another about sampling methods at any time during the field exercise. A separate MRI employee (who did not actually collect any samples) demarcated and assigned strips to the two laboratories. That employee also assigned sample identification labels and kept measurement records of site parameters.

The collected samples (in vacuum bags) were returned to the MRI laboratories in Kansas City for analysis. Again, the specified procedure was followed. The analysis was performed by an individual who was not present in the field.

The results of the validation study are shown in Table 2. (In the table, "A" refers to AlphaTRAC and "M" refers to MRI.) Interlaboratory agreement on measured silt loading was excellent on the roadway areas but poor on the parking lot areas. This poor comparison on the parking lot appears to reflect uneven distributions in silt loading which could not be compensated by the layout of sampling strips.

It is interesting to note that MRI consistently collected a larger total sample mass (with lower silt content) than AlphaTRAC; this is reflected by the significant differences in total loading. However, the sample mass differences were concentrated in particles larger than 75 micrometers, so that the calculated silt loadings were relatively unaffected. In other words, subjective differences in the vacuuming technique appear to affect the total sample mass but not the silt loading, because of its relative ease of pick-up from the road surface.

It is also interesting to compare the silt loadings measured on Kipling and Ohio with those obtained earlier on I-225 and the roads adjacent to the Botanical Gardens. The silt loading on I-225 ranged from 0.184 g/m^2 at the end of the day during which sand was applied to an average of 0.0127 g/m^2 over the next two days. The silt loading at the Botanical Gardens site was 1.47 g/m^2 shortly after a sand application.

Thus the pre-winter baseline on Kipling was only about twice that measured on I-225, at the time when most of the sand had been stripped from the road surface of I-225. Also, the consistency of the measured silt loading on the two sections of Kipling is remarkably good.

It can be concluded that the interlaboratory variation of silt loading measurements in this study was small compared to the expected differences between the pre-winter baseline and the wintertime values of silt loading on roads that are subjected to winter sand application.

Table 2. Interlaboratory Comparison of Silt Loading Data

Date	Site	Lab	Sample Area (ft^2)	Total Loading (g/m^2)	Silt Content (%)	Silt Loading (g/m^2)	Average Silt Loading (g/m^2)
9/10/96	Core Site Parking Lot—Area A (Even Strips)	M	312	95.41	5.3	5.05	3.58
9/10/96	Core Site Parking Lot—Area A (Odd Strips)	A	312	25.58	7.9	2.03	
-	Core Site Parking Lot—Area A (QA Split for Lab A Sample)	-	-	-	8.6	2.20	
9/10/96	Core Site Parking Lot—Area B (Odd Strips)	M	135	72.42	6.4	4.62	12.03
9/10/96	Core Site Parking Lot—Area B (Even Strips)	A	135	80.26	24.2	19.45	
9/10/96	Kipling (North of Cedar)	M	4500	0.25	10.7	0.027	0.028
9/10/96	Kipling (North of Cedar)	A	4250	0.10	29.4	0.030	
9/10/96	Ohio (West of Fenton)	M	320	7.81	6.0	0.47	0.50
9/10/96	Ohio (West of Fenton)	A	320	3.68	14.4	0.53	
9/11/96	Kipling (North of Fletcher School)	M	5890	0.12	17.8	0.021	0.025
9/11/96	Kipling (North of Fletcher School)	A	5875	0.11	26.2	0.028	

Section 4
Correlation Studies: Test Methods

The subject scope of work called for the performance of "Correlation Studies" in the Denver area, to examine what relationship exists between road surface loading and roadway emissions (on either a mass per VMT or a mass per road mile per hour basis). These studies, which were conducted under Task 1, combined roadway surface sampling with near-source air quality (4- to 6-hr periods) upwind and downwind of the roadway source with emphasis on investigating the air quality effects of winter storm events at Denver test sites. Specifically, the period of enhanced paved road particulate emissions subsequent to drying of the sanded road surface is of greatest interest.

4.1 Test Sites—Year 1

The siting criteria for the paved road test site were difficult to meet in the Denver area. The criteria, in order of priority, are as follows:

1. At least 3,000 passes per day between 10:00 a.m. and 6:00 p.m.

2. Location in open, relatively flat terrain with road orientation roughly normal to expected wind direction.

3. Divided road (maximum of three lanes in either direction) with 30 ft median

   -or-

   4-lane, undivided road with possible fifth (turn) lane, or narrow median.

4. Visible evidence of elevated surface loading, e.g., due to residual antiskid material.

Two road sites were selected for testing during Year 1:

- I-225 south of I-70: high volume, high speed traffic.

- One-way facilities adjacent to Botanical Gardens: high volume, low speed traffic

These sites were selected primarily on the basis of road facility type (traffic volume and speed) with a center city representation.

After a given storm event, it was intended to test on three consecutive days (up to 6 hr sampling duration per day) after the road surface dried at the specific site identified for the test series. In the event that test days were lost because of unfavorable winds or rewetting of the road surface, testing would cease after a 5-day period. The goal was to accomplish three tests under conditions that met the criteria for suitability. It was recognized that sanding the test roads under a lower than normal snow depth threshold might be necessary so that testing could proceed even if major storms did not occur.

It should be noted that, as a general rule, a test had to be initiated by no later than 11:00 a.m. to provide sufficient time for collecting adequate sample mass prior to evening disorganization of winds and to avoid interfering with the evening rush hours. Therefore, if the given test road dried in the early afternoon, for example, it was necessary to postpone testing until the next day.

4.2 Test Site—Year 2

Because of the problems of achieving adequate testing efficiency at the first two sites during the winter of 1996,[3] it was decided to take two steps in redesigning the remainder of the Correlation Studies.

1. Move to a new "core" sampling site in an area with full wind exposure and other conditions that would expedite plume profiling, and

2. Combine (a) the testing of "artificial" sanding and wetting, during periods of moderate weather (autumn), with (b) the testing of significant wintertime storm events.

The main purpose of these changes was to increase the efficiency of profiling data collection and to increase PM-10 and PM-2.5 sample masses above the 1 mg adequacy threshold for chemical determination of elemental abundances.

It was recognized that the pre-winter sand applications would be removed from the test road more quickly by traffic in comparison with the sand removal rate from freshly dried roads after a winter snow/ice event. This effect would result primarily from more rapid evaporation of residual moisture films in the prewinter testing and unavailability of trapped sand in packed snow/ice strips between lanes and along the edges of the road. However, it was believed that the primary result would be simply to "speed up" the removal process from the three to four days that it would consume in the winter to a period of about two days in the autumn. Furthermore, the results of the autumn studies could be

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[3] In the original MRI/AlphaTRAC proposal dated October 2, 1995, the correlation studies were to be performed under moderate weather conditions with predictable winds. However, when it became evident that control of winter sanding was the primary basis for CDOT emission reduction plans, the correlation studies were shifted to coincide with winter snow events.

transferred to the wintertime based on a comparison of the silt loading decay curves for the two periods.

A test location on Kipling just east of the Denver Federal Center was selected as the Core Site. The core site specifications are given in Table 3.

Table 3. Core Site Specifications

- Location: Kipling just east of the Denver Federal Center
- Road configuration
  - N-S orientation
  - Median between N and S lanes
- Wind exposure: Unobstructed on E and W sides
- ADT: Approximately 15,000
- Vehicle Speed: 40-45 mph
- Jurisdiction: CDOT and City of Lakewood
- Security: Suitable for fencing

At the Core Site, CDOT committed to providing:

1. Line power for sampling equipment, on both sides of the divided roadway
2. Security fencing for sampling equipment, on both sides of the roadway.
3. Sand application on predetermined test days, as soon after the morning rush hour as possible.
4. Midday traffic control so that road surface samples could be collected on test days.
5. Traffic counters for the full test series.

Because CDOT personnel were not available to install line power at the sampling locations, it was necessary to utilize project funds to hire an electrician for this purpose.

During Year 2, it was intended that plume profiling (and associated surface sampling) would be performed at the Core Site, as follows:

Test Series	Test Period
3 pre-winter baseline emission tests	mid-October 1996
9 pre-storm correlation tests (with sand application)	late October/early November 1996
3 post-storm correlation tests	February or early March 1997

Because of the low anticipated pre-winter loadings at the Core Site (already confirmed by the validation tests), it was realized that the baseline studies might be only marginally suitable for relating emissions to road surface loadings. Nevertheless, the pre-winter baseline emission levels were needed to establish the emission impacts of anti-skid materials, so that credits could be assigned to emission reductions resulting from (a) reduced sand application, (b) more effective removal of residual sand, or (c) use of chemical deicers with, or in place of, sand. (Alternatively, the pre-winter baseline emission levels could be projected from the pre-winter baseline silt loadings.)[4]

During the pre-winter tests with sand application, it was anticipated that plume profiling tests would be performed in 2-day or 3-day groups, depending on how long it took for the silt loading to return to the pre-winter baseline. On the first day of an individual series, the initial loading of sand would be measured by having the distribution truck deposit a short strip of sand in the parking lot adjacent to the core site. Once the sand was applied to Kipling, it would be wetted to simulate the effects of melting ice/snow. When the road surface had dried, plume profiling would begin (assuming that wind conditions are acceptable) and continue for several hours.

During the latter part of the day 1 test, the surface silt loading on Kipling would be resampled so that the average silt loading during the test can be determined. Surface sampling had to be completed by 3 p.m. on any given day, to avoid interference with the evening traffic load. It was anticipated that the two outside lanes (northbound and southbound) would be vacuumed to collect a sample.

Plume sampling would continue on the second (and possibly the third day) after sand application. The road surface silt loading would be sampled during each day so that the average silt loading for each plume profiling test can be determined. Successively larger areas of the road surface would be sampled on successive days after sand application, to provide for collection of adequate silt mass as the silt loading was depleted.

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[4] The question arises as to whether the winter baseline emission levels would be more appropriate for calculating emission reduction credits, because the winter baseline emission levels may be higher than the pre-winter baseline emission levels.

4.3 Air Sampling Equipment and Techniques

The source-directed field sampling conducted in this study employed an "exposure profiling" approach to characterize near-source particulate mass concentrations and particle size distributions by height.

Exposure Profiling

The "exposure profiling" technique is based on the profiling concept used in conventional (stack) testing. The passage of airborne pollutant immediately downwind of the source is measured directly by means of simultaneous, multipoint sampling over the effective cross section of the open dust source plume. This technique, which uses a mass flux measurement scheme similar to USEPA Method 5 for stack testing, does not require an indirect emission rate calculation through the application of a generalized atmospheric dispersion model. Further details of the exposure profiling method can be found in earlier technical reports, such as the 1986 USEPA collaborative study (Pyle and McCain, 1986).

For measurement of particulate emissions from the paved test roads, a three- to five-point vertical array of high-volume cyclone samplers was positioned approximately 5 m downwind from the edge of the road. The Sierra Model 230CP cyclone preseparator exhibits an effective 50% cutoff diameter (D_{50}) of approximately 10 µm when operated at a constant flow rate of 40 cfm (68 m^3/hr). The downwind distance of 5 m is far enough that sampling interferences due to traffic-generated turbulence are minimal, but close enough to the source that the vertical plume extent can be adequately characterized with a maximum sampling height of about 7 m. In a similar manner, the 10-m distance upwind from the road's edge is far enough from the source that: (a) source turbulence does not affect sampling, and (b) a brief reversal in wind directions will not substantially impact the upwind samplers. The 10-m distance is, however, close enough to the road to provide the representative background concentration values needed to determine the net mass flux (i.e., due to the source).

Sampler Deployment for Year 1

As shown in Table 4, the equipment deployment scheme for Year 1 made use of a variety of sampling instruments. The principal downwind plume reference height was 2 m. A reference PM-10 high-volume sampler (Wedding inlet) provided PM-10 samples for analysis of particle morphology. The deployment of sampling equipment is illustrated in Figure 1.

Table 4. Air Sampling Matrix for Year 1

Sampler/filter type	Location	Remarks
Cyclone/glass fiber (40 cfm)	2 m U 7 m U	Used to define upwind PM-10 contribution to downwind plume.
	1 m D 3 m D 5 m D 7 m D	Used to define PM-10 plume and calculate PM-10 emission factor.
Wedding/quartz (40 cfm)	2 m D	Used for PM-10 comparison against cyclones. Provides samples for analysis by (optical) morphological analysis.
Cyclone-impactor[a] glass fiber (20 cfm)	2 m U	Used to define upwind particle size distribution. Provides samples for analysis by (optical) morphological analysis.
	2 m D	Used to define downwind particle size distribution. Will also provide samples for analysis by (optical) morphological analysis.
Dichot/Teflon (16.7 Lpm)	2 m U	Used to define upwind particle size distribution. Provides samples for analysis by X-ray fluorescence.
	2 m D	Used to define downwind particle size distribution. Provides samples for analysis by X-ray fluorescence.
Dichot/quartz (16.7 Lpm)	2 m U	Used to define upwind particle size distribution. Provides samples for analysis by thermal/optical reflectance, ion chromatography.
	2 m D	Used to define downwind particle size distribution. Provides samples for analysis by thermal/optical reflectance, ion chromatography.

[a] Three impaction stages: 10.2 µmA, 4.2 µmA, and 2.1 µmA.

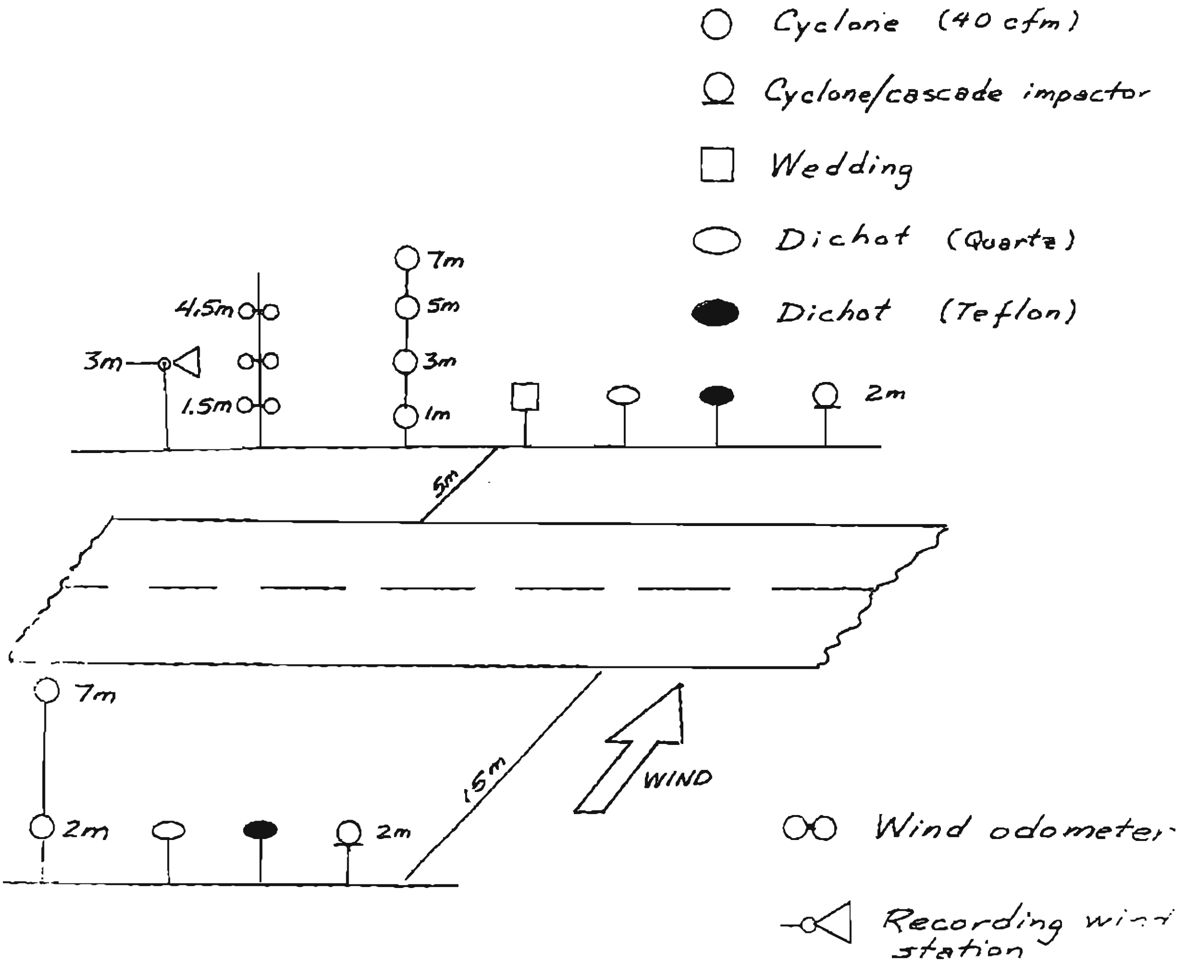

Figure 1. Deployment of Air Sampling Equipment—Year 1

For particle sizing, high-volume air samplers equipped with cyclone preseparators and parallel-slot, three-stage cascade impactors were used. This equipment is consistent with that used to develop the particle size multipliers that accompany the AP-42 predictive emissions factor equations for paved roads. The Sierra Model 230CP cyclone preseparator exhibits an effective 50% cutoff diameter (D_{50}) of approximately 15 µm (µm) in aerodynamic diameter when operated at a constant flow rate of 20 cfm (34 m^3/hr). The corresponding 50% cutoff aerodynamic diameters of the three-stage Sierra Model 233 cascade impactor are 10.2 µm, 4.2 µm, and 2.1 µm. The backup filter provides a PM-2.1 sample, with much larger sample mass than the fine fraction filters from the dichotomous samplers discussed below. The PM-2.1 sample was to be used for analysis of particle morphology.

The other set of particle-sizing samplers consisted of Sierra Anderson Model 245 dichotomous samplers with cut points of 10 μm and 2.5 μm. These samplers were operated in pairs at both the upwind and downwind locations. Within each set of paired dichotomous samplers, one was operated with Teflon filters and the other with quartz fiber filters. These sampling media were required for the chemical analyses that are described later.

Throughout each test, wind speed was monitored by "wind odometers" mounted at three downwind heights. The vertical wind speed profile was determined using data from these sensors, assuming a logarithmic distribution. Horizontal wind direction was also monitored at a single height using an R. M. Young wind monitor. The cyclone sampling intakes were adjusted for proper directional orientation based on the approximate average wind direction measured during consecutive observation periods.

Sampler Deployment for Year 2/Wind Activation

The air sampling matrix for Year 1 was carried over to Year 2, which was initiated with the fall 1996 test period at the Core Site. However, because shifting winds limited the run time on most test days, most filters were exposed on more than one test day in the hope of achieving sample masses that would be sufficient for chemical characterization. The exception was the profiling cyclones, for which filters were changed after every test.

Because of persistent wind problems, a change in the wintertime sampling strategy for Year 2 was recommended by MRI to make the "storm chasing" approach technically and economically feasible. This involved using sampling arrays that were activated by wind direction sensors, so that they would operate only when the wind direction was within the acceptable range for a period of at least 2 minutes. Samplers would operate as long as acceptable wind conditions prevailed, without being restricted only to daylight non-rush hour periods, as was previously the case.

The wind activation system was configured as follows. Separate Wong activator wind vanes were configured to operate the upwind samplers and the downwind samplers whenever the wind direction fell within a range of 135° (centered on the perpendicular to the road orientation). The wind vanes were mounted at a height of 3 meters on the upwind and downwind sides of the road. The signal from each vane was transmitted to a separate wind direction controller box, where the elapsed run time was recorded. Upon activation, output voltage from the controller box energized a series of relays. One relay was required for every two samplers. The samplers were activated until the wind direction fell outside the 135° range.

To keep a record of sampling duration, battery powered event recorders were mounted to one upwind and one downwind sampler motor. These units kept record of on and off times, which were then downloaded and displayed on a computer.

To record wind speed and direction continuously, the R.M. Young wind monitor was connected to a data logger. Data from this unit were also downloaded to a computer. All of the electronic equipment was mounted in weatherproof enclosure.

Table 5 shows the revised sampler deployment scheme that was used with the wind activation system. The sampling array was deployed in anticipation of easterly winds, i.e., the downwind sampler array was deployed on the west side of Kipling. From the fall 1996 sampling at the Core Site, it was evident that west winds occurred much less frequently and tended to have significantly higher velocity, causing plume dilution and lengthening the required run time.

Table 5. Revised Core Site Sampling Matrix—Year 2 (Wintertime)

Particle Size	Sampler/Filter Type	Intake Location	Remarks
PM-10	Cyclone/glass fiber— 40 cfm (5 units)	2 mU 6 mU	Used to define upwind contribution to plume
		2 mD 4 mD 6 mD	Used to define plume and calculate PM-10 emission factor
PM-10	Wedding/quartz— 40 cfm (2 units)	2 mU 2 mD	Used for comparison against cyclones. Also provides samples for analysis by X-ray fluorescence
PM-3.0/10	Wedding-impactor/ quartz—20 cfm (2 units)	2 mU 2 mD	Used to define upwind/downwind particle size distribution. Also provides samples for analysis by thermal/ optical reflectance
PM-10	MiniVOL/Teflon— 5 Lpm (2 units)	2 mU 2 mD	Provides samples for analysis by X-ray fluorescence.
PM-2.5	MiniVOL/Teflon— 5 Lpm (2 units)	2 mU 2 mD	Provides samples for analysis by X-ray fluorescence.

A reference sampling height of 2 m was used for all but the cyclones on the profiling towers. This height was reasonably representative of plume core conditions. As such, it was an appropriate height for collection of plume samples for comparison with samples of road dust resuspended in the laboratory to capture its PM-10 and PM-2.5 components.

When the Core Site test road (Kipling) dried following a winter storm, AlphaTRAC personnel loaded filters and activated the sampling array. The samplers operated whenever the wind direction was within about 65° of the perpendicular to the roadway orientation. The elapsed run time meters were checked periodically, so that when run time was sufficient (not only for reliable gravimetric analysis of collected particulate matter, but also for reliable chemical analysis of the samples), the filters were changed.

Note that during the Year 2 winter testing, Airmetrics MiniVOL samplers were used for collection of PM-10 and PM-2.5 samples on 47-mm Teflon filters (for metals analysis by X-ray fluorescence). MiniVOL samplers replaced the dichotomous samplers that had been used previously. Unlike the dichotomous samplers, the MiniVOL samplers could easily be transported to an enclosed environment for change-out of the filters, so that losses of collected sample mass could be significantly reduced.

4.4 Testing Procedures

Preparation of Sample Collection Media

Except for the dichotomous samplers (used in Year 1 and during fall testing in Year 2) and the MiniVOL samplers (used during winter testing in Year 2), particulate samples were collected on either glass fiber (impactor substrates and back-up filters) or QM-A microquartz filters (Wedding PM-10 reference sampler). Impactor substrates were greased by spraying with a solution prepared by dissolving 140 g of stopcock grease in 1 L of reagent grade toluene. For the dichotomous samplers, coarse and fine fraction particulate samples were collected on 37-mm Teflon membrane filters and QM-A microquartz filters. MiniVOL samples utilized 47-mm Teflon filters.

Prior to the initial weighing, the filters were equilibrated for 24 hr at constant temperature and humidity in a special weighing room. During weighing, the balance was checked at frequent intervals with standard (Class S) weights to ensure accuracy. The filters remained in the same controlled environment for a second 24-hr period, after which a second analyst reweighed them as a precision check. If a filter did not pass audit limits, the entire lot was reweighed. Ten percent (10%) of the filters taken to the field were used as blanks. The quality control guidelines pertaining to preparation of sample collection media are presented in Table 6.

As indicated in Table 6, a minimum of 10% field blanks were collected for quality control (QC) purposes. This procedure involved handling at least one filter in every 10 in an identical manner as the others to determine systematic weight changes. These changes were then used to mathematically correct the net weight gain determined from gravimetric analysis of the filter samples. During field blank collection, filters were loaded into samplers and then recovered without air being passed through the media.

Table 6. Quality Control Procedures for Sampling Media

Activity	QA check/requirement
Preparation	Inspect and imprint glass fiber media with identification numbers.
Conditioning	Equilibrate media for 24 h in clean controlled room with a relative humidity of 40% (variation of less than ±5%) and with a temperature of 23°C (variation of less than ±1%).
Weighing	Weigh hi-vol filters to nearest 0.05 mg.
Auditing of weights	For tare weights, conduct a 100% audit. Reweigh tare weight of any filters that deviate by more than ±1.0 mg. Independently verify final weights of 10% of filters (at least four from each batch). Reweigh batch if weights of any hi-vol filters deviate by more than ±2.0 mg.
Correction for handling effects[a]	Weigh and handle at least one blank for each 10 filters of each type for each test.
Calibration of balance	Balance to be calibrated once per year by certified manufacturer's representative. Check prior to each use with laboratory Class S weights.

[a] Includes field blanks (see text).

Pretest Procedures/Evaluation of Sampling Conditions

Prior to actual sample collection, a number of decisions were made as to the potential for acceptable source-testing conditions. These decisions were based on forecast information obtained from the local U.S. Weather Service office. If conditions were considered acceptable, the sampling equipment was prepared for testing. Pretest preparations included calibration checks of the various air sampling instruments, insertion of filters, and so forth. The quality control guidelines governing this activity are found in Table 7.

Table 7. Quality Control Procedures for Sampling Flow Rates

Activity	QC check/requirement
Air samplers	Multipoint calibration check using calibration orifice upon arrival at test site for comparison against standard table.
Orifice (transfer standard)	Calibrate against displaced volume test meter annually.

Once the source testing equipment was set up and the filters inserted, air sampling was conducted. As stated earlier, sampling was generally initiated by 11 a.m. in order to capture sufficient sample mass without infringing on the evening rush hour period.

Information recorded on specially designed reporting forms included:

- Air samples—Start/stop times, filter IDs, approach wind speeds at sampler intakes, and sampler flow rates (see Table 8 for QC procedures.)
- Traffic count by vehicle type and speed.
- General meteorology—Wind speed, wind direction, temperature, and barometric pressure.

Table 8. Quality Control Procedures for Sampling Equipment

Activity	QC check/requirement
Maintenance	Check motors, gaskets, timers, and flow measuring devices prior to testing.
Timing	Start and stop all downwind samplers during time span not exceeding 1 min.
Isokinetic sampling (cyclones)	Adjust sampling intake orientation whenever mean wind direction dictates.
Prevention of static mode deposition	Cap sampler inlets prior to and immediately after sampling.

Criteria for suspending or terminating a source test are presented in Table 9.

Table 9. Criteria for Suspending or Terminating a Test

A test may be suspended or terminated if:

1. Precipitation ensues during equipment setup or when sampling is in progress.
2. Mean wind speed during sampling moves outside the 1.3- to 8.9-m/s (2- to 20-mph) acceptable range for more than 20% of the sampling time.
3. The angle between mean wind direction and the perpendicular to the path of the moving point source during sampling exceeds 45 degrees for two consecutive averaging periods.
4. Daylight is insufficient for safe equipment operation.
5. Source condition deviates from predetermined criteria (e.g., occurrence of wet pavement conditions).

Handling of Exposed Collection Media

To prevent particulate losses, the exposed air sampling media were carefully transported in special containers to MRI's main laboratory. In the laboratory, exposed filters were equilibrated under the same conditions as the initial weighing. After reweighing, 10% of the filters were audited to check weighing accuracy.

Surface Sample Collection and Analysis

In conjunction with the emission tests, samples of the dust on the road surface were obtained. These samples were needed to characterize the test roads in terms of dust loading, texture, chemical composition, and particle mircoscopy. The specific procedures used to collect and analyze paved road surface samples to determine texture and loading are generally described in AP-42, Appendices C1 and C2 (USEPA, 1995). The road surface sampling procedure, as modified during the Silt Loading Validation Study described in Section 3, is presented in Appendix A to this report.

Where practical, road surface sampling focused on the segment of the particular road being tested. For each test, a composite sample of at least three or four component surface areas was accumulated. Each component area had a width that matched an active travel lane and a length dimension that was based on the observed surface loading in comparison with the requirement for sufficient sample mass.

Note that the road surface samples for each of the "best" exposure profiling tests were to be subdivided into the following subsamples, to be analyzed for particle chemistry and morphology:

Silt: particles passing a 200-mesh screen upon conventional dry sieving

PM-10: particles resuspended in MRI's Dustiness Test Chamber and collected by a PM-10 sampler onto appropriate filer media within the chamber

PM-2.5: particles resuspended in MRI's Dustiness Test Chamber and collected by a PM-2.5 sampler onto appropriate filer media within the chamber

The MRI dustiness test chamber (Figure 2), as developed by Cowherd et. al. (1989), was used to suspend the road surface material for collection as PM-10 and PM-2.5 samples. The test chamber is a bench-scale device that generates and samples airborne particulate resulting from the dropping of bulk material (0.27 L) over a 25 cm distance to the floor of the chamber. In its standard configuration, air is drawn at 8.3 L/min through an open-faced 47 mm diameter filter at the top of the chamber for a period of 10 min beginning with the start of the 30 sec pouring period.

For this series of tests, the chamber was modified from its standard configuration to incorporate a MiniVOL sampler with a PM-10 or a PM-2.5 inlet (see Figure 3) mounted in an inverted position with the rain cap removed. The MiniVOL sampler drew air from the chamber at 5.0 L/min as contrasted with the standard flowrate of 8.3 L/min. The size-selective inlets consisted of PM-10 or PM-2.5 greased impactors preceding the 47-m filter. The test procedure was also modified to begin sampling only after larger particles had settled, which consumed a 1-min period following the end of each pouring event. If necessary, multiple pours of the same test material were made, so that a quantitiable sample mass was obtained.

Because the MiniVOLs with PM-2.5 inlets were observed in prior field tests to be subject to severe particle bounce problems, resulting in higher PM-2.5 values than PM-10 (a physical impossibility), steps were taken to mitigate this problem during the resuspension tests. The 2.5 μm inlets were greased on both the forward and rearward impactor faces to provide two surfaces for bouncing particles larger than PM 2.5 to be captured. This effort and a 1-min wait period to for coarse particle settling (prior to the sampling of suspended dust within the chamber) appeared to eliminate the particle bounce problem for the dustiness tests.

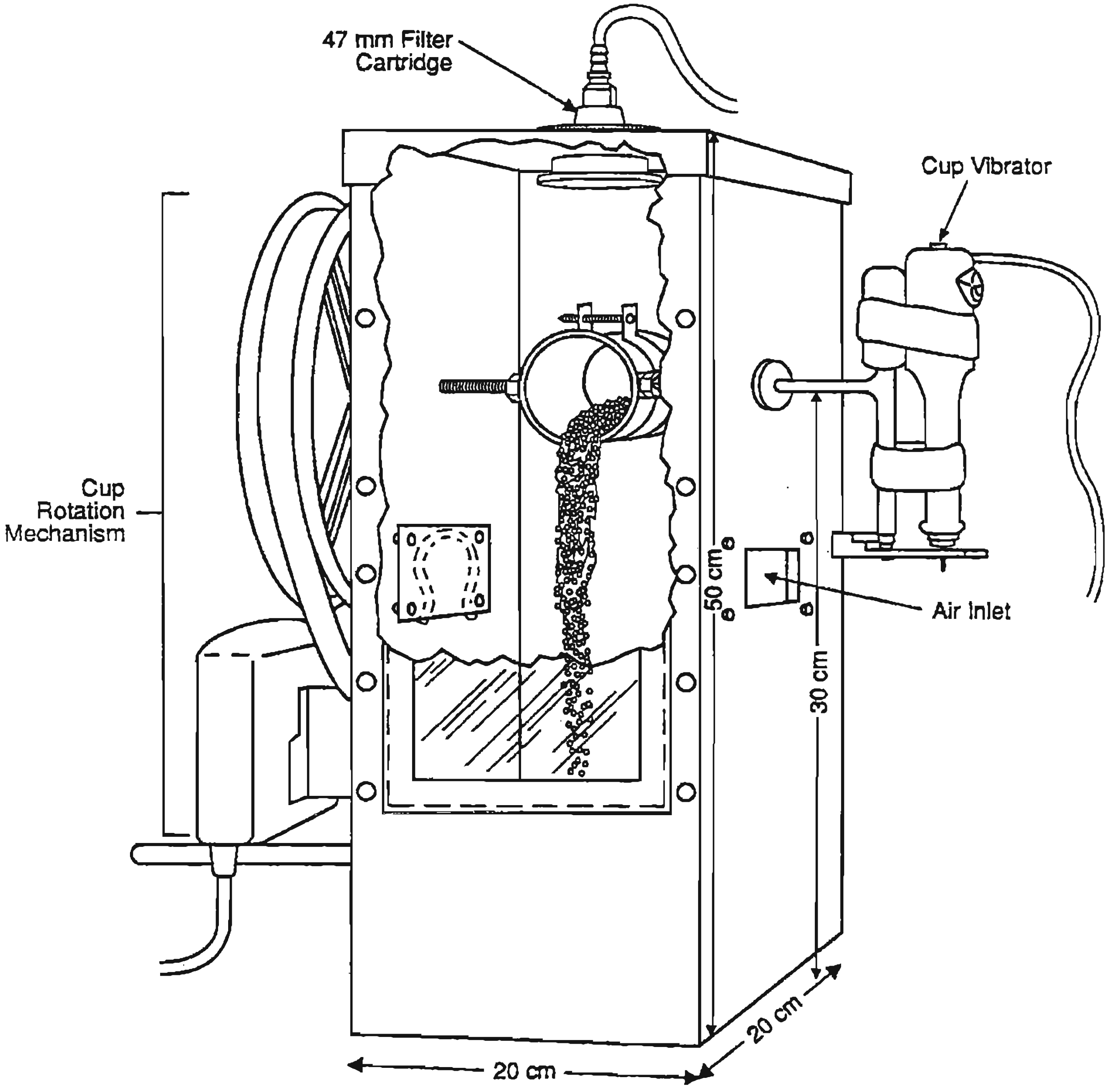

Figure 2. MRI Dustiness Test Chamber

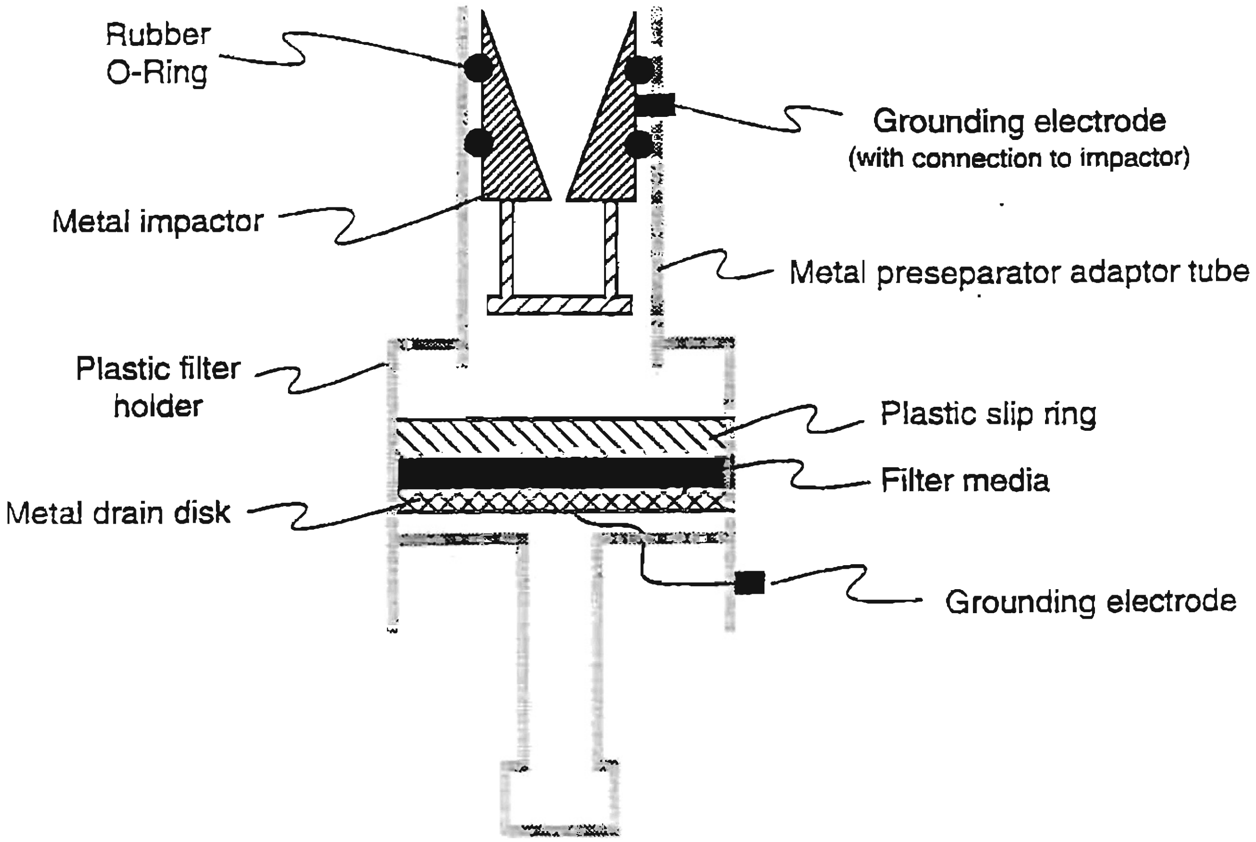

Figure 3. Modified MiniVOL Inlet Assembly (upright orientation)

The net weights of particular matter captured on quartz fiber and Teflon membrane filters were used to calculate the dustiness index (or emission factor)—in units of mg of suspended matter per kg of material poured. The PM-2.5/PM-10 ratio in the suspended particulate was of special interest in this study and was determined by comparing the respective dustiness indices.

The appropriateness of the MRI Dustiness Test Chamber as a particle resuspension device has been discussed by Cowherd and Grelinger (1997).

Source Activity Monitoring

Vehicle-related parameters were obtained using a combination of manual and automated counting techniques. Periodic manual traffic observation was used to acquire traffic volume data and to obtain traffic mix information. In addition, CDOT provided daily cycles of traffic volume for the Core Site on Kipling adjacent to the Denver Federal Center.

Chemical and Microscopical Analysis

The four "best" tests from this phase of the project[5] were selected for "correlation analysis," beyond the normal requirements for sample mass determination by gravimetry. Selection of these tests was based on occurrence of favorable conditions of wind and road surface condition. With regard to the later, rapid drying of the test road in the presence of high initial surface loadings was desirable. Such surface conditions are believed to produce the highest emission rates for the paved road source category.

For each of the four tests selected for correlation analysis, the following analyses (chemistry and particle microscopy) were performed during Year 3:

X-ray Fluorescence (XRF): 37 elements

- 4 dichotomous samples (2 samplers; coarse fraction and PM-2.5 components for each sampler)
- 2 surface samples (resuspended PM-10 and PM-2.5 on Teflon membrane filters)

Ion Chromatography (IC): chloride, nitrate and sulfate

- 4 dichotomous samples (2 samplers; coarse fraction and PM-2.5 components for each sampler)

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[5] As noted earlier in this report, the Year 2 correlation studies had to be completed before the "best test" selection was made.

- 2 surface samples (resuspended PM-10 and PM-2.5 on Teflon membrane filters)

Thermal/Optical Reflectance (TOR)

- 4 dichotomous samples (2 samplers; coarse fraction and PM-2.5 components for each sampler)

- 2 surface samples (resuspended PM-10 and PM-2.5 on Teflon membrane filters)

Polarized Light Microscopy (PLM):

- 4 dichotomous samples (2 samplers; coarse fraction and PM-2.5 components for each sampler)

For direct microscopical analysis, filter sections were mounted in immersion oil which closely matched the refractive index of the filter fibers, rendering the sections transparent. This filter "clearing" process permits examining and identifying particles on, within, and at the bottom of the filters.

Particle identification was based on the optical (crystallographic) and morphological properties of the aerosols, which often permit simple distinction among chemically similar components (such as carbon combustion products from diverse fuels). Quantitative analysis of the selected particle size was derived from counting and sizing each particle to produce a mass per unit area of particles on each filter. The mass was computed from the size and density (published rather than measured densities); filter areas were defined by a calibrated counting graticule in the microscope.

The precision and accuracy of quantitative microscopical particle analysis depends on application of an appropriate shape factor to compute particle volume and the total number of particles counted within a size range. Shape factors were derived by measuring the aspect ratio of representative particles in each size range. The total counts of particles in a sample were based on stratified counting with the goal of trying to obtain at least 30 particles per size range. Representative photomicrographs of the key morphological properties of the particles were obtained as part of the analysis documentation.

Concentration/Emission Calculation Procedure

To calculate emission rates from exposure profiling data, a conservation of mass approach is used. The passage of airborne particulate (i.e., the quantity of emissions per unit of source activity) is obtained by spatial integration of distributed measurements of exposure (mass/area) over the effective cross section of the plume. Exposure is the point value of the flux (mass/area-time) of airborne particulate integrated over the time of measurement or, equivalently, the net particulate mass passing through a unit area normal to the mean wind direction during the test. The steps in the calculation procedure are described below.

The concentration of PM-10 measured by a sampler is given by:

$$C = 10^3 \frac{m}{Qt} \tag{7}$$

where: C = PM-10 concentration ($\mu g/m^3$)
m = PM-10 sample weight (mg)
q = sampler flow rate (m^3/min)
t = duration of sampling (min)

The isokinetic flow ratio (IFR) is the ratio of a directional (i.e., cyclone) sampler's intake air speed to the mean wind speed approaching the sampler. It is given by:

$$IFR = \frac{Q}{aU} \tag{8}$$

where: Q = sampler flow rate (m^3/min)
a = intake area of sampler (m^2)
U = mean wind speed at height of sampler (m/min)

The above ratio is of interest only in the sampling of total particulate, since isokinetic sampling ensures that particles of all sizes are sampled without bias. Note that because the primary interest in this program is directed to PM-10 emissions, sampling under moderately nonisokinetic conditions poses no difficulty. It is accepted that 10 µm (aerodynamic diameter) and smaller particles have weak inertial characteristics at normal wind speeds and, thus, are relatively unaffected by anisokinesis.

Exposure represents the net passage of mass through a unit area normal to the direction of plume transport (wind direction) and is calculated by:

$$E_{10} = 10^{-7} \times CUt \tag{9}$$

where: E_{10} = PM-10 exposure (mg/cm^2)
C = net concentration ($\mu g/m^3$)
U = approaching wind speed (m/s)
t = duration of sampling (s)

Exposure values vary over the spatial extent of the plume. If exposure is integrated over the plume-effective cross section, then the quantity obtained represents the total passage of airborne particulate matter (i.e., mass flux) due to the source.

For the test roadway, a one-dimensional integration scheme will be used:

$$I = \int_{O}^{H} E_{10} \, dh \tag{10}$$

where: I = integrated PM-10 exposure (m-mg/cm^2)
E_{10} = PM-10 exposure (mg/cm^2)
h = vertical distance coordinate (m)
H = effective extent of plume above ground (m)

The effective height of the plume *(H)* in Eq. 10 is found by linear extrapolation of the uppermost net concentrations to a value of zero.

Because exposures are measured at discrete heights of the plume, a numerical integration is necessary to determine *I*. The exposure must equal zero at the vertical extremes of the profile (i.e., at the ground where the wind velocity equals zero and at the effective height of the plume where the net concentration equals zero). However, the maximum exposure usually occurs below a height of 1 m so that there is a sharp decay in exposure near the ground. To account for this sharp decay, the value of exposure at ground level is set equal to the value at a height of 1 m. The integration is then performed from 1 m to the plume height, *H*, using Simpson's approximation.

The emission factor for PM-10 generated by vehicular traffic on roadways, expressed in grams of emissions per vehicle-kilometer traveled (VKT), is given by:

$$e = 10^4 \, \frac{I}{N} \tag{11}$$

where: e = PM-10 emission factor (g/VKT)
I = integrated PM-10 exposure (m-mg/cm^2)
N = number of vehicle passes (dimensionless)

An example of the above calculation procedure, using the actual data from a Correlation Study test run, is presented in Appendix C.

Section 5
Correlation Studies: Test Results

This section presents the results of the correlation studies performed during Year 1 and Year 2. The purpose of the correlation studies was to determine the relationship between road surface particulate matter and fine particle emissions.

5.1 Site Conditions—Year 1

During late February and March of 1996, emission profiling tests were performed under Task 1 at two test sites:

- I-225 south of I-70: high volume, high speed traffic
- One-way facilities adjacent to Botanical Gardens: high volume, low speed traffic

These sites were selected primarily on the basis of road facility type (traffic volume, traffic speed). It was projected that wintertime winds at these locations would meet sufficiency criteria for emission testing.

Table 10 lists the sampling periods for the exposure profiling tests. The sampling team was available for testing over the 30-day period beginning February 26, 1996, and was on-site in Denver for most of this period.

Table 10. Winter 1996 Sampling Periods

Run No.	Test site	Date	Start time	Sampling duration (min)
BH-1	I-225	2/28/96	11:40	163
BH-2	I-225	3/1/96	09:46	360
BH-3	I-225	3/2/96	08:46	360
BH-4	I-225	3/2/96	–	Blank run
BH-5	Botanical Gardens	3/7/96	–	Blank run
BH-6	Botanical Gardens	3/16/96	09:09	240

The average site conditions for the Year 1 test runs are shown in Table 11. This includes the vehicle passes occurring during each sampling period. Note that wind speeds were marginally low during runs BH-1 and BH-6. During run BH-1 on I-225, the unusual wind speed maximum at the 1.5 m height is believed to reflect the effect of high speed traffic pushing air to the side of the roadway.

Table 11. Winter 1996 Site Conditions

Run No.	Test site	Vehicle passes	Temp (°F)	Wind speed (mph) 1.5 m	Wind speed (mph) 3.0 m	Wind speed (mph) 4.5 m	Road surface material s (%)	Road surface material L (g/m²)	Road surface material sL (g/m²)
BH-1	I-225	6,561	18	3.6	2.6	2.8	10.6	1.95	0.184
BH-2	I-225	17,568	37	14.5	16.2	17.5	41.0	0.031	0.0127
BH-3	I-225	14,616	46	14.3	16.7	17.7	41.0	0.031	0.0127
BH-6	Botanica I Gardens	3,112	48	2.3	2.8	3.3	1.12	125	1.47

L = Loading (g/m²)
s = Silt content (%)
sL = Silt loading (g/m²)

For tests BH-4 and BH-5, although favorable wind conditions were predicted, actual winds were unfavorable, so that these became blank runs. On five additional days (March 8, 9, 19, 20, and 21), wind conditions were not forecast to be favorable for the required sampling period of at least 4 hours, so that no emission testing was attempted; however, on those days PM-10/PM-2.5 concentrations and particle size data were collected at the intersection of 7th Avenue and Josephine, in connection with the tire particle study separately funded by Colorado State University. The particle size data from that study will be useful to the subject study as well.

To the extent possible, each of the emission tests identified in Table 11 was performed during periods following snowfall, after the test road surface had dried. In most cases, sand application was ordered, because the relatively light snow conditions characteristic of the 1996 winter did not trigger routine sand application.

Also shown in Table 11 are the road surface material parameters. The silt loading for run BH-1 was determined from surface sampling near the end of the run. The road had been sanded near the beginning of the run. The much lower silt loading obtained for runs BH-2 and BH-3 reflected a very effective removal of the sand by traffic flow, making it necessary to composite the samples from both runs. The silt loading value represents a very clean surface, i.e., falling below the 10 percentile of silt loading values reported in AP-42 for high-ADT roadways. The much higher silt loading obtained during run BH-6 reflected the impact of sand application early in the test. Note that bulk samples of antiskid materials applied during runs BH-1 and BH-6 yielded silt contents of 1.47% and 1.17%, respectively.

This testing experience demonstrated that Denver wind conditions after a winter storm event tend to change frequently in relation to the 4-6 hour period required for collection of adequate airborne particulate sample mass, especially in the areas lying well within the perimeter interstate highway system. At the site adjacent to the Denver Botanical Gardens, for example, wind conditions were consistently disorganized after winter storm events. This made the task of plume profiling on a quantitative basis after such events very difficult.

On the other hand, at the I-225 site, wind conditions were more stable. However, because road sand was quickly thrown from the active roadway, once the surface had dried, little emission impact of the residual sand was suspected to be shown by the test results.

5.2 Concentrations/Emissions—Year 1

This subsection presents the calculated particulate concentrations and emissions for the Year 1 Correlation Studies.

Concentrations

Table 12 shows the average PM-10 concentrations measured upwind and downwind of the test road during each test period.

Table 12. Winter 1996 PM-10 Concentrations ($\mu g/m^3$)

	Background					Downwind							
Run	C/I 2 m	DT 2 m	DQ 2 m	C 2 m	C 7 m	C/I 2 m	DT 2 m	DQ 2 m	W 2 m	C 1 m	C 3 m	C 5 m	C 7 m
BH-1	< 41	21	< 9.5	NA	NA	43	**41**	**33**	**33**	**74**	**63**	**233**	**183**
BH-2	< 11	**17**	< 3.7	NA	NA	16	**22**	< 20	**15**	**29**	**16**	**13**	**27**
BH-3	< 9.0	6.7	**15**	NA	NA	< 12	12	**17**	**11**	**13**	**13**	**10**	**8.5**
BH-6	**52**	**42**	< 48	**40**	**27**	**70**	< 46	**100**	**53**	**295**	**338**	**64**	**46**

C/I = Cyclone/impactor
DT = Dichotomous sampler (Teflon filters)
DQ = Dichotomous sampler (quartz filters)
C = Cyclone
W = Wedding PM-10 sampler

A bold value in Table 12 indicates an instance where the blank-corrected net weight of each component collection medium (filter or impaction substrate) comprising a sample is at least 3 times the standard deviation of the blank correction for that collection medium in the given test series. Values preceded by a " <" indicate instances where at least one blank-corrected net weight is less than 1 standard deviation of the blank correction. In the latter case, the standard deviation of the blank correction is used in place of the net filter weight to calculate the concentration. This procedure is illustrated at the end of Appendix B.

Generally, Table 12 shows that the agreement between the different types of PM-10 samplers operated at the 2-m height was most consistent for runs BH-2 and BH-3, which had wind speeds that fully met the suitability for plume exposure profiling criteria. During those runs the downwind PM-10 concentrations were low, showing only slight increases above background levels, because of effective ventilation of the plume.

An unusual effect was observed for run BH-1, which had a maximum in the PM-10 concentration at a height of 5 m above the surface. This effect is believed to reflect buoyant plume rise from engine heat, under conditions of light winds and cold ambient temperatures. The effect is particularly important because it indicates that "ground-level" ambient monitoring (i.e., using a sampling height of about 2 m) is not appropriate for representing the full impact of the roadway emission plume. Accordingly, use of the "upwind-downwind" method for back-calculation of the emission rate through the application of a standard atmospheric dispersion model would significantly underestimate the emission rate, if the monitored concentration is taken to represent plume core conditions.

Another unusual effect was observed during run BH-6 in that downwind PM-10 concentrations measured by the cyclone at 1 and 3 m were above the value measured by the Wedding PM-10 samples at a height of 2 m. Generally in the past we have found good agreement between these two types of PM-10 sampling devices. This result may represent an interference effect of emissions from the Botanical Gardens parking lot under the light and somewhat variable wind conditions occurring during this test. The test was conducted on a Saturday, when the parking lot is most active.

The low PM-10 concentration values determined from the dichotomous sampler with the quartz filters may be indicative of the problems with fiber loss during filter handling. This problem is causing USEPA to specify only Teflon filters in the new reference method that is being developed for PM-2.5 (Merrifield, 1996). The PM-2.5 reference method will utilize a flow rate and an inlet design identical to the dichotomous sampler.

Table 13 shows the average PM-2.5 concentrations measured upwind and downwind of the test road. (The comments about types of entries in Table 12 also apply to Table 13). It is clear from Table 13 that the cyclone/impactor tends to yield PM-2.5 concentration values that are higher than those given by the dichotomous samplers. The problem with low concentrations from the dichotomous samplers with quartz filters persists. For the tests with the most suitable wind conditions (runs BH-2 and BH-3), the downwind PM-2.5 concentrations show only slight increases above background levels.

Table 13. Winter 1996 PM-2.5 Concentrations ($\mu g/m^3$)

Run	Background C/I 2 m	Background DT 2 m	Background DQ 2 m	Downwind C/I 2 m	Downwind DT 2 m	Downwind DQ 2 m
BH-1	33	10	< 3.7	27	8.3	41
BH-2	6.1	3.7	< 2.0	9.3	7.4	< 2.0
BH-3	5.1	5.6	7.4	6.4	1.9	3.7
BH-6	20	5.6	< 3.1	24	< 1.4	22

C/I = Cyclone/Impactor
DT = Dichotomous sampler (Teflon filters)
DQ = Dichotomous sampler (quartz filters)

Emissions

The PM-10 emission factors calculated from the test data are shown in Table 14. They span nearly two orders of magnitude. The measured factors are compared with those calculated from the AP-42 predictive emission factor equation for paved roads. An average vehicle weight of 2.2 tons was used as input to the AP-42 equation, along with silt loading values from Table 11. A multiplier of 0.707 was used to reflect an average angle of about 45 degrees between the wind direction and the road direction.

Table 14. Winter 1996 PM-10 Emission Factor Comparison

Run	sL (g/m^2)	PM-10 emission factor AP-42 (g/VMT)	PM-10 emission factor AP-42 (g/VKT)	PM-10 emission factor Observed (g/VKT)	Ratio of Predicted to Observed
BH-1	0.184	0.977	0.613	1.08	0.58
BH-2	0.0127	0.172	0.108	0.102	1.06
BH-6	1.47	3.77	2.36	4.68	0.50

As indicated in Table 14, the measured PM-10 emission factors generally exceeded the values predicted by the AP-42 equation. However, the differences were well within the normal range of predictive capability for the equation. This result supports the use of silt loading as a predictor of PM-10 emissions. In other words, the large variation in emission factor is attributable to the large variation in silt loading which in turn reflects the time since sand application.

To determine the ratios of PM-2.5 to PM-10 in the roadway emission plumes, the most reliable concentration values from Tables 12 and 13 were used. The results are shown in

Table 15. As expected, the test runs showing the greatest paved roadway impacts also showed the lowest percentages of PM-2.5 in PM-10. For example, run BH-2 on I-225 had a low net PM-10 concentration and a high percentage of PM-2.5 in PM-10. On the other hand, run BH-6 on the freshly sanded center city arterial showed a high net PM-10 concentration with a low percentage of PM-2.5 in PM-10. For comparison, the AP-42 predictive emission factor equation for paved roads gives a PM 2.5/PM-10 ratio of 0.46.

Table 15. Percentage of PM-2.5 in PM-10—Denver Paved Road[a]

Run	Background			Downwind		
	C/I[b] (2 m)	DT (2 m)	DQ (2 m)	C/I[b] (2 m)	DT (2 m)	DQ (2 m)
BH-1	92	48	47	63	20	12
BH-2	62	22	54	58	34	11
BH-3	72	84	49	58	16	22
BH-6	38	13	7	34	3	22

[a] Numbers If parentheses are sampling heights.
[b] PM-2.1 as a percentage of PM-10.2.

5.3 Site Conditions—Year 2/Fall 1996

During October and November 1996, emission profiling tests were performed under Task 1 at the Core Site on Kipling. Table 16 lists the sampling periods for the exposure profiling tests.

Table 16. Fall 1996 Sampling Periods

Run No.	Date	Start Time	Duration (min)	Comments
BL-1	10/24/96	1240	244	Baseline test
BL-2	10/25/96	0948	281	Baseline test
BL-3	10/26/96	0959	99	Baseline test
BL-4	10/28/96	1025	164	Baseline test
-	10/29/96	-	-	Wind storm (90 mph) and equipment repair
BL-5	10/30/96	-	-	Equipment repair and blank run
BL-6	11/1/96	1128	1141[a]	Baseline test[b] (colocated samplers)
BL-7	11/2/96	1128	248	Day 1 sanding cycle (first sanding)
BL-8	11/3/96	1204	210	Day 2 sanding cycle (second sanding)
BL-9	11/4/96	1125	95	Day 1 sanding cycle (second sanding)
BL-10	11/5/96	1035	133	Day 2 sanding cycle
BL-11	11/6/96	1100	240	Day 3 sanding cycle

[a] Power to most samplers lost during night because of loss of municipal electrical service.
[b] Sand not available, although prescheduled.

The average site conditions for the Year 2/Fall 1996 test runs are shown in Table 17. This includes vehicle passes during each sampling period. Note that wind speeds were marginally low during run BL-4 and run BL-7.

Also shown in Table 17 are the road surface material parameters. As expected, the silt loading increased sharply (above the fall baseline) for run BL-7, which was performed at the beginning of the first sanding cycle. Another sharp increase in silt loading was observed after beginning of the second sanding cycle (run BL-9). However, the silt loading dropped substantially on the second day of the sanding cycle (run BL-10) because of the rapid removal of road surface material by roadway traffic. It should be noted that a single composite road surface sample was collected for the baseline tests (Runs BL-1 through BL-4) because of the very low surface loading.

Table 17. Fall 1996 Site Conditions

			Mean Wind Speed (mph)						Road Surface Material		
Run No.	Vehicle Passes*	Temp (°F)	2 m	3 m	5 m	7 m	7.5 m	10 m	s (%)	L (g/m^2)	sL (g/m^2)
BL-1	12,853	60	2.7	3.0	3.5	3.8	3.8	4.1	23.4	0.095	0.02
BL-2	11,045	51	3.1	3.9	4.9	5.5	-	6.2	23.4	0.095	0.02
BL-3	4,613	39	7.1	8.1	9.3	10.2		-	23.4	0.095	0.02
BL-4	6,486	54	1.5	1.8	2.2	2.5	2.5	2.7	23.4	0.095	0.02
BL-7	12,299	56	1.1	1.5	2.0	2.3	2.4	2.7	2.18	17.6	0.38
BL-8	7,609	58	-	1.9	-	-	-		-	-	-
BL-9	4,179	60	6.7	7.8	9.2	10.1	-	11.1	1.55	65.3	1.01
BL-10	5,538	62	7.7	8.0	8.4	8.6	-	8.9	21.9	0.24	0.05
BL-11	9,916	45	2.1	2.5	3.0	3.3	3.4	3.7	14.8	0.31	0.05

* Vehicle passes based on traffic counter data and visual observation of traffic mix.

5.4 Concentrations/Emissions—Year 2/Fall 1996

Concentrations

Table 18 shows the average PM-10 concentrations measured upwind and downwind of the Core Site test road during each test period. Except for the cyclones, most of the samplers were operated for more than one run in attempt to obtain sample masses sufficient for reliable quantitation. The last three runs contained a number of colocated samplers, although the second sampler in a colocated set was occasionally operated for more than one run.

Table 18. Fall 1996 PM-10 Concentrations (μg/m^3)

Run No.	Background							Downwind								
	C/I 3 m	DT 3 m	W 3 m	C 2 m	C 5 m	C 7 m	C 10 m	C/I 3 m	DT 3 m	W 3 m	C 2 m	C 3 m	C 5 m	C 7 m	C 10 m
BL-1	-	-	12	30	12	16	-	-	-	16	15	18	13	22[c]	12
BL-2	<24	18[a]	16[a]	22	21	-	21	35	43[a]	22	26	31	24	22	-
BL-3	<28	18[a]	16[a]	< 2.8	3, 4	-	-	<20	43[a]	< 8.1	8.2	14	13	7.3	-
BL-4	<27	18[a]	16[a]	26	25	22	-	39	43[a]	21	31	32	28	25[c]	23
BL-7	42	56	31	43	37	30	-	110	116	62	109	79	66	59[c]	42
BL-8	<27	-	-	-	-	-	-	18	-	25, 19[b]	-	25, 27[b]	-	-	-
BL-9	<8.2[a]	16[a]	7.5[a]	12	7.2	-	8.0	<47, 44[b]	45[a] 29[a,b]	26, 19[a,b]	40	35, 31[b]	21	19	-
BL-10	<8.2[a]	16[a]	7.5[a]	< 3.0	< 2.9	-	< 2.9	<28, <22[b]	45[a] 29[a]	20 19[a,b]	16	12, 3.0[b]	< 2.8	3.4	-
BL-11	<8.2[a]	-	7.5[a]	11	7.5	10	-	<15, <18[b]		12 19[a,b]	24	28, 12[b]	17	19[c]	11

[a] Sampler operated for more than one run.
[b] Colocated samplers.
[c] Sampler at 7.5 m height.

C/I = Cyclone/impactor combination.
DT = Dichotomous sampler (Teflon filters).
W = Wedding sampler.
C = Cyclone sampler.

A bold value in Table 18 indicates an instance where the blank-corrected net weight of each component collection medium (filter or impaction substrate) comprising a sample is at least 3 times the standard deviation of the blank correction for that collection medium in the given test series. Values preceded by a "<" indicate instances where at least one blank-corrected net weight is less than 1 standard deviation of the blank correction. In the latter case, the standard deviation of the blank correction is used in place of the net filter weight to calculate the concentration.

Table 19 shows the average PM-2.5 concentrations measured upwind and downwind of the test road. (The comments about types of entries in Table 18 also apply to Table 19.) Note that the cyclone/impactions generate PM-2.1 concentrations.

Table 19. Fall 1996 PM 2.5 Concentrations (µg/m^3)

	Background		Downwind	
Run	C/I 3 m	DT 3 m	C/I 3 m	DT 3 m
BL-2	**19[a]**	**4.7[a]**	**26**	**12[a]**
BL-3	**19[a]**	**4.7[a]**	<7.8	**12[a]**
BL-4	**19[a]**	**4.7[a]**	**26**	**12[a]**
BL-7	**30**	**16**	**56**	**16**
BL-8	**19**	-	9.2	-
BL-9	<5.6[a]	**5.8[a]**	**28** **13[a,b]**	5.8, < 2.9 [a,b]
BL-10	<5.6[a]	**5.8[a]**	**19** **13[a,b]**	5.8, < 2.9 [a,b]
BL-11	<5.6[a]	-	**10** **13[a,b]**	-

[a] Sampler operated for more than one run.
[b] Colocated samplers.

Emissions

The PM-10 emission factors calculated from the test data are shown in Table 20. The measured factors are compared with those calculated from the AP-42 predictive emission factor equation for paved roads. An average vehicle weight of 2.2 tons was used as input, along with the silt loading values from Table 17.

In general, AP-42 predicted emission factors exceeded observed emission factors. However, agreement w as still within the factor of three range usually assigned as the confidence interval for the AP-42 paved road equation.

Table 20. Fall 1996 PM-10 Emission Factor Comparison

Run No.	sL (g/m2)	PM-10 Emission Factor			Ratio of Predicted to Observed
		AP-42		Observed	
		(g/VMT)	(g/VKT)	(g/VKT)	
BL-2	0.02	0.294	0.115	0.0762	1.6
BL-3	0.02	0.294	0.115	0.281	0.41
BL-4	0.02	0.294	0.115	0.0447	2.6
BL-7	0.38	1.57	0.981	0.307	3.2
BL-9	1.01	3.42	1.85	0.745	2.5
BL-10	0.05	0.487	0.263	0.306	0.86
BL-11	0.05	0.487	0.263	0.160	1.6
					Avg. 1.8

5.5 Site Conditions—Year 2/Winter 1997

During January through March of 1997, emission profiling tests were performed under Task 1 at the Core Site on Kipling. The wind activated sampling system was used for this test series. Table 21 lists the sampling periods for the exposure profiling tests.

The average site conditions for the Year 2/Winter 1997 test runs are shown in Table 22. Also shown in Table 22 are the road surface material parameters. Multiple surface samples were collected during runs BM-4, BM-6 and BM-7. The silt loading generally ranged between 0.2 and 0.3 g/m^3 except during run BM-6, which had more than double the typical silt loading.

5.6 Concentrations/Emissions—Year 2/Winter 1997

Table 23 shows the average PM-10 concentrations measured upwind and downwind of the Core Site test road during each test period.

A bold value in Table 23 indicates an instance where the blank-corrected net weight of each component collection medium (filter or impaction substrate) comprising a sample is at least 3 times the standard deviation of the blank correction for that collection medium in the given test series. Values preceded by a " <" indicate instances where at least one blank-corrected net weight is less than 1 standard deviation of the blank correction. In the latter case, the standard deviation of the blank correction is used in place of the net filter weight to calculate the concentration.

Table 21. Winter 1997 Sampling Periods—Wind Activated Samplers

			Sampling Duration (min)	
Run No.	Date	Sampler	Upwind	Downwind)
BM-2	1/15-16/97	Cyclone	-	-
		Wed/Imp	-	1123
		MiniVOL PM-2.5	**1281**	**1189**
		MiniVOl PM-10	**1280**	**1198**
		Wedding	-	-
BM-3	2/22-23/97	Cyclone	**1399**	**1302**
		Wed/Imp	-	**1303**
		MiniVOL PM-2.5	–	–
		MiniVOl PM-10	**1327**	**1293**
		Wedding	-	–
BM-4	2/26/97	Cyclone	176	135
		Wed/Imp	–	135
		MiniVOL PM-2.5	–	**711**
		MiniVOl PM-10	**758**	**782**
		Wedding	–	–
BM-5	2/27/97	Cyclone	163	201
		Wed/Imp	163	–
		MiniVOL PM-2.5	-	**767**
		MiniVOl PM-10	**768**	**768**
		Wedding	–	–
BM-6	3/2/97	Cyclone	147	206
		Wed/Imp	147	206
		MiniVOL PM-2.5	**682**	**759**
		MiniVOl PM-10	**752**	**153**
		Wedding	**720**	**654**
BM-7	3/15-16/97	Cyclone	406	450
		Wed/Imp	406	450
		MiniVOL PM-2.5	**1333**	**1339**
		MiniVOl PM-10	**1337**	**1331**
		Wedding	318	**1341**
BM-8	3/16-17/97	Cyclone	355	416
		Wed/Imp	355	416
		MiniVOL PM-2.5	**1372**	**1378**
		MiniVOl PM-10	**1370**	**1378**
		Wedding	360	**1369**

Bold indicates that the sampler ran continuously.
Wed/Imp denotes a Wedding PM-10 inlet followed by a two-stage cascade impactor and a backup filter.

Table 22. Winter 1997 Site Conditions

Run No.	Vehicle Passes[a]	Temp (°F)	Mean Wind Speed (mph) 2 m	4 m	6 m	Road Surface Material s (%)	L (g/m²)	sL (g/m²)
BM-2	32,900	ND				–	–	–
BM-3	30,200	22			5.6	4.53	5.56	0.30
BM-4	5,550	37	3.4	4.2	4.6	7.54	3.12	0.24
						16.25	1.29	0.21
						12.78	2.24	0.29
BM-5	9,570	32	ND	ND	ND	6	4.53	0.27
BM-6	7,140	37	3.6	4.4	4.9	2.66	24.3	0.65
						-	40.4	-
BM-7	10,500	52	2.8	3.4	3.8	6.16	2.17	0.13
						3.39	8.18	0.28
BM-8	10,200	48	3.5	4.3	4.8	-	-	-

[a] Vehicle passes based upon CDOT traffic counts from 2/5/97-2/15/97.

Table 23. Winter 1997 PM-10 Concentrations ($\mu g/m^3$)

Run No.	Background C 2 m	C 6 m	MT 2 m	W/I 2 m	W 2 m	Downwind C 2 m	C 4 m	C 6 m	MT 2 m	W/I 2 m	W 2 m
BM-2	–		20	–					40	13	-
BM-3	3.7	3.8	26	-	-	-	–	5.6	23	8.5	-
BM-4	48	66	55	-	-	63	42	56	23	60	-
BM-5	99	90	99	58	-	175	4.6	74	< 4.9	-	-
BM-6	122	35	13	-	36	37	58	73	196	-	36
BM-7	27	31	25	<19	29	54	40	28	32	<28	23
BM-8	19	10	25	14	14	28	28	30	70	24	15

C = Cyclone sampler.
MT = MiniVOL with a Teflon filter.
W/I = Wedding/impactor combination.
W = Wedding sampler.

Table 24 shows the average PM-2.5 concentrations measured upwind and downwind of the test road. (The comments about types of entries in Table 23 also apply to Table 24.)

Table 24. Winter 1997 PM-2.5 Concentrations ($\mu g/m^3$)

	Background		Downwind	
Run No.	MT 2 m	W/I[a] 2 m	MT 2 m	W/I[a] 2 m
BM-2	28		37	10
BM-3	-	-	-	7.0
BM-4	-	-	343	46
BM-5		37	787	-
BM-6	5.9	-	5.3	-
BM-7	14	17	4.5	22
BM-8	12	8.6	8.7	15

[a] Wedding/Impactor concentrations are for PM-3.

Emissions

The PM-10 emission factors calculated from the test data are shown in Table 25. The measured factors are compared with those calculated from the AP-42 predictive emission factor equation for paved roads. An average weight of 2.2 tons was used as input, along with the silt loading values for Table 22.

Table 25. Winter 1997 PM-10 Emission Factor Comparison

		PM-10 Emission Factor			
		AP-42		Observed	
Run No.	sL (g/m2)[a]	(g/VMT)	(g/VKT)	(g/VKT)	Ratio
BM-7	0.13 0.28	1.05	0.657	0.347	1.9
BM-8	-	-	-	0.522	-

[a] Two road surface samples were taken for run BM-7, but no road surface sample was taken for run BM-8 which was performed on the same day that run BM-7 ended.

5.7 Emission Correlations

As stated in the Introduction, one of the major objectives of this study was to determine the relationship between PM-10 emissions and silt loading, without relying on the AP-42 predictive emission factor equation for paved roads, provided as Equation 1 in Section 2 of this report. This section presents the results of independent statistical analyses of the test data from the Correlation Studies. The data used in the analyses are shown in Table 26. These data represent the most reliable measures of emissions because of the favorable wind conditions that were encountered during the specified test runs.

Table 26. Test Data Used in Model Development

			Surface material properties			PM-10
Run	Road type	Test condition	Silt content (%)	Total loading (g/m²)	Silt loading (g/m²)	Emission factor (g/vkt)
BH-1	Expwy	Sanded	10.6	1.95	0.184	1.08
BH-2	Expwy	Sanded	41	0.031	0.0127	0.102
BH-6	Prin Art	Sander	1.12	124	1.47	4.68
BL-2	Prin Art	Baseline	23.4	0.095	0.022	0.0762
BL-3	Prin Art	Baseline	23.4	0.095	0.022	0.281
BL-4	Prin Art	Baseline	23.4	0.095	0.022	0.0447
BL-7	Prin Art	Sand Cycle Day 1	2.18	17.6	0.38	0.307
BL-9	Prin Art	Sand Cycle Day 1	1.55	65.3	1.01	0.745
BL-10	Prin Art	Sand Cycle Day 2	21.9	0.24	0.053	0.306
BL-11	Prin Art	Sand Cycle Day 3	14.8	0.31	0.046	0.16
BM-7	Prin Art	Sanded	6.16	2.17	0.13	0.347

When test runs with "low" (< ~0.1 g/m^2) and enhanced silt loadings are considered together, stepwise regression analysis shows that there is a significant relationship between the PM-10 emission factor and silt loading. This is illustrated in Figure 4, which plots the observed PM-10 emission factor against the surface silt loading. The log-linear fit of the data in Figure 4 leads to a predictive emission factor represented by the following equation:

$$e* = 2.4\ (sL/2)^{0.67} \qquad (12)$$

where: e* = predicted emission factor (g/VKT)
sL = surface silt loading (g/m^2)

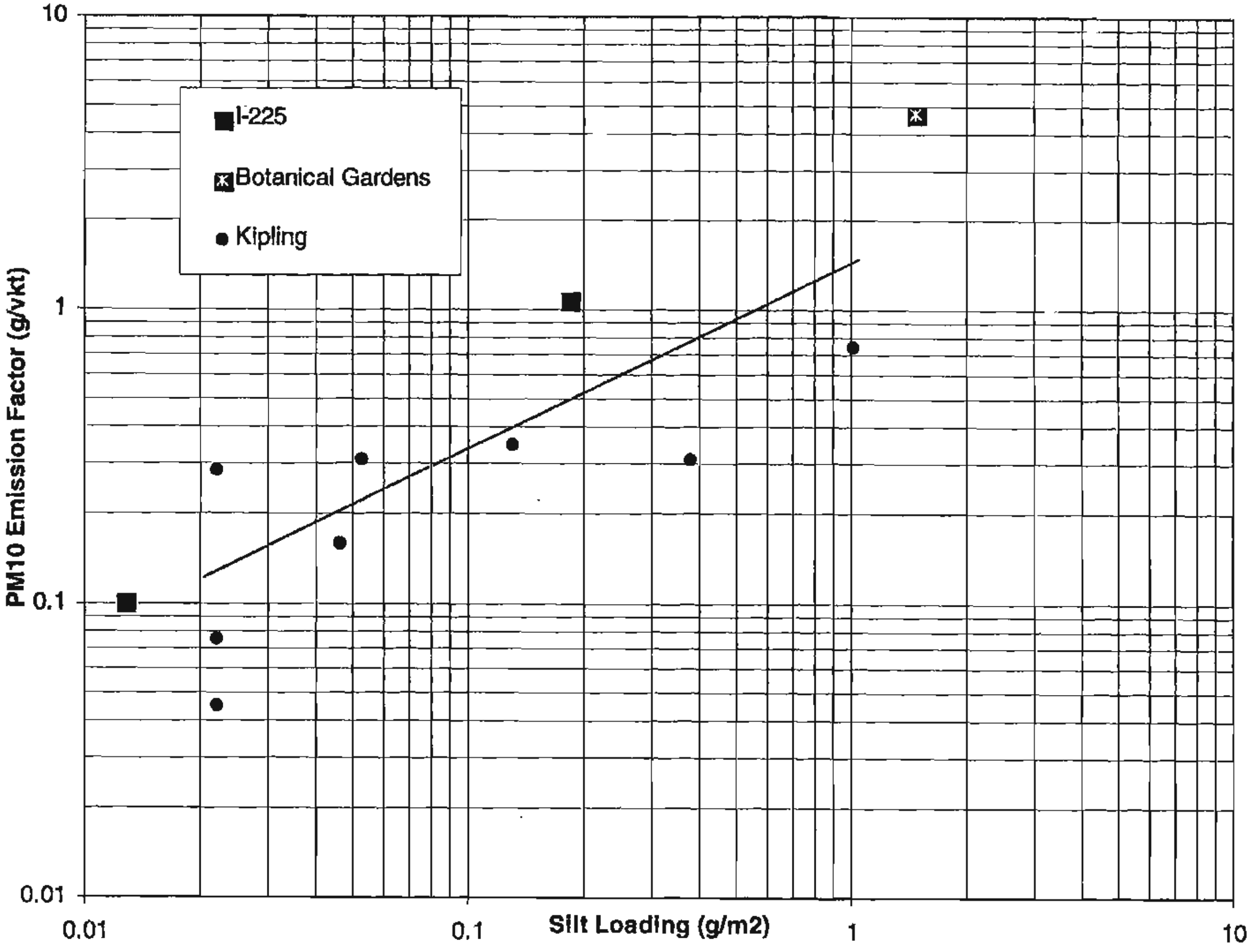

Figure 4. Variation in Emission Factor with Silt Loading

The R-squared value for Equation 12 is 0.71, which implies that 71% of the variation in emission factors can be explained by the functional relationship with silt loading.

Equation 12 compares very favorably with the AP-42 Section 13.2.1 emission factor, in which silt loading is raised to 0.65 power. The average vehicle weight correction term in the AP-42 equation does not vary substantially on public roads in urban areas which are dominated by light-duty vehicles. If the representative average vehicle weight of 2.2 tons is used in the AP-42 equation, the coefficient becomes 2.9 g/VKT. Thus, an increase or decrease in silt loading leads to a reasonably predictable change in the emission factor.

Another way to express this dependency is to use a model of the general form:

$$e* = e_b + e_x = e_b + B(sL - sL_b)p \qquad (13)$$

where the quantities are as defined earlier and

e_b = baseline emission factor
e_x = excess emission factor due to sanding
B = empirical constant
sL_b = baseline surface silt loading
p = empirical constant

Equation 13 has the benefit that the increase in emissions attributable to sanding is more easily envisioned as separate from the independent contributions of emission components, such as vehicle exhaust, that are not dependent on silt loading. When the five sanded Kipling data sets are fitted to a model of the form in Equation 13, the following emission factor is obtained.

$$e* = e_b + 0.52\,(sL - sL_b)^{0.54} \qquad (14)$$

The R-squared value for Equation 13 is 0.63

Although both Equations 12 and 13 show that silt loading can be used to successfully predict emission factors, a silt-loading-based model must account for the fact that the silt loading is a very rapidly changing function of time during the period of a sanding event. Figure 5 illustrates this phenomenon for Runs BL-9 through BL-11. Note that silt loading after sanding can be 50 times higher than the baseline value before sanding, but it rapidly returns to near-baseline conditions once the road surface has dried. Selection of the appropriate value for sL—or for that matter, choosing a time after sanding to collect a surface sample—requires the characterization of the "typical" silt loading cycle associated with a sanding event.

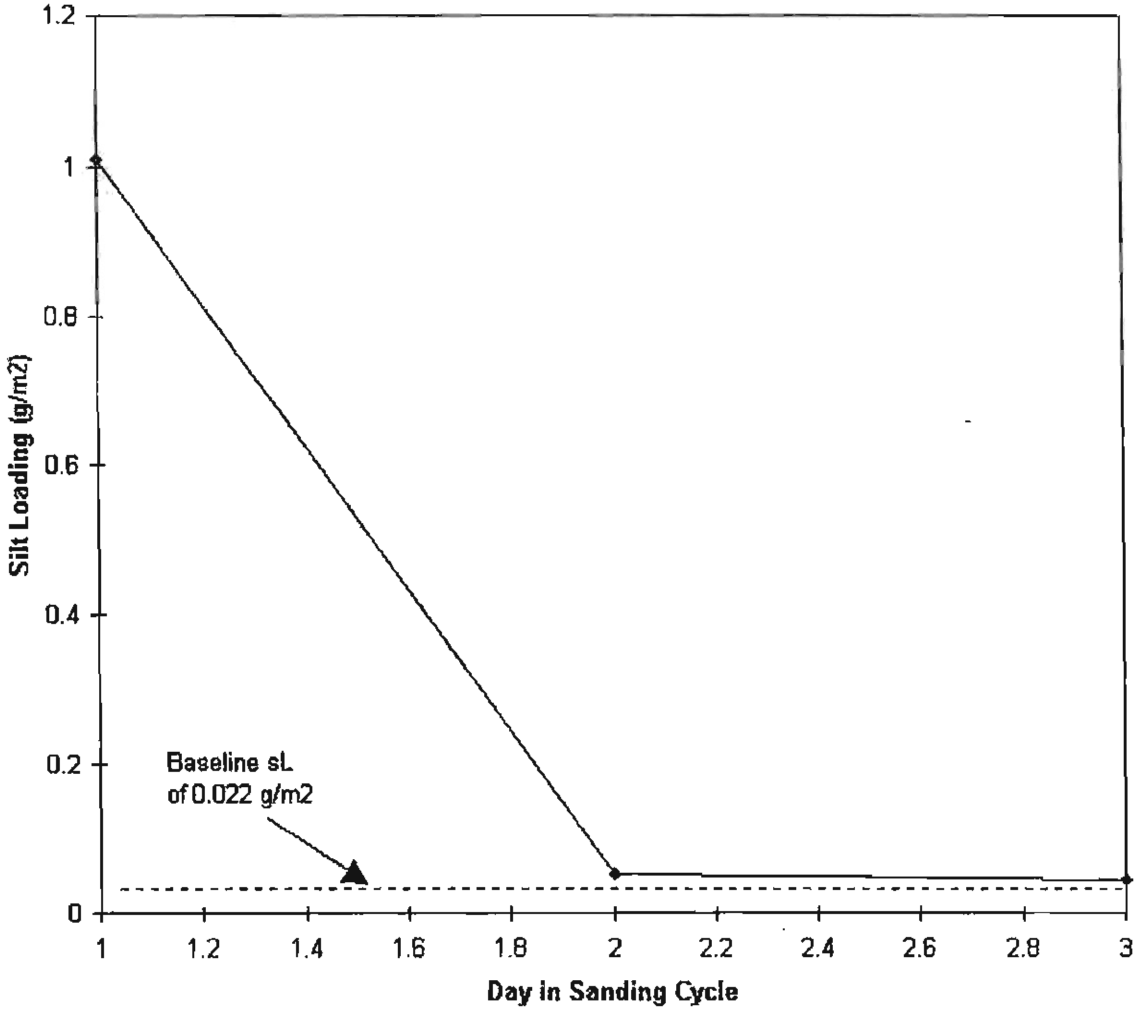

Figure 5. Variation of Silt Loading During Sand Cycle

Because of the potential problems involving specification of representative silt loading during periods of sanding, it was also decided to consider another form of emission model for sanded paved roads. In this case, the equation becomes:

$$e* = e_b + F(t) \tag{15}$$

where e* and e_b again denote predicted and baseline emission factors, respectively, and F(t) represents a function of time (expressed in days after surface dries). F(t) accounts for the increase in emissions above the baseline level.

The function F(t) was estimated on the basis of results from Runs BL-9 through BL-11:

$$F(t) = 0.68 \exp(-1.6t) \tag{16}$$

where "exp" denotes the exponential function. The exponential fit ($R^2 = 0.988$) to the Run BL-9 through BL-11 data (from the late autumn "artificial" sanding series) is shown in Figure 6. Note that after sanding, there was a considerable enhancement of emissions over the first 2 days after the road dried, but the emissions returned to near-baseline conditions by the third day. After a winter sanding event, the return to near-baseline conditions would take a longer time, except on high-speed roadways.

The results of the present study were compared against other wintertime PM-10 emission data that have been collected for paved roads in the Denver metropolitan area. Figure 7 plots the PM-10 emission factors against the silt loading values[6] for tests from the present study and for earlier tests reported by PEI (1989). The earlier study was undertaken during 1989 to characterize PM-10 emissions from six streets in the Denver area. Summary data for those tests are given below. Note that both baseline and sanded roads were tested.

		PM-10 emission factor (g/VKT)	
Test site	No. of tests	Geometric mean	Range
Colfax	17	1.33	0.53 - 9.01
York	1	1.07	1.07
Belleview	4	1.62	1.10 - 4.77
I-225	9	0.31	0.17 - 0.51
Evans	29	1.06	0.21 - 7.83
Louisiana	7	0.96	0.42 - 1.73

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[6] The axes in Figure 7 are incremented in logarithmic scale because of the larger ranges of data being compared.

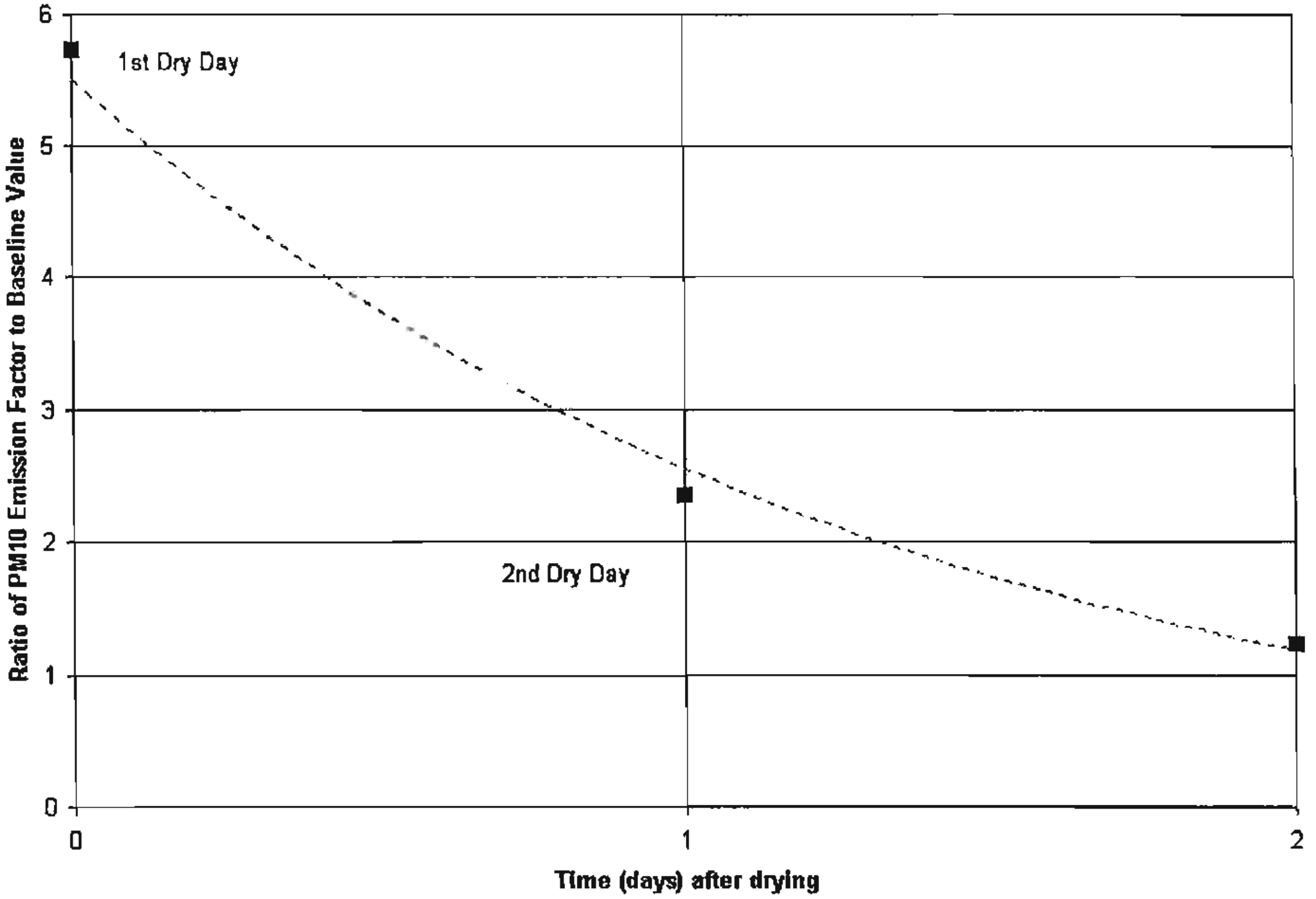

Figure 6. Decrease in PM-10 Emissions After Drying of the Sanded Road

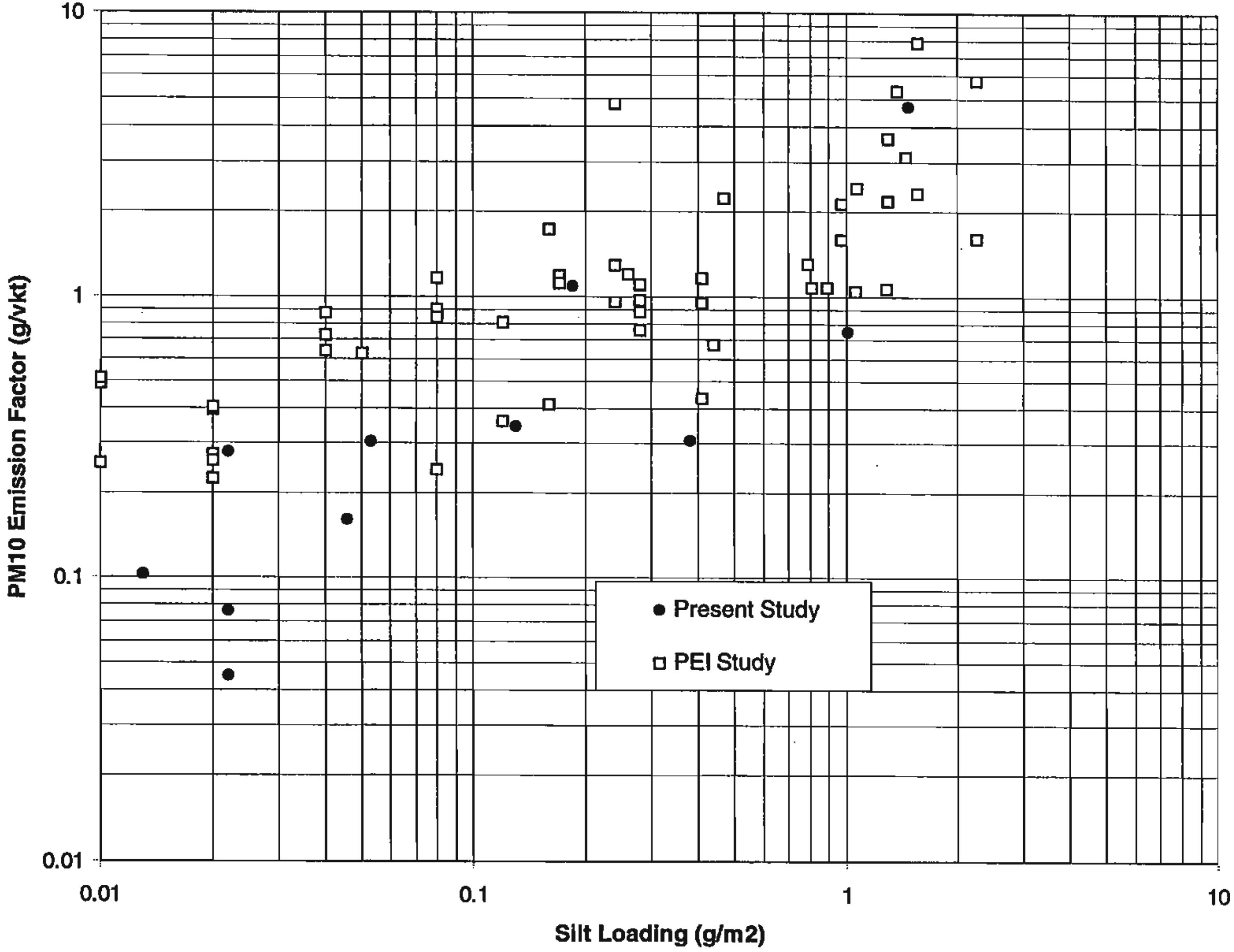

Figure 7. Comparison of PEI Data with Data from Present Study

The 1989 tests employed six to eight PM-10 samplers at a single intake height arranged in two different upwind/downwind configurations. The study collected data on 24 different days and backcalculated a total of 69 emission factors using the CALINE3 dispersion model. The test report cited difficulties for some tests in defining upwind/background concentrations and also ruled some tests as invalid for reasons such as wet road surfaces, nearby dust sources, or downwind concentrations that increased with distance from the roadway.

Figure 7 indicates that the results from the current study compare very well with those from the 1989 Denver study under both baseline and sanded roadway conditions. The silt loadings from the two studies span approximately the same range. Emission factors in the present program tend to be lower than those from the 1989 tests, particularly at the lowest (baseline) silt loading values. This could be due in part to an average lowering of the PM component in vehicle exhaust over the past decade. Both data sets exhibit correlations between silt loading and emission factors that are significant at the 1% level.

Section 6
Particulate Chemistry/Constituents

A key part of Correlation Studies involved comparing the characteristics of airborne particles collected downwind of a test road with the resuspended portions of the collected samples of road surface material. For the defined particle size fractions, particle characteristics of interest were chemical composition and major constituents determined by microscopical analysis.

6.1 Sample Selection

In selecting the filters and surface samples for analysis, the "best" profiling tests were determined: BH-6, BL-7, BM-7 and BM-8. These tests were selected based on the following criteria:

1. Suitability of plume profiling test data for calculation of a PM-10 emission factor based on reliability of net concentrations, consistency of wind conditions and availability of coincident traffic data.
2. Availability of one or more road surface samples that represent the given test period.
3. The extent to which the actual test conditions represent conditions that enhance the air quality impacts of road sanding.

The purpose of this chemical/microscopical analysis work was to characterize the degree of similarity between the constituents of the road surface material and the airborne material in the roadway emission plume from a given test site and sampling period. It was intended that for each of the specified tests both the surface silt and at least its resuspended PM-10 component would be chemically and microscopically speciated along with the corresponding filter samples (from a plume core reference height of 2 to 3 m).

The list of filters from the upwind/downwind samplers operated at a height of 2 to 3 m during the four specified test runs is provided in Table 27. In each case the particle size of the collected sample is listed. The Teflon filters were analyzed for elemental abundance by X-ray fluorescence (XRF) and the quartz fiber filters for carbon analysis by thermal/optical reflectance (TOR). Quartz filters were also analyzed for anions by ion chromatography (IC). The filters with low net weights of collected particulate matter were used as field blanks. The chemical analyses were performed by Desert Research Institute (DRI) in Reno, Nevada.

Table 27. Samples of Plume Particles for Chemical Analysis

Run	Sampler	Filter number	Location	Filter	Particle size	Net Wt (mg)
BH-6	Dichot/Coarse	9559041	2m UW	37 mm Teflon	2.5-10 µmA	**0.15**
	Dichot/Fine	9559042	2m UW	37 mm Teflon	<2.5 µmA	0.02
	Dichot/Coarse	9550025	2m UW	37 mm quartz	2.5-10 µmA	**0.18**
	Dichot/Fine	9550027	2m UW	37 mm quartz	<2.5 µmA	-0.01
	Dichot/Coarse	9559043	2m DW	37 mm Teflon	2.5-10 µmA	**0.18**
	Dichot/Fine	9559044	2m DW	37 mm Teflon	<2.5 µmA	0.00
	Dichot/Coarse	9550029	2m DW	37 mm quartz	2.51-0 µmA	**0.32**
	Dichot/Fine	9550028	2m DW	37 mm quartz	<2.5 µmA	0.08
BL-7	Dichot/Coarse	9629133	3m UW	37 mm Teflon	2.5-10 µmA	0.17
	Dichot/Fine	9629134	3m UW	37 mm Teflon	<2.5 µmA	0.06
	Dichot/Coarse	9629139	3m DW	37 mm Teflon	2.5-10 µmA	**0.42**
	Dichot/Fine	9629140	3m DW	37 mm Teflon	<2.5 µmA	0.06
	Wedding	9623023	3m UW	8 x 10 in quartz	<10 µmA	**9.01**
	Wedding	9623024	3m DW	8 x 10 in quartz	<10 µmA	**18.26**
	Cyclone/Impactor	9623020	3m UW	8 x 10 in quartz	<2.1 µmA	**4.20**
	Cyclone/Impactor	9623026	3m UW	8 x 10 in quartz	<2.1 µmA	**7.90**
BM-7	Wedding	9623070	2m UW	8 x 10 in quartz	<10 µmA	**10.27**
	Wedding	9623072	2m DW	8 x 10 in quartz	<10 µmA	**35.17**
	Wedding/Impactor	9623073	2m UW	8 x 10 in quartz	<3.0 µmA	**7.76**
	Wedding/Impactor	9623068	2m DW	8 x 10 in quartz	<3.0 µmA	**11.16**
	MiniVOL	9625022	2m UW	47 mm Teflon	<10 µmA	**0.17**
	MiniVOL	9625024	2m UW	47 mm Teflon	<2.5µmA	0.09
	MiniVOL	9625021	2m DW	47 mm Teflon	<10 µmA	**0.21**
	MiniVOL	9625025	2m DW	47 mm Teflon	<2.5 µmA	0.03
BM-8	Wedding	9623075	2m UW	8 x 10 in quartz	<10 µmA	**5.67**
	Wedding	9623074	2m DW	8 x 10 in quartz	<10 µmA	**23.67**
	Wedding/Impactor	9623077	2m UW	8 x 10 in quartz	<3.0 µmA	**3.46**
	Wedding/Impactor	9623076	2m DW	8 x 10 in quartz	<3.0 µmA	**6.86**
	MiniVOL	9625023	2m UW	47 mm Teflon	<10 µmA	**0.17**
	MiniVOL	9625027	2m UW	47 mm Teflon	<2.5µmA	0.08
	MiniVOL	9625026	2m DW	47 mm Teflon	<10 µmA	**0.48**
	MiniVOL	9625028	2m DW	47 mm Teflon	<2.5 µmA	0.06

* Bold denotes at least half of the minimum desirable sample mass.

The road surface samples from runs BH-6, BL-7 and BM-7 were also analyzed chemically. (The second surface sample collected for run BM-7 was also used to represent run BM-8, which was initiated on the same day that run BM-7 ended.) Table 28 lists the characteristics of the road surface samples that were analyzed by DRI.

Table 28. Road Surface Samples for Analysis

Date	Corresponding profiling test	Sweeper bag No.	Total loading (g/m^2)	Silt content (%)	Silt loading (g/m^2)
3/16/96	BH-6	694	125	1.12	1.47
11/2/96	BL-7	719	17.6	2.18	0.38
3/15/97	BM-7	823 (north)	2.17	6.16	0.13
3/16/97	BM-8	848 (south)	8.18	3.39	0.28

Portions of the quartz filters were also analyzed by polarized light microscopy (PLM) to identify particle components. Specifically, the polarized light microscopy was performed by IIT Research Institute (IITRI) in Chicago, Illinois. Particle identification was based on the optical (crystallographic) and morphological properties of the aerosols, which often permit simple distinction among chemically similar components.

6.2 Sample Preparation

Quartz filters were cut into strips so that portions could be analyzed by TOR, IC, and PLM (as discussed below). In a few cases, two strips from the same filter (blind duplicates) were analyzed by the same method to determine a measure of analytical reproducibility.

Three particle size fractions of the road surface material samples collected in vacuum sweeper bags were segregated for analysis:

- Silt particles passing a 200-mesh screen upon dry sieving
- Resuspended PM-10 from the total road surface sample, as collected on 47-mm filters in the MRI Dustiness Test Chamber
- Resuspended PM-2.5 from the total road surface sample, as collected on 47-mm filters in the Dustiness Test Chamber (if sample masses were sufficient)

Table 29 presents the laboratory results of the road surface material resuspensions to collect PM-10 and PM-2.5 components in the MRI Dustiness Test Chamber. The average ratio of PM-2.5 to PM-10 for the resuspended road dust is 0.204.

6.3 Chemical Analysis Results

This section presents the chemical analysis results for the ambient and resuspended PM samples that were obtained as part of the Correlation Studies for the subject program. As stated earlier, the chemical analyses were performed by Desert Research Institute (DRI). The three classes of analytes were (a) elements [by x-ray fluorescence], (b) elemental and organic carbon [by thermal/optical reflectance], and (c) anions [by ion chromatography].

The work-up of the chemical analysis data required a considerable effort, using the raw analytical data files provided by DRI. This began with blank corrections to the analytical results. With regard to elemental abundance results determined by x-ray fluorescence, the summary tables presented in this section are limited to elements that represented at least 1% of the sample mass, on average. The raw chemical analysis data are presented in Appendix D.

The work-up of the analytical data involved the following steps:

Table 29. Resuspension Components of Paved Road Surface Material

Run No.	Sample Inlet	Sample Media	No. of Pours	Sampling Delay, Time (sec)	Total Mass Dropped (g)	Dustiness Index (mg/kg)
BH-6	PM-10	teflon	2	30	841.8	3.1
BH-6	PM-2.5	teflon	10	30	4,450.1	0.3
BH-6	PM-10	quartz	2	30	718.1	3.1
BH-6	PM-2.5	quartz	8	30	3,538.2	0.7
BL-7	PM-10	teflon	2	30	856.3	1.8
BL-7	PM-2.5	teflon	8	30	3,419.8	0.3
BL-7	PM-10	quartz	2	30	810.2	2.7
BL-7	PM-2.5	quartz	6	30	2,460.2	0.5
BM-7	PM-10	teflon	2	30	376.0	5.2
BM-7	PM-2.5	teflon	14	30	2,566.5	0.6
BM-7	PM-10	quartz	2	30	365.0	11.0
BM-7	PM-2.5	quartz	19	30	3,562.4	0.2
BM-8[a]	PM-10	teflon	1	30	441.8	4.1
BM-8[a]	PM-2.5	teflon	3	30	1,327.8	1.0
BM-8[a]	PM-10	quartz	1	30	442.0	2.6
BM-8[a]	PM-2.5	quartz	3	30	1,326.7	1.5
Blank	N.A.	teflon	N.A.	N.A.	N.A.	N.A.
Blank	N.A.	quartz	N.A.	N.A.	N.A.	N.A.
Blank	N.A.	teflon	N.A.	N.A.	N.A.	N.A.
Blank	N.A.	quartz	N.A.	N.A.	N.A.	N.A.

[a] The second road surface sample collected during run BM-7 was used to represent run BM-8, which began on the same day.

1. The tabulated analytical results for each analyte category were separated by particle size within a test run, and then combined into a single spreadsheet.

2. For a given sample (filter), the measured abundance of each analyte (µg/filter) was divided by the net PM sample mass (µg/filter) to get a series of percentages.

3. The percentage of each analyte was multiplied by the PM concentration (µg/m^3) represented by the sample to determine the concentration of analyte in the sample.

4. The upwind concentration of each analyte was subtracted from the downwind concentration to determine the concentration increment (impact) due to roadway emissions.

5. The roadway concentration increments were divided by the difference between the upwind and downwind concentrations, to obtain the percentage distribution of analytes in the roadway impact concentration.

6. The analyte masses in the resuspension filters were divided by the net sample mass on each filter to obtain the mass percentage contribution of each analyte.

7. An adjustment correction ratio was determined as follows:

   $$r = A\text{-}B/A$$

   where A is the cumulative percentage of analytes in the roadway impact concentration and B is the cumulative percentage of analytes of those elements in the roadway impact concentration that are not expected in significant amounts in the corresponding resuspended sample of road dust: sulfur, elemental carbon, nitrate, and sulfate.

8. The analyte percentages from Step 6 were each multiplied by the adjustment ratio from Step 7 to obtain adjusted analyte percentages in each resuspended road dust sample. The adjusted percentages reflected the hypothetical addition of the "missing" constituents (identified in Step 7) to the resuspended road dust composition.

9. The adjusted analyte percentages in the resuspended road dust sample were compared to the analyte percentages in the roadway impact concentration (downwind minus upwind concentration) for the same test run.

The tables below show the analyte mass concentrations and mass percentages determined according to the above procedure. Tables 30 through 32 give the PM-10 analyses results for Runs BL-7, BM-7, and BM-8, respectively. Table 33 provides the average concentrations and percentages for runs BL-7 and BM-7 in combination. Tables 34 through 36 give the PM-2.5 analysis results for Runs BL-7, BM-7, and BM-8, respectively.

Table 30. PM-10 Chemical Analysis Results for Run No. BL-7

	Upwind		Downwind		Difference		Resuspension	
Sampler								
. teflon filter	Dichot/Sum		Dichot/Sum		Dichot/Sum		MiniVOL	
. quartz filter	Wedding		Wedding		Wedding		MiniVOL	
Particle Size								
. teflon filter	<10 µmA		<10 µmA		<10 µmA		<10 µmA	
. quartz filter	<10 µmA		<10 µmA		<10 µmA		<10 µmA	
PM Conc. (µg/m^3)	-	44	-	89	45	-	raw	adjusted
Composition	%	µg/m^3	%	µg/m^3	µg/m^3	%	%	%
Silicon	9.4	4.1	14.8	13.2	9.0	20.1	18.2	10.9
Aluminum	3.8	1.7	4.5	4.0	2.3	5.2	5.7	3.4
Chlorine	7.0	3.1	13.7	12.2	9.1	20.3	24.9	14.9
Sulfur	1.3	0.6	1.8	1.6	1.0	2.3	0.7	-
Iron	0.4	0.2	0.5	0.4	0.3	0.6	2.1	1.2
Calcium	1.3	0.6	1.5	1.3	0.8	1.7	2.9	1.7
Potassium	1.0	0.4	1.6	1.4	1.0	2.2	2.0	1.2
Sodium	2.7	1.2	3.7	3.3	2.1	4.7	7.5	4.5
Carbon, Organ..	18.7	8.2	12.2	10.9	2.6	5.8	1.5	0.9
Carbon, Elem.	6.8	3.0	4.4	3.9	0.9	2.1	0.1	-
Chloride	1.1	0.5	9.8	8.7	8.2	18.3	20.0	12.0
Nitrate	19.8	8.7	11.1	9.9	1.2	2.6	0.1	-
Sulfate	5.6	2.5	3.5	3.1	0.7	1.4	2.3	-
TOTALS	78.9	34.7	83.1	74.0	39.2	87.2	88.0	50.7

Table 31. PM-10 Chemical Analysis Results for Run No. BM-7

	Upwind		Downwind		Difference		Resuspension	
Sampler								
. teflon filter	Dichot/Sum		Dichot/Sum		Dichot/Sum		MiniVOL	
. quartz filter	Wedding		Wedding		Wedding		MiniVOL	
Particle Size								
. teflon filter	<10 μmA		<10 μmA		<10 μmA		<10 μmA	
. quartz filter	<10 μmA		<10 μmA		<10 μmA		<10 μmA	
PM Conc. (μg/m^3)	-	27	-	44	17	-	raw	adjusted
Composition	%	μg/m^3	%	μg/m^3	μg/m^3	%	%	%
Silicon	9.1	2.5	8.0	3.5	1.1	6.3	31.8	9.4
Aluminum	2.4	0.6	2.6	1.1	0.5	2.9	9.8	2.9
Chlorine	1.7	0.5	1.6	0.7	0.2	1.4	2.4	0.7
Sulfur	1.7	0.5	1.7	0.7	0.3	1.7	0.3	-
Iron	1.3	0.4	1.2	0.5	0.2	1.0	3.3	1.0
Calcium	0.9	0.2	0.9	0.4	0.2	0.9	4.0	1.2
Potassium	0.9	0.2	0.9	0.4	0.2	0.9	3.2	0.9
Sodium	0.4	0.1	0.7	0.3	0.2	1.2	0.6	0.2
Carbon, Organ.	15.8	4.3	12.2	5.4	1.1	6.5	8.5	2.5
Carbon, Elem.	5.2	1.4	6.5	2.9	1.5	8.6	0.7	-
Chloride	0.5	0.1	0.5	0.2	0.1	0.5	3.9	1.1
Nitrate	14.1	3.8	17.1	7.5	3.7	21.9	0.0	-
Sulfate	12.3	3.3	9.9	4.4	1.0	6.1	0.4	-
TOTALS	66.3	17.9	63.8	28.1	10.2	59.8	68.9	19.9

Table 32. PM-10 Chemical Analysis Results for Run No. BM-8

	Upwind		Downwind		Average		Resuspension	
Sampler								
. teflon filter	MiniVOL		MiniVOL		MiniVOL		MiniVOL	
. quartz filter	Wedding		Wedding		Wedding		MiniVOL	
Particle Size								
. teflon filter	<10 µmA		<10 µmA		<10 µmA		<10 µmA	
. quartz filter	<10 µmA		<10 µmA		<10 µmA		<10 µmA	
PM Conc. (µg/m^3)	-	19	-	24	22	-	raw	adjusted
Composition	%	µg/m^3	%	µg/m^3	µg/m^3	%	%	%
Silicon	16.9	3.2	1.2	0.3	1.7	8.0	30.5	16.6
Aluminum	5.4	1.0	0.3	0.1	0.5	2.5	10.3	5.6
Chlorine	3.2	0.6	0.3	0.1	0.3	1.5	6.9	3.7
Sulfur	0.7	0.1	0.0	0.0	0.1	0.3	0.5	-
Iron	2.6	0.5	0.1	0.0	0.3	1.2	4.1	2.2
Calcium	1.7	0.3	0.1	0.0	0.2	0.8	2.4	1.3
Potassium	1.7	0.3	0.1	0.0	0.2	0.8	3.2	1.7
Sodium	1.2	0.2	0.2	0.0	0.1	0.6	1.9	1.0
Carbon, Organ.	14.0	2.7	17.1	4.1	3.4	15.4	2.9	1.6
Carbon, Elem.	5.6	1.1	9.3	2.2	1.6	7.5	0.7	-
Chloride	1.7	0.3	2.9	0.7	0.5	2.3	5.2	2.8
Nitrate	4.7	0.9	3.1	0.7	0.8	3.7	0.0	-
Sulfate	4.7	0.9	4.0	1.0	0.9	4.2	0.6	-
TOTALS	64.1	12.2	38.7	9.3	10.7	48.8	69.2	36.5

Table 33. Average Chemical Abundance in PM-10 Samples

	Upwind		Downwind		Difference		Resuspension	
Particle Size . teflon filter . quartz filter	<10 µmA <10 µmA		<10 µmA <10 µmA		<10 µmA <10 µmA		<10 µmA <10 µmA	
PM Conc. (µg/m^3)	35.5	-	66.5	-	31	-	raw	adjusted
Composition	µg/m^3	%	µg/m^3	%	µg/m^3	%	%	%
Silicon	3.3	9.3	8.3	12.6	5.0	16.3	25.0	10.2
Aluminum	1.2	3.3	2.6	3.9	1.4	4.6	7.8	3.2
Chloride	0.5	1.3	0.7	1.1	0.2	0.8	13.7	7.8
Sulfur	0.5	1.5	1.2	1.8	0.7	2.1	0.5	-
Iron	0.3	0.7	0.5	0.7	0.2	0.7	2.7	1.1
Calcium	0.4	1.1	0.9	1.3	0.5	1.5	3.5	1.5
Potassium	0.3	1.0	0.9	1.4	0.6	1.8	2.6	1.1
Sodium	0.6	1.8	1.8	2.7	1.2	3.7	4.1	2.4
Carbon, Organ.	6.2	17.6	8.1	12.2	1.9	6.0	5.0	1.7
Carbon, Elem.	2.2	6.2	3.4	5.1	1.2	3.8	0.4	-
Chlorine	0.1	0.4	0.2	0.3	0.1	0.3	12.0	
Nitrate	6.3	17.6	8.7	13.1	2.4	7.9	0.1	-
Sulfate	2.9	8.1	3.7	5.6	0.8	2.7	1.4	-
TOTALS	24.8	69.9	41.0	61.7	16.2	52.2	78.5	28.8

Table 34. PM-2.5 Chemical Analysis Results for Run No. BL-7

	Upwind		Downwind		Difference		Resuspension	
Sampler								
. teflon filter	MiniVOL		MiniVOL		MiniVOL		MiniVOL	
. quartz filter	Cyclone/Impactor		Cyclone/Impactor		Cyclone/Impactor		MiniVOL	
Particle Size								
. teflon filter	<2.5 µmA		<2.5 µmA		<2.5 µmA		<2.5 µmA	
. quartz filter	<2.1 µmA		<2.1 µmA		<2.1 µmA		<2.1 µmA	
PM Conc. (µg/m^3)	-	23	-	36	13	-	raw	adjusted
Composition	%	µg/m^3	%	µg/m^3	µg/m^3	%	%	%
Silicon	ND	ND	4.0	1.4	-	-	9.3	3.8
Aluminum	1.7	0.4	1.9	0.7	0.3	2.3	2.7	1.1
Chlorine	ND	ND	ND	ND	-	-	17.6	7.1
Sulfur	1.3	0.3	1.8	0.6	0.3	2.7	0.7	-
Iron	0.4	0.1	1.4	0.5	0.4	3.2	2.1	0.9
Calcium	ND	ND	0.4	0.1	-	-	2.3	0.9
Potassium	ND	ND	0.5	0.2	-	-	1.6	0.7
Sodium	2.3	0.5	2.2	0.8	0.3	2.0	7.8	3.2
Carbon, Organ.	7.5	1.7	12.0	4.3	2.6	20.0	1.0	0.4
Carbon, Elem.	3.0	0.7	5.7	2.1	1.4	10.5	0.2	-
Chloride	1.2	0.3	5.3	1.9	1.6	12.6	25.3	10.2
Nitrate	20.3	4.7	13.4	4.8	0.2	1.2	0.1	-
Sulfate	6.4	1.5	4.2	1.5	0.0	0.3	2.4	-
TOTALS	44.1	10.1	52.8	19.0	7.1	54.6	73.1	28.3

Table 35. PM-2.5 Chemical Analysis Results for Run No. BM-7

	Upwind		Downwind		Difference		Resuspension	
Sampler								
. teflon filter	MiniVOL		MiniVOL		MiniVOL		MiniVOL	
. quartz filter	Wedding/Impactor		Wedding/Impactor		Wedding/Impactor		MiniVOL	
Particle Size								
. teflon filter	<2.5 μmA		<2.5 μmA		<2.5 μmA		<2.5 μmA	
. quartz filter	<3.0 μmA		<3.0 μmA		<3.0 μmA		<2.5 μmA	
PM Conc. (μg/m^3)	-	15	-	22	7	-	raw	adjusted
Composition	%	μg/m^3	%	μg/m^3	μg/m^3	%	%	%
Silicon	3.8	0.6	ND	ND	ND	ND	14.6	3.0
Aluminum	0.7	0.1	ND	ND	ND	ND	4.3	0.9
Chlorine	1.1	0.2	ND	ND	ND	ND	2.9	0.6
Sulfur	1.0	0.2	ND	ND	ND	ND	0.6	-
Iron	1.4	0.2	ND	ND	ND	ND	3.3	0.7
Calcium	0.9	0.1	ND	ND	ND	ND	3.4	0.7
Potassium	0.6	0.1	ND	ND	ND	ND	2.3	0.5
Sodium	2.2	0.3	ND	ND	ND	ND	0.9	0.2
Carbon, Organ.	10.1	1.5	ND	ND	ND	ND	4.2	0.9
Carbon, Elem.	6.5	1.0	ND	ND	ND	ND	0.7	-
Chloride	0.4	0.1	ND	ND	ND	ND	3.0	0.6
Nitrate	21.9	3.3	16.1	3.5	0.3	3.7	0.2	-
Sulfate	13.4	2.0	16.1	3.5	1.5	21.9	0.2	-
TOTALS	64.0	9.6	32.2	7.1	1.8	25.6	40.6	8.1

Table 36. PM-2.5 Chemical Analysis Results for Run No. BM-8

	Upwind		Downwind		Average		Resuspension	
Sampler								
. teflon filter	MiniVOL		MiniVOL		MiniVOL		MiniVOL	
. quartz filter	Wedding/Impactor		Wedding/Impactor		Wedding/Impactor		MiniVOL	
Particle Size								
. teflon filter	<2.5 µmA		<2.5 µmA		<2.5 µmA		<2.5 µmA	
. quartz filter	<3.0 µmA		<3.0 µmA		<3.0 µmA		<2.5 µmA	
PM Conc. (µg/m³)	-	10	-	12	11	-	raw	adjusted
Composition	%	µg/m³	%	µg/m³	µg/m³	%	%	%
Silicon	3.8	0.4	5.3	0.6	0.5	4.6	15.8	10.3
Aluminum	0.7	0.1	1.0	0.1	0.1	0.9	4.6	3.0
Chlorine	1.1	0.1	1.3	0.2	0.1	1.2	5.7	3.7
Sulfur	1.0	0.1	1.4	0.2	0.1	1.2	0.6	-
Iron	1.4	0.1	1.7	0.2	0.2	1.6	4.2	2.8
Calcium	0.9	0.1	0.7	0.1	0.1	0.8	2.0	1.3
Potassium	0.6	0.1	1.0	0.1	0.1	0.8	2.5	1.7
Sodium	2.2	0.2	2.0	0.2	0.2	2.1	2.4	1.6
Carbon, Organ.	37.2	3.7	17.5	2.1	2.9	26.5	8.7	5.7
Carbon, Elem.	8.5	0.9	11.0	1.3	1.1	9.9	1.1	-
Chloride	1.9	0.2	2.0	0.2	0.2	2.0	0.5	0.3
Nitrate	6.2	0.6	3.3	0.4	0.5	4.6	0.0	-
Sulfate	7.4	0.7	5.0	0.6	0.7	6.1	0.5	-
TOTALS	72.9	7.3	53.2	6.4	6.8	62.2	48.6	30.4

The chemical analysis results for Run BL-7 are especially important because the sample masses collected on Teflon and quartz filters were well above the threshold values for reliable quantitation of chemical constituents. In addition, the relatively high silt loading (0.38 g/m^2) and the consistent winds during the test run produced a high PM-10 concentration increment (45 $\mu g/m^3$ at the reference height) attributable to the roadway traffic. This run was from the artificial sanding series conducted at the Core Site in the late autumn of 1996.

As evident from Table 30, there was good agreement between the constituent percentages in the roadway PM-10 impact (i.e., the "difference" column) and in the resuspended PM-10 (unadjusted) from the collected road dust sample. This is shown in Figure 8. Both silicon and chlorine were present at about the 20% level, as determined by XRF. The IC results also showed chloride ion at about the 20% level. The TOR results showed that organic carbon was present at much higher levels in the roadway PM-10 impact than in the resuspended PM-10. This finding agrees with other recent results indicating that tire particles (as the primary source of organic carbon)[7] are directly emitted without passing through the particle "reservoir" on the road surface. Furthermore, little nitrate or elemental carbon was found in the resuspended PM-10 from the road surface sample, as expected.

The distribution of major components in the PM-10 roadway impact from Run BL-7 are shown in Figure 9. These components were estimated from the upwind/downwind "difference" percentages from Table 30, as follows:

1. The silicon was assumed to be present mostly as SiO_2 (quartz) associated with the sand/salt mixture applied to Denver roadways in the winter for antiskid purposes.

2. The chlorine was assumed to be in the form of sodium chloride, also associated with the sand/salt antiskid material.

3. The organic carbon was assumed to be associated with tire wear particles, using a multiplier of three to account for the presence of other elements in the tire particle composition.

As shown in Figure 9, 75% of the PM-10 impact from the artificially sanded test roadway was associated with the sand/salt application. Because of the friability of the salt, it was enriched in the road surface silt loading. In actual wintertime applications, most of the salt would be dissolved in the snow/ice, thus largely removing it from subsequent release to the atmosphere as PM-10. Under lower (baseline) wintertime silt loading conditions, the quartz component of PM-10 emissions would be reduced (according to the 0.65-power relationship), and tire particle emissions would also be reduced because of the less abrasive road surface.

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[7] The attribution of organic carbon to tire particles is supported by the results of microscopical analysis as described later in this section.

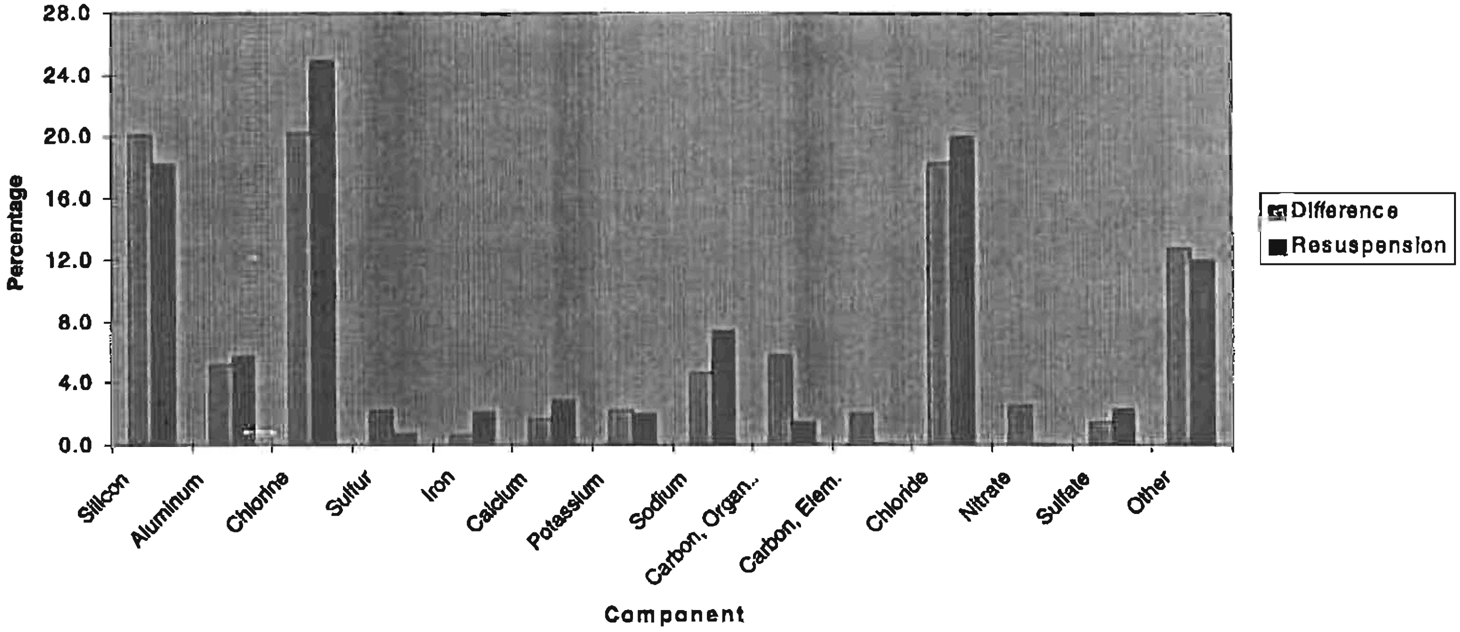

Figure 8. Comparison of PM-10 Contribution from Calculation and Resuspension Methods from Denver Paved Roads—Run BL-7

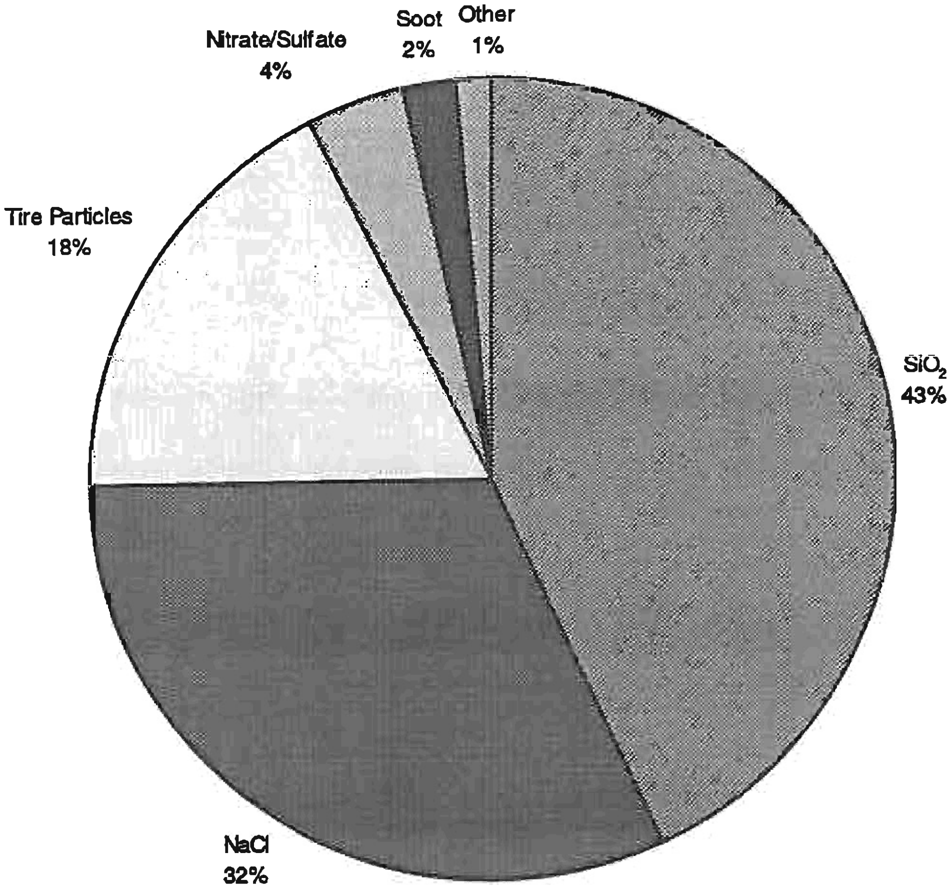

Figure 9. Chemical Abundance in PM-10 Contribution from Denver Artificially Sanded Road—Run BL-7

Table 31 shows a less favorable PM-10 constituent comparison for Run BM-7, which was conducted after a winter storm in early 1997. The chemical analysis of the PM-10 resuspended from the road surface sample shows a reasonable distribution of constituent percentages. There is a strong silicon component from the sand, but the chlorine is reduced to less than 5 percent because of the dissolving of the salt component. The analytical results for the roadway PM-10 impact appear reasonable except for the high percentage of nitrate. In addition, the elemental percentages from XRF all appear to be low, possibly reflecting the partial loss of relatively small PM-10 sample masses from the Teflon filters during shipment of the filters to DRI for analysis.

In Table 32, the upwind and downwind constituent percentages for Run BM-8 were averaged rather than subtracted, because of the lack of a strong roadway impact (mostly due to variable winds). It seems clear from the XRF results that much of the PM-10 sample mass was lost from the downwind Teflon filter during shipment. Once again, the organic carbon in the roadway PM-10 impact may be attributed largely to the presence of directly emitted tire particles.

The average chemical abundance in the PM-10 roadway samples may be represented by combining the results from runs BL-7 and BM-7, as given in Table 33. The corresponding distribution of major components in the roadway PM-10 impact as estimated from the "difference" column in Table 33, is shown in Figure 10. Note that the NaCl concentration from BM-7 was also assigned to run BL-7 in the averaging process, to account for the relative unavailability of salt for resuspension after actual winter storm events.

With regard to PM-2.5, the analytical results for Run BL-7 again show generally good agreement between the distribution of constituents in the roadway PM-2.5 impact and the PM-2.5 resuspended from the road surface sample (unadjusted), as shown in Table 34. However, the roadway PM-2.5 impact results show more pronounced effects of limitations in sample mass, especially for upwind XRF analyses.

The roadway PM-2.5 impact for Run BL-7 exhibits an abundance of silicon, chloride and organic carbon, which again can be associated with the application of the salt/sand mixture and with the emissions of tire particles. However, no chlorine was detected by XRF in either the upwind or downwind PM-2.5 samples, probably as a result of limitations of original sample mass (or loss of sample mass during shipment of Teflon filters to DRI). The resuspended PM-2.5 sample shows large silicon and chlorine/chloride components but negligible organic carbon.

The component analysis of the roadway PM-2.5 impact from Run BL-7 is similar to that presented for PM-10, except that only half the organic carbon is assumed to be associated with tire particles. As expected, soot (elemental carbon from unburned fuel) constitutes a larger fractional component in PM-2.5 than in PM-10. Once again, during winter storms, most of the salt component in these samples from artificially sanded roads would be dissolved and removed in the snow/ice melt, with little residue available for subsequent PM-2.5 emissions.

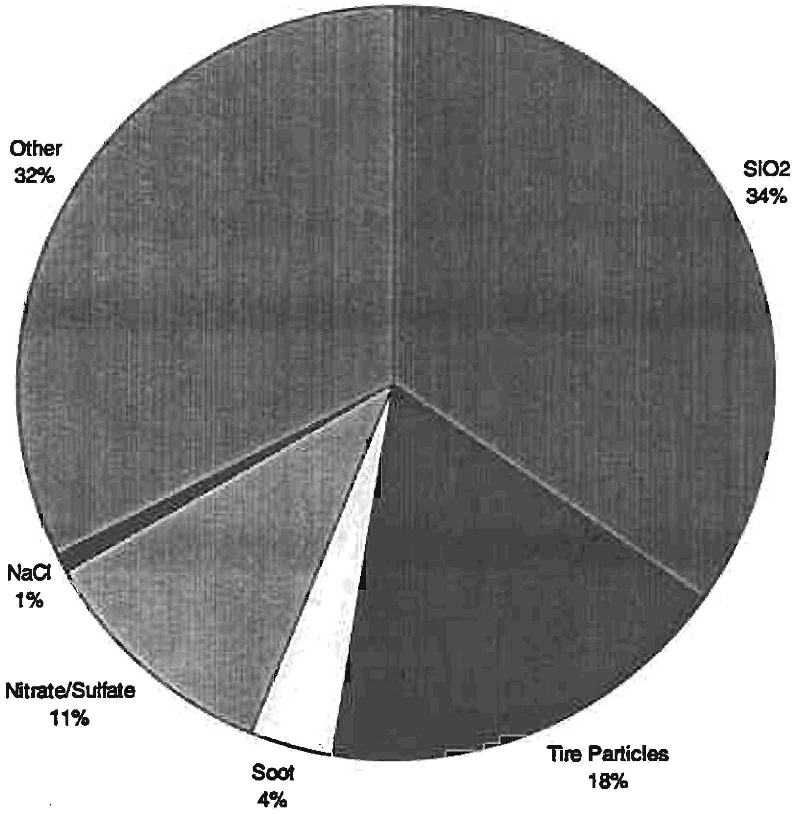

Figure 10. Average Chemical Abundance in PM-10 Contribution from Denver Paved Roads—Runs BL-7 and BM-7

The PM-2.5 chemical analysis results for Run BM-7 also show the effects of inadequate sample mass. None of the target elements were detected by XRF in the downwind sample. Also, the large sulfate component in the roadway PM-2.5 impact appears problematic. The analytical results for the resuspended PM-2.5 again appear reasonable, showing a prevalence of silicon with lesser amounts of the other key elements.

The analytical results for Run BM-8 show good agreement between the upwind and downwind PM-2.5. For this run, use of the wind activated sampling system provided larger sample masses, even though the upwind and downwind PM-10 concentrations were very low and indistinguishable from each other. Organic carbon is the most abundant component in PM-2.5, and it is assumed that at least half of which can be attributed to directly emitted tire particles. The resuspended PM-2.5 from the road dust sample showed a larger fraction of silicon and organic carbon. The organic carbon in the resuspended fraction is believed to be related mostly to sources other than tire particles.

6.4 Microscopical Analysis of Results

This section presents the results of the microscopical analysis of upwind and downwind PM-10 and PM-2.5 filters from the selected correlation study test runs. Tables 37 through 40 present the PM-10 microscopical analysis results for runs BH-6, BL-7, BM-7, and BM-8, respectively. Table 41 gives the average PM-10 results from a combination of tests (runs BH-6, BL-7, and BM-7). Tables 42 through 45 present the PM-2.5 microscopical analysis results for the same test runs.

The anion percentages in the tables are expressed in association with the most likely component, consistent with the microscopical observations. The anion masses were taken from the DRI chemical analysis results.

The percentages of silicate minerals, rubber tire fragments, and elemental carbon are based on particle number/volume counts. Using standard densities for observed particle types, the particle number/volume counts were converted to equivalent particle masses. The six constituents listed in the tables of microscopical analysis results were assumed to encompass all of the particle mass.

Typically the microscopical analysis results show that silicate minerals account for the largest portion of the sample masses on the filters analyzed. These minerals consist mostly of quartz (SiO_2) and feldspars with minor concentrations of mica. Mineral particles were deposited on the filters as individual particles rather than agglomerates.

Tire particles and ammonium nitrate typically account for the next largest portions of sample mass, although ammonium sulfate (fine particles) occasionally contributes a comparable mass fraction. The primary carbon containing components are tire particles and elemental carbon. There were only very slight traces of wood burning carbon with distinguishable wood structure and only in a few samples. There was little to no asphaltic material coating pavement mineral fragments in the samples. Alternately, these minerals could be fragments from road sanding or some combination of these two sources.

The average component abundance in the PM-10 roadway samples may be represented by combining the results from runs BH-6, BL-7, and BM-7, as given in Table 41. The corresponding distribution of major components in the roadway PM-10 impact, as taken from the "difference" column in Table 41, is shown in Figure 11.

An unusual phenomenon was observed in the clustering of ammonium nitrate, sodium chloride, and tire particles. These were often co-deposited on filters as agglomerates. This gave evidence of a splash effect indicating a common arrival on the filter leading to co-crystallization of the wet agglomerates after deposition on the filters.

The areal concentrations of particles on the filters were low enough in every sample so that this co-crystallization had to have occurred as the result of the arrival of a droplet containing chloride, nitrate, and one or more rubber tire fragments rather than resulting from a chance contact on the filter.

Sodium chloride was also seen agglomerated with nitrate particles but without rubber tire fragments. Nitrate was also found alone, but sodium chloride was always associated with nitrate, tire fragments, or both. Nitrate was not found with tire fragments unless sodium chloride was also part of the agglomerate. Mineral particles were not found with sodium chloride or nitrate particles, but were occasionally seen attached to tire fragments.

Table 37. PM-10 Microscopical Analysis Results for Run No. BH-6

	Upwind		Downwind		Difference	
Sampler	Dichot Sum		Dichot Sum		Dichot Sum	
Filter	37 mm Teflon		37 mm Teflon		37 mm Teflon	
Particle Size	<2.5-10 µmA		<2.5-10 µmA		<2.5-10 µmA	
PM Conc. (µg/m3)	-	45	-	74	29	-
Composition	%	µg/m³	%	µg/m³	µg/m³	%
Chloride as NaCl	7.5	3.4	8.9	6.6	3.2	11.1
Nitrate as (NH4)NO3	7.7	3.5	3.1	2.3	-.2	-4.0
Sulfate as (NH4)2SO4	4.0	1.8	6.1	4.5	2.7	9.4
Silicate Minerals	74.6	33.6	61.7	45.6	12.0	41.5
Rubber Tire Fragments	4.5	2.0	17.6	13.0	11.0	38.0
Elemental Carbon	1.7	0.8	2.6	2.0	1.2	4.1
TOTAL	100.0	45.0	100.0	74.0	29.0	100.0

Table 38. PM-10 Microscopical Analysis for Run No. BL-7

	Upwind		Downwind		Difference	
Sampler	Wedding/Impactor		Wedding/Impactor		Wedding/Impactor	
Filter	8 X 10 quartz		8 X 10 quartz		8 X 10 quartz	
Particle Size	<10 µmA		<10 µmA		<10 µmA	
PM Conc. (µg/m³)	-	44	-	89	45	-
Composition	%	µg/m³	%	µg/m³	µg/m³	%
Chloride as NaCl	6.7	2.9	19.4	17.3	14.3	31.8
Nitrate as (NH4)NO3	25.5	11.2	14.3	12.7	1.5	3.3
Sulfate as (NH4)2SO4	7.7	3.4	4.8	4.3	0.9	2.0
Silicate Minerals	37.8	16.6	55.4	49.3	32.7	72.6
Rubber Tire Fragments	20.4	9.0	4.2	3.7	-5.3	-11.7
Elemental Carbon	1.8	0.8	1.9	1.7	0.9	2.0
TOTALS	100.0	44.0	100.0	89.0	45.0	100.0

Table 39. PM-10 Microscopical Analysis for Run No. BM-7

	Upwind		Downwind		Difference	
Sampler	Wedding/Impactor		Wedding/Impactor		Wedding/Impactor	
Filter	8 X 10 quartz		8 X 10 quartz		8 X 10 quartz	
Particle Size	<10 μmA		<10 μmA		<10 μmA	
PM Conc. (μg/m^3)	-	27	-	44	17	-
Composition	%	μg/m^3	%	μg/m^3	μg/m^3	%
Chloride as NaCl	1.8	0.5	1.7	0.7	0.3	1.5
Nitrate as (NH4)NO3	18.2	4.9	22.1	9.7	4.8	28.3
Sulfate as (NH4)2SO4	16.9	4.6	13.6	6.0	1.4	8.4
Silicate Minerals	44.7	12.1	39.2	17.3	5.2	30.5
Rubber Tire Fragments	15.7	4.3	19.5	8.6	4.3	25.6
Elemental Carbon	2.7	0.7	3.8	1.7	1.0	5.7
TOTALS	100.0	27.0	100.0	44.0	17.0	100.0

Table 40. PM-10 Microscopical Analysis Results for Run No. BM-8

	Upwind		Downwind		Average	
Sampler	Wedding/Impactor		Wedding/Impactor		Wedding/Impactor	
Filter	8 X 10 quartz		8 X 10 quartz		8 X 10 quartz	
Particle Size	<10 μmA		10 μmA		<10 μmA	
PM Conc. (μg/m^3)	-	19	-	24	21.5	-
Composition	%	μg/m^3	%	μg/m^3	μg/m^3	%
Chloride as NaCl	4.0	0.8	4.8	1.2	1.0	4.4
Nitrate as (NH4)NO3	6.1	1.2	4.0	1.0	1.1	4.9
Sulfate as (NH4)2SO4	6.5	1.2	5.5	1.3	1.3	5.9
Silicate Minerals	68.6	13.0	59.7	14.3	13.7	63.6
Rubber Tire Fragments	12.6	2.4	21.4	5.1	3.8	17.5
Elemental Carbon	2.2	0.4	4.6	1.1	0.8	3.5
TOTALS	100.0	19.0	100.0	24.0	21.5	100.0

Table 41. Average Component Abundances in PM-10 Samples From Runs BH-6, BL-7, and BM-7

	Upwind		Downwind		Difference	
Particle Size	<10 µmA		<10 µmA		<10 µmA	
PM Conc. (µg/m^3)	38.7	-	69.0	-	30.3	-
Composition	µg/m^3	%	µg/m^3	%	µg/m^3	%
Chloride as NaCl	2.3	5.9	8.2	11.9	5.9	19.6
Nitrate as (NH4)NO3	6.5	16.9	8.2	12.0	1.7	5.7
Sulfate as (NH4)2SO4	3.2	8.4	4.9	7.1	1.7	5.5
Silicate Minerals	20.8	53.6	37.4	54.2	16.6	54.9
Rubber Tire Fragments	5.1	13.1	8.4	12.2	3.4	11.1
Elemental Carbon	0.8	2.0	1.8	2.6	1.0	3.4
TOTALS	38.7	99.9	69.0	100.0	30.3	100.2

Table 42. PM-2.5 Microcopical Analysis Results for Run No. BH-6

	Upwind		Downwind		Difference	
Sampler	Dichot/Fine		Dichot/Fine		Dichot/Fine	
Filter	37 mm Teflon		37 mm Teflon		37 mm Teflon	
Particle Size	<2.5 µmA		<2.5 µmA		<2.5 µmA	
PM Conc. (µg/m3)	-	13	-	23	10	-
Composition	%	µg/m^3	%	µg/m^3	µg/m^3	%
Chloride as NaCl	-	-	-	-	-	-
Nitrate as (NH4)NO3	23.0	3.0	8.1	1.9	-1.1	-11.2
Sulfate as (NH4)2SO4	-	-	16.1	3.7	-	-
Silicate Minerals	21.8	2.8	43.5	10.0	7.2	71.7
Rubber Tire Fragments	1.0	0.1	5.7	1.3	1.2	11.8
Elemental Carbon	4.7	0.6	7.5	1.7	1.1	11.1
TOTAL	50.5	6.6	81.0	18.6	8.3	83.5

Table 43. PM-2.5 Microscopical Analysis for Run No. BL-7

	Upwind		Downwind		Difference	
Sampler	Cyclone/Impactor		Cyclone/Impactor		Cyclone/Impactor	
Filter	8 X 10 quartz		8 X 10 quartz		8 X 10 quartz	
Particle Size	<2.1 µmA		<2.1 µmA		<2.1 µmA	
PM Conc. (µg/m^3)	-	23	-	36	13	-
Composition	%	µg/m^3	%	µg/m^3	µg/m^3	%
Chloride as NaCl	2.0	0.5	8.7	3.1	2.7	20.6
Nitrate as (NH4)NO3	26.2	6.0	17.3	6.2	0.2	1.6
Sulfate as (NH4)2SO4	8.8	2.0	5.8	2.1	0.1	0.5
Silicate Minerals	33.8	7.8	52.4	18.9	11.1	85.3
Rubber Tire Fragments	19.4	4.5	15.3	5.5	1.1	8.2
Elemental Carbon	9.8	2.3	0.4	0.2	-2.1	-16.1
TOTALS	100.0	23.0	100.0	36.0	13.0	100.0

Table 44. PM-2.5 Microscopical Analysis Results for Run No. BM-7

	Upwind		Downwind		Difference	
Sampler	Wedding/Impactor		Wedding/Impactor		Wedding/Impactor	
Filter	8 X 10 quartz		8 X 10 quartz		8 X 10 quartz	
Particle Size	<3.0 µmA		<3.0 µmA		<3.0 µmA	
PM Conc. (µg/m^3)	-	15	-	22	7	-
Composition	%	µg/m^3	%	µg/m^3	µg/m^3	%
Chloride as NaCl	1.2	0.2	0.7	0.2	0.0	-0.2
Nitrate as (NH4)NO3	28.3	4.2	20.8	4.6	0.3	2.5
Sulfate as (NH4)2SO4	18.4	2.8	22.1	4.9	2.1	16.2
Silicate Minerals	42.3	6.3	24.2	5.3	-1.0	-7.7
Rubber Tire Fragments	5.2	0.8	18.2	4.0	3.2	24.6
Elemental Carbon	4.7	0.7	14.0	3.1	2.4	18.5
TOTALS	100.0	15.0	100.0	22.0	7.0	53.9

Table 45. PM-2.5 Microscopical Analysis Results for Run No. BM-8

	Upwind		Downwind		Average	
Sampler	Wedding/Impactor		Wedding/Impactor		Wedding/Impactor	
Filter	8 X 10 quartz		8 X 10 quartz		8 X 10 quartz	
Particle Size	<3.0 µmA		<3.0 µmA		<3.0 µmA	
PM Conc. (µg/m^3)	-	10	-	12	11	-
Composition	%	µg/m^3	%	µg/m^3	µg/m^3	%
Chloride as NaCl	2.5	0.3	2.7	0.3	0.3	2.6
Nitrate as (NH4)NO3	8.0	0.8	4.3	0.5	0.7	6.0
Sulfate as (NH4)2SO4	10.1	1.0	6.8	0.8	0.9	8.3
Silicate Minerals	66.7	6.7	60.4	7.3	7.0	63.3
Rubber Tire Fragments	6.5	0.7	14.2	1.7	1.2	10.7
Elemental Carbon	6.1	0.6	11.6	1.4	1.0	9.1
TOTALS	100.0	10.0	100.0	12.0	11.0	100.0

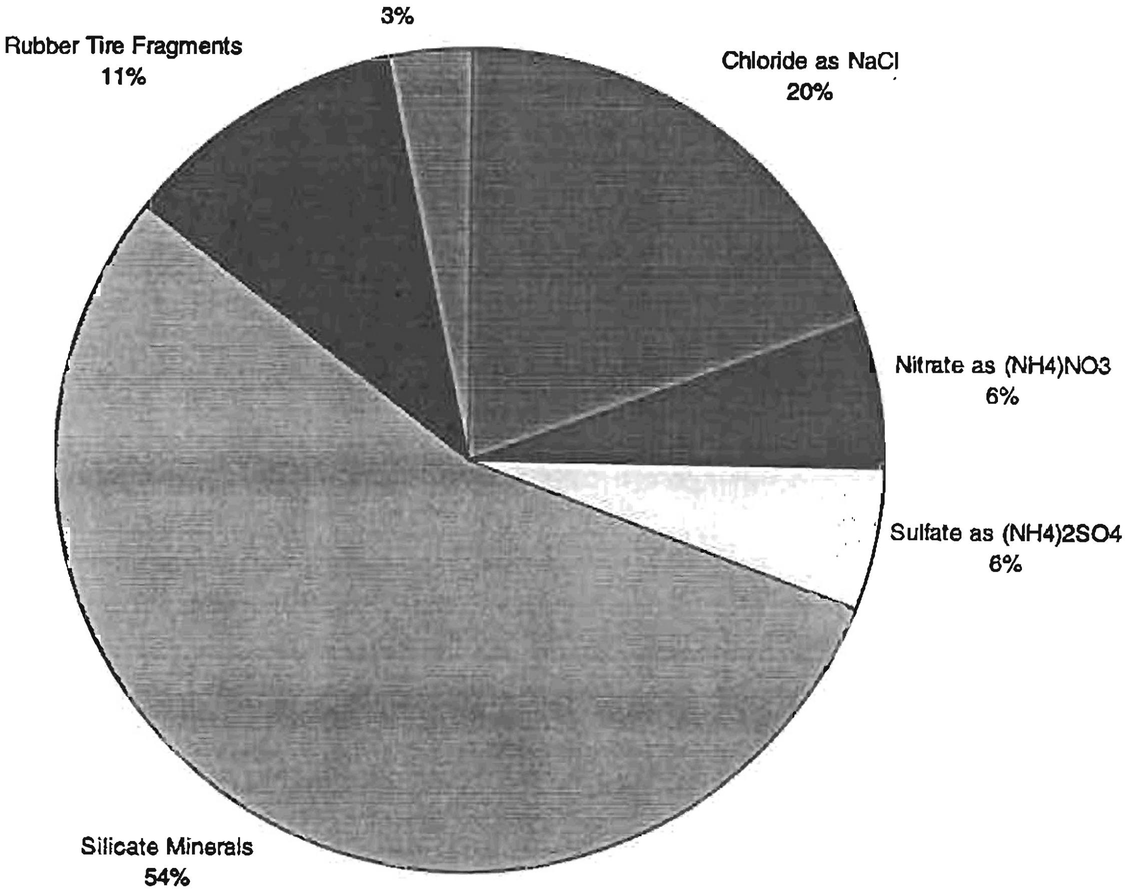

Figure 11. Average Component Abundance in PM-10 Contribution from Denver Paved Roads—Runs BH-6, BL-7, and BM-7

Section 7
Composite Road Surface Sampling

7.1 Sampling Methodology

Composite samples were collected from Denver area arterial roadways as part of Task 1 during Year 2. These samples were obtained to provide the information about the time variations in amount and size distribution of road surface material. This information is useful in estimating the corresponding variations in air emissions, using the results from the Correlation Studies. To account for spatial variation during each sampling period, each surface sample was composited from 4 or 5 different sub-samples collected from different locations along a given road (with similar-ADT) in a general geographic area (approximately 1 to 5 square miles).

There were 3 composite road surface sampling "areas" in metropolitan Denver and 1 "area" in a rural nonattainment area (Aspen, Colorado). The procedure for composite road surface sampling is given in Figure 12. The two Denver area test roads other than Kipling (Jewell and Speer) were selected because they both featured an abrupt change in road surface treatment for antiskid control. Both used alternative materials to sand as indicated below.

Location	Material
Jewell	
East of Sheridan	Sand
West of Kendall	Realite
Speer	
Bannock to 11th	Sand (south of Colfax)
Lawrence to Kalamath	$MgCl_2$ (north of Colfax)

7.2 Test Results

The test results of composite surface sampling on Jewell and Speer are shown in Tables 46 and 47, respectively.

When the silt loading variations are compared between sanded roads and roads treated with an alternative snow/ice control, several observations can be made:

1. On the first day ("Day 1") after the surface of a sanded road dries enough to be sampled, there is a substantial increase (2 to 5 times higher) in silt loading when referenced to baseline/background levels.

1. Mark Colorado roads for sampling:
    a. Kipling
    b. Another road subject to wintertime sanding, outside the Denver area.
    c. Two other Denver area roads subject to alternate deicing schemes.

2. Each composite sample should consist of four increments spaced along the road over a distance of approximately one mile with approximately the same freely flowing vehicle speed. If not all four areas are located on the same road, they should be located on nearby roads of the same facility type and vehicle speed.

3. Each increment should cover at least all lanes in one traffic direction [subject to modification].

4. Each increment location should be marked* with four successively larger areas progressing against the traffic flow as shown in the attached figure. On the day that the road dries after the snow event, the four smallest areas of the given road will be sampled; on the next day, the next largest areas will be sampled; and so forth. The successively larger areas will offset the decrease in loading as time progresses following a snow event.

* Spray paint the corners of each incremental area (where "pins" can be located) or mark the curbing or adjacent sidewalk.

Figure 12. Procedure for Composite Surface Sampling

2. The effect of alternative snow/ice controls is most pronounced on Day 1. Both Realite and magnesium chloride resulted in 80% lower Day 1 silt loadings when compared to the corresponding sanded road surface. This leads to approximately 60% reduction in the PM-10 emission factor estimated for Day 1.

3. After Day 1, the effect of the alternative snow/ice control is far less pronounced. On average only a 20 to 30% reduction in silt loading was found when compared to the sanded road surface. Furthermore, in some cases no net reduction was observed. Because of the sublinear relationship between silt loading and PM-10 emissions, the low level of reduction in silt loading indicates that PM-10 control efficiency is negligible.

4. Finally, the data suggest that the differences in silt loading across various roads becomes less well defined during winter. For example, November sampling results showed both Jewel and the northern portion of Speer (i.e., Lawrence to Klamath) to be far cleaner than the southern portion of Speer (i.e., Bannock to 11th). However, by the end of the third or fourth dry day after a winter storm, this distinction is not seen. In essence, dry baseline conditions in Denver appear to have the effect of creating a reasonably uniform baseline level of silt loading over roads in the area.

Table 46. Jewell Paved Road Samples

Date	Sampling Location	Traffic Direction	Remarks	Total Area (m^2)	Bag No.	Total Loading (g/m^2)	Silt Content (%)	Silt Loading (g/m^2)
10/25/96	W of Kendall	E	Background sample	231.9	717	8.63	-	-
11/15/96	E of Sheridan	W	Background sample	221.6	712	0.45	21.14	0.10
	E of Sheridan	W	Background sample	221.6	709	0.12	26.74	0.03
12/21/96	W of Kendall	E	Day 1—5 days after snow	51.1	835^	0.61	47.95	0.29
	W of Kendall	E	Day 1—5 days after snow	51.1	826	23.60	6.03	1.42
	E of Sheridan	W	Day 1—5 days after snow	50.2	833^	25.19	15	3.78
	E of Sheridan	W	Day 1—5 days after snow	50.2	834^	30.76	21.56	6.63
12/22/96	W of Kendall	E	Day 2—6 days after snow	208.1	829	3.65	6.94	0.25
	E of Sheridan	W	Day 2—6 days after snow		827* "			
	E of Sheridan	W	Day 2—6 days after snow	153.3	828** "	est. 26		
12/23/96	W of Kendall	E	Day 3—7 days after snow	234.1	836	6.09	14.03	0.85
	E of Sheridan	W	Day 3—7 days after snow	159.8	804	7.58	9.04	0.69
12/24/96	W of Kendall	E	Day 4—8 days after snow	204.4	800	8.39	7.17	0.60
	E of Sheridan	W	Day 4—8 days after snow	151.9	805	7.78	11.95	11.95

Days 1 and 2 refer to successive dry road days after a winter storm.

* Because of equipment failure, filter bag 827 is invalid.

** The mass of sample and bag for 828 exceeded the capacity of the balance.

" Note #1: Bags 827 and 828 were weighed together at a later date.

^ Note #2: An extra bag of material labeled 834 835 was discovered. On 7/11/97, Mike McCarter suggested that it should be labeled 833 834.

Table 47. Speer Paved Road Samples

Date	Sampling Location	Traffic Direction	Remarks	Total Area (m^2)	Bag No.	Total Loading (g/m^2)	Silt Content (%)	Silt Loading (g/m^2)
11/14/96	Bannock to 11th	NW	Background sample	223.0	706	0.74	39.99	0.30
	Bannock to 11th	NW	Background sample	223.0	708	1.68	34.36	0.58
	Lawrence to Kalamath	SE	Background sample	191.6	695	1.23	5.88	0.07
	Lawrence to Kalamath	SE	Background sample	239.2	713	0.17	22.13	0.04
12/20/96	Bannock to 11th	NW	Day 1—4 days after snow	59.2	807	18.06	7.37	1.33
	Bannock to 11th	NW	Day 1—4 days after snow	59.2	806	3.61	21.89	0.79
	Lawrence to Kalamath	SE	Day 1—4 days after snow	73.2	710	0.90	16.08	0.14
	Lawrence to Kalamath	SE	Day 1—4 days after snow	73.2	711	3.94	8.19	0.32
12/21/96	Bannock to 11th	NW	Day 2—5 days after snow	79.0	832	6.82	6.37	0.43
	Bannock to 11th	NW	Day 2—5 days after snow	79.0	831	34.89	-	
	Lawrence to Kalamath	SE	Day 2—5 days after snow	82.7	802	4.92	18.87	0.93
	Lawrence to Kalamath	SE	Day 2—5 days after snow	82.7	801	19.25	16.84	3.24
12/22/96	Bannock to 11th	NW	Day 3—6 days after snow	179.8	803	2.39	23.17	0.55
12/24/96	Lawrence to Kalamath	SE	Day 3—6 days after snow	124.8	839	5.76	6.41	0.37

It is believed the roads were swept between days 1 and 2, 5 days after the snow (wintertime background, after sweeping).
Days 1 and 2 refer to successive dry road days after a winter storm.

7.3 Test Results—Aspen

The test results of composite surface sampling in Aspen are shown in Table 48.

Table 48. Aspen Paved Road Samples

Date	Sampling Location	Traffic Direction	Total Area (m^2)	Bag No.	Total Loading (g/m^2)	Silt Content (%)	Silt Loading (g/m^2)
3/9/97	Maroon Creek Road	S	46.4	NC122	-	-	-
3/9/97	Maroon Creek Road	N	49.2	NC121	-	-	-
3/9/97	Castle Creek Road	S	46.7	NC118	-	-	-
3/9/97	Main bet 4th & 5th, inside lanes	W, E	46.5	NC117	-	-	-
3/9/97	Main bet 4th & 5th, turn lane	W, E	7.4	NC116	-	-	-
3/9/97	Main bet 4th & 5th, bus lane	W	7.4	NC115	-	-	-
3/9/97	Main bet 1st & Griminch, inside lanes	W, E	46.5	849	3.66	16.1	0.59
3/9/97	Main east of Griminch, inside lanes	W, E	46.5	840	3.29	16.6	0.55
3/9/97	Hunter 25 ft north of Hyman	N, S	28.4	846	28.11	13.5	3.79
3/9/97	Hunter bet Hopkins & Hyman	N, S	24.0	822	27.21	13.6	3.69
3/9/97	Castle Creek Road	N	47.8	NC119	-	-	-
3/9/97	Hopkins between 2nd & 3rd	W, E	33.4	845	42.09	15.1	6.35
3/15/97	Main & 4th, inside lanes by intersection	W, E	46.5	825	-	-	-
3/20/97	Airport, outside lane	S	28.6	847	47.44	6.6	3.13
3/20/97	Airport		5.1	304	139.08	9.7	13.43
3/20/97	Airport		8.2	830	75.91	17.1	13.01
3/29/97	Maroon Creek Rd & Hwy 87		14.0	306	24.49	17.9	4.39
3/20/97	Maroon Creek & Hwy 82		61.0	307	-	-	-
3/20/97	Maroon Creek Rd & Hwy 87		62.6	837	6.61	12.3	0.81
3/19-20/97	Hwy 82 & Airport		57.7	823			
	Hwy 82 & Maroon Creek Rd		5.4	838	107.00	18.2	19.50
	Hwy 82 & Maroon Creek Rd		15.0	300	10.6	28.0	2.97

7.4 Test Results—Sweeping Effectiveness

On June 11, 1997, MRI measured the effectiveness of broom sweeping (Elgin Pelican Sweeper) and vacuum sweeping (Elgin Whirlwind Sweeper) on Decatur Street in the City of Denver. Several days earlier, road sand had been applied to the road surface to simulate road surface loadings after a wintertime snow event, but most of the sand was subsequently washed off the road by a hail storm. Thus, the "before sweeping" sand loadings were much higher than normally encountered under wintertime conditions.

The test results for the sweeping tests are shown in Table 49. In the case of the broom sweeper, the removal efficiency for total loading was much higher than the efficiency for silt loading. In contrast, the vacuum sweeper exhibited nearly the same removal efficiency for total loading and silt loading. Because of the fractional power dependence of PM-10 emissions in silt loading, the corresponding PM-10 control efficiencies are correspondingly lower.

Table 49. Street Sweeper Performance Test

	Bag No.	Total loading (g/m^2)	Silt loading (g/m^2)	PM-10 control efficiency
Elgin Pelican Sweeper (broom type)				
Before Sweeping (100 ft^2)	930/931	1070	78.2	
After Sweeping (80 ft^2)	932	53.2	20.2	
Removal Efficiency		95%	74%	59%
Elgin Whirlwind Sweeper (vacuum type)				
Before Sweeping (100 ft^2)	933/934	501	43.4	
After Sweeping (120 ft^2)	935	68.4	6.96	
Removal Efficiency		86%	84%	70%

It should be noted that the PM-10 control efficiencies in Table 45 are much higher than would be expected under more typical surface loading conditions. On the other hand, the calculated efficiencies are based on the effectiveness of silt loading removal from the traveled portion of the roadway.

An equally important aspect of wintertime road cleaning is the removal of large accumulations of sand in gutter areas that act as supply reservoirs from which grindable materials can feed the active roadway for much longer time periods.

Section 8
Study Findings

This section summarizes the findings from both Year 1 and Year 2 of the study.

8.1 Surface/Ambient Correlations

Year 1 Testing

The Year 1 testing provided initial data on the mass concentrations/loadings and particle size distributions of in-place road surface material and airborne emissions at the two test sites after winter storm events. It also yielded emission factors that could be compared with the predictive model found in AP-42. The measured emissions were generally higher than the AP-42 predictions but well within the predictive accuracy of the AP-42 equation. Moreover, the measured emission factors correlated strongly with silt loading.

Lack of favorable wind conditions after winter storm events, which created significant problems in meeting the acceptance criteria for testing, limited the amount of testing that could be accomplished, especially at the site adjacent to the Denver Botanical Gardens. This difficulty was compounded by attempting to track winter storm events, rather than performing the correlation studies in more moderate weather, as originally proposed.

As in prior studies, there was some disagreement between the particle size data yielded by the high-volume cyclone/impactors in comparison to the low-volume dichotomous samplers. (Only low-volume samplers could be used to determine the particle size of the road surface samples that were resuspended in the MRI Dustiness Test Chamber).

The comparability questions about fugitive dust particle sizing devices have been addressed in a separate study funded by USEPA (MRI, 1997). That study involved colocation of the two devices used in the Denver Correlation Studies along with continuous monitoring equipment provided by USEPA. The particle sizing instruments were operated next to paved and unpaved test roads in Reno, Nevada; Kansas City, Missouri; and Raleigh, North Carolina. The final report was issued by MRI in April of 1997.

The testing at the I-225 site showed that the impact of wintertime sand application on high-speed high-volume roads with limited access is short-lived. Once the road surface dries, the residual sand is quickly thrown from the active road surface except in confined locations around ramps. This finding is significant in concluding that the air quality impact of such roadways appears to be relatively insignificant.

Shift to Core Site

The Year 1 experience also demonstrated the need for selecting an additional test site with the more favorable wind exposure to accomplish more efficient field data acquisition for the remainder of Correlation Studies. The criteria for the new "Core Site" were defined as follows:

- Consistent winds over the 4-6 hour sampling period.
- Relatively high traffic volume but with a speed not exceeding about 45 mph.
- Ease of lane blockage for brief periods to facilitate road surface sampling.
- Control of timing on sand application in relation to the daytime sampling periods.

This site would feature relatively stable wind conditions coupled with low-to-moderate vehicle speed. It would probably be removed from the center city area. A CDOT-maintained road would be best, from the standpoint of traffic control as well as sand application. It is anticipated that correlation study testing efficiency would be greatly improved at such a site.

Another key question related to whether it was necessary to restrict the correlation testing to post-winter storm periods. If sand (and water for wetting) could be applied to a road segment when temperature conditions are more moderate and wind conditions more stable (and predictable), a much higher rate of correlation test data acquisition would be forthcoming.

If the relationship between the road condition and the fine particle emission rate could be established under this condition, it then could be used to track the air quality impact of a winter storm event. This would be accomplished by coupling the emission versus surface loading relationship with monitored data on the changes in surface loading after winter storm events, for the most important facility types. The standardized road surface sampling technique would be used to track the surface condition based on the analysis of composite samples representing each important facility type.

As a result of the agreement reached at the Project Status Meeting of May 8, 1996, a revised approach was used in completing the Correlation Studies to determine the relationship between road surface particulate matter and fine particle emissions.

A new site on Kipling Street just east of the Denver Federal Center was selected as the "Core Site" for a multiple series of tests that were performed in October and early November 1996:

Series 1. The pre-winter baseline silt loading (before winter storm events).

Series 2. The impacts of sand application under conditions that simulate road drying after a winter storm event.

Series 3. The impacts of sand application associated with an actual winter storm event.

Series 4. The winter baseline silt loading after the winter storm event(s).

The core site (a CDOT road) was selected because of its more persistent winds coupled with high-volume, low-speed traffic and greater suitability for expedited sand application, surface sampling, and low-cost security.

After measurement of the pre-winter baseline silt loading (Series 1), the main test series (Series 2) was directed to studying the emissions resulting from sand application under simulated high-impact wintertime conditions of the road surface. At the beginning of a test day, the sand was applied and then immediately wetted. When the road surface had dried, the emission sampling began. Each test included both a full plume (exposure) profiling and a surface loading characterization.

As expected, in the absence of the "holding capacity" of snow and ice cover, the sand was thrown from the road much more rapidly than would occur during a significant wintertime snow event. This appeared to account for higher ratios of predicted to observed PM-10 emissions, due to the lack of opportunity for the silt to grind into finer components.

During this test series, a number of profiling samples were composited, to provide sample masses that were adequate for reliable chemical analysis. Compositing was done mostly for upwind samples and low-volume downwind samples.

Wind Activation

Test Series 3 was conducted during the period immediately following an actual winter snow event that required sand application. It was used to validate (to the extent possible) the relationships developed from the Series 2 tests of controlled sanding. Once again, full profiling and surface characterization was undertaken.

A wind activation system was proposed and implemented for Test Series 3 so that cumulative sampling times could be lengthened. This was intended to overcome severe limitations in suitable wind conditions. In the previous test series, shifts in wind direction were frequently encountered during the usual 10 a.m. to 3 p.m. window for manually activated exposure profiling tests. For security, the areas immediately surrounding trailer-mounted profiling towers were temporarily fenced. These fenced areas were located so that sampling can be undertaken under a range of expected daytime winds having either a predominant easterly or westerly component.

The final testing (Series 4) determined the new surface loading baseline that was established after winter storm events began. The baseline was measured at times outside the high impact periods that encompassed individual winter storm events.

The samples collected during this period were combined with those collected earlier in determining chemical and morphological fingerprints of road surface and airborne particulate matter. Along with the mass concentration/loading and particle size data, this information will help establish the relationship between the road surface condition and the air quality impact over the winter storm cycle.

Percentage of Road Dust in PM-10 Emissions

Traffic generated paved road emissions consist of four components: vehicle exhaust, tire and brake wear, sloughing of underbody deposits, and suspended road dust. Of these components, only vehicle exhaust resides primarily in the fine fraction (PM-2.5) of PM-10. Background PM-10 on a "neighborhood" scale in a populated area surrounding an arterial roadway consists of roughly equal coarse and fine fractions.

The test data suggest that for clean arterial roadways, PM-10 emissions from the roadway also have coarse and fine fractions that are roughly equal. In other words, the vehicle exhaust emissions are approximately equal to the contributions from the other road emission components.

However, for the 24-hr period following a winter snow/road sanding event (i.e., just after the roadway has dried), the data indicate that the 24-hr average silt loading on an arterial roadway is in the range of 3 to 10 times higher than the winter baseline silt loading. For example in February 1997, the silt loading at the Core Site on Kipling was consistently about 0.25 g/m^2 until the day after a sanding event, when it increased to about 0.70 g/m^2 On the other hand in the winter of 1996, the silt loading on I-225 immediately after a sanding event (0.184 g/m^2) dropped to 0.0127 g/m^2 over the following two days.

Consistent with the PM-10 emission factor equation for paved roadways, the PM-10 emissions during a period with a 5-fold increase in silt loading, will increase by a factor of about 3 (above the baseline emission rate). Because virtually all of these increased emissions are in the form of road dust, the percentage of the total PM-10 emissions from road traffic that consist of road dust increases from about 50% to as much as 80% or 90% during the "high impact" 24-hr period following road sanding.

Percentage of PM-2.5 in PM-10 Emissions

Prior tests of emissions from unpaved roadways and from heavily loaded paved roadways (MRI, 1997) indicate that as little as about 10% of the PM-10 road dust emissions reside in the fine fraction (PM-2.5). Thus, for dry paved roadways that have been recently sanded, with more than 80% of the emissions are in the form of road dust, the ratio of PM-2.5 to PM-10 in the road emissions may be as low as 10 to 15%. As the roadway returns to its baseline ("clean") condition for the season, the ratio of PM-2.5 to PM-10 emissions increases to roughly 50%.

Results of Chemical and Microscopical Analyses

The chemical and microscopical analysis results provide important data that can be used to answer the following three questions:

1. What are the sources of dust on paved roads (in Colorado)?
2. What are the size and composition of paved road dust emissions?
3. What is the relationship between surface dust loading and PM-10 emissions?

The results of chemical analysis show that silicon is the most abundant element in both the PM-10 source emissions and the resuspended PM-10 components of associated road dust samples. These element is related to the composition of road sand used in Denver for wintertime antiskid control. Chlorine was also found to be an abundant element when the sand/salt mixture was applied to dry roads (artificial sanding).

Organic carbon is also abundant in the PM-10 emission samples, but much less so in the resuspended road dust. The microscopical analysis results show that organic carbon can be associated mostly with tire wear particles. The relative absence of organic carbon in the resuspended PM-10 component of the road dust substantiates other recent findings that tire particles are directly emitted, rather than resuspended, from the road surface. Substantial amounts of nitrate and sulfate are also present in the upwind and downwind PM-10 samples, but not in the resuspended road dust.

The roadway PM-2.5 impact also exhibits an abundance of silicon, chlorine (after artificial sanding), and organic carbon. Once again, these can be associated with the application of the salt/sand moisture and with the emissions of tire particles. The resuspended road dust PM-2.5 samples show a large silicon component but negligible organic carbon. As expected, soot (elemental carbon from unburned fuel) constitutes a larger fractional component in PM-2.5 than in PM-10.

8.2 Silt Loading Variations

Method Validation

The results of the laboratory testing conducted during Year 1 showed high recovery of surface silt from smooth and textured surfaces. This indicates that the inherent errors associated with the vacuuming process for silt loading recovery are small in relation to the natural variations in silt loading (spatial and temporal). Questions still remained, however, on the influence of operator subjectivity in deciding where to sample, i.e., specifically the boundaries of the traveled portion of the roadway. These questions were resolved by the collaborative field testing performed during Year 2.

Also during Year 1, a description of a standard method for determination of paved road silt loading was prepared under this contract. It has been included in this report as Appendix A. Although the standard method has many of the features of the version developed for AP-42, clarification and specificity was added, to provide for ease of implementation. In particular, special attention was given to sample compositing for greater representativeness and to the conversion of field and laboratory data to calculated silt loading values.

With regard to the validation of the standardized procedure for determination of road surface silt loading, essential work was also performed in Year 2. This entailed collaborative testing of the proposed standard method by two independent groups, managed by MRI and AlphaTRAC, respectively to determine operator impacts on method reproducibility. These groups collected composite samples from colocated areas that alternated over the test road segment of the Core Site and in an adjacent parking lot. The embedding of collection areas helped assure that the areas sampled by each organization are essentially equivalent.

Effect of Sanding

An analysis of the effect of sanding on winter baseline emissions in Denver can be based on a comparison of silt loading measurements in the fall of 1996 and in the winter of 1997. These measurements were made at the Core Site (Kipling, north of Alameda), Speer (on both sides of the intersection with Colfax) and Jewell (on both sides of the intersection with Sheridan). Only the areas of Speer and Jewell that were treated with sand are considered.

According to the predictive emission factor equation in AP-42, PM-10 emissions are proportional to silt loading raised to the 0.65 power. Therefore, by examining the pre-winter baseline silt loading and the winter baseline silt loading for roads with wintertime sanding, the fractional increase in emissions can be projected. This increase in emissions represents a seasonal condition, without the enhanced impacts of individual sanding events during snowstorms.

When sanded roads dry after such winter sanding events, the silt loadings (and PM-10 emissions) tend to be at a maximum. These high emission periods extend in time until the silt loading has returned to the winter baseline level. The time needed to return to the baseline conditioned ranges from only a few hours, for high-speed limited-access roadways, to a week or more for residential roadways. For arterial roadways, which account for a substantial portion of the paved road particulate emissions, the time to return to the baseline condition is the order of a few days, depending on the amount of sand applied and the length of time for the snow melt on the roadway surface.

The baseline silt loading results are summarized as follows:

Site	Baseline Silt Loading (g/m^2)	
	Prewinter	Winter
Kipling	0.05 (November 6, 1996)	0.30 (March 15, 1997)
Jewell (East of Sheridan)	0.10 (November 15, 1996)	0.70 (December 23, 1996)
Speer (South of Colfax)	0.30 (November 14, 1996)	0.50 (December 22, 1996)

The ratios of winter to prewinter baseline silt loadings range from about 2 to 6. The corresponding range of PM-10 emission ratios is approximately 1.5 to 3.

8.3 Emission Control Effectiveness

In an effort to reduce the air quality impacts of wintertime sanding, various portions of the Denver Metropolitan Area have committed to reductions in sand application and to street sweeping programs to remove residual sand, as required to meet the goals of transportation conformity. The base year for determining the reductions is 1989. Sanding reductions for individual subareas, to be achieved by the year 2000, range from about 30% to as much as 75 %. Statistics on Denver area sand application already show substantial reductions in sand application over the past few years. The 1994-1995 application rate typically represents a reduction of at least 30% in comparison with the period around 1990.

Also within the 6-county area, alternative deicers are being tested in many localities. Magnesium chloride is the most commonly used chemical. It is being tested as a pre-wetting agent, an anti-icer, and a deicer.

Reduced sand application has an immediate, and predictable, effect on reduced PM-10 emissions. This applies not only to the period of greatest air quality impact, when the road surface has dried immediately after a winter storm event, but also to the wintertime baseline condition. Less preferable as a control method is sweeping to mitigate the effects of road sanding. Year 2 testing of broom and vacuum sweeping effectiveness showed PM-10 control efficiencies that were enhanced by the unrealistically high silt loading that was applied to a dry road for test purposes. While more typical silt loadings for sanded roads are more difficult to remove by sweeping, the pick-up of larger sand accumulations in gutter and other infrequently traveled areas eliminates supply reservoirs that feed the active roadway for much longer periods. In effect, these reservoirs otherwise tend to raise the wintertime baseline silt loading that encompasses multiple winter storm events.

Section 9
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Appendix A

Sampling Procedure for Paved Road Silt Loading

Sampling Procedure for Paved Road Silt Loading

Background

The overall objective in a paved road surface sampling program is to inventory the mass of particulate emissions from one or more roads within a study area. This is typically done by:

1. Collecting "representative" samples of the loose surface material from the roads that represent each functional category;
2. Analyzing the samples to determine the silt fraction; and
3. Combining the results with traffic data for each road category to calculate particulate emissions generated by that road category using a predictive emission factor model.

Before a field sampling program is undertaken, it is necessary first to define the study area of interest and then to determine the number of paved road samples that will be collected and analyzed. For example, in a well-defined study area such as an industrial plant, it is advantageous (and usually feasible) to collect a separate sample from each major paved road, because the inventory resolution can be useful in developing cost-effective emission reduction plans. Similarly, in geographically large study areas, although sampling of a large number of roads is not practical, it may be feasible to aggregate several sample increments in obtaining samples representative of given road types within the area.

Paved road surface sampling necessarily involves consideration as to types of equipment to be used. Specifically, provisions must be made to accommodate the characteristics of the vacuum cleaner chosen, specifically the size and weight of the "tared" filter bag. Upright "stick broom" vacuums use relatively small, lightweight filter bags, while bags for industrial-type vacuums are bulky and heavy. Because the mass collected should be several times greater than the bag tare weight, uprights are better suited for collecting samples from lightly loaded road surfaces. On the other hand, for heavily loaded roads, the larger industrial-type vacuum bags are easier to use in aggregating incremental samples from all road surfaces.

Appendix C-1 to AP-42 (USEPA, 1995) provides guidelines on how many samples should be collected from different lengths of road, depending upon the desired definition of the study area. The remainder of this protocol describes in detail the mechanics of how a sample should be collected, but does not present any additional guidance on how to design an overall sampling program. In other words, it is assumed that the investigator will already have decided upon the major features of the sampling program, including:

- how many roads should be sampled
- how many times each road should be sampled to characterize seasons of the year, impacts of snow events, and so on
- whether incremental samples should be aggregated within a single vacuum bag
- what type of vacuum sweeper will be used
- what quality assurance activities will be conducted
- what safety precautions and lane closure procedures/permits need to be obtained

Procedure

The following steps describe the collection method for samples (increments).

Inspecting the Vacuum Cleaner

Vacuum cleaners be carefully inspected prior to field use for collecting surface material samples. It is recommended that the measurements shown in Table A-1 be made at the time a new vacuum is purchased. Thereafter, prior to the start of a field testing exercise, the measurements should be repeated. The vacuum cleaner not be used for sampling if the new measurement is not at least 80% of the original value.

Table A-1

Variable	Method	Common Range of Values
Vacuum drawn	Mercury-in-tube manometer or digital manometer	2 to 5 in Hg
Pressure drop across cleaning head	Digital manometer	1 to 2 in H20

Finally, prior to each use in field, a simple leak check should be performed after the empty bag has been loaded. The leak check consists of placing a cover or hand over the inlet and listening to the motor. If the motor does not quickly strain under the load, the device should re-assembled and checked.

Preparing Vacuum Bags

Begin by numbering and then tare weighing the individual vacuum bags. Using a permanent ink marker, associate each bag with a unique identification number. Then weigh the bag to the nearest 0.1 g. Record the bag identification number and tare weight in a laboratory notebook. Also write the bag identification number and tare weight on a resealable envelope. Seal the bag within the envelope, double checking the identification number and weight. Include two rubber bands in the envelope. Transport the bags to the sample collection site, using reasonable precautions—such as placing envelopes in a closed cardboard box—to keep the envelopes and bags clean.

Selecting/Marking the Sampling Site

1. Safety Consideration: For the safety of the field crew, ensure the sampling site offers an unobstructed view of traffic; conversely, sampling personnel must be visible to the drivers. Sampling crews should consist of at least two persons at all times, so that one crew member can "spot" and route traffic safely around another person collecting the surface sample (increment). The ability to safely collect the sample is the most important feature of any site.

2. Identifying Sampling Areas: Determine the traveled portion of the roadway encompassing all travel lanes. The area should include the portion of the road over which vehicles routinely pass and should not include shoulders, gutters, parking lanes, and so on. The traffic should be observed at the site for at least 5 minutes in making this determination. On roads with painted side markings, the traveled area normally extends "from white line to white line" (but excludes centerline mounds). Otherwise, the outside edges of the traveled area (parallel to traffic direction) are usually indicated by a band of increased discoloration (loading) that extends to the curbing.

   The width of the collection area (distance parallel to travel direction) is dependent on the anticipated surface loading and the number of increments to be gathered in providing adequate sample mass. If increments are being aggregated, all sampled areas should be within 10% of the same size. The widths may be varied between 0.3 m (1 ft) for visibly dirty roads and 3 m (10 ft) for clean roads. When an industrial-type vacuum is used to sample lightly loaded roads, a width greater than 3 m (10 ft) may be necessary to meet sample specifications, unless increments are being combined. For public roadways, even if increments are being combined, it may be necessary to sweep several hundred square feet of road surface for each increment in order to obtain adequate sample mass.

3. Marking the Areas: Using suitable markers (or quick drying spray paint), mark the outside edges of the traveled portion of the road. Using string or other suitable markers, mark the sampling width across the road. (WARNING: Do not mark the collection area with a chalk line or in any other method likely to introduce fine material into the sample.)

Collecting the Coarse Sample

Collect any large, loose material present on the surface with a whisk broom and dustpan. NOTE: Collect material only from the portion of the road over which the wheels and carriages routinely travel (i.e., not from berms or any "mounds" along the road centerline). The swept material should be stored in a clean, labeled container of suitable size, such as a metal or plastic 19 L (5 gal) bucket, with a sealable polyethylene liner. Once the vacuum sample has been collected, the broom swept material is added to the vacuum bag.

Collecting the Fine Sample

Remove a clean vacuum bag and record its identification number and tare weight on a data form of the type shown in Figure A-1. Load the bag into the vacuum cleaner according to the manufacturer's instructions, obeying any markings that indicate "UP," "FRONT," etc.

Vacuum the marked area, going over the total area at least twice. When beginning vacuum cleaner operation, if noticeable dust is observed at the vacuum exhaust port, discard the bag and refit with a new bag. If sampling is interrupted because of passing traffic, mentally note the area last swept so that you may return to the same spot when traffic clears. The same filter bag may be used for compositing increments of the sample collected from different segments of the test roadway or from multiple roadways.

For heavily loaded roads, you may notice that the vacuum device becomes less effective in removing the loading. In that case, more than 1 filter bag may be needed for a sample (increment). Remove the first bag (see handling instructions below) and place a new bag in the vacuum device. Record the new bag identification and tare weight on the data form and indicate in the comment section that more than one bag was used.

Retrieving the Sample

Carefully remove the bag from the vacuum sweeper and check for tears or leaks. Seal broom-swept material in a clean, labeled plastic jar for transport. (Alternatively, the swept material may be placed in the vacuum filter bag.) Fold the unused portion of the filter bag, wrap two rubber bands around the folded bag, replace the bag within its own envelope, and store the bag for transport. On the sample collection sheet (Figure A-1), record the required information, including a general description of the sampling area, the dimensions of the sample area, approximate time that the sample was taken, whether or not the surface was broom swept and, if so, whether the mass was added to the bag.

Weighing the Sample

Once sampling activities are completed, measure and record in a laboratory notebook the full weight of each vacuuming, preferably using the same balance as used for the tare weights. When broom swept samples are collected, they should be at least 400 g (1 lb) for silt analysis. Vacuum swept samples should be at least 200 g (0.5 lb). Also, the weight of an "exposed" filter bag should be at least 3 times greater than the tare weight. Additional increments should be taken until these sample mass goals have been attained.

SAMPLING DATA FOR PAVED ROADS

Date Collected __________ Recorded by __________

Sampling location* ______________________________ No. of Lanes __________

Surface type (e.g., asphalt, concrete, etc.)____

Surface condition (e.g., good, rutted, etc.) ____

* Use code given on plant or road map for segment identification. Indication sampling location on map.

METHOD:

1. Sampling device: portable vacuum cleaner (whisk broom and dustpan if heavy loading present)
2. Sampling depth: loose surface material (do not sample curb areas or other untravelled portions of the road)
3. Sample container: tared and numbered vacuum cleaner bags (bucket with sealable liner if heavy loading present)
4. Gross sample specifications: Vacuum swept samples should be at least 200 g (0.5 lb), with the exposed filter bag weight should be at least 3 to 5 times greater than the empty bag tare weight.

Refer to AP-42 Appendix C.1 for more detailed instructions.

Indicate any deviations from the above: ____

____

____

SAMPLING DATA COLLECTED:

Sample No.	Vacuum Bag ID	Vacuum Bag Tare Wgt (g)	Sampling Surface Dimensions (l x w)	Time	Mass of Broom-Swept Sample +

\+ Enter "0" if no broom sweeping is performed.

Figure A-1. Example Data Form for Paved Roads

Recovering the Sample

The following steps describe how the sample is recovered from the vacuum bag for analysis:

1. Cover a working area on a bench or a table top with (a) aluminum foil, (b) commercially available laboratory material (such as BenchKote), or (c) other suitable non-porous material.

2. After removing the bag from the envelope and placing it on the storage working area, carefully open one seam of the bag (being careful not to lose any pieces of the bag) and pour the material into a container such as a plastic or glass (Mason) jar. Add the material from the broom swept portion of the sample. (The most important feature of the container is that it must allow one to completely recover the material.)

3. To recover the material adhering to the interior of the bag, open all seams of the bag completely. Unfold the bag until it lies flat on the working surface. Do not discard any pieces of the bag. Use a moderately stiff, short-bristle brush (a toothbrush is acceptable) to recover material attached to bag surface. As material is removed, place it in the same sample jar as used earlier. Take care not to abrade the bag itself. Store the recovered sample to be analyzed for particle size distribution.

4. Once you have recovered as much material as practical, reweigh the empty bag (including any loose pieces) and record the empty bag weight in a laboratory notebook.

Calculations

The total mass loading "L" is found by:

$$L = (F-T)/A$$

where: L = surface loading (g/m^2)
F = vacuum bag final weight (g)
T = vacuum bag tare weight (g)
A = total area sampled (m^2)

Because not all material can be recovered from the vacuum bag, it is useful to define both upper and lower bounds on the silt loading (sL). The upper bound assumes that all material left in the bag (i.e., the difference between the "empty" and tare weights) consists of silt, i.e., particles smaller than 200 mesh (75 µm physical diameter). In that case, an upper bound on the silt loading is found by:

$$(sL)_u = s\,(F - E)/A + (E - T)/A$$

where: $(SL)_u$ = upper bound on surface silt loading (g/m^2)

s = silt fraction (<200 mesh) of the recovered sample

E = empty vacuum bag weight after sample recovery (g)

A = total road surface area sampled (m^2)

A lower bound on the silt loading results when one assumes that the material remaining within the bag has the same size distribution as the recovered material. Thus, the lower bound is found by:

$$(sL)_l = s\,(F - T)/A$$

where: sL_l = lower bound on surface silt loading (g/m^2).

Appendix B

Field and Laboratory Data from Correlation Studies

B	C	D	E	F	G	H	I	J	K	L
Run	Date	Sampler Location	Sampler ID	Sampler Start Time	Sampler Stop Time	Sampler Run Time (min)	Avg. Temp. (deg. F)	Avg. B.P. (in. Hg)	Avg. Filter Pressure (in. H2O)	Flowrate (ft^3/min)
BH-1	02/28/96	Cyclone 1m DW	68	11:40	14:23	163	18	24.86	15.82	38.97
		Cyclone 3m DW	69	11:40	14:23	163	18	24.86	15.93	39.25
		Cyclone 5m DW	77	11:40	14:23	163	18	24.86	15.97	39.27
		Cyclone 7m DW	74	11:40	14:23	163	18	24.86	15.65	39.39
		Wedding 2m DW	1598	11:40	14:23	163	18	24.86	15.85	39.54
BH-2	03/01/96	Cyclone 1m DW	77	09:46	15:46	360	37	24.54	17.12	39.78
		Cyclone 3m DW	68	09:46	15:46	360	37	24.54	17.20	39.48
		Cyclone 5m DW	69	09:46	15:46	360	37	24.54	17.49	39.72
		Cyclone 7m DW	74	09:46	15:46	360	37	24.54	16.93	39.86
		Wedding 2m DW	1598	09:46	15:46	360	37	24.54	16.78	40.13
BH-3	03/02/96	Cyclone 1m DW	77	08:46	14:46	360	46	24.55	16.64	40.14
		Cyclone 3m DW	68	08:46	14:46	360	46	24.55	17.29	39.75
		Cyclone 5m DW	69	08:46	14:46	360	46	24.55	18.13	39.94
		Cyclone 7m DW	74	08:46	14:46	360	46	24.55	17.78	40.09
		Wedding 2m DW	1598	08:46	14:46	360	46	24.55	16.55	40.45
BH-6	03/16/96	Cyclone 1m DW	68	09:18	13:18	240	48	24.62	17.15	39.86
		Cyclone 3m DW	74	09:09	13:09	240	48	24.62	17.53	40.21
		Cyclone 5m DW	69	09:09	13:09	240	48	24.62	17.12	40.15
		Cyclone 7m DW	78	09:09	13:09	240	48	24.62	16.84	40.21
		Wedding 2m DW	1598	09:09	13:09	240	48	24.62	18.14	40.29
		Cyclone 2m UW	77	08:59	12:59	240	48	24.62	16.59	40.21
		Cyclone 7m UW	76	08:59	12:59	240	48	24.62	16.63	40.29

M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
2													
3										PM10			
4							Wt. after		PM10	Concentration	Mean Wind		PM10
5		Sampler	Filter	Tare Wt.	Final Wt.	Net Wt.	Blank		Concentration	(upwind	Speed		Exposure
6	Run	Location	Number	(mg)	(mg)	(mg)	Correction		(ug/m^3)	corrected)	(mph)	IFR	(mg/cm^2)
7													
8	BH-1	Cyclone 1m DW	9551021	4516.65	4529.00	12.35	13.29		74	33	4.0	2.5	0.0575
9		Cyclone 3m DW	9551022	4526.05	4536.45	10.40	11.34		63	22	2.9	3.5	0.0274
10		Cyclone 5m DW	9551023	4516.45	4557.70	41.25	42.19		233	192	2.4	4.3	0.2012
11		Cyclone 7m DW	9551024	4498.20	4530.50	32.30	33.24		183	142	2.1	4.9	0.1302
12		Wedding 2m DW	9552011	4163.90	4169.90	6.00	6.00		33		3.3		
13													
14	BH-2	Cyclone 1m DW	9551031	4596.25	4606.95	10.70	11.64		29	18	13.4	1.0	0.2290
15		Cyclone 3m DW	9551032	4455.00	4460.35	5.35	6.29		16	4.6	16.3	0.9	0.0728
16		Cyclone 5m DW	9551033	4477.45	4481.70	4.25	5.19		13	1.8	17.7	1.1	0.0310
17		Cyclone 7m DW	9551034	4493.90	4503.80	9.90	10.84		27	16	18.6	1.0	0.2815
18		Wedding 2m DW	9552012	4168.25	4174.20	5.95	5.95		15		15.2		
19													
20	BH-3	Cyclone 1m DW	9551038	4557.30	4561.60	4.30	5.24		13	3.8	13.1	1.1	0.0481
21		Cyclone 3m DW	9551039	4491.95	4496.20	4.25	5.19		13	3.8	16.5	0.9	0.0404
22		Cyclone 5m DW	9551040	4528.90	4532.20	3.30	4.24		10	1.4	18.1	1.1	0.0165
23		Cyclone 7m DW	9551041	4523.20	4525.75	2.55	3.49		9	0.0	19.2	1.0	0.0000
24		Wedding 2m DW	9552013	4152.65	4157.20	4.55	4.55		11		15.3		
25													
26	BH-6	Cyclone 1m DW	9551067	4471.45	4550.55	79.10	79.93		295	252	1.4	7.4	0.2275
27		Cyclone 3m DW	9551066	4461.70	4553.25	91.55	92.38		338	301	2.8	3.7	0.5419
28		Cyclone 5m DW	9551065	4455.70	4472.45	16.75	17.58		64	32	3.4	3.1	0.0705
29		Cyclone 7m DW	9551064	4445.10	4456.80	11.70	12.53		46	19	3.8	2.8	0.0461
30		Wedding 2m DW	9552016	4455.35	4469.95	14.60	14.50		53		2.3		
31		Cyclone 2m UW	9551069	4538.35	4548.35	10.00	10.83		40		2.3	4.5	
32		Cyclone 7m UW	9551068	4524.86	4531.35	6.50	7.33		27		3.8	2.8	
33													
34	<u>FIELD BLANKS</u>												
35													
36	BH-4		9551044	4543.85	4542.75	-1.10							
37			9551045	4515.10	4514.35	-0.75							
38			9551046	4490.05	4488.95	-1.10							
39			9551047	4493.60	4492.80	-0.80							
40			9552014	4148.55	4148.55	0.00							
41													
42	I-225 glass fiber blank average = -0.94, Sx = 0.19												
43	I-225 quartz blank average = 0.00												
44													
45	BH-5		9551048	4527.60	4526.80	-0.80							
46			9551049	4525.70	4525.15	-0.55							
47			9551050	4498.65	4495.80	-0.85							
48			9551051	4506.25	4505.15	-1.10							
49			9552015	4386.80	4386.90	0.10							
50													
51	Botanic garden glass fiber blank average = -0.83, Sx = 0.23												
52	Botanic garden quartz blank average = 0.10												
53													
54													
55													
56	S8=R8-Q8												
57	T8=S8+0.94 for BH-1-3 glass fiber,=S8 +0.00 for BH-1-3 quartz, =S8+0.83 for BH-6 glass fiber, =S8-0.10 for BH-6 quartz												
58	V8=(T8*1000)/(L8*H8*0.02832)												
59	Z8=W8*1E-07*X8*H8*0.44704*60												
60													

B	C	D	E	F	G	H	I	J	K
Run	Date	Sampler Location	Sampler ID	Sampler Start Time	Sampler Stop Time	Sampler Run Time (min)	Avg. Temp. (deg. F)	Avg. B.P. (in. Hg)	Flowrate (ft^3/min)
BH-1	02/28/96	Cyc/Imp 2m UW	731	11:21	14:23	182	18	24.86	20
		Cyc/Imp 2m DW	73	11:40	14:23	163	18	24.86	20
BH-2	03/01/96	Cyc/Imp 2m UW	731	08:45	14:45	360	37	24.54	20
		Cyc/Imp 2m DW	73	09:46	15:46	360	37	24.54	20
BH-3	03/02/96	Cyc/Imp 2m UW	731	08:23	14:23	360	46	24.55	20
		Cyc/Imp 2m DW	73	08:46	14:46	360	46	24.55	20
BH-6	03/16/96	Cyc/Imp 2m UW	731	08:59	12:59	240	48	24.62	20
		Cyc/Imp 2m DW	73	09:09	13:09	240	48	24.62	20

1	M	N	O	P	Q	R	S	T
4–6	Run	Sampler Location	Stage Number	Filter Number	Tare Wt. (mg)	Final Wt. (mg)	Net Wt. (mg)	Wt. after Blank Correction
8	BH-1	Cyc/Imp 2m UW	S-1	9558112	1522.40	1520.70	-1.70	-0.66
9			S-2	9558113	1510.55	1509.40	-1.15	-0.11
10			S-3	9558114	1515.20	1513.95	-1.25	-0.21
11			Backup	9551027	4488.80	4491.35	2.55	3.40
13		Cyc/Imp 2m DW	S-1	9558169	1510.40	1510.00	-0.40	0.64
14			S-2	9558170	1513.70	1513.60	-0.10	0.94
15			S-3	9558171	1510.95	1510.45	-0.50	0.54
16			Backup	9558028	4421.40	4423.05	1.65	2.50
18	BH-2	Cyc/Imp 2m UW	S-1	9558164	1519.45	1519.00	-0.45	0.59
19			S-2	9558167	1489.50	1489.00	-0.50	0.54
20			S-3	9558168	1509.15	1508.15	-1.00	0.04
21			Backup	9551029	4442.10	4442.50	0.40	1.25
23		Cyc/Imp 2m DW	S-1	9558162	1523.15	1523.20	0.05	1.09
24			S-2	9558163	1511.70	1511.45	-0.25	0.79
25			S-3	9558168	1499.65	1499.10	-0.55	0.49
26			Backup	9551030	4444.50	4445.55	1.05	1.90
28	BH-3	Cyc/Imp 2m UW	S-1	9558172	1533.50	1532.45	-1.05	-0.01
29			S-2	9558173	1511.15	1510.15	-1.00	0.04
30			S-3	9558174	1517.35	1515.95	-1.40	-0.36
31			Backup	9551037	4505.50	4505.70	0.20	1.05
33		Cyc/Imp 2m DW	S-1	9558175	1498.70	1497.95	-0.75	0.29
34			S-2	9558177	1519.90	1519.70	-0.20	0.84
35			S-3	9558178	1537.05	1536.35	-0.70	0.34
36			Backup	9551036	4478.75	4479.20	0.45	1.30
38	BH-6	Cyc/Imp 2m UW	S-1	9558190	1522.60	1523.45	0.85	2.12
39			S-2	9558191	1517.60	1519.20	1.60	2.87
40			S-3	9558192	1528.35	1528.55	0.20	1.47
41			Backup	9551056	4583.25	4585.25	2.00	2.75
43		Cyc/Imp 2m DW	S-1	9558111	1533.55	1534.20	0.65	1.92
44			S-2	9558124	1493.20	1495.55	2.35	3.62
45			S-3	9558125	1509.35	1510.80	1.45	2.72
46			Backup	9551057	4580.70	4583.15	2.45	3.20

49 FIELD BLANKS

	M	N	O	P	Q	R	S
51	BH-4	Cyc/Imp 2m UW	S-1	9558181	1524.50	1523.55	-0.95
52			S-2	9558182	1531.10	1530.10	-1.00
53			S-3	9558183	1523.40	1521.60	-1.80
54			Backup	9551042	4514.90	4514.00	-0.90
56		Cyc/Imp 2m DW	S-1	9558188	1515.80	1515.15	-0.65
57			S-2	9558189	1525.75	1524.75	-1.00
58			S-3	9558180	1516.60	1515.75	-0.85
59			Backup	9551043	4548.00	4547.20	-0.80

61 I-225 4 X 5 blank average = -1.04, Sx = 0.39
62 I-225 8 X 10 blank average = -0.85, Sx = 0.071

	M	N	O	P	Q	R	S
65	BH-5	Cyc/Imp 2m UW	S-1	9558185	1547.20	1545.90	-1.30
66			S-2	9558186	1546.45	1545.15	-1.30
67			S-3	9558187	1536.30	1535.10	-1.20
68			Backup	9551052	4531.25	4530.50	-0.75
70		Cyc/Imp 2m DW	S-1	9558193	1514.95	1513.60	-1.35
71			S-2	9558194	1504.30	1503.10	-1.20
72			S-3	9558184	1525.05	1523.80	-1.25
73			Backup	9551053	4548.05	4547.30	-0.75

75 Botanic garden 4 X 5 blank average = -1.27, Sx = 0.061
76 Botanic garden 8 X 10 blank average = -0.75, Sx = 0.0

78 S8=R8-Q8
79 T8=S8+1.04 for I-225 4 X 5, =S8+0.85 for I-225 8 X 10, =S8+1.27 for botanic garden 4 X 5, and
80 =S8+.85 for botanic garden 8 X 10

		Particulate Concentration (ug/m^3) less than stated size	
Run	Sampler Location	2.1 um	10.2 um
BH-1	Cyc/Imp 2m UW	**33**	< 41
	Cyc/Imp 2m DW	**27**	**43**
BH-2	Cyc/Imp 2m UW	6.1	< 11
	Cyc/Imp 2m DW	**9.3**	**16**
BH-3	Cyc/Imp 2m UW	5.1	< 9.0
	Cyc/Imp 2m DW	6.4	<12
BH-6	Cyc/Imp 2m UW	**20**	**52**
	Cyc/Imp 2m DW	**24**	**70**

Bold values indicate where blank corrected net filter weights are at least 3 times the standard deviation of the blank correction.

Values preceded by a < indicate instances where at least one blank corrected net filter weight is less than 1 standard deviation of the blank correction. The standard deviation of the blank correction is used in place of the net filter weight to calculate the concentration.

Run	Date	Sampler Location	Sampler ID	Sampler Start Time	Sampler Stop Time	Sampler Run Time (min)	Avg. Temp. (deg. F)	Avg. B.P. (in. Hg)	Aerosol Fraction	Flowrate (liter/min)
BH-1	02/28/96	Dichot/T 2m UW	421707	11:07	14:23	196	18	24.86	Coarse	1.67
									Fine	15.00
		Dichot/Q 2m UW	174242	11:07	14:23	196	18	24.86	Coarse	1.67
									Fine	15.00
		Dichot/T 2m DW	933053	11:42	14:23	161	18	24.86	Coarse	1.67
									Fine	15.00
		Dichot/Q 2m DW	933057	11:42	14:23	161	18	24.86	Coarse	1.67
									Fine	15.00
BH-2	03/01/96	Dichot/T 2m UW	421707	08:45	14:45	360	37	24.54	Coarse	1.67
									Fine	15.00
		Dichot/Q 2m UW	174242	08:45	14:45	360	37	24.54	Coarse	1.67
									Fine	15.00
		Dichot/T 2m DW	933053	09:46	15:46	360	37	24.54	Coarse	1.67
									Fine	15.00
		Dichot/Q 2m DW	933057	09:46	15:46	360	37	24.54	Coarse	1.67
									Fine	15.00
BH-3	03/02/96	Dichot/T 2m UW	421707	08:23	14:23	360	46	24.55	Coarse	1.67
									Fine	15.00
		Dichot/Q 2m UW	174242	08:23	14:23	360	46	24.55	Coarse	1.67
									Fine	15.00
		Dichot/T 2m DW	933053	08:46	14:46	360	46	24.55	Coarse	1.67
									Fine	15.00
		Dichot/Q 2m DW	933057	08:46	14:46	360	46	24.55	Coarse	1.67
									Fine	15.00
BH-6	03/16/96	Dichot/T 2m UW	421707	08:59	12:59	240	48	24.62	Coarse	1.67
									Fine	15.00
		Dichot/Q 2m UW	174242	08:59	12:59	240	48	24.62	Coarse	1.67
									Fine	15.00
		Dichot/T 2m DW	933053	09:09	13:09	240	48	24.62	Coarse	1.67
									Fine	15.00
		Dichot/Q 2m DW	933057	09:09	13:09	240	48	24.62	Coarse	1.67
									Fine	15.00

M	N	O	P	Q	R	S	T	U	V	W
	Run	Sampler Location	Filter Number	Tare Wt. (mg)	Final Wt. (mg)	Net Wt. (mg)	Wt. after Blank Correction (mg)		PM2.5 Concentration (ug/m^3)	PM10 Concentration (ug/m^3)
8	BH-1	Dichot/T 2m UW	9559086	114.16	114.21	0.05	0.04		10.20	21.39
9			9559087	117.12	117.16	0.04	0.03			
10		Dichot/Q 2m UW	9550078	92.39	92.29	0.00	0.01		< 0	< 3.1
11			9550081	93.34	93.31	-0.03	-0.02			
12		Dichot/T 2m DW	9559093	111.61	111.71	0.10	0.09		8.28	40.91
13			9559094	115.52	115.55	0.03	0.02			
14		Dichot/Q 2m DW	9550076	92.32	92.38	0.06	0.07		0.00	26.03
15			9550077	90.49	90.48	-0.01	0.00			
16										
17	BH-2	Dichot/T 2m UW	9559088	114.42	114.51	0.09	0.08		3.70	16.63
18			9559089	114.77	114.80	0.03	0.02			
19		Dichot/Q 2m UW	9550072	92.52	92.50	-0.02	-0.01		< 0	< 0
20			9550073	92.18	92.14	-0.04	-0.03			
21		Dichot/T 2m DW	9559090	112.39	112.49	0.10	0.09		7.41	21.62
22			9559091	113.76	113.81	0.05	0.04			
23		Dichot/Q 2m DW	9550074	91.10	91.19	0.09	0.10		< 0	< 17
24			9550075	91.92	91.90	-0.02	-0.01			
25										
26	BH-3	Dichot/T 2m UW	9559057	115.55	115.57	0.02	0.01		5.58	6.65
27			9559058	115.29	115.33	0.04	0.03			
28		Dichot/Q 2m UW	9550043	91.51	91.54	0.03	0.04		5.56	11.64
29			9550044	91.90	91.92	0.02	0.03			
30		Dichot/T 2m DW	9559059	116.12	116.19	0.07	0.08		1.85	11.64
31			9559092	115.89	115.91	0.02	0.01			
32		Dichot/Q 2m DW	9550045	92.47	92.53	0.06	0.07		1.85	13.31
33			9550046	89.84	89.84	0.00	0.01			
34										
35	BH-6	Dichot/T 2m UW	9559041	122.79	122.95	0.16	0.15		5.58	42.42
36			9559042	123.35	123.38	0.03	0.02			
37		Dichot/Q 2m UW	9550025	91.64	91.82	0.18	0.18		< 2.7	< 53
38			9550027	90.92	90.91	-0.01	-0.01			
39		Dichot/T 2m DW	9559043	116.36	116.55	0.19	0.18		< 1.4	< 46
40			9559044	123.95	123.96	0.01	0.00			
41		Dichot/Q 2m DW	9550029	90.32	90.64	0.32	0.32		22.22	99.80
42			9550028	92.35	92.43	0.08	0.08			

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45 FIELD BLANKS

	N	P	Q	R	S
47	BH-4	9559053	117.59	117.59	0.00
48		9559054	115.53	115.54	0.01
49		9559055	117.00	117.01	0.01
50		9559056	116.32	116.32	0.00
51					
52		9550039	92.10	92.09	-0.01
53		3550040	93.72	93.71	-0.01
54		9550041	92.24	92.23	-0.01
55		9550042	92.19	92.18	-0.01

57 I-225 Teflon blank average = 0.01, Sx = 0.0058
58 I-225 quartz blank average = -0.01, Sx = 0.00

	N	P	Q	R	S
60	BH-5	9559049	121.18	121.19	0.01
61		9559C50	113.61	113.62	0.01
62		9559051	117.65	117.66	0.01
63		9559052	117.17	117.17	0.00
64					
65		9550034	92.21	92.20	-0.01
66		9550035	90.88	90.89	0.01
67		9550036	90.95	90.96	0.01
68		9550037	92.38	92.38	0.00

70 Botanic garden Teflon blank average = 0.01, Sx = 0.005
71 Botanic garden quartz blank average = 0.00, Sx = 0.0096

73 S8=R8-Q8
74 T8=S8-appropriate blank average
75 V8=T9*1000/(15*0.001*H8)
76 W8=(T8+T9)*1000/(16.7*0.001*H8)

M	N	O	P	Q	R	S	T	U	V	W
2										
3							Wt. after			
4							Blank		PM2.5	PM10
5		Sampler	Filter	Tare Wt.	Final Wt.	Net Wt.	Correction		Concentration	Concentration
6	Run	Location	Number	(mg)	(mg)	(mg)	(mg)		(ug/m^3)	(ug/m^3)
7										
8	BH-1	Dichot/T 2m UW	9559086	114.16	114.21	0.05	0.04		10.20	21.39
9			9559087	117.12	117.16	0.04	0.03			
10		Dichot/Q 2m UW	9550078	92.39	92.39	0.00	0.02		< 3.7	< 9.5
11			9550081	93.34	93.31	-0.03	-0.01			
12		Dichot/T 2m DW	9559093	111.61	111.71	0.10	0.09		8.28	40.91
13			9559094	115.52	115.55	0.03	0.02			
14		Dichot/Q 2m DW	9550076	92.32	92.38	0.06	0.08		4.14	33.47
15			9550077	90.49	90.48	-0.01	0.01			
16										
17	BH-2	Dichot/T 2m UW	9559088	114.42	114.51	0.09	0.08		3.70	18.63
18			9559089	114.77	114.80	0.03	0.02			
19		Dichot/Q 2m UW	9550072	92.52	92.50	-0.02	0.00		< 2.0	< 3.7
20			9550073	92.18	92.14	-0.04	-0.02			
21		Dichot/T 2m DW	9559090	112.39	112.49	0.10	0.09		7.41	21.62
22			9559091	113.76	113.81	0.05	0.04			
23		Dichot/Q 2m DW	9550074	91.10	91.19	0.09	0.11		< 2.0	< 20
24			9550075	91.92	91.90	-0.02	0.00			
25										
26	BH-3	Dichot/T 2m UW	9559057	115.55	115.57	0.02	0.01		5.58	6.65
27			9559058	115.29	115.33	0.04	0.03			
28		Dichot/Q 2m UW	9550043	91.51	91.54	0.03	0.05		7.41	14.97
29			9550044	91.90	91.92	0.02	0.04			
30		Dichot/T 2m DW	9559059	116.12	116.19	0.07	0.06		1.85	11.64
31			9559092	115.89	115.91	0.02	0.01			
32		Dichot/Q 2m DW	9550045	92.47	92.53	0.06	0.09		3.70	16.63
33			9550046	89.84	89.84	0.00	0.02			
34										
35	BH-6	Dichot/T 2m UW	9559041	122.79	122.95	0.16	0.15		5.56	42.42
36			9559042	123.35	123.38	0.03	0.02			
37		Dichot/Q 2m UW	9550025	91.64	91.82	0.18	0.18		< 3.1	< 48
38			9550027	90.92	90.91	-0.01	-0.01			
39		Dichot/T 2m DW	9559043	116.36	116.55	0.19	0.18		< 1.4	< 46
40			9559044	123.96	123.96	0.01	0.00			
41		Dichot/Q 2m DW	9550029	90.32	90.54	0.32	0.32		22.22	99.80
42			9550028	92.35	92.43	0.08	0.08			
43										
44										
45	FIELD BLANKS									
46										
47	BH-4		9559053	117.59	117.59	0.00				
48			9559054	115.53	115.54	0.01				
49			9559055	117.00	117.01	0.01				
50			9559056	116.32	116.32	0.00				
51										
52			9550039	92.10	92.09	-0.01				
53			9550040	93.72	93.71	-0.01				
54			9550041	92.24	92.23	-0.01				
55			9550042	92.19	92.18	-0.01				
56			9550081	93.34	93.31	-0.03				
57			9550077	90.49	90.48	-0.01				
58			9550072	92.52	92.50	-0.02				
59			9550073	92.18	92.14	-0.04				
60			9550075	91.92	91.90	-0.02				
61										
62	I-225 Teflon blank average = 0.01, Sx = 0.0058									
63	I-225 quartz blank average = -0.02, Sx = 0.011									
64										
65	BH-5		9559049	121.18	121.19	0.01				
66			9559050	113.61	113.62	0.01				
67			9559051	117.65	117.66	0.01				
68			9559052	117.17	117.17	0.00				
69										
70			9550034	92.21	92.20	-0.01				
71			9550035	90.88	90.89	0.01				
72			9550036	90.95	90.96	0.01				
73			9550037	92.38	92.38	0.00				
74			9550027	90.92	90.91	-0.01				
75										
76	Botanic garden Teflon blank average = 0.01, Sx = 0.005									
77	Botanic garden quartz blank average = 0.00, Sx = 0.012									
78										
79	S8=R8-Q8									
80	T8=S8-appropriate blank average									
81	V8=T9*1000/(15*0.001*H8)									
82	W8=(T8+T9)*1000/(16.7*0.001*H8)									

Bold values indicate where blank corrected net filter weights are at least 3 times the standard deviation of the blank correction.

Values preceded by a < indicate instances where at least one blank corrected net filter weight is less than 1 standard deviation of the blank correction. The standard deviation of the blank correction is used in place of the net filter weight to calculate the concentration.

Run	Date	Sampler Location	Sampler ID	Sampler Start Time	Sampler Stop Time	Sampler Run Time (min)	Avg. Temp. (deg. F)	Avg. B.P. (in. Hg)	Avg. Filter Pressure (in. H2O)	Flowrate (acfm)
BL-1	10/24/96	Cyclone 2m UW	68	12:44	16:48	244	60	24.18	14.77	40.55
		Cyclone 5m UW	75	12:44	16:48	244	60	24.18	14.67	41.02
		Cyclone 7m UW	66	12:44	16:48	244	60	24.18	14.80	40.72
		Wedding 3m UW	1598	12:44	16:48	244	60	24.18	14.10	41.47
		Cyclone 2m DW	69	12:40	16:44	244	60	24.18	14.64	40.88
		Cyclone 3m DW	74	12:40	16:44	244	60	24.18	15.31	40.85
		Cyclone 5m DW	67	12:40	16:44	244	60	24.18	14.96	41.07
		Cyclone 7.5m DW	78	12:40	16:44	244	60	24.18	14.82	40.12
		Cyclone 10m DW	77	12:40	16:44	244	60	24.18	14.97	40.66
		Wedding 3m DW	1600	12:40	16:44	244	60	24.18	14.17	41.86
BL-2 (a	10/25/96	Cyclone 2m UW	69	09:53	16:06	274	51	24.00	14.43	40.57
		Cyclone 5m UW	67	09:53	16:06	274	51	24.00	14.44	40.80
		Cyclone 10m UW	77	09:53	16:06	274	51-	24.00	14.80	40.55
	(b	Wedding 3m UW	1600, 1598			566	49	24.06	13.91	41.40
		Cyclone 2m DW	68	09:48	16:08	281	51	24.00	14.60	40.24
		Cyclone 3m DW	76	09:48	16:08	281	51	24.00	14.62	40.62
		Cyclone 5m DW	75	09:48	16:08	281	51	24.00	14.89	40.66
		Cyclone 7m DW	66	09:48	16:08	281	51	24.00	14.77	40.41
		Wedding 3m DW	1598	09:48	16:08	281	51	24.00	13.50	41.25
BL-3	10/26/96	Cyclone 2m UW	67	09:27	11:40	133	39	24.20	14.63	40.37
		Cyclone 5m UW	77	09:27	11:40	133	39	24.20	14.37	40.18
		Cyclone 2m DW	68	09:59	11:38	99	39	24.20	14.04	39.90
		Cyclone 3m DW	76	09:59	11:38	99	39	24.20	14.45	40.24
		Cyclone 5m DW	75	09:59	11:38	99	39	24.20	15.12	40.23
		Cyclone 7m DW	66	09:59	11:38	99	39	24.20	14.73	39.99
		Wedding 3m DW	1598	09:59	11:38	99	39	24.20	13.18	40.82
BL-4	10/28/96	Cyclone 2m UW	68	10:29	13:08	159	54	24.04	14.41	40.38
		Cyclone 5m UW	75	10:29	13:08	159	54	24.04	14.59	40.81
		Cyclone 7m UW	66	10:29	13:08	159	54	24.04	14.54	40.56
		Cyclone 2m DW	69	10:25	13:09	164	54	24.04	14.65	40.62
		Cyclone 3m DW	74	10:25	13:09	164	54	24.04	14.41	40.78
		Cyclone 5m DW	67	10:25	13:09	164	54	24.04	15.07	40.82
		Cyclone 7.5m DW	78	10:25	13:09	164	54	24.04	14.43	39.98
		Cyclone 10m DW	77	10:25	13:09	164	54	24.04	14.83	40.65
		Wedding 3m DW	1600	10:25	13:09	164	54	24.04	13.58	41.76
BL-7	11/02/96	Cyclone 2m UW	68	11:24	15:32	248	58	24.73	14.99	40.48
		Cyclone 5m UW	75	11:24	15:32	248	58	24.73	16.01	40.95
		Cyclone 7m UW	66	11:24	15:32	248	58	24.73	15.06	40.85
		Wedding 3m UW	1598	11:24	15:32	248	58	24.73	14.07	41.46
		Cyclone 2m DW	70	11:28	15:36	248	58	24.73	14.98	40.57
		Cyclone 3m DW	74	11:28	15:36	248	58	24.73	14.83	40.92
		Cyclone 5m DW	67	11:28	15:36	248	58	24.73	14.74	41.05
		Cyclone 7.5m DW	78	11:28	15:36	248	58	24.73	14.02	40.16
		Cyclone 10m DW	77	11:28	15:36	248	58	24.73	14.42	40.68
		Wedding 3m DW	1600	11:28	15:36	248	58	24.73	13.89	41.92
BL-8	11/03/96	Cyclone 3m DW	77	12:04	15:34	210	58	24.39	14.02	40.93
		Wedding 3m DW	1600	12:04	15:34	210	58	24.39	13.61	41.65
	(c	Cyclone 3m DW	76	12:04	15:34	210	58	24.39	14.03	41.00
	(d	Wedding 3m DW	1599	12:04	15:34	210	58	24.39	13.41	41.81
BL-9	11/04/96	Cyclone 2m UW	70	11:12	12:56	104	60	24.50	14.80	40.84
		Cyclone 5m UW	67	11:12	12:56	104	60	24.50	13.96	41.21
		Cyclone 10m UW	77	11:12	12:56	104	60	24.50	13.98	41.00
	(e	Wedding 3m UW	1600, 1598			470	53	24.45	14.00	41.43
		Cyclone 2m DW	68	11:25	13:00	95	60	24.50	14.04	40.68
		Cyclone 3m DW	76	11:25	13:00	95	60	24.50	13.96	41.07
		Cyclone 5m DW	75	11:25	13:00	95	60	24.50	13.85	41.15
		Cyclone 7m DW	66	11:25	13:00	95	60	24.50	14.02	40.86
		Wedding 3m DW	1598	11:25	13:00	95	60	24.50	14.13	41.54
	(f	Cyclone 3m DW	74	11:25	13:00	95	60	24.50	14.01	41.13
	(g	Wedding 3m DW	1599			466	53	24.44	13.72	41.36
BL-10	11/05/96	Cyclone 2m UW	70	10:40	12:46	126	62	24.30	14.07	40.80
		Cyclone 5m UW	67	10:40	12:46	126	62	24.30	14.38	41.24
		Cyclone 10m UW	77	10:40	12:46	126	62	24.30	14.24	41.02
		Cyclone 2m DW	68	10:35	12:48	133	62	24.30	14.07	40.71
		Cyclone 3m DW	76	10:35	12:48	133	62	24.30	14.68	41.05
		Cyclone 5m DW	75	10:35	12:48	133	62	24.30	14.32	41.18
		Cyclone 7m DW	66	10:35	12:48	133	62	24.30	14.34	40.88
		Wedding 3m DW	1598	10:35	12:48	133	62	24.30	13.78	41.61
	(h	Cyclone 3m DW	74	10:35	12:48	133	62	24.30	14.32	41.11
BL-11	11/06/96	Cyclone 2m UW	68	10:55	14:55	240	45	24.50	13.65	40.20
		Cyclone 5m UW	75	10:55	14:55	240	45	24.50	13.59	40.87
		Cyclone 7m UW	66	10:55	14:55	240	45	24.50	13.78	40.36
		Cyclone 2m DW	70	11:00	15:00	240	45	24.50	13.62	40.29
		Cyclone 3m DW	74	11:00	15:00	240	45	24.50	13.71	40.59
		Cyclone 5m DW	67	11:00	15:00	240	45	24.50	13.74	40.72
		Cyclone 7.5m DW	78	11:00	15:00	240	45	24.50	13.41	39.82
		Cyclone 10m DW	77	11:00	15:00	240	45	24.50	13.79	40.51
		Wedding 3m DW	1600	11:00	15:00	240	45	24.50	13.88	41.30
	(i	Cyclone 3m DW	76	11:00	15:00	240	45	24.50	13.81	40.59

(a Samplers were shut off from 11:25 - 13:04 due to unfavorable wind.
(b Upwind Wedding is a composite of runs BL-2, 3, and 4.
(c Colocated with Cyclone # 77.
(d Colocated with Wedding # 1600.
(e Upwind Wedding is a composite of runs BL-9, 10, and 11.
(f Colocated with Cyclone # 78.
(g Downwind Wedding is a composite of runs BL-9, 10, and 11.
(h Colocated with Cyclone # 78.
(i Colocated with Cyclone # 74.

N	O	P	Q	R	S	T	U	V	W	X	Y	Z
Run	Sampler Location	Filter Number	Tare Wt. (mg)	Final Wt. (mg)	Net Wt. (mg)	Wt. after Blank Correction (mg)		PM10 Concentration (ug/m^3)	PM10 Concentration (upwind corrected)	Mean Wind Speed (mph)	IFR	PM10 Exposure (mg/cm^2)
BL-1	Cyclone 2m UW	9622004	4363.30	4371.20	7.90	8.42		30		2.7	3.9	
	Cyclone 5m UW	9622006	4291.70	4294.70	3.00	3.52		12		3.5	3.0	
	Cyclone 7m UW	9622007	4267.40	4271.35	3.95	4.47		16		3.8	2.8	
	Wedding 3m UW	9623004	3395.95	3398.55	2.60	3.41		12		3.0	3.8	
	Cyclone 2m DW	9622001	4273.00	4276.60	3.60	4.12		15	0	2.7	3.9	0.0000
	Cyclone 3m DW	9622005	4326.55	4331.25	4.70	5.22		18	0	3.0	3.5	0 0000
	Cyclone 5m DW	9622002	4321.10	4324.40	3.30	3.82		13	0	3.5	3.1	0.0000
	Cyclone 7.5m DW	9622008	4237.75	4243.25	5.50	6.02		22	3	3.8	2.7	0.0075
	Cyclone 10m DW	9622003	4336.30	4339.30	3.00	3.52		12	0	4.1	2.6	0.0000
	Wedding 3m DW	9623003	3382.85	3386.55	3.70	4.51		16	4	3.0		0.0079
BL-2	Cyclone 2m UW	9622009	4231.05	4237.50	6.45	6.97		22		3.1	3.4	
	Cyclone 5m UW	9622010	4238.30	4244.40	6.10	6.62		21		4.9	2.2	
	Cyclone 10m UW	9622011	4271.15	4277.15	6.00	6.52		21		6.2	1.7	
(b	Wedding 3m UW	9623005	3329.25	3338.75	9.50	10.31		16		4.3		
	Cyclone 2m DW	9622012	4270.00	4277.95	7.95	8.47		28	5	3.1	3.4	0.0117
	Cyclone 3m DW	9622013	4257.05	4266.45	9.40	9.92		31	10	3.9	2.7	0.0294
	Cyclone 5m DW	9622014	4299.45	4306.80	7.35	7.87		24	3	4.9	2.2	0.0111
	Cyclone 7m DW	9622015	4262.05	4268.75	6.70	7.22		22	1	5.5	1.9	0.0041
	Wedding 3m DW	9623006	3319.20	3325.55	6.35	7.16		22	5	3.8		0.0147
BL-3	Cyclone 2m UW	9622018	4195.15	4194.75	-0.40	0.12		1		7.1	1.6	
	Cyclone 5m UW	9622019	4125.30	4125.30	0.00	0.52		3		9.3	1.6	
	Cyclone 2m DW	9622020	4106.50	4106.90	0.40	0.92		6	6	7.1	1.7	0.0113
	Cyclone 3m DW	9622021	4155.90	4156.95	1.05	1.57		14	12	8.1	1.5	0.0258
	Cyclone 5m DW	9622022	4239.35	4240.30	0.95	1.47		13	11	9.3	1.5	0.0272
	Cyclone 7m DW	9622023	4257.10	4257.40	0.30	0.82		7	5	10.2	1.4	0.0135
	Wedding 3m DW	9623007	3319.55	3318.75	-0.80	0.01		0	0	8.1		0.0000
BL-4	Cyclone 2m UW	9622017	4235.00	4239.20	4.20	4.72		26		1.5	7.0	
	Cyclone 5m UW	9622025	4170.60	4174.65	4.05	4.57		25		2.2	4.8	
	Cyclone 7m UW	9622026	4175.85	4179.40	3.55	4.07		22		2.5	4.2	
	Cyclone 2m DW	9622027	4185.70	4190.95	5.25	5.77		31	7	1.5	7.0	0.0046
	Cyclone 3m DW	9622028	4169.60	4175.15	5.55	6.07		32	8	1.8	5.9	0.0063
	Cyclone 5m DW	9622029	4189.65	4194.45	4.80	5.32		28	4	2.2	4.8	0.0039
	Cyclone 7.5m DW	9622030	4182.00	4186.20	4.20	4.72		25	1	2.5	4.2	0.0011
	Cyclone 10m DW	9622024	4210.30	4214.20	3.90	4.42		23	0	2.7	3.9	0.0000
	Wedding 3m DW	9623009	3360.70	3363.90	3.20	4.01		21	5	1.8		0.0040
BL-7	Cyclone 2m UW	9622047	4127.45	4139.25	11.80	12.32		43		1.1	9.6	
	Cyclone 5m UW	9622048	4120.45	4130.55	10.10	10.62		37		2.0	5.3	
	Cyclone 7m UW	9622049	4140.05	4148.20	8.15	8.67		30		2.3	4.6	
	Wedding 3m UW	9623023	3341.65	3349.85	8.20	9.01		31		1.5		
	Cyclone 2m DW	9622045	4163.80	4194.25	30.45	30.97		109	72	1.1	9.6	0.0527
	Cyclone 3m DW	9622046	4133.85	4155.90	22.05	22.57		79	42	1.5	7.1	0.0419
	Cyclone 5m DW	9622033	4141.45	4160.10	18.65	19.17		68	29	2.0	5.3	0.0366
	Cyclone 7.5m DW	9622039	4103.10	4119.35	16.25	16.77		59	22	2.4	4.4	0.0351
	Cyclone 10m DW	9622040	4081.15	4092.80	11.65	12.17		42	5	2.7	3.9	0.0090
	Wedding 3m DW	9623024	3379.75	3397.20	17.45	18.26		62	31	1.6		0.0309
BL-8	Cyclone 3m DW	9622054	4445.70	4451.35	5.65	6.17		25		1.9	5.8	0.0000
	Wedding 3m DW	9623025	3378.65	3384.15	5.50	6.31		25		1.9		0.0000
	Cyclone 3m DW	9622058	4452.60	4458.55	5.95	6.47		27		1.9	5.8	0.0000
	Wedding 3m DW	9623029	3304.65	3308.45	3.80	4.61		19		1.9		0.0000
BL-9	Cyclone 2m UW	9622050	4146.45	4147.35	0.90	1.42		12		6.7	1.8	
	Cyclone 5m UW	9622051	4451.25	4451.60	0.35	0.87		7		9.2	1.2	
	Cyclone 10m UW	9622052	4439.05	4439.50	0.45	0.97		8		11.1	1.0	
(e	Wedding 3m UW	9623035	3345.95	3349.25	3.30	4.11		7		5.1		
	Cyclone 2m DW	9622053	4426.30	4430.20	3.90	4.42		40	31	6.7	1.6	0.0529
	Cyclone 3m DW	9622059	4436.45	4439.85	3.40	3.92		35	26	7.8	1.4	0.0517
	Cyclone 5m DW	9622056	4436.75	4438.60	1.85	2.37		21	12	9.2	1.2	0.0281
	Cyclone 7m DW	9622057	4449.25	4450.85	1.60	2.12		19	10	10.1	1.1	0.0257
	Wedding 3m DW	9623036	3328.30	3330.45	2.15	2.96		26	19	7.8		0.0378
(f	Cyclone 3m DW	9622060	4444.30	4447.25	2.95	3.47		31	22	7.8	1.4	0.0437
(g	Wedding 3m DW	9623037	3397.05	3406.65	9.60	10.41		19		5.1		
BL-10	Cyclone 2m UW	9622066	4446.75	4446.10	-0.65	-0.13		0		7.7	1.4	
	Cyclone 5m UW	9622067	4456.75	4456.60	-0.15	0.37		3		8.4	1.3	
	Cyclone 10m UW	9622068	4464.15	4463.85	-0.30	0.22		2		8.9	1.2	
	Cyclone 2m DW	9622061	4448.30	4450.25	1.95	2.47		16	14	7.7	1.4	0.0366
	Cyclone 3m DW	9622062	4456.00	4457.35	1.35	1.87		12	10	8.0	1.3	0.0265
	Cyclone 5m DW	9622055	4451.70	4447.80	-3.90	-3.38		0	0	8.4	1.3	0.0000
	Cyclone 7m DW	9622063	4442.50	4442.50	0.00	0.52		3	1	8.6	1.2	0.0031
	Wedding 3m DW	9623041	3331.55	3333.80	2.25	3.06		20	13	8.0		0.0371
(h	Cyclone 3m DW	9622065	4458.45	4458.40	-0.05	0.47		3	1	6.0	1.3	0.0029
BL-11	Cyclone 2m UW	9622075	4474.65	4477.10	2.45	2.97		11		2.1	5.0	
	Cyclone 5m UW	9622076	4465.45	4467.00	1.55	2.07		7		3.0	3.5	
	Cyclone 7m UW	9622064	4464.20	4466.40	2.20	2.72		10		3.3	3.2	
	Cyclone 2m DW	9622069	4455.05	4461.05	6.00	6.52		24	15	2.1	5.0	0.0203
	Cyclone 3m DW	9622070	4468.85	4476.10	7.25	7.77		28	19	2.5	4.2	0.0306
	Cyclone 5m DW	9622071	4478.15	4482.25	4.10	4.62		17	8	3.0	3.5	0.0154
	Cyclone 7.5m DW	9622072	4463.65	4468.15	4.50	5.02		19	10	3.4	3.0	0.0219
	Cyclone 10m DW	9622073	4468.15	4470.60	2.45	2.97		11	2	3.7	2.8	0.0048
	Wedding 3m DW	9623047	3348.00	3350.60	2.60	3.41		12	5	2.5		0.0080
i	Cyclone 3m DW	9622074	4475.80	4478.70	2.90	3.42		12	3	2.5	4.2	0.0048

104
105
106 FIELD BLANKS

107						
108	BL-5	Glass fiber	9622035	4166.50	4165.95	-0.55
109			9622036	4131.90	4131.30	-0.60
110			9622037	4142.00	4141.35	-0.65
111			9622038	4156.10	4155.65	-0.45
112						
113		Quartz	9623012	3365.40	3363.70	-1.70
114			9623014	3369.80	3369.00	-0.80
115			6923015	3372.15	3371.05	-1.10
116						
117	1st sanding	Glass fiber	9622031	4213.35	4213.10	-0.25
118			9622042	4065.00	4063.50	-1.50
119			9622043	4116.45	4115.55	-0.90
120			9622044	4189.25	4188.70	-0.55
121						
122		Quartz	9623017	3383.30	3383.30	0.00
123			9623030	3370.45	3368.40	-2.05
124			9623031	3353.20	3351.45	-1.75
125						
126	2nd sanding	Glass fiber	9622077	4474.15	4473.55	-0.60
127			9622078	4477.00	4476.75	-0.25
128			9622079	4495.55	4495.30	-0.25
129			9622080	4431.10	4431.40	0.30
130						
131		Quartz	9623043	3358.55	3358.75	0.20
132			9623044	3339.50	3340.05	0.55
133			6923045	3341.35	3340.75	-0.60
134						

135 Glass fiber blank average = -0.52, Sx = 0.43
136 Quartz blank average = -0.81, Sx = 0.93
137
138
139 S8=R8-Q8
140 T8=S8-appropriate blank average
141 V10=T10*1000/L10*H10*0.02832
142 W13=V13-appropriate upwind concentration
143 Z13=W13*1E-07*X13*H13*0.44704*60

B	C	D	E	F	G	H	I	J	K
Run	Date	Sampler Location	Sampler ID	Sampler Start Time	Sampler Stop Time	Sampler Run Time (min)	Avg. Temp. (deg. F)	Avg. B.P. (in. Hg)	Flowrate (ft^3/min)
BL-2	10/25/96	Cyc/Imp 3m UW	731	09:53	16:06	274	51	24.00	20
		Cyc/Imp 3m DW	73	09:48	16:08	281	51	24.00	20
BL-3	10/26/96	Cyc/Imp 3m UW	731	09:27	11:40	133	39	24.20	20
		Cyc/Imp 3m DW	73	09:59	11:38	99	39	24.20	20
BL-4	10/28/96	Cyc/Imp 3m UW	73	10:29	13:08	159	54	24.04	20
		Cyc/Imp 3m DW	731	10:25	13:09	164	54	24.04	20
BL-7	11/02/96	Cyc/Imp 3m UW	73	11:24	15:32	248	58	24.73	20
		Cyc/Imp 3m DW	731	11:28	15:36	248	58	24.73	20
BL-8	11/03/96	Cyc/Imp 3m DW	731	12:04	15:34	210	58	24.39	20
		Cyc/Imp 3m DW	1	12:04	15:34	210	58	24.39	20
BL-9	11/04/96	Cyc/Imp 3m UW	731	11:12	12:56	104	60	24.50	20
		Cyc/Imp 3m DW	73	11:25	13:00	95	60	24.50	20
		Cyc/Imp 3m DW	1	11:25	13:00	95	60	24.50	20
BL-10	11/05/96	Cyc/Imp 3m UW	731	10:40	12:46	126	62	24.30	20
		Cyc/Imp 3m DW	73	10:35	12:48	133	62	24.30	20
		Cyc/Imp 3m DW	1	10:35	12:48	133	62	24.30	20
BL-11	11/06/96	Cyc/Imp 3m UW	731	10:55	14:55	240	45	24.50	20
		Cyc/Imp 3m DW	73	11:00	15:00	240	45	24.50	20
		Cyc/Imp 3m DW	1	11:00	15:00	240	45	24.50	20

Run		Sampler Location	Stage Number	Filter Number	Tare Wt. (mg)	Final Wt. (mg)	Net Wt. (mg)	Wt. after Blank Correction
BL-2		Cyc/Imp 3m UW	S-1	9628003	988.81	989.18	0.37	-0.15
			S-2	9628002	982.13	983.05	0.92	0.40
			S-3	9628001	979.12	979.58	0.46	-0.06
	(a		Backup	9623001	3330.70	3335.80	5.10	6.15
		Cyc/Imp 3m DW	S-1	9628006	985.67	986.71	1.04	0.52
			S-2	9628005	1002.81	1004.12	1.31	0.79
			S-3	9628004	985.78	986.94	1.16	0.64
			Backup	9623002	3330.05	3333.20	3.15	4.20
BL-3		Cyc/Imp 3m UW	S-1	9628009	973.59	973.58	-0.01	-0.53
			S-2	9628008	985.31	985.29	-0.02	-0.54
			S-3	9628007	991.85	992.28	0.43	-0.09
	(a		Backup	9623001	3330.70	3335.80	5.10	6.15
		Cyc/Imp 3m DW	S-1	9628012	979.44	979.90	0.46	-0.06
			S-2	9628011	983.53	984.03	0.50	-0.02
			S-3	9628010	953.88	954.01	0.13	-0.39
			Backup	9623008	3357.35	3358.10	-1.25	-0.20
BL-4		Cyc/Imp 3m UW	S-1	9628015	987.35	987.50	0.15	-0.37
			S-2	9628014	982.02	982.44	0.42	-0.10
			S-3	9628013	977.50	977.92	0.42	-0.10
	(a		Backup	9623001	3330.70	3335.80	5.10	6.15
		Cyc/Imp 3m DW	S-1	9628018	990.03	990.61	0.58	0.06
			S-2	9628017	979.91	980.86	0.95	0.43
			S-3	9628016	983.96	985.26	1.30	0.78
			Backup	9623010	3336.75	3338.10	1.35	2.40
BL-7		Cyc/Imp 3m UW	S-1	9628027	982.27	983.22	0.95	0.43
			S-2	9628026	987.42	989.20	1.78	1.26
			S-3	9628025	989.97	990.96	0.99	0.47
			Backup	9623020	3364.20	3367.35	3.15	4.20
		Cyc/Imp 3m CW	S-1	9628036	972.71	976.02	3.31	2.79
			S-2	9628035	978.26	983.14	4.88	4.36
			S-3	9628034	969.98	973.88	3.90	3.38
			Backup	9623026	3372.30	3379.15	6.85	7.90
BL-8		Cyc/Imp 3m DW	S-1	9628039	989.29	990.78	1.49	0.97
			S-2	9628038	981.82	982.87	1.05	0.53
			S-3	9628037	971.20	971.95	0.75	0.23
			Backup	9623027	3431.15	3432.40	1.25	2.30
		Cyc/Imp 3m DW	S-1	9628042	962.04	962.77	0.73	0.21
			S-2	9628041	974.73	975.92	1.19	0.67
			S-3	9628040	982.16	983.07	0.91	0.39
			Backup	9623028	3335.80	3335.85	0.05	1.10
BL-9	(b	Cyc/Imp 3m UW	S-1	9628051	988.68	988.21	-0.47	-0.99
	(c		S-2	9628050	982.96	983.12	0.16	-0.36
	(d		S-3	9628049	989.77	990.36	0.59	0.07
	(e		Backup	9623038	3311.80	3312.25	0.45	1.50
		Cyc/Imp 3m DW	S-1	9628054	968.00	968.57	0.57	0.05
			S-2	9628053	971.48	972.30	0.82	0.30
			S-3	9628052	977.92	979.13	1.21	0.69
			Backup	9623039	3331.00	3331.45	0.45	1.50
		Cyc/Imp 3m DW	S-1	9628057	966.58	967.34	0.76	0.24
			S-2	9628056	973.12	974.26	1.14	0.62
			S-3	9628055	956.98	958.52	1.54	1.02
	(f		Backup	9623040	3341.65	3344.10	2.45	3.50
BL-10	(b	Cyc/Imp 3m UW	S-1	9628051	988.68	988.21	-0.47	-0.99
	(c		S-2	9628050	982.96	983.12	0.16	-0.36
	(d		S-3	9628049	989.77	990.36	0.59	0.07
	(e		Backup	9623038	3311.80	3312.25	0.46	1.50
	(g	Cyc/Imp 3m DW	S-1	9628060	973.94	974.84	0.90	0.38
	(h		S-2	9628059	963.72	964.65	0.93	0.41
	(i		S-3	9628058	981.32	981.17	-0.15	-0.67
			Backup	9623042	3369.80	3370.20	0.40	1.45
	(j	Cyc/Imp 3m DW	S-1	9628063	967.36	968.25	0.89	0.37
	(k		S-2	9628062	971.53	972.39	0.86	0.34
	(l		S-3	9628061	964.65	964.86	0.21	-0.31
	(f		Backup	9623040	3341.65	3344.10	2.45	3.50
BL-11	(b	Cyc/Imp 3m UW	S-1	9628051	988.68	988.21	-0.47	-0.99
	(c		S-2	9628050	982.96	983.12	0.16	-0.36
	(d		S-3	9628049	989.77	990.36	0.59	0.07
	(e		Backup	9623038	3311.80	3312.25	0.45	1.50
	(g	Cyc/Imp 3m DW	S-1	9628060	973.94	974.84	0.90	0.38
	(h		S-2	9628059	963.72	964.85	0.93	0.41
	(i		S-3	9628058	981.32	981.17	-0.15	-0.67
			Backup	9623048	3369.00	3369.35	0.35	1.40
	(j	Cyc/Imp 3m DW	S-1	9628063	967.36	968.25	0.89	0.37
	(k		S-2	9628062	971.53	972.39	0.86	0.34
	(l		S-3	9628061	964.65	964.86	0.21	-0.31
	(f		Backup	9623040	3341.65	3344.10	2.45	3.50

(a Same filter was used in BL-2,3,4.
(b,c,d,e,f Same filter was used in BL-9,10,11.
(g,h,i,j,k,l Same filter was used in BL-10,11.

112	JELD BLANKS						
113							
114	BL-5	Glass fiber	S-1	9628024	970.00	971.04	1.04
115		Glass fiber	S-2	9628023	974.44	975.49	1.05
116		Glass fiber	S-3	9628022	985.93	986.33	0.40
117		Quartz	Backup	9623013	3317.00	3316.20	-0.80
118							
119		Glass fiber	S-1	9628021	988.30	988.85	0.55
120		Glass fiber	S-2	9628020	993.34	994.01	0.67
121		Glass fiber	S-3	9628019	996.55	996.58	0.03
122		Quartz	Backup	9623011	3346.75	3346.30	-0.45
123							
124		Quartz	Backup	9623016	3381.50	3381.00	-0.50
125							
126	1st sanding	Glass fiber	S-1	9628045	976.19	976.65	0.46
127		Glass fiber	S-2	9628044	966.73	966.87	0.14
128		Glass fiber	S-3	9628043	966.87	967.20	0.33
129		Quartz	Backup	9623032	3371.45	3370.10	-1.35
130							
131		Glass fiber	S-1	9628048	974.26	974.53	0.27
132		Glass fiber	S-2	9628047	973.78	973.73	-0.05
133		Glass fiber	S-3	9628046	996.50	996.99	0.49
134		Quartz	Backup	9623033	3319.60	3318.40	-1.20
135							
136		Quartz	Backup	9623034	3290.25	3288.45	-1.80
137							
138	2nd sanding	Glass fiber	S-1	9628066	964.21	964.52	0.31
139		Glass fiber	S-2	9628065	984.11	985.14	1.03
140		Glass fiber	S-3	9628064	968.61	969.48	0.87
141		Quartz	Backup	9623046	3361.40	3360.00	-1.40
142							
143		Glass fiber	S-1	9628069	980.63	980.95	0.32
144		Glass fiber	S-2	9628068	974.71	975.30	0.59
145		Glass fiber	S-3	9628067	963.17	963.97	0.80
146		Quartz	Backup	9623049	3295.00	3293.95	-1.05
147							
148		Quartz	Backup	9623050	3333.80	3332.90	-0.90
149							
150							
151							
152							

153 Glass fiber 4 X 5 blank average = 0.52, Sx = 0.34
154 Quartz blank average = -1.05, Sx = 0.44
155
156 S8=R8-Q8
157 T8=S8-0.52 glass fiber 4 X 5, =S8+1.05 for quartz

Run	Sampler Location	Particulate Concentration (ug/m^3) less than stated size 2.1 um	 10.2 um
BL-2	Cyc/Imp 3m UW	19	<24
	Cyc/Imp 3m DW	26	35
BL-3	Cyc/Imp 3m UW	19	<28
	Cyc/Imp 3m DW	<7.8	<20
BL-4	Cyc/Imp 3m UW	19	<27
	Cyc/Imp 3m DW	26	39
BL-7	Cyc/Imp 3m UW	30	42
	Cyc/Imp 3m DW	56	110
BL-8	Cyc/Imp 3m DW	19	<27
	Cyc/Imp 3m DW	9.2	18
BL-9	Cyc/Imp 3m UW	<5.6	<8.2
	Cyc/Imp 3m DW	28	<47
	Cyc/Imp 3m DW	13	44
BL-10	Cyc/Imp 3m UW	<5.6	<8.2
	Cyc/Imp 3m DW	19	<28
	Cyc/Imp 3m DW	13	<22
BL-11	Cyc/Imp 3m UW	<5.6	<8.2
	Cyc/Imp 3m DW	10	<15
	Cyc/Imp 3m DW	13	<18

Bold values indicate where blank corrected net filter weights are at least 3 times the standard deviation of the blank correction.

Values preceded by a < indicate instances where at least one blank corrected net filter weight is less than 1 standard deviation of the blank correction. The standard deviation of the blank correction is used in place of the net filter weight to calculate the concentration.

Run	Date	Sampler Location	Sampler ID	Sampler Run Time (min)	Aerosol Fraction	Flowrate (liter/min)
BL-2,3,4	10/25-28/96	Dichot/T 3m UW	421707	566	Coarse	1.67
					Fine	15.00
		Dichot/T 3m DW	174242	544	Coarse	1.67
					Fine	15.00
BL-7	11/02/96	Dichot/T 3m UW	174242	248	Coarse	1.67
					Fine	15.00
		Dichot/T 3m DW	421707	248	Coarse	1.67
					Fine	15.00
BL-9,10	11/04-05/97	Dichot/T 3m UW	421707	230	Coarse	1.67
					Fine	15.00
(a		Dichot/T 3m DW	174242	228	Coarse	1.67
					Fine	15.00
(a		Dichot/T 3m DW	933057	228	Coarse	1.67
					Fine	15.00

(a Colocated samplers.

1	J	K	L	M	N	O	P	Q	R	S
2										
3							Wt. after			
4							Blank		PM2.5	PM10
5		Sampler	Filter	Tare Wt.	Final Wt.	Net Wt.	Correction		Concentration	Concentration
6	Run	Location	Number	(mg)	(mg)	(mg)	(mg)		(ug/m^3)	(ug/m^3)
7										
8	BL-2,3,4	Dichot/T 3m UW	9629123	112.38	112.52	0.14	0.13		4.7	18
9			9629124	116.84	116.89	0.05	0.04			
10		Dichot/T 3m DW	9629125	117.82	118.12	0.30	0.29		12	43
11			9629126	115.86	115.97	0.11	0.10			
12										
13	BL-7	Dichot/T 3m UW	9629133	120.59	120.77	0.18	0.17		16	56
14			9629134	114.91	114.98	0.07	0.06			
15		Dichot/T 3m DW	9629139	113.65	114.08	0.43	0.42		16	116
16			9629140	116.81	116.88	0.07	0.06			
17										
18	BL-9,10	Dichot/T 3m UW	9629147	114.16	114.21	0.05	0.04		5.8	16
19			9629148	115.10	115.13	0.03	0.02			
20		Dichot/T 3m DW	9629149	117.82	117.98	0.16	0.15		5.8	45
21			9629150	116.47	116.50	0.03	0.02			
22		Dichot/T 3m DW	9629151	115.77	115.89	0.12	0.11		0	29
23			9629152	116.97	116.98	0.01	0.00			
24										
25									Bold values indicate where blank	
26									corrected net filter weights are at least 3 times	
27	FIELD BLANKS								the standard deviation of the blank correction.	
28										
29	BL-5	Teflon	9629127	116.50	116.51	0.01				
30		Teflon	9629128	117.29	117.29	0.00				
31		Teflon	9629129	116.14	116.15	0.01				
32		Teflon	9629130	116.47	116.48	0.01				
33		Teflon	9629131	114.91	114.92	0.01				
34		Teflon	9629132	115.77	115.78	0.01				
35										
36	1st sanding	Teflon	9629143	116.26	116.29	0.03				
37		Teflon	9629144	117.06	117.08	0.02				
38		Teflon	9629145	110.37	110.39	0.02				
39		Teflon	9629146	113.92	113.93	0.01				
40		Teflon	9629141	116.82	116.84	0.02				
41		Teflon	9629142	116.14	116.16	0.02				
42										
43	2nd sanding	Teflon	9629153	119.86	119.85	-0.01				
44		Teflon	9629154	114.68	114.67	-0.01				
45		Teflon	9629155	117.67	117.68	0.01				
46		Teflon	9629156	115.99	116.00	0.01				
47		Teflon	9629157	118.89	118.89	0.00				
48		Teflon	9629158	116.92	116.93	0.01				
49										
50	Teflon blank average = 0.01, Sx = 0.0103									
51										
52										
53	O8=N8-M8									
54	P8=O8-0.01									
55	R8=P9*1000/(15*0.001*F8)									
56	S8=(P8+P9)*1000/(16.7*0.001*F8)									

Run	Dates		Sampler Location	Sampler ID	Sampler Run Time (min)	Avg. Filter Pressure (in. H2O)	Nominal flowrate (acfm)
BM-2	1/15-16/97	(a	Cyclone 2m UW	67			
		(a	Cyclone 6m UW	74			
		(a	Wed/Imp 2m UW	1600			
		(a	Wedding 2m UW	1424			
		(a	Cyclone 2m DW	78			
		(a	Cyclone 4m DW	77			
		(a	Cyclone 6m DW	70			
		(a	Wedding 2m DW	1599			
BM-3	2/22-23/97	(b	Cyclone 2m UW	67	1399	13.35	40.00
		(b	Cyclone 6m UW	74	1399	12.57	40.00
		(c	Cyclone 2m DW	78			
		(c	Cyclone 4m DW	77			
		(b	Cyclone 6m DW	70	1302	13.22	40.00
BM-4	02/25/97		Cyclone 2m UW	67	176	13.53	40.00
			Cyclone 6m UW	74	176	13.54	40.00
			Cyclone 2m DW	78	135	13.32	40.00
			Cyclone 4m DW	66	135	13.27	40.00
			Cyclone 6m DW	70	135	13.47	40.00
BM-5	02/27/97		Cyclone 2m UW	67	163	11.87	40.00
			Cyclone 6m UW	74	163	13.36	40.00
			Cyclone 2m DW	78	201	13.61	40.00
			Cyclone 4m DW	66	201	13.58	40.00
			Cyclone 6m DW	70	201	13.41	40.00
BM-6	03/02/97		Cyclone 2m UW	67	147	13.52	40.00
			Cyclone 6m UW	74	147	13.81	40.00
		(b	Wedding 2m UW	69	720	13.46	40.00
			Cyclone 2m DW	78	206	13.89	40.00
			Cyclone 4m DW	66	206	13.94	40.00
			Cyclone 6m DW	70	206	13.69	40.00
		(b	Wedding 2m DW	1599	654	13.13	40.00
BM-7	3/15-16/97		Cyclone 2m UW	67	406	13.41	40.00
			Cyclone 6m UW	74	406	13.74	40.00
			Wedding 2m UW	69	318	12.83	40.00
			Cyclone 2m DW	78	450	13.60	40.00
			Cyclone 4m DW	66	450	13.35	40.00
			Cyclone 6m DW	70	450	13.85	40.00
		(b	Wedding 2m DW	1599	1341	13.79	40.00
BM-8	3/16-17/97		Cyclone 2m UW	67	355	14.40	40.00
			Cyclone 6m UW	74	355	14.30	40.00
			Wedding 2m UW	69	360	12.49	40.00
			Cyclone 2m DW	78	416	14.11	40.00
			Cyclone 4m DW	66	416	14.15	40.00
			Cyclone 6m DW	70	416	14.01	40.00
		(b	Wedding 2m DW	1599	1369	14.14	40.00

(a Electrical problems forced these samplers to be aborted.

(b Sampler ran continuously.

(c Electrical power failure.

J	K	L	M	N	O	P	Q	R	S	T	U	V
2												
3							Wt. after			PM10		
4							Blank		PM10	Concentration	Mean Wind	PM10
5		Sampler	Filter	Tare Wt.	Final Wt.	Net Wt.	Correction		Concentration	(upwind	Speed	Exposure
6	Run	Location	Number	(mg)	(mg)	(mg)	(mg)		(ug/m^3)	corrected)	(mph)	(mg/cm^2)
7												
8	BM-3	Cyclone 2m UW	9622091	4440.00	4445.10	5.10	5.79		3.7			
9		Cyclone 6m UW	9622092	4451.20	4456.60	5.40	6.09		3.8			
10												
11		Cyclone 6m DW	9622095	4431.75	4439.35	7.60	8.29		5.6	1.8	5.6	0.0352
12												
13	BM-4	Cyclone 2m UW	9622105	4595.30	4604.20	8.90	9.59		48			
14		Cyclone 6m UW	9622101	4598.80	4611.30	12.50	13.19		66			
15												
16		Cyclone 2m DW	9622102	4597.45	4606.40	8.95	9.64		53	5	3.4	0.0074
17		Cyclone 4m DW	9622103	4610.30	4616.10	5.80	6.49		42	0	4.2	0.0000
18		Cyclone 6m DW	9622104	4597.10	4605.05	7.95	8.64		56	0	4.6	0.0000
19												
20	BM-5	Cyclone 2m UW	9622110	4449.60	4467.20	17.60	18.29		99			
21		Cyclone 6m UW	9622109	4456.20	4472.10	15.90	16.59		90			
22												
23		Cyclone 2m DW	9622108	4446.45	4485.60	39.15	39.84		175	80	no data	0.0000
24		Cyclone 4m DW	9622107	4456.60	4456.95	0.35	1.04		4.8	0	no data	0.0000
25		Cyclone 6m DW	9622106	4577.20	4593.35	16.15	16.84		74	0	no data	0.0000
26												
27	BM-6	Cyclone 2m UW	9622111	4449.15	4468.70	19.55	20.24		122			
28		Cyclone 6m UW	9622115	4452.00	4457.10	5.10	5.79		35			
29		Wedding 2m UW	9623065	3360.65	3390.65	30.00	29.22		36			
30												
31		Cyclone 2m DW	9622112	4448.65	4456.70	8.05	8.74		37	0	3.6	0.0000
32		Cyclone 4m DW	9622113	4447.45	4460.35	12.90	13.59		58	0	4.4	0.0000
33		Cyclone 6m DW	9622114	4443.45	4459.70	16.25	16.94		73	0	4.9	0.0000
34		Wedding 2m DW	9623066	3320.45	3348.00	27.55	26.77		36	0	3.6	0.0000
35												
36	BM-7	Cyclone 2m UW	9622117	4439.60	4451.50	11.90	12.59		27			
37		Cyclone 6m UW	9622118	4454.25	4467.60	13.35	14.04		31			
38		Wedding 2m UW	9623070	3377.35	3388.40	11.05	10.27		29			
39												
40		Cyclone 2m DW	9622116	4441.60	4468.65	27.05	27.74		54	25	2.8	0.0846
41		Cyclone 4m DW	9622119	4455.80	4475.25	19.45	20.14		40	11	3.4	0.0451
42		Cyclone 6m DW	9622120	4453.80	4467.20	13.40	14.09		28	0	3.8	0.0000
43		Wedding 2m DW	9623072	3384.45	3420.40	35.95	35.17		23	0	2.8	0.0000
44												
45	BM-8	Cyclone 2m UW	9622121	4457.30	4464.15	6.85	7.54		19			
46		Cyclone 6m UW	9622122	4455.40	4458.80	3.40	4.09		10			
47		Wedding 2m UW	9623075	3319.45	3325.90	6.45	5.67		14			
48												
49		Cyclone 2m DW	9622123	4464.30	4476.60	12.30	12.99		28	13	3.5	0.0508
50		Cyclone 4m DW	9633125	4469.20	4481.60	12.40	13.09		28	13	4.3	0.0624
51		Cyclone 6m DW	9622124	4454.55	4467.95	13.40	14.09		30	15	4.8	0.0803
52		Wedding 2m DW	9623074	3368.20	3392.65	24.45	23.67		16	1	3.5	0.0129
53												
54												
55	FIELD BLANKS											
56												
57		Cyclone	9622081	4443.20	4443.05	-0.15						
58			9622082	4427.10	4426.95	-0.15						
59			9622083	4434.50	4434.45	-0.05						
60			9622084	4443.00	4442.65	-0.35						
61			9622085	4433.65	4433.20	-0.45						
62			9622099	4457.70	4456.60	-1.10						
63			9622100	4446.60	4445.85	-0.75						
64			9622096	4452.80	4451.85	-0.95						
65			9622097	4452.40	4451.10	-1.30						
66			9622098	4452.40	4450.85	-1.55						
67			9622173	4052.20	4051.40	-0.80						
68			9622172	4063.10	4062.35	-0.75						
69			9622175	4015.95	4015.35	-0.60						
70			9622174	4022.95	4022.35	-0.60						
71			9622171	4070.35	4069.60	-0.75						
72												
73		Wedding	9623051	3339.30	3340.90	1.60						
74			9623062	3336.10	3337.40	1.30						
75			9623078	3352.70	3352.95	0.25						
76			9623079	3269.20	3270.45	1.25						
77			9623081	3321.35	3321.70	0.35						
78			9623080	3325.60	3325.55	-0.05						
79												

80 Cyclone blank average = -0.69, Sx = 0.43
81 Wedding blank average = 0.78, Sx = 0.68
82
83 P8=O8-N8
84 Q8=P8-appropriate blank average
85 S8=Q10*1000/125*G25*0.02832
86 T8=S8-appropriate upwind concentration
87 V11=T11*1E-07*U11*G28*0.44704*60

Run	Dates		Sampler Location	Sampler ID	Sampler Run Time (min)	Avg. Filter Pressure (in. H2O)	Nominal flowrate (ft^3/min)
BM-2	1/15-18/97		Wed/Imp 2m DW	1598	1123	13.50	40.00
BM-3	2/22-23/97	(a	Wed/Imp 2m DW	1598	1303	13.11	40.00
BM-4	02/25/97		Wed/Imp 2m DW	1598	135	13.37	40.00
BM-5	02/27/97		Wed/Imp 2m UW	1600	163	13.22	40.00
		(b	Wed/Imp 2m DW	1598			
BM-6	03/02/97	(c	Wed/Imp 2m UW	1600	147		
		(c	Wed/Imp 2m DW	1598	206		
BM-7	3/15-16/97		Wed/Imp 2m UW	1600	406	13.57	40.00
			Wed/Imp 2m DW	1598	450	13.86	40.00
BM-8	3/16-17/97		Wed/Imp 2m UW	1600	355	14.21	40.00
			Wed/Imp 2m DW	1598	416	14.19	40.00

(a Sampler ran continuously.

(b Motor failed during the run.

(c Sampler operated at a very low flow rate.

J	K	,	M	N	O	P	Q	R
2								
3								
4								Wt. after
5		Sampler	Stage	Filter	Tare Wt.	Final Wt.	Net Wt.	Blank
6	Run	Location	Number	Number	(mg)	(mg)	(mg)	Correction
7								
8	BM-2	Wed/Imp 2m DW	S-1	9628077	967.15	968.05	0.90	0.88
9			S-2	9628076	948.83	950.85	2.02	2.00
10			Backup	9623058	3364.20	3377.90	13.70	13.21
11								
12	BM-3	Wed/Imp 2m DW	S-1	9628079	950.77	951.41	0.64	0.62
13			S-2	9628078	962.12	963.87	1.75	1.73
14			Backup	9623059	3313.35	3324.10	10.75	10.26
15								
16	BM-4	Wed/Imp 2m DW	S-1	9628081	958.36	958.94	0.58	0.56
17			S-2	9628080	961.95	963.53	1.58	1.56
18			Backup	9623060	3354.30	3361.85	7.55	7.06
19								
20	BM-5	Wed/Imp 2m UW	S-1	9628085	959.70	960.15	0.45	0.43
21			S-2	9628084	956.15	959.66	3.51	3.49
22			Backup	9623062	3356.95	3364.20	7.25	6.76
23								
24	BM-7	Wed/Imp 2m UW	S-1	9628097	954.58	954.29	-0.29	-0.31
25			S-2	9628096	945.92	946.74	0.82	0.80
26			Backup	9623073	3326.75	3335.00	8.25	7.76
27								
28		Wed/Imp 2m DW	S-1	9628090	955.83	958.62	2.79	2.77
29			S-2	9628091	947.99	948.06	0.07	0.05
30			Backup	9623068	3348.60	3360.25	11.65	11.16
31								
32	BM-8	Wed/Imp 2m UW	S-1	9628101	949.10	949.81	0.71	0.69
33			S-2	9628100	936.55	938.08	1.53	1.51
34			Backup	9623077	3356.70	3360.65	3.95	3.46
35								
36		Wed/Imp 2m DW	S-1	9628099	937.03	938.98	1.95	1.93
37			S-2	9628098	943.96	946.27	2.31	2.29
38			Backup	9623076	3338.20	3345.55	7.35	6.86
39								
40								
41	FIELD BLANKS							
42								
43		Wed/Imp	S-1	9628071	973.34	973.40	0.06	
44			S-2	9628070	960.59	960.32	-0.27	
45			Backup	9623053	3372.00	3372.80	0.80	
46								
47			S-1	9628073	960.58	960.60	0.02	
48			S-2	9628072	968.24	968.02	-0.22	
49			Backup	9623054	3348.60	3349.85	1.25	
50								
51			S-1	9628102	951.29	951.27	-0.02	
52			S-2	9628103	941.87	941.84	-0.03	
53			Backup	9623082	3310.20	3310.35	0.15	
54								
55			S-1	9628105	945.55	946.02	0.47	
56			S-2	9628104	939.99	940.11	0.12	
57			Backup	9623083	3286.90	3286.65	-0.25	
58								

59 Wed/Imp 4 x 5 blank average = 0.02, Sx = 0.23

60 Wed/Imp backup blank average = 0.49, Sx = 0.67

61

62 Q8=P8-O8

63 R8=Q8-0.02 for 4 X 5, =S8-0.49 for backup

Run	Sampler Location	Particulate Concentration (ug/m^3) less than stated size	
		3.0 um	10 um
BM-2	Wed/Imp 2m DW	10	13
BM-3	Wed/Imp 2m DW	7.0	8.5
BM-4	Wed/Imp 2m DW	46	60
BM-5	Wed/Imp 2m UW	37	58
BM-7	Wed/Imp 2m UW	17	<19
	Wed/Imp 2m DW	22	<28
BM-8	Wed/Imp 2m UW	8.6	14
	Wed/Imp 2m DW	15	24

Bold values indicate where blank corrected net filter weights are at least 3 times the standard deviation of the blank correction.

Values preceded by a < indicate instances where at least one blank corrected net filter weight is less than 1 standard deviation of the blank correction. The standard deviation of the blank correction is used in place of the net filter weight to calculate the concentration.

B	C	D	E	F	G
Run	Dates	Sampler Location	Sampler ID	Sampler Run Time (min)	Flowrate (liter/min)
BM-2	01/15-16/97	Minivol/T PM2.5 2mUW	624	1281	5
		Minivol/T PM10 2mUW	623	1280	5
		Minivol/T PM2.5 2mDW	620	1189	5
		Minivol/T PM10 2mDW	621	1198	5
BM-3	02/22-23/97	Minivol/T PM10 2mUW	623	1327	5
		Minivol/T PM10 2mDW	621	1293	5
BM-4	02/25/97	Minivol/T PM10 2mUW	622	758	5
		Minivol/T PM2.5 2mDW	623	711	5
		Minivol/T PM10 2mDW	624	782	5
BM-5	02/27/97	Minivol/T PM10 2mUW	622	768	5
		Minivol/T PM2.5 2mDW	623	767	5
		Minivol/T PM10 2mDW	624	768	5
BM-6	03/02/97	Minivol/T PM2.5 2mUW	625	682	5
		Minivol/T PM10 2mUW	622	752	5
		Minivol/T PM2.5 2mDW	623	759	5
		Minivol/T PM10 2mDW	624	153	5
BM-7	03/15-16/97	Minivol/T PM2.5 2mUW	623	1333	5
		Minivol/T PM10 2mUW	625	1337	5
		Minivol/T PM2.5 2mDW	621	1339	5
		Minivol/T PM10 2mDW	622	1331	5
BM-8	03/16-17/97	Minivol/T PM2.5 2mUW	623	1372	5
		Minivol/T PM10 2mUW	625	1370	5
		Minivol/T PM2.5 2mDW	622	1378	5
		Minivol/T PM10 2mDW	621	1378	5

H	I	J	K	L	M	N	O	P	Q	R
2										
3							Wt. after			
4							Blank		PM2.5	PM10
5		Sampler	Filter	Tare Wt.	Final Wt.	Net Wt.	Correction		Concentration	Concentration
6	Run	Location	Number	(mg)	(mg)	(mg)	(mg)		(ug/m^3)	(ug/m^3)
7										
8	BM-2	Minivol/T PM2.5 2mUW	9625005	152.40	152.60	0.20	0.18		28	
9		Minivol/T PM10 2mUW	9625006	156.18	156.33	0.15	0.13			20
10										
11		Minivol/T PM2.5 2mDW	9625007	161.67	161.91	0.24	0.22		37	
12		Minivol/T PM10 2mDW	9625008	156.77	157.03	0.26	0.24			40
13										
14	BM-3	Minivol/T PM10 2mUW	9625010	150.56	150.75	0.19	0.17			26
15										
16		Minivol/T PM10 2mDW	9625012	155.55	155.72	0.17	0.15			23
17										
18	BM-4	Minivol/T PM10 2mUW	9625015	152.28	152.51	0.23	0.21			55
19										
20		Minivol/T PM2.5 2mDW	9625011	157.47	158.71	1.24	1.22		343	
21		Minivol/T PM10 2mDW	9625013	156.63	156.74	0.11	0.09			23
22										
23	BM-5	Minivol/T PM10 2mUW	9625016	152.03	152.43	0.40	0.38			99
24										
25		Minivol/T PM2.5 2mDW	9625009	149.76	152.80	3.04	3.02		787	
26		Minivol/T PM10 2mDW	9625014	152.60	151.34	-1.26	-1.28			0
27										
28	BM-6	Minivol/T PM2.5 2mUW	9625020	148.11	148.15	0.04	0.02		5.9	
29		Minivol/T PM10 2mUW	9625017	153.77	153.84	0.07	0.05			13
30										
31		Minivol/T PM2.5 2mDW	9625019	149.42	149.46	0.04	0.02		5.3	
32		Minivol/T PM10 2mDW	9625018	158.30	158.47	0.17	0.15			196
33										
34	BM-7	Minivol/T PM2.5 2mUW	9625024	150.27	150.38	0.11	0.09		14	
35		Minivol/T PM10 2mUW	9625022	156.43	156.62	0.19	0.17			25
36										
37		Minivol/T PM2.5 2mDW	9625025	149.88	149.93	0.05	0.03		4.5	
38		Minivol/T PM10 2mDW	9625021	159.89	160.12	0.23	0.21			32
39										
40	BM-8	Minivol/T PM2.5 2mUW	9625027	190.57	190.67	0.10	0.08		12	
41		Minivol/T PM10 2mUW	9625023	153.29	153.48	0.19	0.17			25
42										
43		Minivol/T PM2.5 2mDW	9625028	189.01	189.09	0.08	0.06		8.7	
44		Minivol/T PM10 2mDW	9625026	192.14	192.64	0.50	0.48			70
45										
46										
47	<u>FIELD BLANKS</u>									
48										
49		Teflon	9625001	170.23	170.27	0.04			Bold values indicate where blank corrected	
50		Teflon	9625002	170.01	170.03	0.02			net filter weights are at least 3 times the	
51		Teflon	9625003	160.93	160.93	0.00			standard deviation of the blank correction.	
52		Teflon	9625004	149.95	149.96	0.01				
53		Teflon	9625032	149.83	149.86	0.03				
54		Teflon	9625029	185.54	185.55	0.01				
55		Teflon	9625031	149.27	149.25	-0.02				
56		Teflon	9625030	177.34	177.37	0.03				
57										
58	Teflon blank average = 0.02, Sx =0.019									
59										
60										
61	N8=M8-L8									
62	O8=N8-0.02									
63	Q8=O8*1000/(5*0.001*F8)									
64	R9=O9*1000/(5*0.001*F9)									

Illustrated below is an example of use of the PM-10 standard deviation of the blank correction in place of the net filter weight to calculate the particulate concentration. This occurs whenever at least one blank-corrected net weight is less than 1 standard deviation of the blank correction. The same is true when ever the blank-corrected net weight is negative.

This example is based on the determination of PM-10 concentration from the downwind MiniVOL sampler (Teflon filter) with a 2 m sampling height.

Normally the PM-10 concentration would be calculated as follows:

PM-10 Concentration = Blank corrected net weight/(flowrate)(sampling time)

$$= \{(-1.28\ \text{mg})(1000\ \mu\text{g}/1\ \text{mg})\}/\{5\ \text{L}/1\ \text{min})(0.001\ \text{m}^3/1\text{L})\ (768\ \text{min})\}$$

$$= -333.3\ \mu\text{g/m}^3$$

Now, using the SD of the blank filters (=0.019 mg):

PM-10 Concentration $= \{(0.019\ \text{mg})(1000\ \mu\text{g}/1\ \text{mg})\}/\{5\text{L}/1\ \text{min})(0.001\ \text{m}^3/1\text{L})(768\ \text{min})\}$

$$= 4.9\ \mu\text{g/m}^3$$

Thus, the PM-10 concentration is assigned a value of < 4.9 μg/m^3 in Table 23 of the report.

Appendix C

Example Exposure Profiling Calculation

This appendix presents an example calculation to convert exposure profiling data to a PM-10 emission factor. The calculation is given for Run BL-7, which was one of the correlation study test runs selected for chemical/morphological analysis of collected samples.

Calculation of PM10 emission factors begins with determination of net (i.e., downwind minus upwind) concentrations. Run BL-7 serves as an example. From Table 18, the following concentration data are found

Height (m)	Downwind PM10 Concentration (µg/m^3)	Upwind PM10 Concentration (µg/m^3)
2	109	43
3	79	
5	66	37
7		30
7.5	59	
10	42	

The average upwind concentration -- 37 (µg/m^3) -- is subtracted from the downwind values to obtain the following

Height (m)	Net Downwind PM10 Concentration (µg/m^3)
2	72
3	42
5	29
7.5	22
10	5

Next, the net exposure is found in the manner described in Equation 9:

$$E_{10} = 10^{-7} x\, C\, U t$$

where E_{10} = PM10 exposure (mg/cm^2)
C = net concentration (µg/m^3)
U = approaching wind speed (m/s)
t = duration of sampling (s)

For Run BL-7, the following values of exposure are found:

Height (m)	Net Downwind PM10 Concentration (µg/m^3)	Wind Speed[a]		Duration[b] (s)	PM10 Exposure (m-mg/cm^2)
2	72	1.1	0.49	14,900	0.0526
3	42	1.5	0.67	"	0.0419
5	29	2.0	0.89	"	0.0386
7.5	22	2.4	1.1	"	0.0351
10	5	2.7	1.2	"	0.00898

[a] Values taken from Table 17. First value in mph, second in m/s. 1 mph = 0.447 m/s.
b Test duration of 248 minutes taken from Table 16.

The integrated exposure is found by integrating the exposure over the effective height of the plume. As noted in connection with Equation 10,

- The plume height is found by extrapolating the net concentrations at the uppermost samplers to a value of zero. For Run BL-7, linear extrapolation of 22 ug/m^3 (at the 7.5-m height) and 5 ug/m^3 (at the 10-m height) leads to a value of 0 ug/m^3 at a height of 10.7 m.

- The exposure at ground level is set equal to the exposure at a height of 1 m. For Run BL-7, linear extrapolation of 0.0419 m-mg/cm^2 (at the 3-m height) and 0.0527 m-mg/cm^2 (at the 2-m height) leads to a 1-m exposure value of 0.0635 m-mg/cm^2.

The integration is accomplished by adding together the areas shown in Figure C-1:

No.	Area (m-mg/cm^2)
1	0.0031
2	0.0551
3	0.0921
4	0.0805
5	0.0473
6	0.0581
7	0.0635
	Sum = 0.3997

The emission factor is found by dividing the integrated exposure (0.3997 m-mg/cm^2) by the number of vehicle passes. For run BL-7, a total of 12,299 vehicle passes is found from Table 17. Thus, the emission factor for BL-7 is found from Equation 11 by

$$\begin{aligned} e &= 10^4\, 0.3997\ /\ (12{,}299) \\ &= 0.325\ \text{g/VKT} \end{aligned}$$

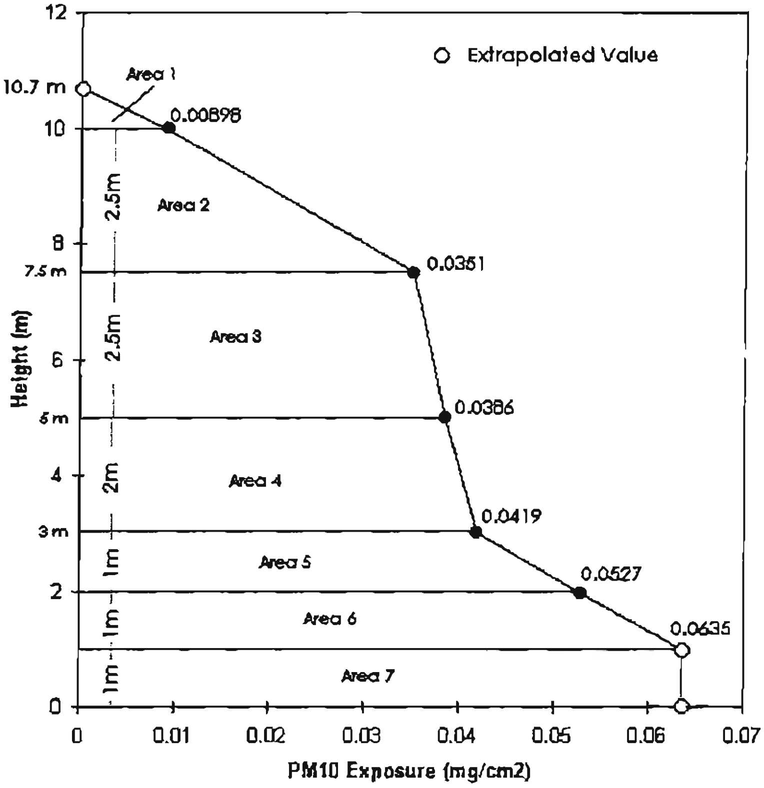

Figure C-1. Exposure Profile for Run BL-7

Appendix D

Field and Laboratory Data for Silt Loading Determinations

Field and Laboratory Data for Silt Loading Determinations

Date	Location	Vacuum Bag I.D. #	Sample Area (m^2)	# of Splits	Bag Tare Weight (grams)	Bag Loaded Weight (grams)	Bag Empty Weight (grams)	Weight on Pan (grams)
03/09/97	aspen	822	24	0	59.5	712.5	68.6	79.3
03/09/97	aspen	840	46.5	0	60.6	213.6	65.6	20.4
03/09/97	aspen	845	33.4	1	60.6	1466.3	72.4	93.1
03/09/97	aspen	846	28.4	1	60.9	859.3	72.4	47.7
03/09/97	aspen	849	46.5	0	61.7	232.1	68.1	20.9
03/19/97	aspen	847	28.6	1	60.6	1417.5	69.2	41.0
03/20/97	aspen	304	5.1	0	61.0	770.3	69.0	60.4
03/20/97	aspen	306	14	0	59.3	402.2	68.4	52.2
03/20/97	aspen	830	8.2	0	60.7	683.2	67.4	99.6
03/20/97	aspen	837	62.6	0	59.8	473.4	67.9	42.5
3/19-20/97	aspen	111-6	57.7	0	58.1	169.7	65.2	22.2
N/A	aspen	300	15	0	59.9	219.0	66.1	37.8
N/A	aspen	838	5.4	0	59.7	637.5	67.6	97.1
11/15/96	jewell	709	221.6	0	60.6	87.2	65.1	2.6
11/15/96	jewell	712	221.6	0	59.2	159.0	65.9	14.3
12/21/96	jewell	826	51.1	1	59.7	1265.6	66.4	28.0
12/21/96	jewell	833	50.2	1	60.6	1325.2	67.5	90.2
12/21/96	jewell	834	50.2	2	60.4	1604.7	68.6	75.2
12/21/96	jewell	835	51.1	0	61.2	92.5	64.9	10.9
12/22/96	jewell	829	208.1	1	61.0	821.0	66.8	20.7
12/23/96	jewell	804	159.8	1	60.3	1271.3	69.2	47.8
12/23/96	jewell	836	234.1	1	60.4	1485.1	70.7	80.4
12/24/96	jewell	800	204.4	1	60.6	1776.0	71.0	60.2
12/24/97	jewell	805	151.9	1	59.8	1242.2	70.7	61.8
10/23/96	kipling	721	1226.3	0	61.3	211.0	67.5	24.1
10/24/96	kipling	722	740.9	0	60.6	115.5	64.5	10.5
11/02/96	kipling	719	49.1	3	61.8	924.6	68.6	7.4
11/04/96	kipling	720	80.1	3	61.2	5295.8	72.1	9.9
11/05/96	kipling	714	153.3	0	62.1	98.4	64.8	5.2
11/06/96	kipling	715	272.9	0	62.0	146.5	65.6	8.9
02/22/97	kipling	824	79.4	0	59.7	205.2	66.1	27.0
02/22/97	kipling	824	79.4	0	60.4	500.7	64.1	19.7
02/25/97	kipling	815	83.6	0	60.5	168.3	62.4	15.4
02/25/97	kipling	816	83.6	0	60.8	248.4	62.4	22.2
02/25/97	kipling	821	79.4	0	59.8	307.5	63.4	15.3
02/27/97	kipling	817	169.3	0	60.6	828.5	65.2	41.3
03/02/97	kipling	820	95.7	1	59.9	2381.2	64.7	31.0
03/03/97	kipling	818	86.4	1	60.0	2132.8	66.8	28.4
03/15/97	kipling	823	90.6	0	59.6	256.3	65.2	6.5
03/15/97	kipling	848	92	0	60.4	812.9	68.3	17.6
11/14/96	speer	695	191.6	0	60.9	295.9	66.7	8.0
11/14/96	speer	706	223	0	62.4	228.1	68.7	60.0
11/14/96	speer	708	223	0	60.3	434.8	68.5	120.1
11/14/96	speer	713	239.2	0	61.2	101.1	64.7	5.3
12/20/96	speer	710	73.2	0	60.8	126.7	65.0	6.4
12/20/96	speer	711	73.2	0	60.0	348.2	67.2	16.4
12/20/96	speer	806	59.2	0	59.5	273.5	66.2	39.9
12/20/96	speer	807	59.2	1	60.0	1129.4	70.0	39.6
12/21/96	speer	801	82.7	2	60.0	1651.6	71.0	65.8
12/21/96	speer	802	82.7	0	60.0	466.9	67.3	69.4
12/21/96	speer	832	79	0	60.3	599.2	65.8	28.8
12/22/96	speer	803	179.8	0	60.3	490.0	68.4	91.0
12/24/96	speer	839	124.8	0	59.3	777.9	66.2	39.1

Field and Laboratory Data for Silt Loading Determinations (continued)

Date	Location	Vacuum Bag I.D. #	Total Sample Recovered (grams)	Unrecovered Silt (grams)	Silt Content (%)	Total Loading (grams/m^2)	Upper Bound Silt Loading (grams/m^2)
03/09/97	aspen	822	642.7	9.1	13.6	27.2	3.69
03/09/97	aspen	840	147.7	5.0	16.6	3.3	0.55
03/09/97	aspen	845	647.8	11.8	15.1	42.1	6.35
03/09/97	aspen	846	390.2	11.5	13.5	28.1	3.79
03/09/97	aspen	849	163.3	6.4	16.1	3.7	0.59
03/19/97	aspen	847	684.1	8.6	6.6	47.4	3.13
03/20/97	aspen	304	700.4	8.0	9.7	139.1	13.43
03/20/97	aspen	306	332.5	9.1	17.9	24.5	4.39
03/20/97	aspen	830	613.5	6.7	17.1	75.9	13.01
03/20/97	aspen	837	404.0	8.1	12.3	6.6	0.81
3/19-20/97	aspen	111-6	102.8	7.1	26.6	1.9	0.51
N/A	aspen	300	151.0	6.2	28.0	10.6	2.97
N/A	aspen	838	568.1	7.9	18.2	107.0	19.50
11/15/96	jewell	709	22.0	4.5	26.7	0.1	0.03
11/15/96	jewell	712	92.5	6.7	21.1	0.5	0.10
12/21/96	jewell	826	508.6	6.7	6.0	23.6	1.42
12/21/96	jewell	833	620.8	6.9	15.0	25.2	3.78
12/21/96	jewell	834	355.7	8.2	21.6	30.8	6.63
12/21/96	jewell	835	26.6	3.7	48.0	0.6	0.29
12/22/96	jewell	829	332.4	5.8	6.9	3.7	0.25
12/23/96	jewell	804	571.0	8.9	9.0	7.6	0.69
12/23/96	jewell	836	599.6	10.3	14.0	6.1	0.85
12/24/96	jewell	800	912.0	10.4	7.2	8.4	0.60
12/24/97	jewell	805	555.4	10.9	11.9	7.8	0.93
10/23/96	kipling	721	143.4	6.2	20.3	0.1	0.02
10/24/96	kipling	722	50.1	3.9	26.6	0.1	0.02
11/02/96	kipling	719	526.5	6.8	2.2	17.6	0.38
11/04/96	kipling	720	734.8	10.9	1.6	65.4	1.01
11/05/96	kipling	714	33.4	2.7	21.8	0.2	0.05
11/06/96	kipling	715	80.7	3.6	14.8	0.3	0.05
02/22/97	kipling	824	139.0	6.4	23.0	1.8	0.42
02/22/97	kipling	824	435.3	3.7	5.3	5.5	0.30
02/25/97	kipling	815	104.4	1.9	16.3	1.3	0.21
02/25/97	kipling	816	184.5	1.6	12.8	2.2	0.29
02/25/97	kipling	821	247.5	3.6	7.5	3.1	0.24
02/27/97	kipling	817	760.8	4.6	6.0	4.5	0.27
03/02/97	kipling	820	1261.1	4.8	2.7	24.3	0.65
03/03/97	kipling	818	1078.8	6.8	3.0	24.0	0.71
03/15/97	kipling	823	190.5	5.6	6.2	2.2	0.13
03/15/97	kipling	848	743.8	7.9	3.4	8.2	0.28
11/14/96	speer	695	229.0	5.8	5.9	1.2	0.07
11/14/96	speer	706	159.5	6.3	40.0	0.7	0.30
11/14/96	speer	708	365.1	8.2	34.4	1.7	0.58
11/14/96	speer	713	36.2	3.5	22.1	0.2	0.04
12/20/96	speer	710	61.7	4.2	16.1	0.9	0.14
12/20/96	speer	711	281.0	7.2	8.2	3.9	0.32
12/20/96	speer	806	206.0	6.7	21.9	3.6	0.79
12/20/96	speer	807	610.1	10.0	7.4	18.1	1.33
12/21/96	speer	801	404.7	11.0	16.8	19.2	3.24
12/21/96	speer	802	399.1	7.3	18.9	4.9	0.93
12/21/96	speer	832	532.6	5.5	6.4	6.8	0.43
12/22/96	speer	803	419.5	8.1	23.2	2.4	0.55
12/24/96	speer	839	710.8	6.9	6.4	5.8	0.37