Assessment of Highway Particulate Impacts: Phase I, Tasks B and C—Field Sampling and Evaluation Program, Final Report

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16. Abstract

This report is the second of two reports developed as part of Phase I of the above-referenced contract. The first report is Report No. FHWA-RD-99-180, Assessment of Highway Particulate Impacts: Phase I, Task A— Problem Evaluation, Final Report. Four highway particulate emission sources were identified as requiring additional understanding: (1) emissions from diesel-powered vehicles; (2) emissions from road sanding and salting operations; (3) resuspension of dust from paved roadways; and (4) emissions from unpaved roadways. This document outlines the sampling and analysis plan for increasing the knowledge and understanding related to particulate emissions from three of these sources. Emissions from unpaved roadways were not targeted for sampling and analysis. This document describes the criteria used to select the field sampling sites, as well as the types of analyses that were performed at those sites. In addition, this document describes the results from the field work component of this study. Chemical mass balance analyses of highway particulate sources were conducted for paved road resuspension at Phoenix, AZ and Spokane, WA. Chemical mass balance analyses were also conducted at two sites to determine the contributions of road sanding and salting operations to ambient levels at Albany, NY and at Reno, NV. Finally a set of experiments designed to assess diesel emissions were performed in the Ft. McHenry Tunnel (outside of Baltimore, MD) and in mid-town Manhattan. The Ft. McHenry Tunnel experiment produced emission factor estimates for heavy-duty diesel emission sources. Chemical mass balance analyses were performed in mid-town Manhattan to assess the contribution to ambient levels resulting from urban bus traffic. Results from the field work phase showed that paved road resuspension and road sanding and salting operations contribute significantly to the ambient levels, in the absence of other sources, contributing, in some cases, up to 60 percent of the total mass collected on the filters. In mid-town Manhattan, diesel emissions also contribute significantly to ambient levels; however, the emission factor results from the Ft. McHenry Tunnel indicated that emissions from heavy-duty diesels were lower than published emission factors by approximately 50 percent. It is important to note that despite these significant contributions to ambient levels, not once was the 24-h ambient air quality standard exceeded.

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FOREWORD

The highway system and its traffic have been found to be a source of particulate matter suspended in air, which can contaminate ambient air.

The national ambient air quality standard for the size of particulate matter when this investigation was underway was $\leq 10\ \mu m$ (PM10) (24-h average of 150 $\mu g/m^3$; annual average of 50 $\mu g/m^3$). This standard replaced a standard for total suspended particulate matter. Since 1997, there has been a new standard for ambient air quality for the size of particulate matter of $\leq 2.5\ \mu m$ (24-h average of 65 $\mu g/m^3$; annual average of 15 $\mu g/m^3$).

Phase I reports are *An Evaluation of the Highway Particulate Impacts* and *Field Sampling and Evaluation Program*. Phase II of the study evaluated procedures for assessing PM10 "emission" and dispersion rates from highways, mitigation measures, and perspectives.

Related studies have been done over many years. Three pertinent efforts recently started under the National Cooperative Highway Research Program (NCHRP) are:

- 25-14, Heavy-Duty Vehicle Emissions.
- 25-17, Transportation Effects of the 1997 Changes to the National Ambient Air Quality Standards.
- 25-18, Particulate Matter (PM2.5 and PM10) Apportionment for On-Road Mobile Sources.

These NCHRP investigations will build on and supplement this FHWA study. Reports are expected in approximately 3 years. The two FHWA Phase I reports, which are being submitted to the National Technical Information Service (NTIS), will be of interest to State and local government personnel, and academic and consulting specialists concerned with the effect of mobile sources on ambient air quality.

T. Paul Teng, P.E.
Director
Office of Infrastructure
Research and Development

NOTICE

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

(Revised September 1993)

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* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	automated colorimetry
ADT	average daily traffic
ADTV	average daily traffic volume
Al	aluminum
APCC	Arizona Portland Cement Company
ADEQ	Arizona Department of Environmental Quality
Ba	barium
Br	bromine
CAA	Clean Air Act
CAAA	Clean Air Act Amendments of 1990
Ca	calcium
CARB	California Air Resources Board
CEB	chemical element balance
CEQA	California Environmental Quality Act
CH_4	methane
Cl	chlorine
CMB	chemical mass balance
CO	carbon monoxide
CO_2	carbon dioxide
CRC	Coordinating Research Council
CSMCS	Carbonaceous Species Methods Comparison Study
Cu	copper
CVSA	Coachella Valley Study Area
DOT	Department of Transportation
DRI	Desert Research Institute
EC	elemental carbon
EEM	Energy & Environmental Management, Inc.
EF	emission factor
EGR	exhaust gas recirculation
EPA	U.S. Environmental Protection Agency
ERT	Environmental Research and Technology
EV	effective variance
FDM	fugitive dust model
Fe	iron
FHWA	Federal Highway Administration
FRG	Federal reformulated gasoline
FTA	Federal Transit Authority
ft^3	cubic feet
ft^3/min	cubic feet per minute
g/mi/s	grams per mile per second
g/bhp/h	grams per brake horsepower-hour
g/mi	grams per mile
g/veh-mi	grams per vehicle mile
GMR	General Motors Research Laboratory
GVWR	Gross Vehicle Weight Rating
HC	hydrocarbon
HCHO	formaldehyde
HDE	heavy-duty engine

HDSI	heavy-duty spark ignition vehicle
HDV	heavy-duty vehicle
IC	Ion Chromatography
I/M	inspection and maintenance
IMPROVE	Interagency Monitoring of Protected Visual Environments
ISCST	industrial source complex model short-term
ISWS	Illinois State Water Survey
K	potassium
km	kilometer
LDSI	light-duty spark ignition vehicle
LDT	light-duty truck
LDV	light-duty vehicle
LEV	low-emission vehicle
LIPM	Laser Integrating Plate Method
L/min	liters per minute
μm	micrometer
$\mu g/m^3$	micrograms per cubic meter
mg/km	milligrams per kilometer
mi/h	miles per hour
Mg	magnesium
MLR	multiple linear regression
Mo	molybdenum
MPO	Metropolitan Planning Organization
MRI	Midwest Research Institute
NAAQS	National Ambient Air Quality Standard
NAPAP	National Acid Precipitation Assessment Program
NEPA	National Environmental Policy Act
NH_3	ammonia
NLEV	National low-emission vehicle
NMHC	nonmethane hydrocarbon
NMOG	nonmethane organic gases
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
OBD	on-board diagnostic
OC	organic carbon
ODEQ	Oregon Department of Environmental Quality
OGC	Oregon Graduate Center
OTR	Ozone Transport Region
PACS	Portland Aerosol Characterization Study
PAG	Pima Association of Governments
Pb	lead
PCA	principal component analysis
PESA	Proton Elastic Scattering Analysis
PIXE	Proton Induced X-ray Emission
PLS	partial least squares
PM	particulate matter
PM-10	particles with an aerodynamic diameter less than or equal to a nominal 10 micrometers
PM-2.5	particles with an aerodynamic diameter less than or equal to a nominal 2.5 micrometers

RESOLVE	Research on Operations Limiting Visual Extinction
RFP	reasonable further progress
RH	relative humidity
RP	respirable particulates
S	sulfur
SBC	Santa Barbara County
SBR	styrene-butadiene rubber
SCAQMD	South Coast Air Quality Management District
SCAQS	Southern California Air Quality Study
SCENIC	Study Cooperative for Emissions and Impact Characterization
SEDAB	Southeast Desert Air Basin
SFS	sequential filter sampler
SJV	San Joaquin Valley
SI	silicon
SIP	State Implementation Plan
Sn	tin
SO_2	sulfur dioxide
SOA	secondary organic aerosols
SVD	singular value decomposition
SVPA	Searles Valley Planning Area
TCMs	Transportation Control Measures
Ti	titanium
TIP	Transportation Improvement Program
TIUS	Truck Inventory and Use Survey
TLEV	transitional low-emission vehicle
TOR	thermal optical reflectance
TSP	total suspended particulate
ULEV	ultra-low emission vehicle
U.S.	United States
USS	United States Steel Corporation
VAQS	Valley Air Quality Study
VIEW	Visibility Investigative Experiment in the West
VMT	vehicle miles traveled
VOC	volatile organic compounds
WFPN	Western Fine Particle Network
XRF	X-ray fluorescence
ZEV	zero-emission vehicle
Zn	zinc

SUMMARY DATA

	Duration	Ambient Value ($\mu g/m^3$)
Current and Proposed Standards		
Current PM-10 Short-term Standard	24 hours	150
Current PM-10 Long-term Standard	Annual	50
Proposed PM-2.5 Short-term Standard	24 hours	65
Proposed PM-2.5 Long-term Standard	Annual	15
Results from the Field Work by Site		
Manhattan, NY	4 hours	35.82 - 82.96
Fort McHenry Tunnel, MD	1 hour	14.2 - 374.0
Albany, NY	6 hours	6.3 - 132.27
Denver, CO	6 hours	3.23 - 82.05
Reno, NV	6 hours	36.84 - 144.37
Phoenix, AZ	6 hours	10.14 - 32.65
Spokane, WA	6 hours	27.02 - 54.91

SUMMARY INFORMATION FROM THE MOUDI SAMPLER RUNS

	Concentration on Sampler Stage Number ($\mu g/m^3$)								
Site/Run	1	2	3	4	5	6	7	8	Total
Phoenix/1	4.6	4.0	4.1	2.5	5.9	7.8	5.0	2.8	36.7
Phoenix/2	4.5	5.0	2.1	1.2	3.8	5.2	5.3	4.4	31.5
Phoenix/3	6.2	1.0	3.0	1.7	4.4	6.8	8.7	2.9	34.7
Phoenix/5	1.5	1.8	1.4	0.8	0.3	4.7	3.8	2.8	17.1
Reno/7	0.7	1.2	3.0	0.9	2.7	5.8	2.1	5.7	22.1
Reno/8	0.0	0.1	0.2	1.9	0.0	0.1	1.2	1.4	4.9

The MOUDI Sampler Stages have the following particle size cutpoints: Stage 1 = 3.16 µm; Stage 2 = 1.78 µm; Stage 3 = 1.00 µm; Stage 4 = 0.54 µm; Stage 5 = 0.37 µm; Stage 6 = 0.15 µm; Stage 7 = 0.11 µm; Stage 8 = 0.05 µm

CHAPTER 1: INTRODUCTION

BACKGROUND

Based on the report Assessment of Highway Particulate Impacts: Problem Evaluation Working Paper (prepared for Phase I, Task A of Federal Highway Administration [FHWA] Contract No. DTFH61-91-C-00005), four sources of particulate emissions from highway sources were identified as emission sources requiring additional knowledge or understanding. These sources were:

1. Emissions from diesel powered vehicles.
2. Emissions from road sanding and salting operations.
3. Resuspension of dust from paved roadways.
4. Emissions from unpaved roadways.

This report details the selection criteria used to select sites and the results obtained for the field sampling and evaluation program designed to increase the knowledge and understanding relative to particulate emissions from three of these sources. Emissions from unpaved roadways were not targeted for sampling and analysis, since one of the provisions of the scope of work for this contract was that efforts to increase the understanding of the nature of particulate emissions from highway sources should concentrate on emissions from paved roadways. As a consequence, unpaved road particulate emissions were not to be sampled as part of the work performed in the sampling and analysis phase of this contract.

The National Ambient Air Quality Standards (NAAQS) for particles at the time field sampling was performed was for particles with an aerodynamic diameter less than or equal to a nominal 10 micrometers (PM-10). There are two forms of the standard: 150 micrograms per cubic meter ($\mu g/m^3$) for a 24-hour average and 50 $\mu g/m^3$ for an annual geometric mean. The particulate standard prior to adoption of the PM-10 standard was based upon the total suspended particulates (TSP). Changing the standard to one for PM-10 directly targeted inhalable particulate matter (i.e., particles likely to be inhaled into the human lung). On July 16, 1997, the U.S. Environmental Protection Agency (EPA) proposed new standards for particulate matter wwith an aerodynamic diameter less than or equal to a nominal 2.5 micrometers (PM-2.5).

Recent studies have demonstrated the importance of the mobile source contribution and have shown that a major contributor to ambient PM-10 levels is primary mobile source emissions (Chow et al., 1991a, 1991b, Gertler et al., 1994, Watson et al., 1988). The individual contributions depend greatly upon the time of year and the local meteorological conditions. Mobile source contributions as high as 50 percent of the observed PM-10 level have been seen in Phoenix in the winter of 1989-90 (Chow et al., 1991a), while a year round average of 17 percent was observed in Bullhead City, AZ during 1988-89 (Gertler et al., 1994). The magnitude of the various contributions from this source requires an improvement in our understanding of the impact of mobile sources on ambient PM-10 levels.

One of the mechanisms for mobile source production of PM-10 is direct tailpipe particulate emissions. The most complete review of previous studies performed to calculate the particulate emission factors of both automobiles and diesel trucks was reported by Pierson and Brachaczek (1983). This paper included the compilation of data for the Allegheny and Tuscarora Mountain Tunnels on the Pennsylvania Turnpike between 1975 and 1981. Pierson and Brachaczek (1983) reported a particulate emission factor for gasoline powered vehicles (latest model year, 1981) of 0.040 ± 0.035 grams per vehicle mile (g/veh-mi) whereas the average result for diesel trucks from studies performed from 1975 to 1981 was 1.40 ± 0.16 g/veh-mi. Since this study, automobile emissions have changed greatly due to the increased use of catalysts, the phase-out of leaded fuel, and the increased use of computers in regulating automobile operating conditions. Diesel technology has changed only slightly, mainly in the areas of combustion efficiency and the use of cleaner fuel.

Recent studies have also demonstrated the importance of resuspended road dust to ambient PM-10 concentrations. Chow et al. (1991b) demonstrated that as much as 60 percent of the PM-10 in Phoenix during the winter of 1989-90 was resuspended road dust. Similar observations in Tucson (Chow et al., 1991b) during the winter of 1989 to 1990 showed levels as high as 50 percent resulting from the resuspension of road dust. Using the Chemical Element Balance (CEB) Model, this is the same as the Chemical Mass Balance (CMB) Model used for analysis in this report), Scheff et al. (1984) showed that over 44 percent of the observed TSP in Chicago, Illinois, was attributed to soils, of which a great portion is resuspended road dust. During winter months, resuspended road sand and salt may also contribute significantly to resuspended PM-10 from roads.

The goal of this report is to provide a greater understanding of the impact of mobile sources on ambient PM-10. The three major mechanisms discussed in this report are tailpipe emissions from diesel vehicles, resuspended road sand and salt material, and resuspended road dust. Other possible mechanisms can include particulate emissions from tire wear and brake wear, but these sources are not addressed in this report.

Emissions from Diesel Powered Vehicles

Work completed in 1992 by E.H. Pechan and Associates, Inc. for the EPA had concluded that particulate emissions less than 10 microns (i.e., PM-10) from diesel powered vehicles (especially urban buses and heavy duty diesel vehicles) predicted using current emission factors may significantly under-predict emissions (Pechan, 1992). These findings, coupled with the information presented relative to diesel powered vehicles in the problem evaluation paper prepared in Phase I, Task A, resulted in our selection of emissions from diesel powered vehicles as a source requiring additional sampling and analysis. Sampling of diesel particulates was carried out using "tunnel study" methods. These methods, when the appropriate site is selected, allow the analyst to selectively sample a captive air stream containing emissions predominantly from this source. Details on the methodology and the site selected for this source are given below.

Emissions from Road Sanding and Salting Operations

In the problem evaluation paper prepared for this contract in Phase I, Task A, several nonattainment areas identified road sanding and salting operations during winter months for snow and ice removal as either one of, or the major highway particulate source.

Although in the strictest sense this source could be considered as a paved road resuspension problem, the nature of the materials used on the road allow it to be effectively sampled and analyzed using chemical mass balance (CMB) methods. Details of the methodology are given below.

Resuspension of Dust from Paved Roadways

Resuspended dust from paved roadways has been identified in both local and national level emission inventories as a major contributor to highway particulate emissions. Several of the emission inventories examined in the problem evaluation paper prepared during Phase I, Task A of this contract identified resuspended road dust (either from paved or unpaved roads) as a major component of the PM-10 emission inventories. However, the emission factors used to develop these estimates have a large uncertainty associated with them. As a consequence, this source was selected for further sampling and analysis, in order to try to more effectively determine the contribution attributable to this source. Paved road resuspension was selected in order to be consistent with the contracts orientation towards emissions from paved roadways. The approach for sampling and analysis for this source is detailed below.

GUIDE TO REPORT

Chapter 1 provides the necessary background information with respect to the possible contributions of mobile particulate emissions. It also provides an overview of the criteria used in site selection for the field work, and states the objectives of this study.

Equipment, analytical methodology, and the description of emission factor calculations are described in chapter 2, while the CMB modeling methodology is discussed in detail in chapter 3. Chapter 4 describes the sampling sites and the area surrounding them.

Chapter 5 of this report focuses on the particulate emissions from heavy duty diesel trucks and buses. The data for the truck portion was collected at the Fort McHenry Tunnel in Baltimore Maryland, while the data for bus portion was amassed at a site in Manhattan, New York. On-road particulate emission factors were calculated in the Fort McHenry Tunnel, while the Manhattan data were apportioned using the CMB model.

Chapter 6 of this report focuses on the impact of road sanding and salting material on ambient PM-10 concentrations. Measurements to determine the impact of road salting were taken at a site in Albany, New York during the winter of 1993.

The sanding portion of the study included two parts. The first part, described in chapter 6, was to measure the impact of sanding material, in a typical setting, on ambient PM-10 concentrations. This was done in Denver, Colorado.

Part two of the sanding portion of the study, also detailed in chapter 6, was performed in Reno, Nevada, at a site which received large amounts of snow, and thus large amounts of road sanding material, over a short period of time.

The resuspended road dust portion of this study, described in chapter 7, is primarily directed at determining the impacts of resuspended road dust entrained by the action of motor vehicles on paved roadways. Both CMB apportionment and dispersion modeling were used to assess these impacts. Particle size distribution information for roadway surface material was also determined for Reno, Denver, Phoenix, and Spokane. That evaluation looked at the size distribution of material on paved roadways following sieving to remove particles larger than 100 µm. Finally, ambient fine particle (≤ 3.6 µm) size distributions from motor vehicles were measured in both Phoenix and Reno. The roadway surface material information and the ambient fine particle information are also presented in chapter 7.

Chapter 8 is a brief summary of the results found from analysis of the seven different sites, while chapter 9 puts forth recommendations for future study. References are located in chapter 10.

CRITERIA USED IN SELECTING SAMPLING SITES

Five different criteria were used to choose the sampling sites that were selected for the field sampling. These criteria were:

1) The attainment status of the sampling area;
2) The existence of one of the three emission sources selected for further analysis in the area where samples were obtained;
3) The existence of current monitoring or other sampling programs in the sampling area or the existence of recent data from the sampling area;
4) The suitability of the site to isolation of the emissions source; and
5) The availability of other personnel locally to assist with sampling at the proposed sites.

The reasoning behind each of the criteria are discussed below.

Attainment Status of the Area

Since one of the contract objectives was to provide an adequate perspective, selected representative measurements, and environmental assessments to determine the role of highways on compliance of various pertinent receptor locations, areas, and regions with the NAAQS for fine particulate (at that time, PM-10) concentrations, the first criteria selected for use in determining the sites selected for sampling and analysis was the attainment status of the proposed sampling area. Attainment status is the designation EPA gives to an area based upon the concentrations of pollutants monitored in a particular area. If an area shows measured concentrations of a criteria pollutant that exceed the levels specified by the NAAQS, then the area is designated as nonattainment. Thus a PM-10 nonattainment area has measured violations of the NAAQS for PM-10. There are currently over 70 areas that are listed as nonattainment for PM-10. However, many of these areas attribute the cause of their violations to sources other than highway vehicle impacts. Thus the nonattainment status was used to specify areas that could potentially prove useful in a sampling and analysis program, but it was not sufficient to use as the sole selection criteria.

Existence of Problem Area in Area where Samples will be Obtained

Since many of the PM-10 nonattainment areas attribute their exceedances to a variety of sources (including highway sources, in some cases), we determined whether an area considered for a sampling site had the particular highway source (diesel, road sanding and salting or dust resuspension) as one of the major sources in that area. This helped refine the search to areas with known problems, and that the source of interest was a major component of the problem. For sites that were not in nonattainment areas, the site had to have emissions from the source that could be easily studied.

Suitability of Site to Isolation of the Source

In order for sites not within nonattainment areas to be considered, the site had to have emissions from one of the sources of interest that could be easily studied. This meant that the source could be easily isolated or that the emissions were persistent over a longer period of time during which monitoring could take place. In addition, if the site provided easily isolated or persistent conditions, and either historic or on-going monitoring or sampling programs had been carried out there, or local personnel (from other federal or state agencies) were available to assist in sampling, then the site was considered for inclusion in the sampling and analysis program detailed below.

Existence of Current Monitoring or Other Sampling Program

Sites that either had sampling and/or monitoring programs or had recently completed studies carried out (so that historic data were available for use with the data developed here for analysis) were also given consideration in the assessment of potential sites. One of the other reasons that these sites were given consideration is that frequently (especially for ongoing programs) personnel that are involved with these programs are agreeable to assisting in the sample collection required for a program such as that presented here.

Availability of Other Personnel Locally to Assist in Sampling

The final criteria used to identify the potential sites for sampling and analysis was the availability of other personnel locally to assist in the sampling required. Having this resource available locally helped keep costs down and increased the odds of solving problems such as sampler problems, logistic support problems (such as clearance required to locate a sampler) and selection of alternative areas within the area for siting samplers.

PRELIMINARY SITE SELECTION

Based upon the criteria detailed in the previous section, the six preliminary sites selected (and the source type being sampled for) were:

Fort McHenry (Baltimore, MD) tunnel (diesel);
Albany, NY (road sanding and salting);
Reno, NV (road sanding and salting/dust resuspension);
Spokane, WA (dust resuspension);
Denver, CO (road sanding and salting); and
Tucson, AZ (dust resuspension).

Using the preliminary sites selected, Pechan and Desert Research Institute ([DRI] - Pechan's subcontractor for performing the sampling and analysis work) contacted personnel at each site. In addition, Pechan discussed possible alternative sites with the FHWA technical representative. The sites that were selected for the field work were:

Fort McHenry (Baltimore, MD) tunnel (diesel);
Albany, NY (road sanding and salting);
Reno, NV (road sanding and salting);
Spokane, WA (dust resuspension);
Denver, CO (road sanding and salting); and
Phoenix, AZ (dust resuspension).

In addition, during the discussions with FHWA and personnel that would be assisting with the sampling at the Albany, NY site, a decision was made to conduct opportunistic sampling in mid-town Manhattan, NY near a bus stop heavily influenced by diesel emissions.

Table 1 clearly shows that each of these sites meets at least three of the five selection criteria.

Table 1. Selection Criteria Satisfied by Each Potential Sampling Site

Site	Attainment Status of Area (X means nonattainment for PM-10)	Existence of Source Emissions Type in Area	Suitability of Site to Isolation of Source	Existence of Current Monitoring or Other Sampling Program (including historic programs)	Availability of Other Personnel Locally to Assist in Sampling
Fort McHenry Tunnel		✓	✓	✓	
Albany, NY		✓	✓		✓
Reno, NV	✓	✓	✓	✓	✓
Spokane, WA	✓	✓		✓	
Denver, CO	✓	✓		✓	
Phoenix, AZ	✓	✓	✓	✓	✓
Manhattan, NY	✓	✓	✓	✓	✓

The sampling sites identified for the assessment of diesel emissions, road sanding/salting, and dust resuspension are described later in this report. A major advantage of the Fort McHenry, Reno, Denver, and Phoenix sites was that CMB profiles of major PM-10 sources were available from previous air quality studies.

OBJECTIVES

The objectives of the field work component of this study were:

- Calculate, in a highway tunnel, the on-road particulate emission factors for both gasoline powered vehicles and diesel trucks (Fort McHenry tunnel).

- Calculate the impact of diesel bus emissions on ambient PM-10 concentrations at a site heavily influenced by diesel traffic (mid-town Manhattan, NY).

- To determine, for a worst case scenario, the contribution of resuspended salting material to ambient PM-10 concentrations in Albany, NY.

- To determine, for a "typical" setting in Denver, CO, the contribution of resuspended sanding material to ambient PM-10 concentrations.

- To determine, for a worst case scenario in Reno, NV, the contribution of resuspended sanding material to ambient PM-10 concentrations.

- To determine, for a major city not impacted by extreme winter conditions, the contribution of resuspended road dust on ambient PM-10 concentrations (Phoenix, AZ).

- To determine, for Spokane WA, the contribution of resuspended road dust to ambient PM-10 concentrations.

CHAPTER 2: EXPERIMENTAL METHODS

This chapter discusses the sampling equipment, analytical processes, and the calculation of emission factors used throughout this report.

SAMPLER DESCRIPTION

Two different types of sequential samplers were used for this study. For Manhattan, Albany, Denver, Reno, Phoenix, and Spokane, the sampler used was a recent model Desert Research Institute (DRI) medium volume (MEDVOL) sequential sampler using Savillex filter holders (Gertler et al., 1993) (see figure 1). Sampling at the Fort McHenry Tunnel employed an older version of the DRI medium volume sequential sampler (figure 2), which made use of Nucleapore filter holders (Chow et al., 1993a). Both types of samplers employed a Sierra Anderson SA-254 PM-10 inlet to determine the size fraction transmitted into the sampler.

During sampling, the PM-10 size fraction is transmitted through the size-selective inlet and into a plenum. The flow rate is controlled by maintaining a constant pressure across a valve with a differential pressure regulator. For the size selective inlet to properly work, a flow rate of 113 liters per minute (L/min) is maintained through the sampler. Flow rates of 20 L/min through each filter were standard for these studies because they provided adequate sample loadings for analysis without overloading the filters. This flow rate is drawn simultaneously through two separate filter packs, one with a Teflon substrate and one with a quartz substrate. The remaining flow rate of 73 L/min needed by the inlet is drawn through a makeup air port. The flow rates were each set with calibration filters and calibrated rotometer and were monitored with the same rotometer at each sample change.

ANALYTICAL METHODOLOGY

The initial analysis of all filters used in sampling consisted of weighing of the Teflon filters by gravimetry on a Cahn 31 Electro-Microbalance upon return from the field. Quartz filters were stored at 4°C and held for additional analyses at a future date. Samples from the Fort McHenry site were subjected only to mass determinations.

Chemical analyses were performed on selected sets of filters from Albany, Denver, Reno, and Phoenix, while all 12 sets of filters collected during sampling at the Manhattan Site and all three sets of filters from the Spokane site were analyzed. Mass was measured as described above. The Teflon filters were also analyzed for elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Y, Zr, Mo, Pd, Ag, Cd, In, Sn, Sb, Ba, La, Au, Hg, Tl, Pb, and U) by X-ray fluorescence (XRF) using a Kevex 700/800 analyzer. One-half of the quartz filter was extracted with distilled-deionized water. The extract was analyzed for chloride, nitrate and sulfate ions by ion chromatography (IC) using a Dionex 4000i ion chromatograph, for ammonium ion by automated colorimetry (AC) using a TRAACS 800 Technicon autoanalyzer, and for sodium and potassium anions by a Perkin-Elmer Model 2380 Double Beam Atomic Absorption (AA) Spectrometer. Organic and elemental carbon were measured by thermal optical reflectance (TOR) using a DRI/OGC thermal/optical carbon analyzer (Chow et al., 1993b)

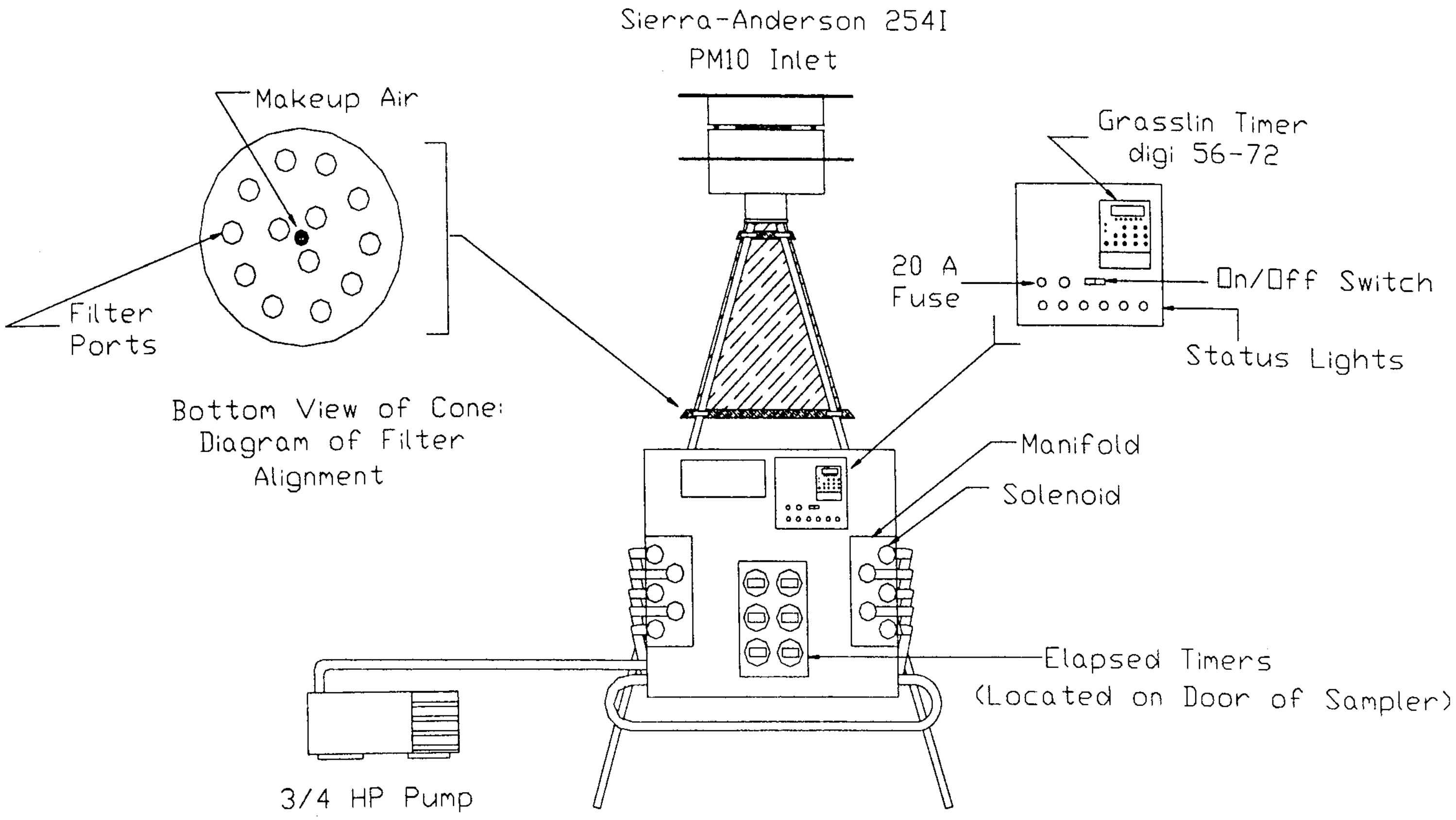

Figure 1. Schematic of DRI MEDVOL particle sampler.

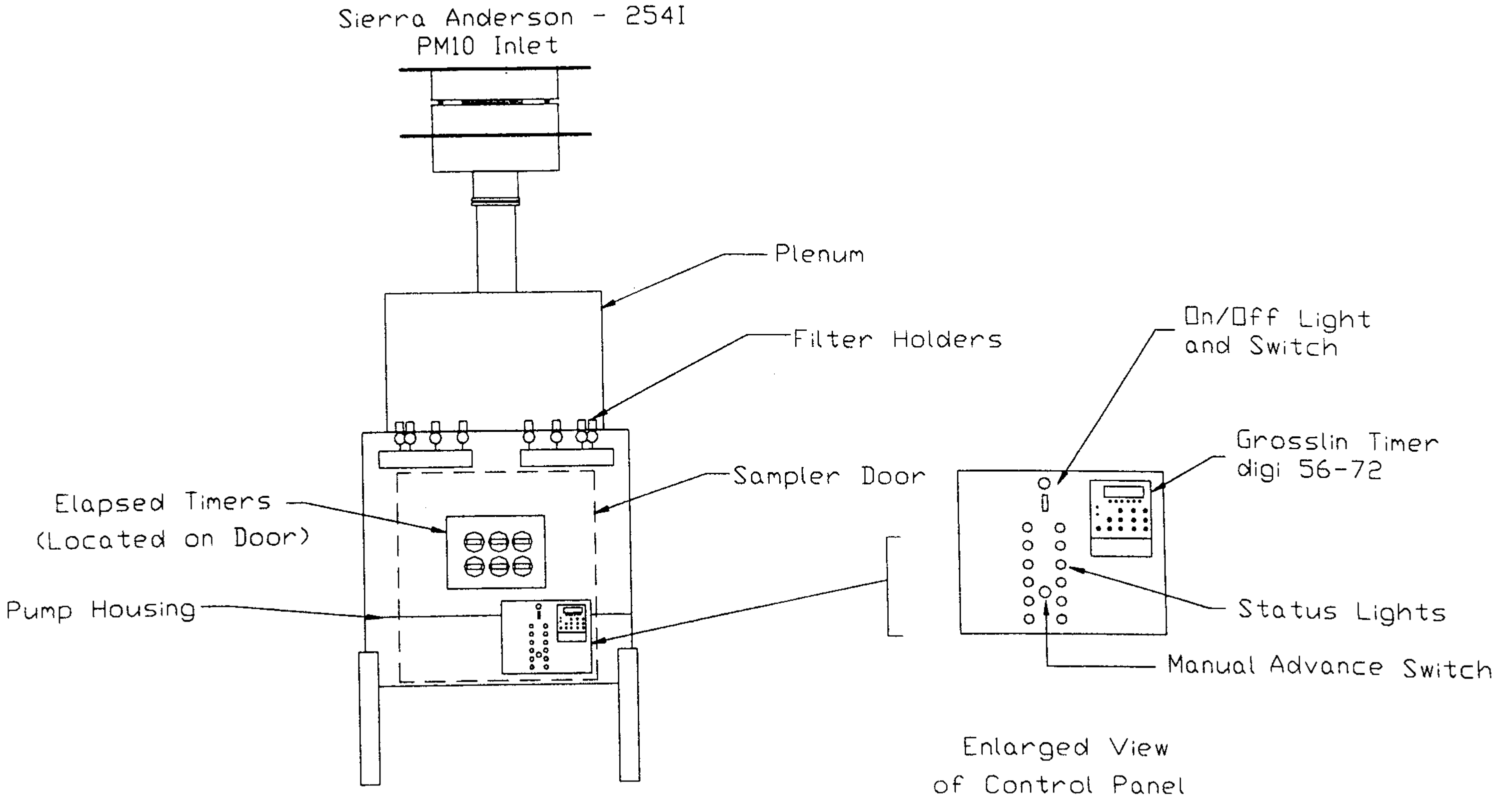

Figure 2. Schematic of DRI sequential filter sampler.

on 0.5 cm^2 punches taken from the remaining half of the quartz filter. The chemical analyses applied in this study are described in more detail by Watson and Chow (1994).

A total of 54 sets of filters were collected at the Reno site, 56 at the Albany site, and 59 at the Denver site. Each set of filters consisted of one Teflon and one Quartz filter. Of these filters, the Teflon filter was weighed on a Cahn 31 Electro-Microbalance both before and after sampling and was used to determine the ambient concentrations during the sampling periods. The concentrations were then used to help make a determination about which of the filters were to be used for further analysis. A total of 20 filters from the Reno site, 21 from the Albany site, and 24 from the Denver site were selected for analysis. This determination was made by considering the observed mass concentration and the time of day represented by the filter.

Of the 56 active filters taken at the Phoenix site, only 14 were analyzed. The determination of the filters to be analyzed was achieved simply by the site of the sampler. There were a total of four sampling sites for the Phoenix study. Only the filters from the downwind, bottom sampler were analyzed (see figure 3).

CALCULATION OF EMISSION FACTORS

At Fort McHenry, anemometers were set up next to the PM-10 samplers in the tunnel to obtain average wind speeds during the runs. These wind speeds were then used to calculate the total air flow through the tunnel during the sampling period. These values were measured in one minute time intervals over the course of the entire sampling period, and then averaged over the entire run. Wind speed values measured in the tunnel were supplemented with previously measured values for the east and west supply vents. Flow values in the tunnel were supplemented with volume flow of 2.28 x 10^5 and 2.25 x 10^5 cubic meters per hour (m^3/h) for the west and east supply vents, respectively (Pierson, 1992).

The theory behind these measurements is described in detail elsewhere (Pierson and Brachaczek, 1983, Pierson et al., 1990, 1993, 1994). Briefly, the calculation of the total amount of PM-10 mass produced in the tunnel is performed by measuring simultaneously the particulate concentrations of the air coming into the tunnel entrance, the incoming ventilation air, and the air exiting the tunnel. This data coupled with the air volume flow through the entrance, exit, and ventilation ducts during the sampling time period, can allow one to calculate the mass produced in the tunnel via the relationship:

$$M = \Sigma_i \, (C_{out} V_{out})_i - \Sigma_j (C_{in} V_{in})_j$$

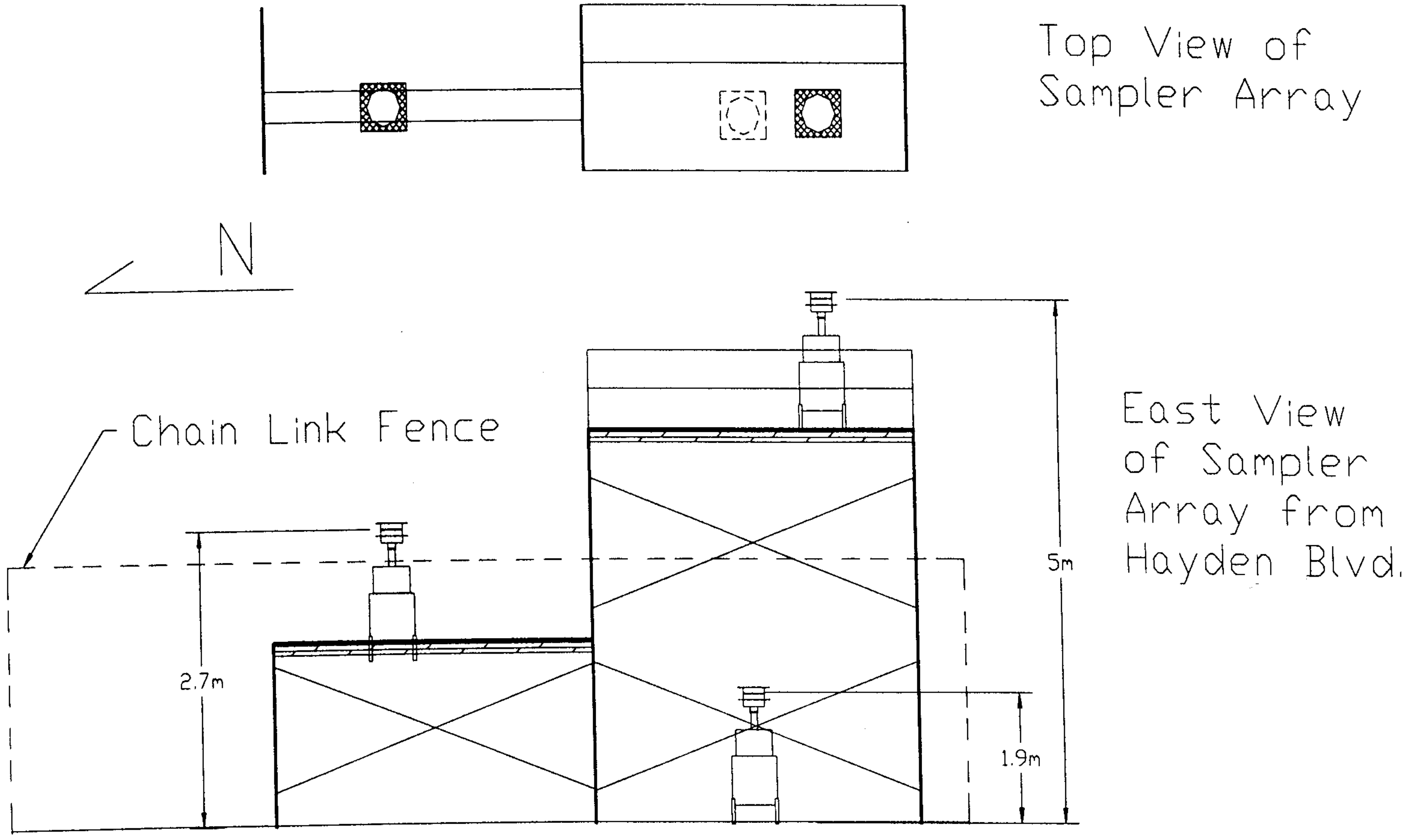

Figure 3. Sampling array on the north side of Hayden Blvd. at the Phoenix, AZ site.

Here, $(C_{out}V_{out})$ is the product of the concentration, C_{out}, of air and the total volume of air flow, V_{out} through exit channels and similarly for $(C_{in}V_{in})$, the entrances for the air into the tunnel. Combining the mass produced in the tunnel along with the length of the tunnel, L, and the total number of vehicles passing through the tunnel during the sampling period, N, then the particulate emission factor, EMF, can be calculated by:

$$EMF = M / (NL)$$

For the purpose of this study, the vehicle fleet is broken down into two different categories. The first category, spark ignition vehicles, is composed of motorcycles (MC), light-duty spark ignition vehicles (LDSI), including cars, minivans, pickup trucks, and multi-purpose vehicles, and heavy-duty spark ignition vehicles (HDSI) including cargo vans, panel vans, and tow trucks. The second category of vehicles are the heavy-duty diesel vehicles. This includes buses, all tractor-trailer combinations, all trailerless semi-trucks, shuttle trucks, and concrete trucks.

The emission factors can be said to be a linear combination of the percent of the spark ignition vehicles, x_n, times the emission rate of the spark ignition vehicles, L, plus the percent of heavy duty diesel vehicles, y_n, times the emission rate of the heavy duty diesel vehicles, H. For the nth case, this can be written as:

$$EMF = x_n L + y_n H$$

Assuming that $x_n + y_n = 1$, or that we can classify the vehicle fleet as either spark ignition vehicles or heavy-duty diesel vehicles, y_n can be rewritten as $1 - x_n$ to get:

$$EMF = (L-H)x_n + H$$

The emission rate for the heavy-duty diesel vehicles can then be distinguished from the experimental data by performing a linear regression of the plotted observed emission factor, EMF, versus the percentage of spark ignition vehicles, x_n. The examination of the extremes for this regression will reveal that there are two cases that are of interest. The first case is when x_n is equal to 0.00. This is the case in which there are 0 percent spark ignition vehicles and 100 percent heavy duty diesel vehicles. This is the point which signifies the emission factors for heavy-duty diesel vehicles. The second point is when x_n is 1.00, or where the fraction of spark ignition vehicles is 100 percent. This signifies the emission factor for the spark ignition vehicles. This methodology is explained in detail by Pierson et al. (1994).

PAVED ROAD RESUSPENSION

As indicated in figure 3, aerosol samples were collected at the Phoenix site from both upwind and downwind locations. On the downwind side, a vertical array of samplers was utilized with the sampler heads located at heights of 1.9, 2.7, and 5 meters. Although only samples from the downwind, bottom sampler were utilized in the CMB analyses, aerosol mass was determined for all samples. In addition, wind speed and direction were determined at 15-minute intervals during the sampling period which was from 1200 to 1800 hours each day.

The mass contributed by the vehicle traffic on the road on each filter was determined by subtracting the mass measured on the upwind sample from each of the values measured for the downwind samplers. This contribution was assumed to be the result of resuspended materials from the road surface.

Emission factors were determined based on the dispersion equation for an infinite line source (Turner, 1994). The equation for dispersion from an infinite line source is:

$$\chi(x,y,0,H) = \frac{2q}{\sin\varphi\ (2\pi)^{\frac{1}{2}}\ \sigma_z\ u} \exp\left[- \frac{H}{2\sigma_z^2} \right]$$

where:

χ = concentration in mass per volume (g m^{-3})
q = source strength per unit distance (g s^{-1} m^{-1})
u = wind speed (m s^{-1})
σ_z = standard deviation of the concentration distribution in the vertical direction, m, at the downwind distance x.
π = pi
H = the effective height of the centerline of the plume
φ = angle of the wind from perpendicular.

The equation for an infinite line source can be rewritten to solve for q, which when multiplied by the time period of collection and divided by the number of vehicle passes provides an emission factor of the form g VKT^{-1}. Concentrations measured on the downwind side (corrected for background concentrations using the upwind sampler) at the Phoenix site were utilized in the equation above to determine emission factors. The above equation should only be used for situation where the wind angle is less than 45° from perpendicular to the road. As a consequence, only samples collected under the appropriate average wind conditions were utilized to determine the emission factors. The results are presented in chapter 7.

CHAPTER 3: MODELING METHODOLOGY

This chapter discusses in detail the theory and usage of the Chemical Mass Balance (CMB) Model.

CHEMICAL MASS BALANCE METHODOLOGY

The Chemical Mass Balance (CMB) model constructs a least-squares solution to a set of linear equations which expresses each receptor concentration of a chemical species as a linear sum of products of source profile species weighted as source contributions. The source profile species (the fractional amount of the species in the emissions from each source type) and the receptor concentrations, each with uncertainties determined by the measurement limits of the chemical analyses combined with laboratory background measurements, serve as input data to the CMB model. The output consists of the contributions for each source type to the total ambient aerosol mass, as well as to individual chemical species concentrations. The model calculates values for contributions from each source and the uncertainties of those values. Input data uncertainties are used both to weigh the relative importance of the input data to the model solution and to estimate the uncertainties of the source contributions.

CMB software currently in use is the CMB Version 7.0, or CMB7 (Watson et al., 1990). This software applies the effective variance solution developed and tested by Watson et al. (1984). The advantages of this software are 1) it calculates realistic uncertainties of source contributions from both the source and receptor uncertainties; and 2) chemical species measured more precisely in both source and receptor samples are given greater influence in the solution than are less precisely measured species. The CMB model, as specified by United States Environmental Protection Agency (EPA) guidance for State Implementation Plan (SIP) development (Pace and Watson, 1987) is applied to this portion of the Highway study.

Watson (1979) observed that individual sources with similar source profiles, such as different soils and road dusts, would yield unreliable source strength estimates if used in the same CMB. Henry (1982, 1992) proposed a quantitative method of identifying this interference among similar source compositions, which is known as "collinearity." Henry's "singular value decomposition" defines an "estimable space in which resolvable sources should lie" (Henry, 1982, 1992). The source types which do not fall into this estimable space are collinear, or too similar to be resolved from a combination of one or more of the source types which do lie within the estimable space. Henry (1982, 1992) further proposed that linear combinations of source contributions resulting from collinear source compositions would be more representative of the summed contributions of these sources. Analytical measures of collinearity and Henry's linear combination method are available in the EPA/DRI Version 7.0 of the CMB model (Pace and Watson, 1987).

The CMB modeling procedure requires: 1) identification of the contributing source types; 2) selection of chemical species to be included; 3) estimation of the fractions of each chemical species contained in each source type (i.e., the source profiles); 4) estimation of the uncertainties of both ambient concentrations and source compositions; and 5) solution of the chemical mass balance equations. These procedures are described in an applications and validation protocol (Watson et al., 1991) which has been assembled for PM-10 source assessment.

The CMB applications and validation protocol consists of seven steps: 1) determination of model applicability; 2) initial source contribution estimates; 3) examination of model outputs and performance measures; 4) identification of deviations from model assumptions; 5) identification and correction of model input errors; 6) verification of the consistency and stability of source contribution estimates; and 7) evaluation of the results of the CMB analysis with respect to other source assessment methods.

The requirements for CMB model applicability are as follows: 1) a sufficient number of receptor samples are taken with an accepted method to evaluate the sources in the area; 2) samples are analyzed for chemical species which are also present in source emissions; 3) potential source contributors have been identified and chemically characterized; and 4) the number of non-collinear source types is less than the number of measured species. These requirements were met.

Samples were taken through well-characterized Sierra-Anderson PM-10 inlets during the field programs. All of these samples were submitted to the DRI in Reno, NV, for analysis for mass, elements by XRF and AA (Na and K), carbon (by TOR), and ion concentrations by IC and automated colormetric methods. Analytical procedures employed standard QA/QC methods. The analytical technique for carbon is performed using a thermal/optical method (Chow et al., 1993b). Major source types were identified and profiles from DRI's source profile library were used in the modeling.

Several species were omitted before performing the CMB modeling. Copper (Cu) and zinc (Zn) were omitted because they are often seen as contaminants from the sampler pump, while the use of elemental sodium (Na), sulfur (S), and chlorine (Cl) are often at odds in the modeling process with their respective ions.

SOURCE PROFILES

Applying receptor modeling to source apportionment requires information about the chemical characteristics of the emissions sources which are likely to affect pollutant concentrations at a receptor. For the CMB receptor model, the required information is the fractional composition of each chemical species in the source emissions and an estimate of the variability of those compositions.

Manhattan, NY Site

The potential source types which contribute to primary PM-10 in Midtown Manhattan are: 1) geological material (fugitive dust from paved roads and, possibly, construction); 2) motor vehicle exhaust (from cars, trucks, and buses fueled with diesel, leaded gasoline, and unleaded gasoline); 3) marine aerosol transported from the Atlantic Ocean; and 4) secondary particles (ammonium sulfate, ammonium nitrate, and residual organic carbon from fossil fuel combustion). Non-tailpipe vehicle particulate emissions such as brake wear or tire wear would be enclosed within the geological source profile, and could not possibly be separated out by this method. A "source type" does not necessarily correspond to a particular emitter. For the primary contributors, several source sub-types may exist within some of these categories which are not easily distinguishable from each other by receptor models using commonly measured chemical species. The source type perceived at a receptor may be a mixture of these different sub-types, and the profile which best explains the receptor measurement should represent this mixture.

Table 2 lists the source types, a short identifier for each specific profile and the weight percentage of the species for each profile. For resuspended road dust (RD), a profile obtained in Phoenix was used. Primary auto (AUTO) and diesel (DIESEL) profiles were obtained from inspection and maintenance lanes in Phoenix (Chow et al., 1991b). While these fleets may differ from the New York fleet (i.e., slightly older) the overall profiles would be expected to be similar since emissions are based on technology rather than location. A fresh sea salt profile (MARINE), profiles indicative of long-range transport (AMSUL ($(NH_4)_2SO_4$) and AMNIT (NH_4NO_3)), a residual oil combustion profile (REOILC) indicative of oil heating, and a profile containing iron (FEORE) were used in the final model calculations. This last profile was required to make up an observed deficiency in iron which was either lacking in the road dust profile (i.e., more iron in New York dirt than in Phoenix dirt), a source of iron near the site (i.e., manufacturing), or an increased amount of rust (e.g., vehicle rusting).

Accurate CMB analysis of the source data requires that the individual sources not be collinear, or have the same relative proportionalities of elemental concentrations. The individual auto and diesel profiles are collinear, and thus the CMB cannot distinguish between each individual source. In order to separate auto from diesel, combined source profiles were compiled. These were developed by combining the two mobile source profiles listed in table 1. Profiles covering the range of 100 percent diesel (D) to 100 percent auto (A) were evaluated (the combinations were 100 percent D-0 percent A, 95 percent D-5 percent A, 90 percent D-10 percent A, 85 percent D-15 percent A, 80 percent D-20 percent A, 75 percent D-25 percent A, 60 percent D-40 percent A, 50 percent D-50 percent A, 25 percent D-75 percent A, and 0 percent D-100 percent A). In all samples the 100 percent diesel profile fit the mobile source data, although better fits were obtained using the combined profiles. The light-duty (AUTO) profile alone did not account for the observations in any sample.

For this study, the model optimization criteria took into account several different factors. The basic ones were the fitting parameters of R-square (r^2) and chi-square (χ^2). The maximization of these, R-square approaching 1.00 and chi-square approaching 0.00, accounted for approximately 40 percent of the fitting determination. The fitting of the organic and elemental carbon, accounting for approximately 40 percent of the total determination of the fit, was done by optimizing the (calculated)/(measured) ratio. The last 20 percent of the fitting criteria was determined by the optimization of the (calculated)/(measured) ratio of both lead (Pb) and bromide (Br); these elements are the two key tracers in the signatures of automobiles.

Albany, NY; Denver, CO; and Reno, NV Sites

The potential source types which contributed to primary PM-10 at the Albany, Denver, and Reno sites are: 1) road sanding material (resuspended road dust); 2) motor vehicle exhaust (from cars, trucks, and buses fueled with diesel, leaded gasoline, and unleaded gasoline); 3) road salting material (produced by the resuspension of road salt); 4) secondary particles (ammonium sulfate, ammonium bisulfate, and ammonium nitrate); and 5) a constructed pure salt profile (NACL). A "source type" does not necessarily

Table 2. Source Profiles Expressed as Percent Contribution for the Midtown Manhattan Site*

Species	RD	AUTO	DIESEL	MARINE	AMSUL	AMNIT	REOILC	FEORE
Cl-	0.15	0.64	1.62	57.37	0.00	0.00	0.00	0.00
NO_3-	0.16	3.89	0.31	0.00	0.00	77.50	0.65	0.00
SO_4=	0.22	2.29	2.44	8.00	72.70	0.00	48.10	0.00
NH_4+	0.06	1.67	0.87	0.00	27.30	22.55	0.00	0.00
Na+	0.00	0.00	0.00	31.98	0.00	0.00	0.00	0.00
K+	0.20	0.39	0.39	0.00	0.00	0.00	0.00	0.00
OC	10.16	30.08	40.10	0.00	0.00	0.00	7.80	0.00
EC	0.68	13.50	32.92	0.00	0.00	0.00	2.42	0.00
Na	0.00	0.00	0.00	31.98	0.00	0.00	3.50	0.00
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.26	0.41	0.17	0.00	0.00	0.00	0.53	1.72
Si	13.77	1.64	0.46	0.01	0.00	0.00	0.96	4.54
P	0.08	0.11	0.06	0.00	0.00	0.00	0.00	0.09
S	0.25	1.01	1.24	2.67	24.27	0.00	13.30	0.41
Cl	0.22	0.34	0.03	57.37	0.00	0.00	0.00	0.25
K	1.99	0.25	0.04	1.18	0.00	0.00	0.28	0.23
Ca	5.07	0.71	0.16	1.22	0.00	0.00	1.58	13.58
Ti	0.46	0.07	0.00	0.00	0.00	0.00	0.11	0.28
V	0.03	0.00	0.00	0.00	0.00	0.00	3.44	0.05
Cr	0.03	0.02	0.00	0.00	0.00	0.00	0.05	0.10
Mn	0.11	0.10	0.01	0.00	0.00	0.00	0.05	0.58
Fe	4.80	0.68	0.16	0.00	0.00	0.00	2.97	30.55
Co	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.01	0.01	0.00	0.00	0.00	0.00	5.36	0.01
Cu	0.03	0.07	0.01	0.00	0.00	0.00	0.08	0.03
Zn	0.12	0.27	0.07	0.00	0.00	0.00	0.40	0.03
Ga	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Se	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Br	0.01	0.03	0.00	0.20	0.00	0.00	0.01	0.01
Rb	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Sr	0.10	0.01	0.00	0.02	0.00	0.00	0.00	0.02
Y	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Zr	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Mo	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.03
Pd	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Cd	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.06
In	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Sn	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01
Sb	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.01
Ba	0.08	0.06	0.14	0.00	0.00	0.00	0.00	0.00
La	0.01	0.15	0.18	0.00	0.00	0.00	0.00	0.00
Au	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Tl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pb	0.09	0.16	0.01	0.00	0.00	0.00	0.11	0.05
U	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00

* Nominal Uncertainty is ± 10 percent

correspond to a particular emitter. For the primary contributors, several source sub-types may exist within some of these categories which are not easily distinguishable from each other by receptor models using commonly measured chemical species. The source type perceived at a receptor may be a mixture of these different sub-types, and the profile which best explains the receptor measurement should represent this mixture.

Tables 3a and 3b list the source types, a short identifier for each specific profile and the weight percent of the species for each profile. Two different primary motor vehicle profiles (Motor Vehicle) were used in the modeling. A profile obtained from roadside sampling in Reno, Nevada (MVRENO) was used for modeling the Reno data (Chow et al., 1989) and a roadside profile from Phoenix, Arizona (MVPHNX) was used in the modeling in Albany and Denver (Chow et al., 1991b). While the fleets that both of these profiles represent may be several years older than the fleets at Albany, Denver, or present day Reno, they were utilized because of their ability to fit the data in the modeling process. It should also be noted that these profiles had the road dust portion subtracted from the original data to obtain the "pure" motor vehicle profile. There were also profiles obtained via resuspension of road sanding material (at Denver and Reno, i.e. RNODST, RNODRT, and DENSND), and of road salting material (at Albany, i.e. ALBSLT). The modeling at Denver and Reno required that a "pure" salt profile be constructed. This profile is named NACL. The road sand used in the Albany, and eventually Denver, modeling (SAND) was obtained from a previous study in Denver (Watson et al., 1988) in 1987. Profiles indicative of long-range transport (AMSUL ($(NH_4)_2SO_4$), AMBSUL (NH_4HSO_4), and AMNIT (NH_4NO_3), were lumped into the category "Secondaries") round out the last of the profiles used in this modeling process. The acronyms for the source profiles are described in table 4.

For these sites, the model optimization criteria took into account several different factors. The basic ones were the fitting parameters of R-square (r^2) and chi-square (chi^2). The maximization of these, R-square approaching 1.00 and chi-square approaching 0.00, accounted for approximately 30 percent of the fitting determination. The fitting of the organic and elemental carbon, accounting for approximately 20 percent of the total determination of the fit, was done by optimizing the (calculated)/(measured) ratio. The fitting of two of the primary sand constituents, silicon and aluminum, at Denver and Reno accounted for another 20 percent of the final fit, while at Albany, the fitting of the Na^+ and Cl^- accounted for this 20 percent of the fit. The last 30 percent of the fitting criteria was determined by the optimization of the percent mass, with optimum being 100 percent.

Phoenix, AZ, and Spokane, WA Sites

The potential source types which contributed to primary PM-10 at the Phoenix and Spokane Reno sites are: 1) resuspended road dust (roadside geological material); 2) motor vehicle exhaust (from cars, trucks, and buses fueled with diesel, leaded gasoline, and unleaded gasoline); 3) secondary particles (ammonium bisulfate, NH_4HSO_4), and 4) a constructed pure salt profile (NACL).

Tables 3a, 3b, and 4 list the source types, a short identifier for each specific profile and the weight percent of the species for each profile. Only one primary motor vehicle profile (MVPHNX) was used in the modeling. This profile was obtained from roadside sampling in Phoenix, Arizona in a previous study (Chow et al., 1991b). It should also be

Table 3a. Source Profiles Expressed as Percent Contribution for Albany, Denver, Reno, Phoenix, and Spokane Sites*

	Secondary			Motor Vehicle	
Species	AMSUL	AMBSUL	AMNIT	MVPHNX	MVRENO
Cl-	0.00	0.00	0.00	1.16	0.36
NO_3-	0.00	0.00	77.50	11.03	1.84
SO_4=	72.70	83.45	0.00	6.01	1.30
NH_4+	27.30	15.67	22.55	4.11	0.03
Na+	0.00	0.00	0.00	0.00	0.00
K+	0.00	0.00	0.00	0.76	0.79
OC	0.00	0.00	0.00	39.00	50.37
EC	0.00	0.00	0.00	36.47	28.50
Na	0.00	0.00	0.00	0.00	0.00
Mg	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.07	0.00
Si	0.00	0.00	0.00	0.08	0.11
P	0.00	0.00	0.00	0.08	0.22
S	24.27	27.86	0.00	2.02	1.39
Cl	0.00	0.00	0.00	0.56	0.28
K	0.00	0.00	0.00	0.22	0.16
Ca	0.00	0.00	0.00	0.13	0.03
Ti	0.00	0.00	0.00	0.09	0.09
V	0.00	0.00	0.00	0.02	0.04
Cr	0.00	0.00	0.00	0.02	0.01
Mn	0.00	0.00	0.00	0.18	0.05
Fe	0.00	0.00	0.00	0.93	0.05
Co	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.00	0.02	0.01
Cu	0.00	0.00	0.00	0.36	0.20
Zn	0.00	0.00	0.00	0.51	0.21
Ga	0.00	0.00	0.00	0.01	0.00
As	0.00	0.00	0.00	0.01	0.00
Se	0.00	0.00	0.00	0.00	0.01
Br	0.00	0.00	0.00	0.06	0.09
Rb	0.00	0.00	0.00	0.00	0.00
Sr	0.00	0.00	0.00	0.00	0.02
Y	0.00	0.00	0.00	0.01	0.00
Zr	0.00	0.00	0.00	0.01	0.02
Mo	0.00	0.00	0.00	0.01	0.00
Pd	0.00	0.00	0.00	0.02	0.00
Ag	0.00	0.00	0.00	0.01	0.00
Cd	0.00	0.00	0.00	0.03	0.06
In	0.00	0.00	0.00	0.01	0.00
Sn	0.00	0.00	0.00	0.06	0.00
Sb	0.00	0.00	0.00	0.10	0.06
Ba	0.00	0.00	0.00	0.20	0.30
La	0.00	0.00	0.00	0.36	0.00
Au	0.00	0.00	0.00	0.01	0.00
Hg	0.00	0.00	0.00	0.00	0.00
Tl	0.00	0.00	0.00	0.00	0.00
Pb	0.00	0.00	0.00	0.27	0.51
U	0.00	0.00	0.00	0.01	0.00

* Nominal Uncertainty is ± 10 percent.

Table 3b. Source Profiles Expressed as Percent Contribution for Albany, Denver, Reno, Phoenix, and Spokane Sites*

	Reno		Road Sand		Road Salt		Phoenix/Spokane	
Species	RNODST	RNODRT	DENSND	SAND	ALBSLT	NACL	PHGEO	SPDIRT
Cl-	0.13	4.10	9.41	0.00	36.53	60.66	0.10	0.11
NO_3-	0.05	0.06	0.03	0.00	0.13	0.00	0.05	0.02
SO_4=	0.05	1.17	0.37	0.90	1.81	0.00	0.08	0.04
NH_4+	0.04	0.04	0.02	0.00	0.05	0.00	0.02	0.02
Na+	0.09	2.37	5.84	0.00	21.51	39.34	0.08	0.07
K+	0.03	0.07	0.65	0.16	0.08	0.00	0.15	0.05
OC	5.40	3.25	2.90	0.00	3.74	0.00	2.58	5.38
EC	0.12	0.00	0.18	0.00	0.01	0.00	0.73	0.83
Na	0.83	2.03	3.31	0.00	11.51	39.34	0.18	0.26
Mg	0.46	0.44	0.10	0.00	0.10	0.00	0.65	0.45
Al	11.12	11.33	8.97	8.09	3.39	0.00	8.81	8.11
Si	33.98	29.56	26.54	24.17	9.34	0.00	26.03	26.42
P	0.05	0.00	0.00	0.07	0.03	0.00	0.05	0.10
S	0.26	0.49	0.11	0.21	0.30	0.00	0.06	0.23
Cl	0.17	6.48	12.77	1.00	38.86	60.66	0.08	0.14
K	2.20	1.99	3.82	4.14	0.86	0.00	2.92	2.33
Ca	4.39	4.82	2.20	1.30	2.78	0.00	4.74	2.54
Ti	0.48	0.47	0.33	0.32	0.10	0.00	0.40	0.70
V	0.01	0.01	0.01	0.03	0.00	0.00	0.01	0.02
Cr	0.01	0.02	0.02	0.02	0.01	0.00	0.01	0.01
Mn	0.10	0.13	0.08	0.13	0.04	0.00	0.15	0.10
Fe	4.47	4.96	3.68	4.40	1.51	0.00	4.46	5.59
Co	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00
Cu	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.01
Zn	0.06	0.03	0.03	0.02	0.02	0.00	0.07	0.08
Ga	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Se	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Br	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00
Rb	0.01	0.01	0.02	0.03	0.01	0.00	0.02	0.01
Sr	0.09	0.06	0.05	0.06	0.03	0.00	0.05	0.02
Y	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.00
Zr	0.01	0.01	0.02	0.02	0.00	0.00	0.01	0.02
Mo	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Pd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
In	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sn	0.00	0.01	0.00	0.03	0.00	0.00	0.01	0.00
Sb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.12	0.17	0.10	0.16	0.07	0.00	0.05	0.10
La	0.07	0.06	0.00	0.00	0.07	0.00	0.00	0.01
Au	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tl	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pb	0.07	0.01	0.01	0.01	0.01	0.00	0.05	0.04
U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

* Nominal Uncertainty is ± 10 percent.

Table 4. Descriptions of the Source Profile Acronyms for the Albany, Denver, Reno, Phoenix, and Spokane Sites

Acronym	Description
RNODST	Reno Road Dust Sample: Resuspended composite of street sweeper material and raw sanding material
RNODRT	Reno Road Dirt Sample: Resuspended composite of three dirt samples taken directly off the streets near the sampling site.
DENSND	Denver Sanding Material: Resuspended composite of four samples taken from area sanding material source piles.
SAND	Sanding Material: Resuspended composite of two road sanding material samples obtained in Denver, CO in 1987.
ALBSLT	Road Salt: Resuspension of road salt material obtained from a source pile in Albany, NY.
NACL	Salt: A constructed salt profile with 60.66 percent Cl- and 39.34 percent Na+.
PHGEO	Phoenix Geological Material: Resuspension of composite of two samples obtained from adjacent to Phoenix sampling sites.
SPDIRT	Spokane Road Dirt: Resuspension of composite of two samples obtained from adjacent to Spokane sampling site.
AMSUL	Secondary Ammonium Sulfate: Constructed profile of $(NH_4)2SO_4$, 27.3 percent NH_4, 72.7 percent SO_4
AMBSUL	Secondary Ammonium Bisulfate: Constructed profile of NH_4HSO_4, 15.7 percent NH_4, 83.4 percent SO_4
AMNIT	Secondary Sodium Nitrate: Constructed profile of $NaNO_3$, 27 percent Na, 73 percent NO_3
MVPHNX	Phoenix Motor Vehicle: Composite of 10 roadside samples obtained in Phoenix, AZ in 1989 after background corrections
MVRENO	Reno Motor Vehicle: Composite of 4 samples obtained in 1986 in Reno, NV after background subtractions.

noted that this profile had the road dust portion subtracted from the original data to obtain the "pure" motor vehicle profile. There were also profiles obtained via resuspension of road dust/geological material for each site. The Phoenix geological material (PHGEO) is a composite of two samples gathered immediately adjacent to the sampling sites. The Spokane road dirt profile (SPRD) used in the modeling was obtained directly from the road adjacent to the sampling site. Also used at each site were constructed profiles of pure salt, NACL, and of ammonium bisulfate (NH_4HSO_4), AMBSUL.

For these sites, the model optimization criteria took into account several different factors. The basic ones were the fitting parameters of r^2 and χ^2. The maximization of these, r^2 approaching 1.00 and χ^2 approaching 0.00, accounted for approximately 30 percent of the fitting determination. The fitting of the organic and elemental carbon, accounting for approximately 10 percent of the total determination of the fit, was done by optimizing the (calculated)/(measured) ratio. The fitting of two of the primary road dirt/geological constituents, silicon and aluminum accounted for approximately 20 percent of the final fit, while the fitting of the Na^+, Cl^-, NH_4^+, and SO_4^{-2} accounted for 10 percent of the fit. The last 30 percent of the fitting criteria was determined by the optimization of the percent mass, with optimum being 100 percent.

RESUSPENDED SOURCE PROFILES

In order to develop local profiles for road sanding and salting material, source samples were collected near the sites and from the area road maintenance facilities. These samples were placed into ziplock polyethylene bags for transport to the DRI laboratory for chemical analysis. Each sample was labeled with respect to sampling location, source type, and sampling method. These samples were dried at 30°C to remove moisture, sieved through a Tyler 400 mesh to provide a powder with nominal particle sizes less than 38 µm physical diameter, and then resuspended into a chamber for sampling onto filters using a PM-10 size-selective inlet (Chow et al., 1994). These samples were used to create the road sanding, road salting, road dust, and geological source profiles contained in table 3b.

CHAPTER 4: SITE DESCRIPTIONS

This chapter describes the sampling sites and the area surrounding them.

DIESEL EMISSION SITES

Fort McHenry Tunnel

The Fort McHenry Tunnel is situated on Interstate 95 in the midst of Baltimore, MD, the third largest seaport on the east coast. It is surrounded by docks, railroad yards, chemical manufacturing plants, petroleum storage tanks, an automobile assembly plant, cargo containers, and on the east entrance, a giant coal transfer facility containing mountainous piles of coal. The presence of these industries, and their subsequent need for distribution via one of the major traffic links along the eastern seaboard, Interstate 95, make it a good location for the study of diesel emissions.

The tunnel itself consists of four bores, two eastbound and two westbound, with each bore containing two lanes of traffic. The bores are designated, in order from north to south, #1, #2, #3, #4. Bores 2 and 3 contain light-duty traffic only, whereas bores 1 and 4 contain a mix of light and heavy-duty traffic. For the purposes of this study, only bore #4 was used. The length of this bore is 2,174 meters and the cross sectional area of the tunnel is 53 m^2. The grade of the tunnel ranges from -3.76 percent to +3.76 percent with no significant level portion. Each tunnel has walkways, one side being 75 cm wide and the other 85 cm wide, on each side of the bore. Figures 4 and 5 show the horizontal and cross sectional layouts of the tunnel.

The individual bores are supplied by two sets of supply ducts, east and west, and two sets of exhaust ducts, also east and west. Each supply duct and exhaust duct is supplied by three 3-speed fans, for a total of 12 fans per tunnel. During the course of this study, the exhaust fans were shut off while only one supply fan running at the lowest speed at each end of the tunnel. These fans are rated at 60 - 65 m^3/s in the lowest speed position (Pierson, 1992).

The study at the Fort McHenry Tunnel consisted of 32 one-hour samples between 00:01 AM EST Monday July 12th and 7:00 AM EST Thursday July 15th, 1993. The sampling periods for this study were 0000-0100, 0100-0200, 0200-0300, 0300-0400, 0600-0700, 1000-1100, 1100-1200, 1200-1300, and 1300-1400. These sampling times were chosen to obtain data for a wide variety of vehicle compositions. Table 5 contains run dates and times, vehicle counts, traffic composition, and the calculated emission factors for each run.

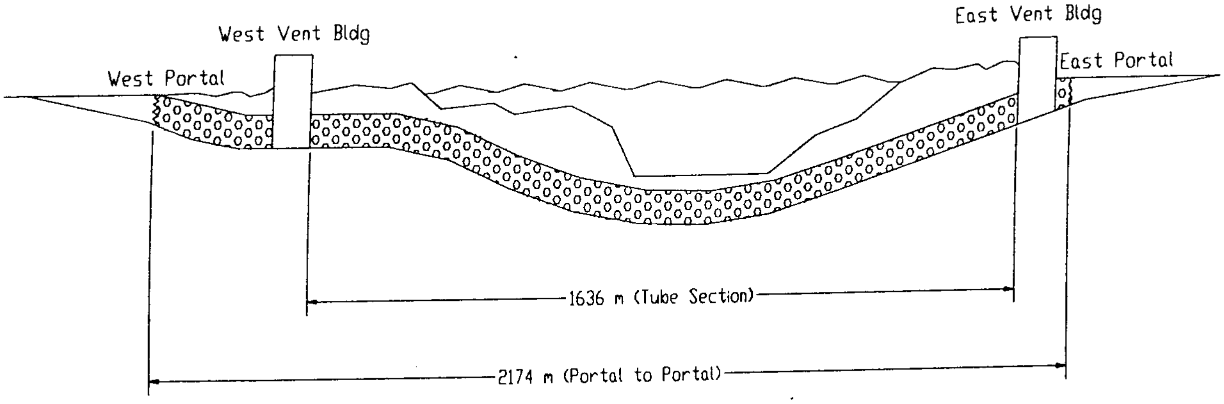

Figure 4. Horizontal view of the Fort McHenry Tunnel.

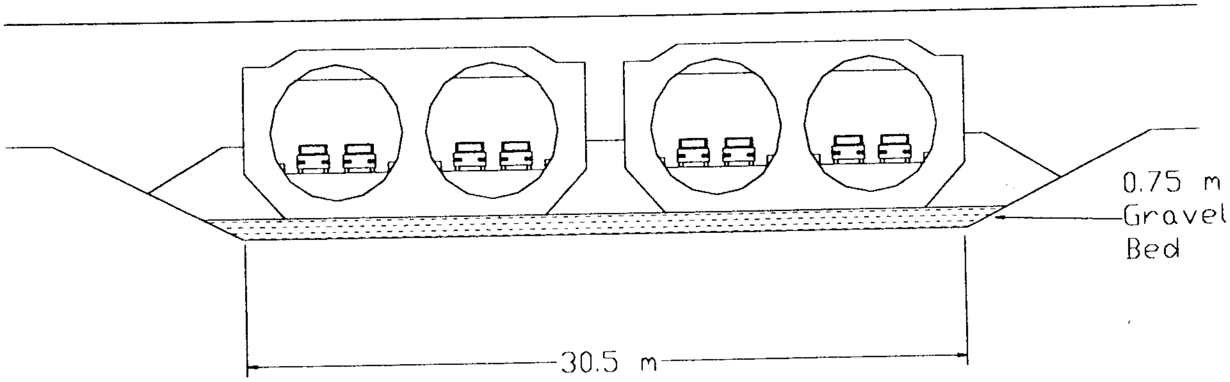

Figure 5. Cross sectional view of the Fort McHenry Tunnel.

Table 5. Run Times, Total Vehicle Counts, Vehicle Fraction, and Emission Factors for the Fort McHenry Tunnel

Run Time			Fraction of Vehicles		Emission Factors
Date	Time (EST)	Total Vehicles	Spark Ignition	Heavy Duty Diesels	(g/veh-mi)
7/12/93	0000 - 0100	659	0.83	0.17	0.168
	0100 - 0200	642	0.74	0.26	0.172
	0200 - 0300	587	0.71	0.29	0.103
	0300 - 0400	491	0.60	0.40	0.235
	0600 - 0700	662	0.72	0.28	0.129
	1000 - 1100	599	0.68	0.32	0.188
	1100 - 1200	901	0.64	0.36	0.193
	1200 - 1300	1196	0.68	0.32	0.116
	1300 - 1400	1486	0.73	0.27	0.111
7/13/93	0000 - 0100	512	0.84	0.16	0.287
	0100 - 0200	531	0.78	0.22	0.250
	0200 - 0300	485	0.71	0.29	0.261
	0300 - 0400	484	0.52	0.48	0.317
	0600 - 0700	676	0.71	0.29	0.236
	1000 - 1100	588	0.64	0.36	0.338
	1100 - 1200	862	0.64	0.36	0.285
	1200 - 1300	1043	0.65	0.35	0.149
	1300 - 1400	1299	0.69	0.31	0.161
7/14/93	0000 - 0100	704	0.86	0.14	0.261
	0100 - 0200	533	0.74	0.26	0.348
	0200 - 0300	382	0.62	0.38	0.370
	0300 - 0400	368	0.43	0.57	0.479
	0600 - 0700	706	0.70	0.30	0.259
	1000 - 1100	692	0.68	0.32	0.219
	1100 - 1200	893	0.67	0.33	0.220
	1200 - 1300	1112	0.70	0.30	0.148
	1300 - 1400	1427	0.72	0.28	0.128
7/15/93	0000 - 0100	193	0.56	0.44	0.589
	0100 - 0200	291	0.48	0.52	0.538
	0200 - 0300	369	0.49	0.51	0.454
	0300 - 0400	393	0.42	0.58	0.418
	0600 - 0700	705	0.70	0.30	0.305

Manhattan, NY Site

The Midtown Manhattan site, figure 6, is positioned on the east side of Madison Avenue between 47th and 48th Streets in New York City. The sampler was placed in a cyclone fence cage of dimensions approximately 2.5 meters long by 1.5 meters wide by 2 meters high and is located on Madison Avenue at street level. The west edge of this cage is less than 0.5 meters from the edge of the sidewalk, while the east edge is approximately 5 meters from the face of the nearest building. This building is 40 stories tall occupying the whole block with major entrances on the south side of the building, facing 47th Street. There is a minor entrance to this building on the west side adjacent to the sampling site. The area between the sampler site and the office building face is always occupied during the daylight hours with many pedestrians walking back and forth and may lead to some contamination from pedestrians smoking as they walk by. Additional surrounding buildings are exclusively small retail stores, with the smallest being approximately four stories tall. The risk of particulate contamination from nearby restaurants is unlikely.

The site is adjacent to a major bus stop on Madison Avenue. The bus stop extends from the southeast corner of Madison and 47th for approximately 100 meters along Madison Avenue. The sampler site itself is approximately 25 meters from the corner of 47th and Madison and surrounded to the north and south by the bus stop. Bus frequency is as great as 240 per hour (this is discussed in greater detail in chapter 2). In addition, there is the added contribution of buses stopping and idling for as long as 10 minutes prior to departure. Idling along with acceleration away from the bus stop may lead to an increase in diesel emissions.

The Midtown Manhattan site is part of the New York State long term monitoring network. Ambient sampling at this site took place between noon on April 14, 1993 and noon April 16, 1993. A total of 12, 4-hour samples were taken during this time period.

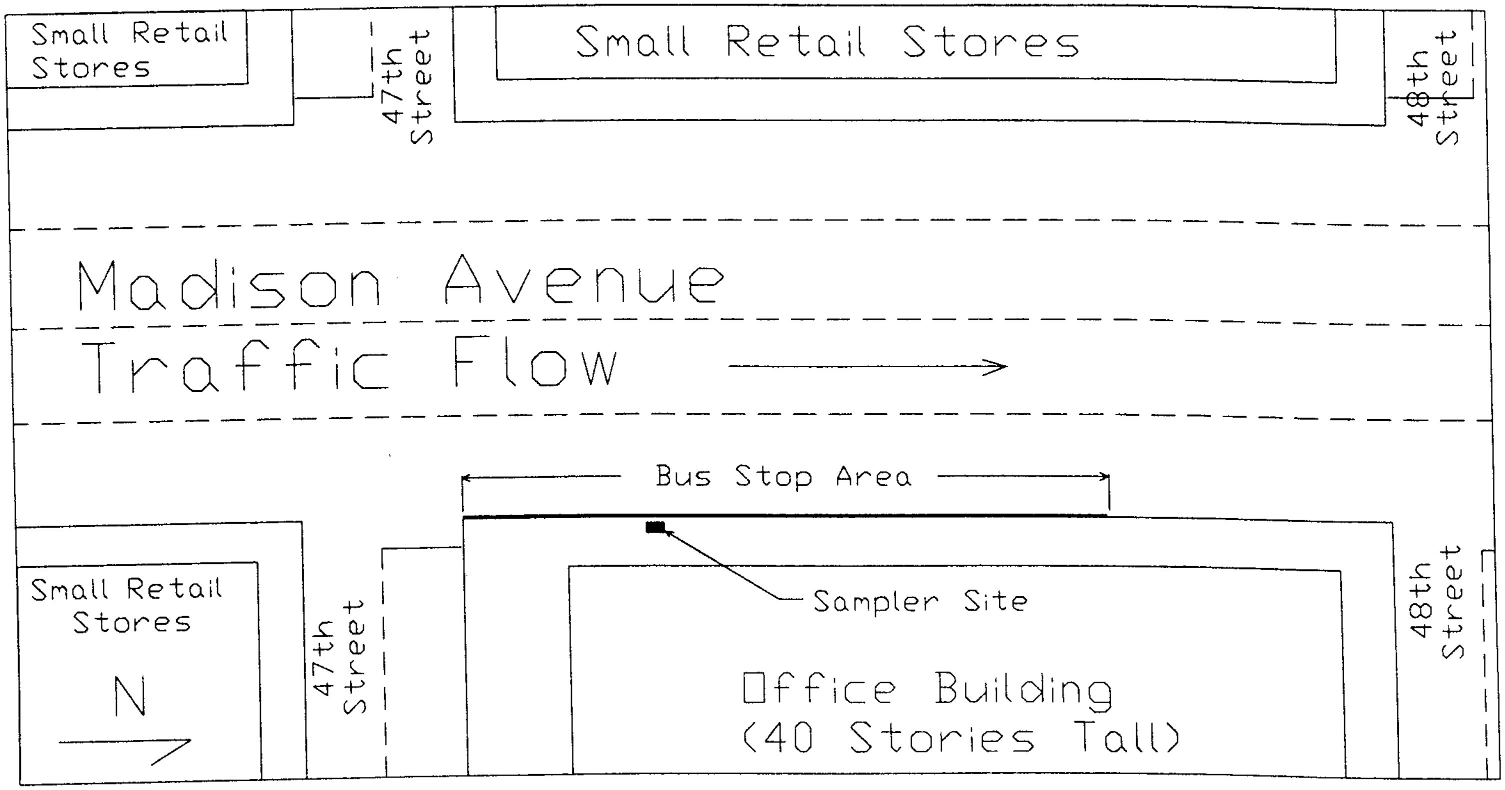

Figure 6. Midtown Manhattan site.

ROAD SANDING AND SALTING SITES

Albany NY Site

The sampling site in Albany, NY was located near the corner of the heavily traveled intersection of State Route 7 and Wade Road. A schematic of the site and the surrounding area is shown in figure 7. The sampler was placed adjacent to state Route 7 on a pallet raised roughly 1.3 meters off the ground. This site was approximately four meters from the edge of Route 7, and was surrounded by snow covered low shrubs and grass. The sampler was positioned 20 meters from the corner of a county administrative complex which lies about 16 meters distance from Route 7. An access road for the county building is located 20 meters to the east of the sampler, and a side road is located 100 meters to the west. These roads could be additional sources of resuspended road salt.

Route 7, which has an average 24-hour traffic flow volume of approximately 13,000 vehicles, is normally salted with a mixture of 10 percent salt and 90 percent sand. However, during March of 1993, the material used was 100 percent salt. Nonetheless, it should be noted that there was sanding material left upon the roads from previous applications. Therefore, during the analysis of this data, it should be possible to separate out a road sand portion from the data, as well as the salting portion. It should also be noted that Route 7 was salted approximately once a day during good weather with the possibility of multiple salt material applications during stormy periods.

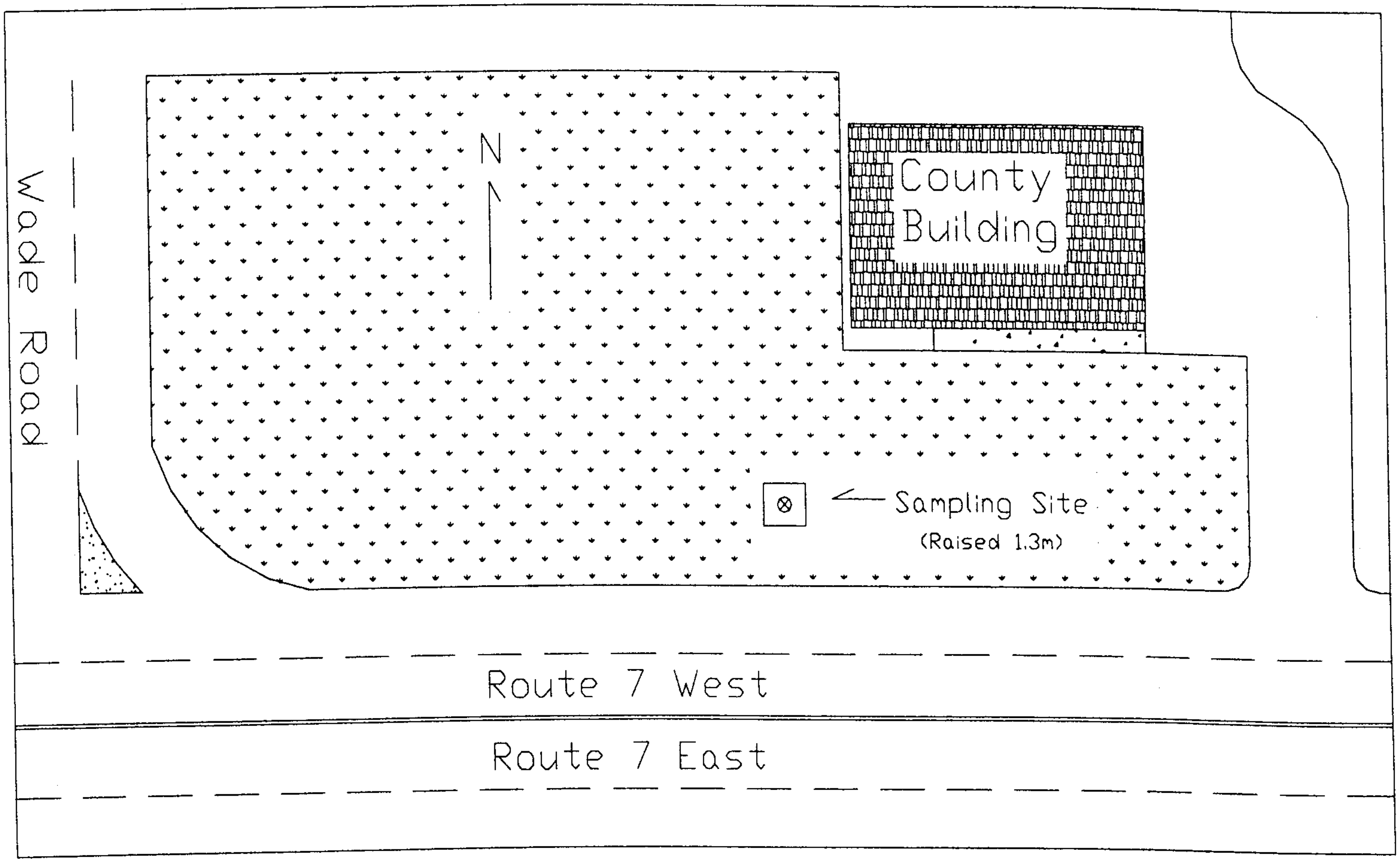

Figure 7. Location of sampler at the Albany, NY site.

Denver, CO Site

The site chosen for sampling in Denver, Colorado was located on a two story building set back approximately 17 meters from the edge of Broadway Boulevard (see figure 8), adjacent to a Colorado Department of Health (CDH) sampler at the same location. Broadway is a major four lane urban road which receives approximately 30,000 thousand vehicles per 24-hour period. The posted speed limit on this road is 35 mph, but speeds of 10 mph higher and lower than the posted speed limit were observed.

The sampler was positioned upon a building in the Gates Rubber Factory complex. This building is separated from the four lane road by a standard width sidewalk and by a stretch of lawn from the sidewalk to the edge of the building. Two hundred meters to the north is a little used access road, while four hundred meters to the south lies a major employee parking lot with a short access road from Broadway.

There was no regular sanding schedule for Broadway. It was sanded approximately every day during storms, and roughly every week between storms.

Interstate 25 is located approximately 0.5 kilometers to the north of the site. The vehicle flow volume on the Interstate is approximately 270,000 per 24-hour period, and could contribute to PM-10 levels at the sampling site.

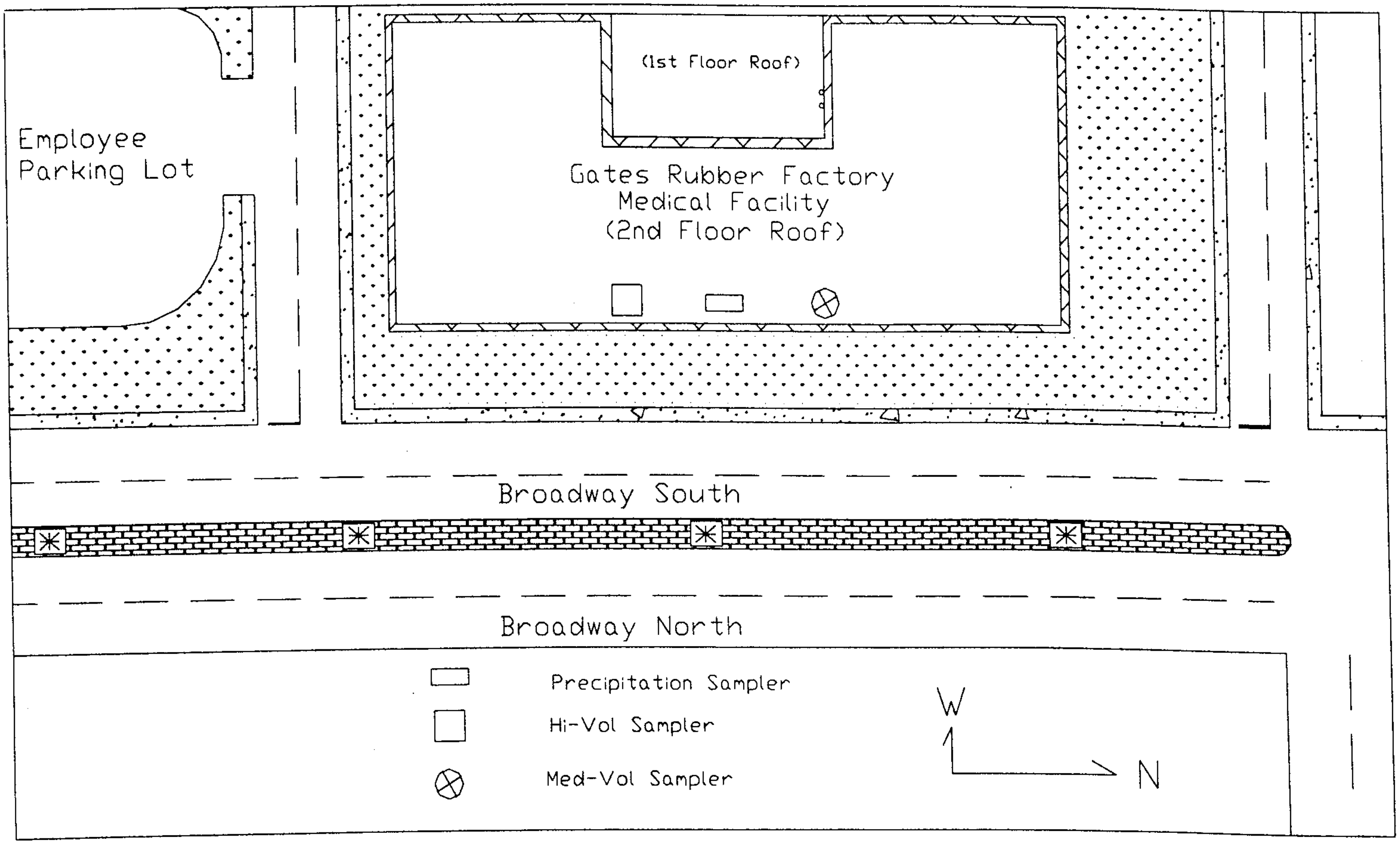

Figure 8. Diagram of sampling site in Denver, CO.

Reno, NV Site

The site in Reno, Nevada made use of the Washoe County Health Department (WCHD) air quality monitoring site positioned in downtown Reno. Approximately three meters from the sampler position was a high-volume sampler operated by the WCHD. The site is positioned on a platform approximately three meters high in an empty parking lot in downtown Reno (see figure 9). Roughly 100 meters to the west of this site was a busy urban four lane road, Lake Boulevard. The area between the site and this road is occupied by a paved parking lot that is sparsely used during the winter. To the south approximately 125 meters was another busy four lane road, East Second Street. There are no buildings directly between the sampling site and East Second, but immediately adjacent to the corner of East Second Street and Lake Boulevard is a older model motel. The motel is surrounded on the north and east by a pay parking lot. This parking lot was half filled during the time of the sample changes (~0730 hours). These two major roads were sanded on a regular basis throughout the course of this study, while vehicle traffic flows were, on average, greater than 10,000 vehicles per road per day.

One hundred meters to the north lay two sets of railroad tracks. These were used very infrequently during the study. A freight company was located roughly 75 meters to the northeast, and had a traffic flow of approximately 3 trucks an hour, with a greater volume in the early morning and in the late afternoon. These trucks were short-trailer, heavy-duty diesels. A two-lane side road curves around the site from an east-west direction 20 meters north of the site to a north-south direction 10 meters east of the site. This street was lined with metered parking, and usually had vehicles present. Immediately to the east of the site was a small unpaved section of ground used for parking. This area was occupied by vehicles daily.

A fire station resides 80 meters to the southeast of the site. The sporadic nature of the fire department activity should not play a major contributing role to the ambient PM-10.

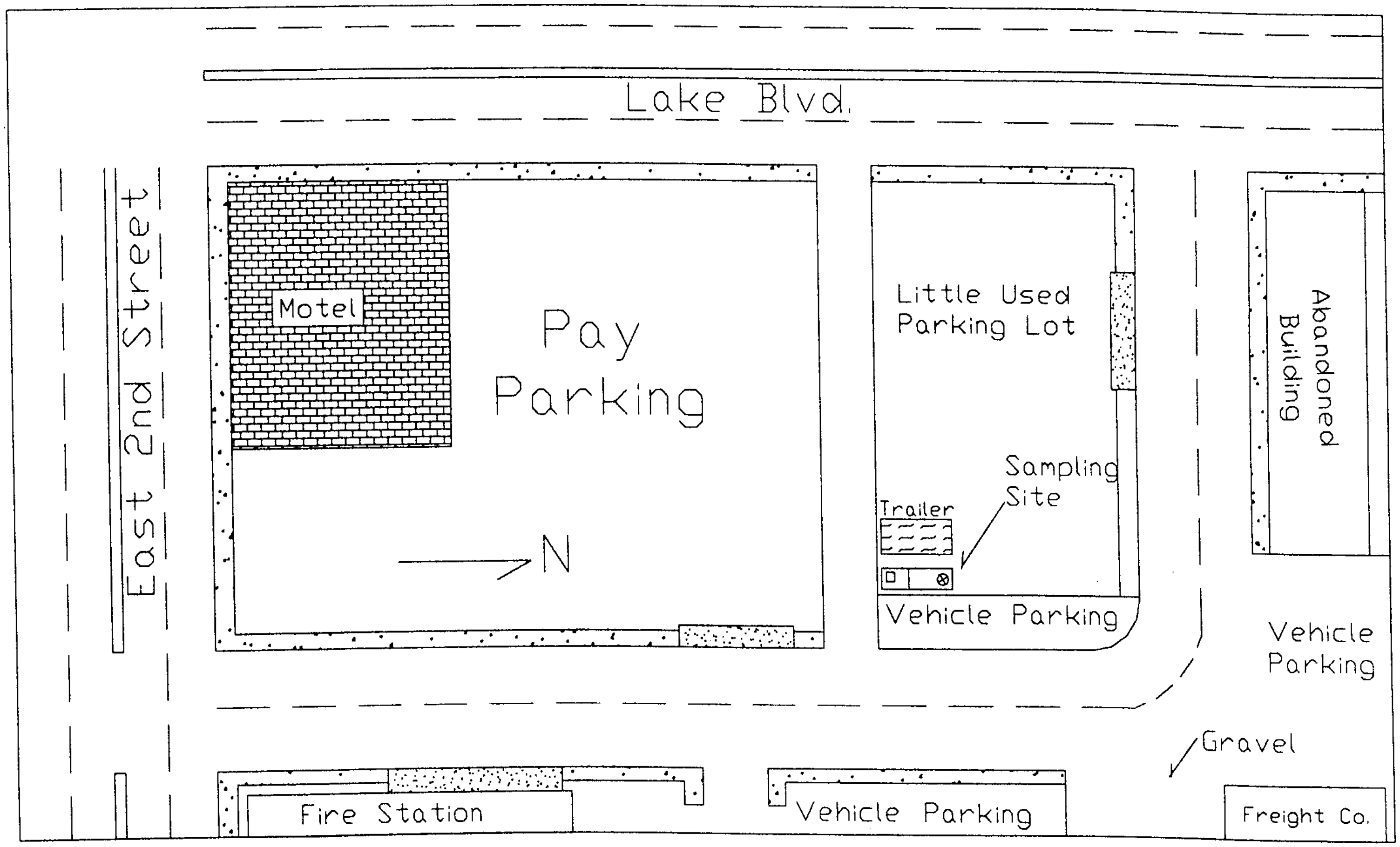

Figure 9. Location of the sampler at the Reno, NV site.

RESUSPENDED ROAD DUST SITES

Phoenix, AZ Site

The Phoenix, AZ sampling site was located immediately adjacent to an urban four lane boulevard, Hayden Blvd., on the outskirts of Phoenix. This site was chosen because of the prevailing afternoon winds, normally perpendicular to the flow of traffic. The site consisted of two areas, the upwind site, located on the west side of Hayden Blvd., and the downwind site, located on the east side of Hayden Blvd. (see figure 10). Equipment at the upwind site included a DRI MEDVOL sampler, a TEOM sampler, and a trailer containing the control equipment for the TEOM sampler. The downwind site contained three DRI Sequential samplers positioned at various heights (see figure 3), a TEOM sampler, a Dichot sampler, and a trailer containing the control instrumentation for the TEOM and Dichot samplers, along with the on-site meteorological instrumentation. Both sites were surrounded by 1.9 meter chain-link fences. Representative vehicle counts are shown in table 6.

Table 6. Representative Traffic Counts for Hayden Blvd. in Phoenix, AZ During the 1200 to 1800 Sampling Periods

Date	North Traffic	South Traffic	Total Traffic
June 2, 1993	8458	10787	19245
June 3, 1993	8847	10981	19828
June 9, 1993	8290	13502	21792

The upwind site was positioned on a gravel/dirt area separating the southbound lanes of Hayden Blvd. and the 1m wall bordering the property of Saint Daniel the Prophet Catholic Church. The DRI sampler sat approximately 4m from the edge of Hayden Boulevard. with a 1.5m sidewalk adjacent to the road. The entrance to the Church parking lot was 24.6 meters to the north of the sampler. The parking lot was lightly used during the week, with a maximum hourly vehicle flow of 10 vehicles per hour after 1600 hours. Traffic flow into the parking lot would be significant on the two Sundays during the study (May 30 and June 6, 1993). However, counts were not available for those time periods.

Approximately 37m south of both sampling sites lay Roosevelt Drive. This two lane road carried approximately 20 percent of the traffic volume carried on Hayden Boulevard. But even with the smaller volume of traffic, this road could conceivably contribute primary mobile source emissions to the sampling sites during periods of unfavorable winds.

The downwind site was located at the east edge of Hayden Boulevard, approximately 3.5m from the edge of the road. The site was placed on a gravel/dirt surface with bushes and shrubs sparsely placed to the north and south of the site. A bus stop was located approximately 30.8m to the north of the samplers. Buses stopped here approximately once every 30 minutes, and would not contribute significantly to ambient PM-10 levels.

For dispersion modeling purposes the samplers at the down wind site were placed in a vertical array with inlet heights of 1.9m, 2.7m, and 5m. Identical to the upwind site, the downwind site was enclosed by a 1.9m high chain link fence.

Spokane, WA Site

The Spokane, WA site was located adjacent to a four-lane commuter road, Division Boulevard, which received heavy traffic flowing southward in the morning and northward in the evening (see figure 11). Traffic counts were not available. The DRI PM-10 Sequential sampler was located on the west side of Division Blvd. and was set approximately 3.7m back from the edge of the road. The sampler inlet was approximately 2m off the ground. The edge of a 1.5m sidewalk was approximately 1.25m from the edge of Division Blvd.. An anemometer was placed approximately 12.5m from the edge of Division Blvd. directly west of the DRI sampler. A generator used for power was placed approximately 3.1 meters to the west of the anemometer. An array of eleven SF_6 samplers were set up in a line immediately adjacent to Division Boulevard, with four portable PM-10 samplers spaced evenly among the SF_6 samplers.

The sampling equipment was set at the edge of a city park which had many trees present around the edge of the outside boundaries. These trees were not immediately adjacent to the DRI PM-10 sampler, or between the sampler and the roadway. Thus, the on-site vegetation would have no immediate effect on the ambient sampling.

The sampling at this site coincided with SF_6 tracer sampling performed by Washington State University (WSU) personnel. The location of these samplers along with that of portable PM-10 samplers used by WSU are shown in figure 11, along with the tracer release site. The scope of this report does not entail any discussion or presentation of results from the WSU sampling. Thus there is no discussion of wind direction/wind speed values in this report.

Examination of the surrounding roadways and sidewalks show that there were large concentrations of geological material (sand, dirt, etc.) present on these paved surfaces. There was also a large amount of geological material present in the grass adjacent to the sampling site and, in general, in the park where the sampling equipment was located. This large concentration of geological material could probably be the source of the geological material seen in chapter 7.

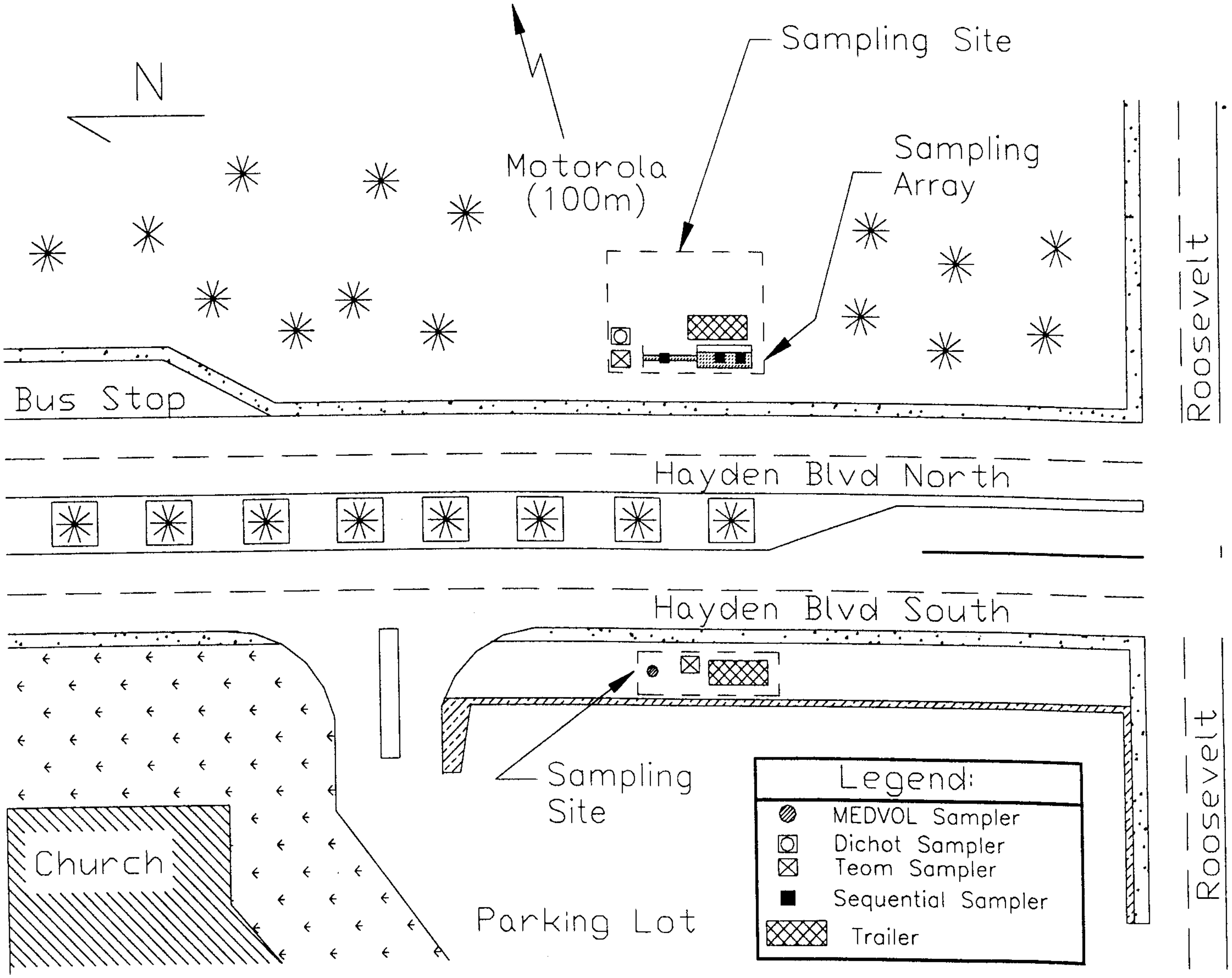

Figure 10. Diagram of Phoenix, AZ sampling site and surrounding area.

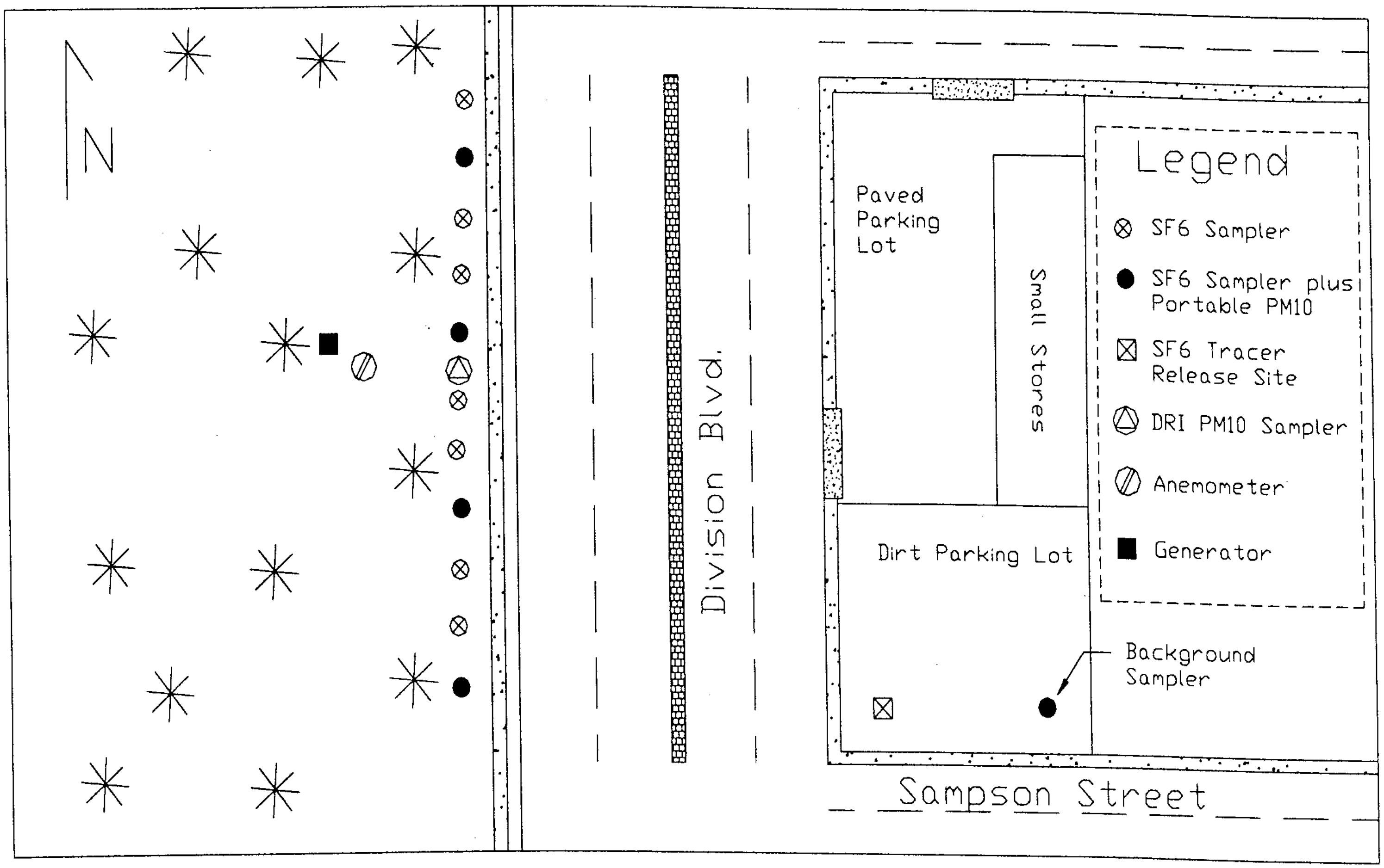

Figure 11. Spokane, WA sampling site.

CHAPTER 5: RESULTS OF DIESEL EMISSIONS STUDY

This chapter focuses on the results of the diesel emissions portion of this study.

FORT MCHENRY TUNNEL

The study at the Fort McHenry Tunnel consisted of a total of 32 separate 1-hour runs (table 5). A plot of emission factor vs. vehicle fraction is shown in figure 12 for the observed fleet. The method for regressing this data used an analytical weighting of the data with respect to the total number of vehicles during the run. In other words, a run with 1400 vehicles would count more strongly than a run with only 200 vehicles. This was performed using the program STATA (STATA Reference Manual, 1992) and its AWEIGHT function. We believe this is more representative of the data set than an unweighted regression. The values obtained were 0.015 ± 0.060 and 0.67 ± 0.13 g/veh-mi for the spark ignition vehicle and the heavy-duty diesel vehicle fleets, respectively. Uncertainties were obtained by using the standard error given by the regressions of the data. This does not take into account any systematic or measured uncertainty.

Particulate emission factors for both the spark ignition and heavy-duty diesel vehicles are lower than the ones reported by Pierson and Brachaczek (1983) (table 7). The main reason for this difference is that the emission factors as reported by Pierson and Brachaczek are for total suspended particulate, not PM-10. Other possible reasons for the differences include, for the spark ignition vehicles, the decrease in automobile emissions due to the increased use of catalysts, the phase-out of leaded fuel, and the increased use of computers in regulating automobile efficiency that have occurred since 1981. These could explain the decrease by a factor of three from the earlier values.

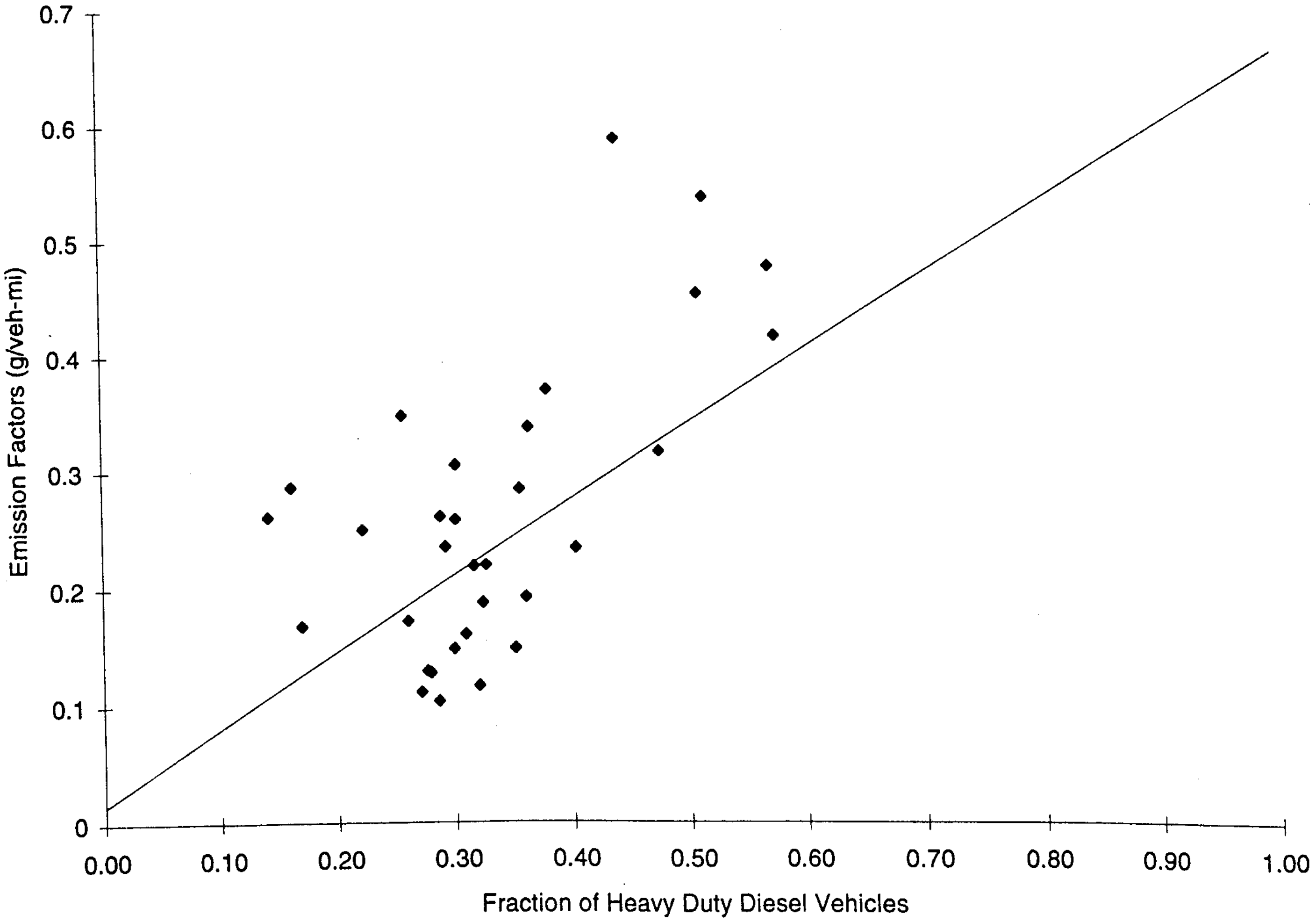

Figure 12. Plot of emission factors vs. fraction of heavy duty diesels.

Table 7. Summary of Previous and Current Values for On-road Vehicle Particulate Emission Factors

Study	Spark Ignition Vehicles	Heavy Duty Diesel Vehicles
Pierson and Brachaczek (1983)	0.040 ± 0.035	1.40 ± 0.16
This Study (1993)	0.015 ± 0.060	0.67 ± 0.13

The observed emission rate of the current heavy duty diesel fleet has decreased compared with the older fleet. The reduction of the particulate emission factors by a factor of two over the older fleet is likely the result of improved technology and/or the change in composition of diesel fuel.

MIDTOWN MANHATTAN SITE

Vehicle Distributions

A minimal number of vehicle counts were obtained during the Manhattan study. The results of these counts are summarized in table 8. The purpose of these counts was not to correlate the observed number of vehicles, but to demonstrate that there is a high percentage of bus traffic by the site. For the two periods the numbers of cars were relatively constant, while numbers of trucks and buses were greatest in the morning.

Table 8. Two Representative Traffic Counts Taken During the Course of the Midtown Manhattan Study

4/14/93	1610 - 1620	4	197	5	17
4/15/93	0850 - 0900	1	202	16	40

CMB Results

The model results for the twelve sampling periods along with the average of the sampling periods are summarized in table 9 and figure 13. For all periods, the diesel component was the major source of the observed PM-10 loadings. Model performance was good with excellent fitting parameters. The model overpredicted the observed mass by 30 percent. This overprediction was centered in the crustal elements due to the use of the Phoenix source sample coupled with the iron sample. It may also be due, in part, to volatilization of some of the organic carbon leading to a low measured mass. Future studies at this site should obtain a site specific road dust sample. If anything, these deficiencies lead to an underestimate of the diesel and light-duty contributions.

For specific time periods, the diesel contribution varied between 30.9 and 67.5 percent of the total particulate loadings with an average contribution of 53 percent of the ambient PM-10 mass. Autos contributed between 0 and 20.6 percent with an average of

5.9 percent. The total mobile source related contribution (diesel, auto, and road dust) was responsible, on average, for over two-thirds of the ambient PM-10 mass. Sea salt contributed approximately 6 percent on average, while ammonium sulfate and nitrate, the transport related components, were responsible for 22 percent of the predicted mass.

The overwhelming contribution of diesel emissions is shown graphically in figure 13. The two lowest fractions are for the midnight to 0400 time period, while the highest contributions are from the early morning, 0400 to 0800, runs. To fully evaluate these results, information on the traffic composition, the traffic flow, and the local meteorological information is required.

Figures 14a and 14b show the apportionment's during the periods of maximum and minimum PM-10 mass. Both cases indicate that the contribution of the diesel overwhelms the other species. Figure 14b indicates that there was a greater than average amount of sea salt present compared to the average amount (figure 14c). This is probably due to an off-ocean air flow, and would also account for the lower than normal amount of diesel emissions. A sea breeze would effectively "clean out" the diesel and auto contributions in the area.

Table 9. Summary of Results of CMB Analysis for Midtown Manhattan Site

	Start Time	Fitting Parameters		Mass (μg/m^3)		Percent Contributions							
Date	(EST)	r^2	c^2	Measured	Predicted	DIESEL	AUTO	RD	MARINE	AMSUL	AMNIT	REOILC	FEORE
4/14/93	1200	0.99	0.11	47.76	79.88	55.09	13.77	11.92	0.52	4.32	10.75	0.43	3.19
4/14/93	1600	0.99	0.19	70.43	91.88	55.74	2.93	10.06	1.30	6.02	18.18	1.06	4.70
4/14/93	2000	0.99	0.20	53.80	72.79	50.29	5.59	7.82	2.71	7.67	19.30	2.44	4.19
4/15/93	0000	0.99	0.08	49.66	61.83	30.90	20.60	4.88	2.38	11.01	25.56	1.17	3.50
4/15/93	0400	0.99	0.25	68.06	80.56	55.32	2.91	6.72	1.04	9.14	20.42	1.21	3.25
4/15/93	0800	1.00	0.04	68.47	100.45	47.79	15.93	9.76	1.28	8.58	11.63	0.41	4.62
4/15/93	1200	1.00	0.07	50.87	70.13	45.72	11.43	10.25	4.18	13.73	11.84	0.44	2.42
4/15/93	1600	0.98	0.30	82.96	96.11	45.84	11.46	6.21	5.40	14.44	11.05	0.78	4.82
4/15/93	2000	0.99	0.21	49.84	55.36	40.87	10.22	4.92	12.37	13.74	11.89	1.20	4.80
4/16/93	0000	0.97	0.46	35.82	41.38	36.86	4.10	9.86	21.47	12.20	11.42	0.89	3.19
4/16/93	0400	0.99	0.15	50.98	63.49	60.51	0.00	8.04	14.43	6.47	6.26	1.62	2.66
4/16/93	0800	0.98	0.29	69.14	95.32	67.52	3.55	5.38	12.37	1.50	3.24	0.87	5.56
Average		1.00	0.07	58.15	75.75	52.81	5.87	8.55	5.90	8.69	13.22	1.00	3.97

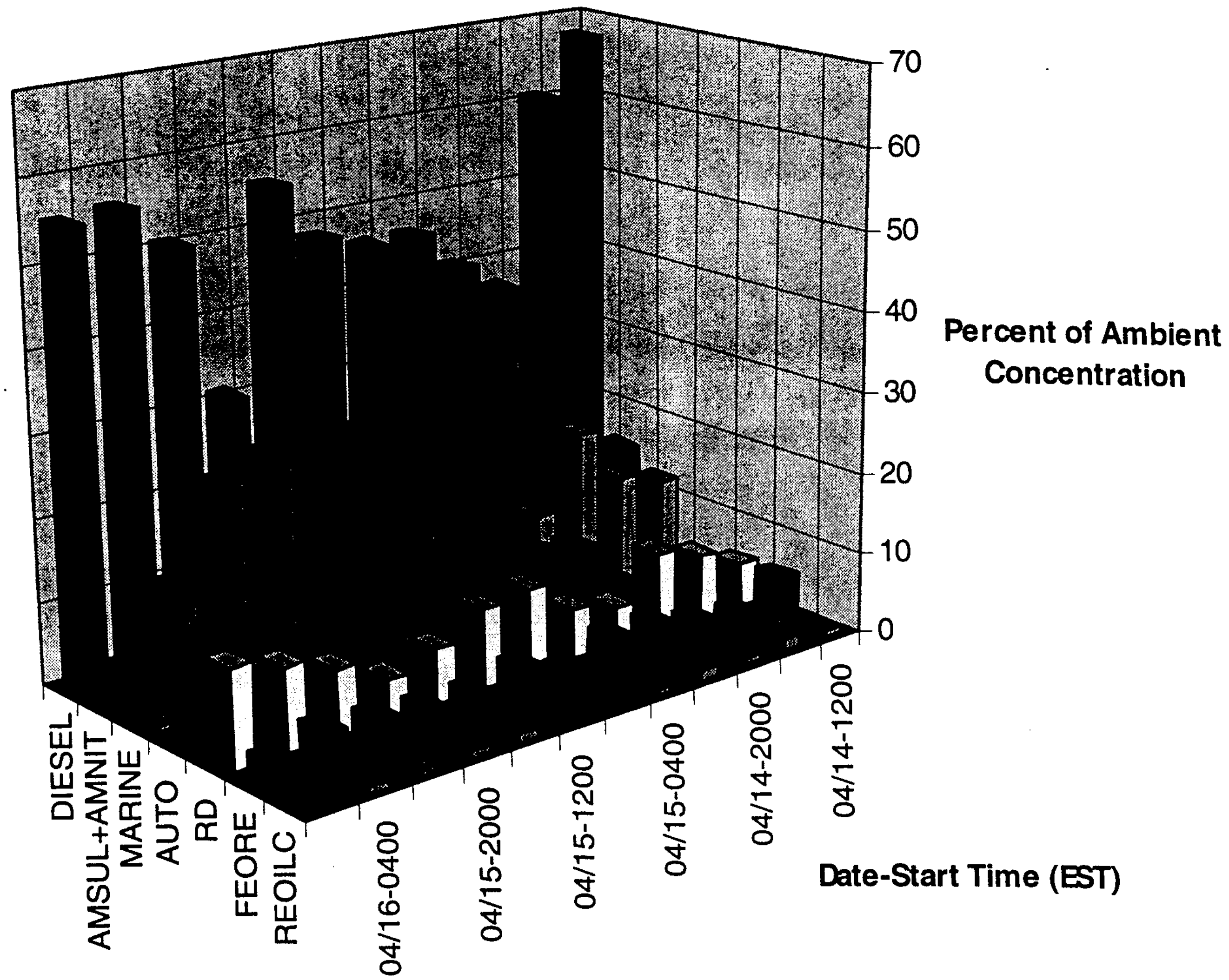

Figure 13. Percent contributions to ambient PM-10 for Midtown Manhattan site.

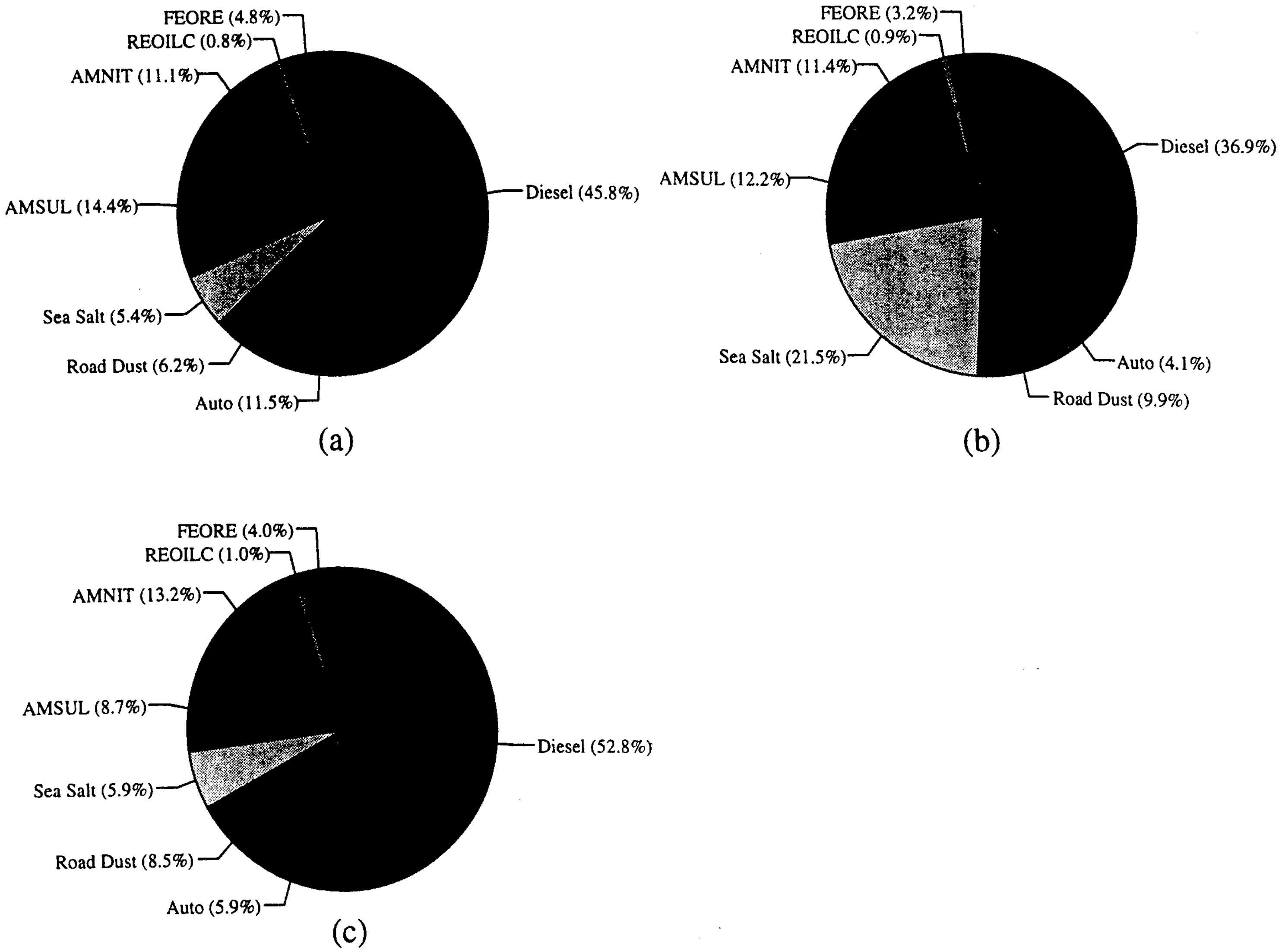

Figure 14. Percent contributions for PM-10 concentrations for the Midtown Manhattan site.

(a) maximum (82.96 μg/m^3), (b) minimum (35.82 μg/m^3), and (c) average (58.15 μg/m^3)

SUMMARY OF DIESEL EMISSIONS STUDY

Studies designed to assess the contributions of heavy duty diesel particulate emissions on ambient PM-10 concentrations were performed in the Fort McHenry Tunnel and at a site in midtown Manhattan. On-road particulate emission factors were measured at the Fort McHenry Tunnel. The observed heavy duty diesel particulate emission factor of 0.67 ± 0.13 g/veh-mi was almost 45 times greater than the spark ignition emission factor of 0.015 ± 0.060 g/veh-mi. The diesel emission factor observed was lower by a factor of two from studies of the same nature performed in the late 1970s.

CMB source apportionments performed at the Manhattan site found, on average, 53 percent of the ambient PM-10 mass was the result of primary diesel emissions. For all the sampling time periods, the observed diesel contribution was between 31 percent and 68 percent. Overall, autos contributed between 0 percent and 21 percent with an average of 6 percent. Diesel emissions combined with auto and resuspended road dust sources accounted for over two-thirds of the observed PM-10 mass. The remainder of the mass was made up of, on average, 6 percent sea salt, 22 percent long range transport, 4 percent iron ore, and <1 percent residual oil combustion.

CHAPTER 6: RESULTS OF ROAD SANDING AND SALTING STUDY

This chapter focuses on the effects of road sanding and salting material on ambient PM-10 levels.

ALBANY, NY SITE

Sampling was performed at the Albany, New York site from March 7 to March 9, 1993 and from March 17 to March 27, 1993. Four 6-hour samples were taken daily during the time periods of 0000-0600, 0600-1200, 1200-1800, and 1800-0000 hours (EDT). A total of 21 of the 56 samples taken were analyzed. The results of these analyses were then used to perform a source apportionment for the site. The summary of the results are shown in table 10.

The reason for sampling during these dates was to determine, for a worst case scenario, the effects of sanding and salting of urban roads after a major storm. The sampler was first started on March 7th , immediately after a storm had just passed through Albany, leaving approximately eight inches of snow on the ground. The sampling was then stopped on the 9th to allow the passage of another major storm moving into the area, which dropped up to 28 inches of snow in the Albany area. This storm lasted approximately seven days and sampling was resumed on the 17th and continued for the next ten days. Meteorological records show that on the 17th, there was 20 inches of snow on the ground, while on the last day of sampling, the 27th, there was approximately 2 inches of snow present.

The modeling of the data was performed using a motor vehicle profile from Phoenix (MVPHNX), an old road sand profile (SAND), a resuspended road salt profile (ALBSLT) obtained from the New York Department of Transportation, and AMNIT, AMBSUL, and AMSUL combined in table 10 under the heading Secondary. Figure 15 graphically shows these results.

The modeling results in table 10 show that the fitting parameters ranged from poor (3/24/93, 0000-0600) to very good, with the overall fittings as good. The mass (predicted)/(measured) ratios, shown graphically in figure 16, also vary widely, ranging in values from ~266 percent (3/21/93, 0600-1200) to as low as 78 percent (3/26/93, 1800-2400). Neglecting the two time periods with predicted mass greater than 190 percent (3/24/93, 1800-0000, and 3/21/93, 0600-1200) the average (predicted)/(measured) mass ratio was over-predicted by ~6 percent. This is within the uncertainty for this model.

Table 10. Summary of Results from the Albany, NY Site

	Start Time	Fitting Parameters		Mass (μg/m^3)		Percent Contributions			
Date	(EDT)	r^2	c^2	measured	predicted	Motor Vehicle	Road Sand	Road Salt	Secondary
3/20/93	0000	0.95	0.52	48.52	47.14	29.10	34.26	22.78	13.85
3/20/93	0600	0.94	0.83	22.42	34.28	24.07	20.54	27.01	28.35
3/20/93	1800	0.96	0.52	22.64	24.66	22.14	20.24	23.36	34.18
3/21/93	0000	0.90	0.89	12.92	18.91	32.52	12.64	10.68	44.16
3/21/93	0600	0.92	0.60	6.30	16.76	23.99	2.33	7.10	66.65
3/22/93	1200	0.92	0.79	12.97	16.79	14.41	12.92	13.76	58.90
3/22/93	1800	0.97	0.32	17.18	19.56	19.63	23.31	15.64	41.41
3/23/93	0600	0.98	0.33	59.86	61.51	15.28	23.20	48.94	12.58
3/23/93	1200	0.98	0.28	30.35	32.54	19.73	37.98	17.15	25.48
3/24/93	0000	0.65	2.83	16.25	20.47	53.54	8.16	2.44	35.81
3/24/93	1800	0.93	0.51	10.12	19.30	42.02	28.24	2.49	27.15
3/25/93	0000	0.98	0.10	10.39	13.05	32.41	13.10	1.38	53.10
3/25/93	1200	0.95	0.43	36.46	29.96	19.19	60.78	11.21	8.78
3/25/93	1800	0.96	0.37	58.60	50.45	14.67	68.84	9.47	7.00
3/26/93	0000	0.94	0.46	36.81	32.68	41.16	30.75	3.64	24.42
3/26/93	0600	0.97	0.46	54.98	52.01	20.21	40.63	18.73	20.23
3/26/93	1200	0.95	0.48	40.37	35.69	17.04	64.22	4.79	13.93
3/26/93	1800	0.93	0.75	132.27	102.99	14.21	74.96	5.52	5.30
3/27/93	0000	0.97	0.36	50.74	49.77	18.97	53.31	3.90	23.83
3/27/93	0600	0.98	0.32	60.47	51.84	11.57	51.50	8.89	28.03
3/27/93	1200	0.97	0.32	35.70	39.21	11.09	63.94	4.95	20.02
Average		0.98	0.28	36.97	36.87	22.32	44.16	13.56	17.28

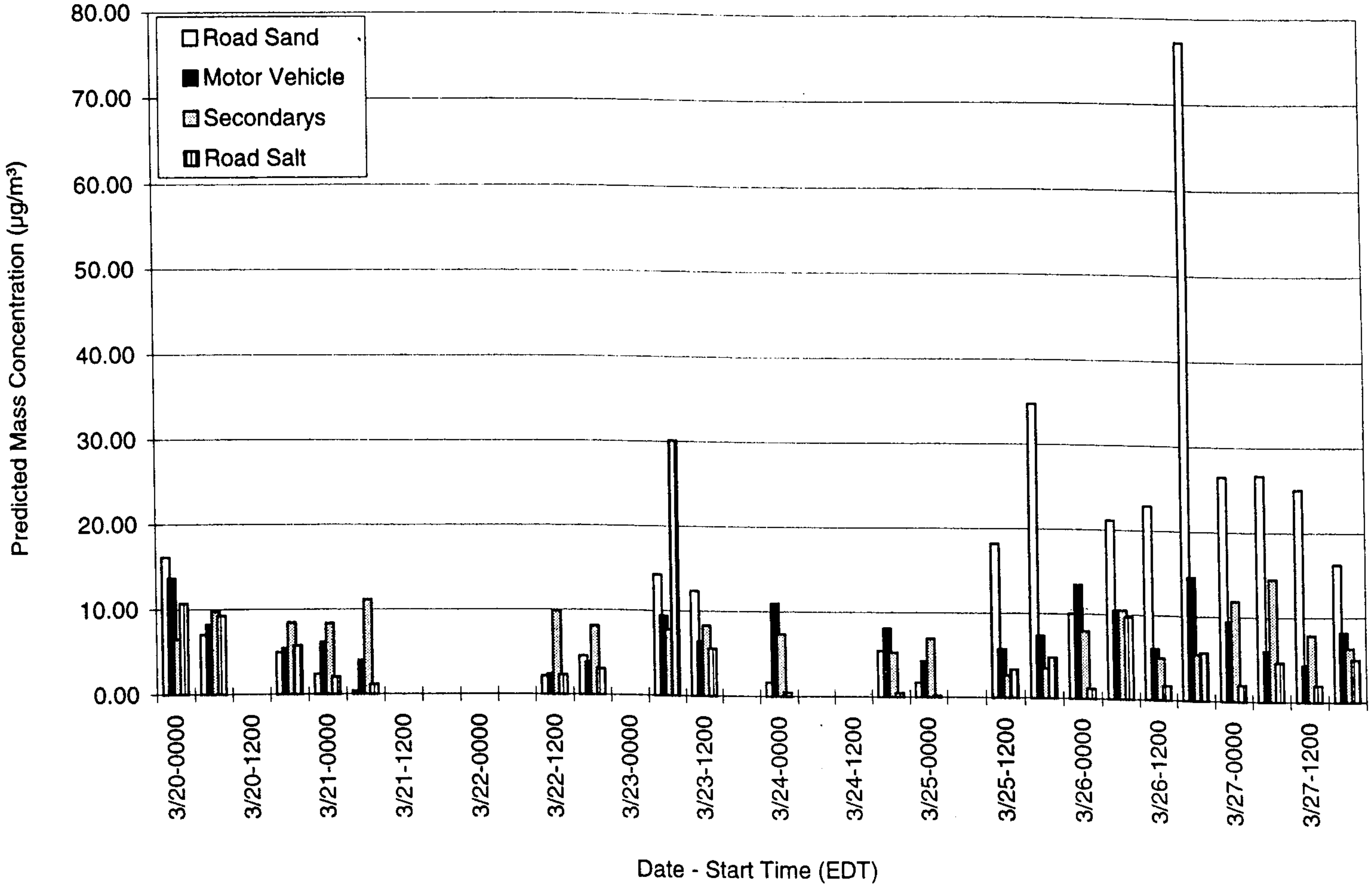

Figure 15. Predicted source contributions to ambient PM-10 at the Albany, NY site.

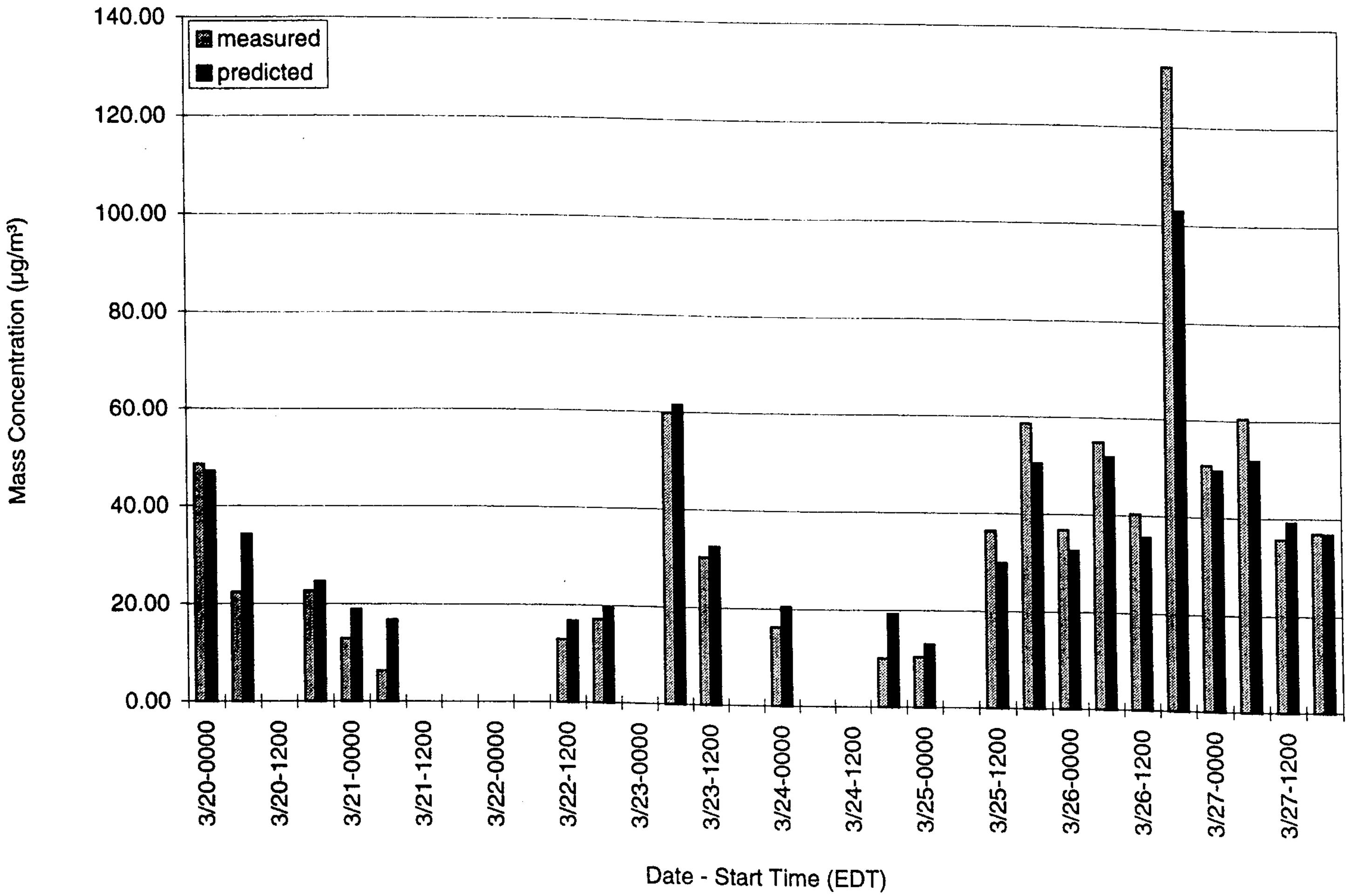

Figure 16. Predicted vs. measured concentrations for the Albany, NY site.

For specific time periods, the contribution of road salt ranged from 1 percent to ~49 percent of the ambient PM-10 levels. Motor vehicle contributions in general ranged from ~11 percent to greater than 54 percent, with an average contribution of ~22 percent. The road sand was unexpectedly high, averaging greater than 44 percent with a high of 75 percent. The secondary material (AMNIT and AMSUL) averaged >17 percent over the sampling periods, with higher levels being built up from 3/20/93 to 3/22/93 and 3/23/93 to 3/25/93. The examination of meteorological data for the area shows that the decrease of secondary pollutant levels on 3/22/93 can be directly attributed to an increase in local wind, whereas the decrease on 3/25/93 cannot be explained by this data.

The amount of contribution by the road sand to ambient concentrations was unexpected since during the month of March, only salting material is used. The road sand profile used during the modeling was very high in aluminum and silicon, but did not contain substantial calcium to fit the data observed. Thus the possibility arises that there is another source of geological or road dust material in the area to contribute to the observed calcium levels. But during the sampling periods, the surrounding area was covered with snow, and thus the additional source of calcium could not be a geological source. Therefore, calcium was not used as a fitting parameter.

Figures 17a and 17b show the apportionments during the periods of maximum and minimum PM-10 mass. During the maximum PM-10 mass, the resuspended sanding material overwhelms the other material present, while during the minimum PM-10 period, the secondary pollutants overwhelm the other fitting constituents. The average contributions, shown in figure 17c, present a more balanced distribution of all the fitting species, but still contain a very large road sanding portion. As discussed previously, the large contribution of road sanding material is surprising considering that sand was not applied during the sampling period and was only present from previous applications.

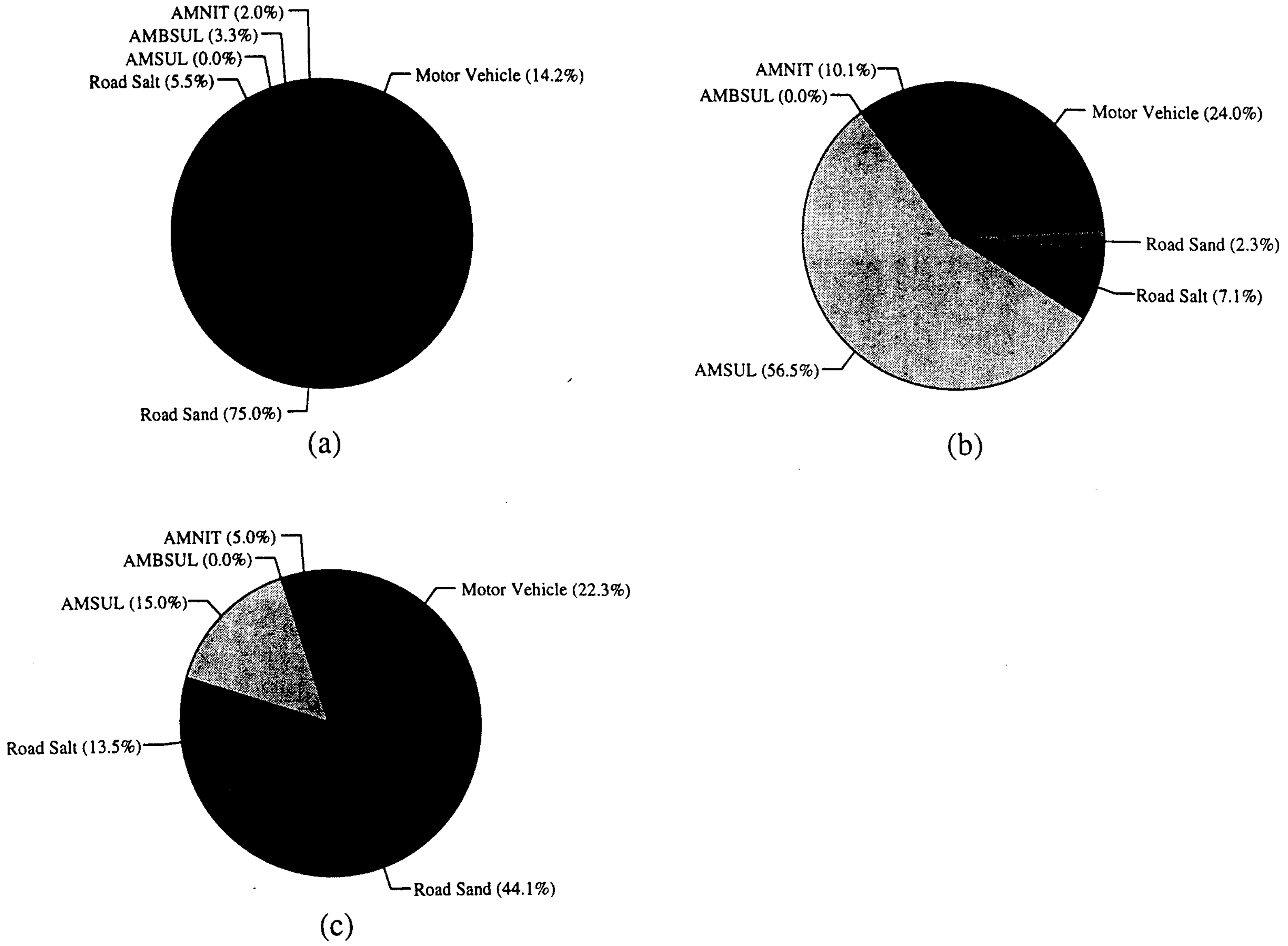

Figure 17. Percent contributions for PM-10 concentrations for the Albany, NY site.

(a) maximum (132.27 μg/m^3), (b) minimum (6.30 μg/m^3), and (c) average (36.97 μg/m^3)

DENVER, CO SITE

The purpose of the sampling at Denver was to observe PM-10 levels and to determine, by modeling, the source apportionment under typical winter conditions. The term "typical" is used here to describe an area which did not experience an unusual snow event, and in which the accompanying road sanding material was present continuously on the streets. Meteorological records show that throughout the entire sampling period, there was minimal or no snow on the ground, and only traces of snowfall throughout the time period.

Sampling was performed at the Denver, Colorado site from March 15 to March 25, 1993. Four 6-hour samples were taken daily during the time periods of 0000-0600, 0600-1200, 1200-1800, and 1800-0000 hours (MDT). A total of 24 of the 59 samples taken were analyzed. The results of these analyses were then used to perform source apportionments for the site. The summary of the results are shown in table 11.

The modeling of the data was performed using a motor vehicle profile (MVPHNX), a resuspended road sanding material profile (SAND), a constructed pure salt profile (NACL), and AMNIT and AMSUL combined in table 11 under the heading Secondary. Figure 18 graphically shows these results.

In general, the fitting parameters ranged from moderate to good (table 11) with r^2 values ranging from 0.83 to 0.98 and χ^2 ranging from 0.83 to 0.21. The mass (predicted)/(measured) ratios, shown graphically in figure 19, varied widely, ranging in values from >400 percent (3/24/93, 1200-1800) to as low as 91 percent (3/18/93, 0000-0600). The run with the (predicted)/(measured) ratio of >400 percent had a mass that was less than the uncertainty associated with that mass. Thus, this sample is not valid and will be discounted in further analyses. On average, the mass was over-predicted by 12 percent. While a little high, it is acceptable when the moderate fitting parameters and the range of the (predicted)/(measured) mass ratios are taken into account.

The modeling of the Denver data had two major difficulties associated with it. The first was the lack of a good sanding source profile. The sanding material from Denver was gathered approximately six months after the sampling took place. Sanding material was gathered at four different sites from two different agencies, City of Denver road maintenance facilities and the State of Colorado road maintenance facilities. These four samples were combined into a composite sample which was resuspended at the DRI facilities in Reno, Nevada. When resuspended, this sand source profile showed high amounts of salt present (table 3b, under Road Sand - DENSND). This salt was not present in the ambient data. Thus to fit the data, either the modeling must be done neglecting the salt component, or another sanding profile must be used. The latter option was chosen, and the sanding profile used for the Albany modeling (SAND) was used along with a pure salt profile (NACL).

Table 11. Summary of Results from the Denver, CO Site

	Start Time	Fitting Parameters		Mass (µg/m^3)		Percent Contributions			
Date	(MDT)	r^2	c^2	measured	predicted	Motor Vehicle	Road Sand	Road Salt	Secondary
3/17/93	0000	0.95	0.50	16.44	15.96	20.11	22.49	1.07	56.33
3/17/93	0600	0.94	0.68	30.40	27.74	23.29	33.89	3.82	38.97
3/17/93	1200	0.95	0.70	48.15	45.71	15.45	36.34	1.84	46.36
3/18/93	0000	0.98	0.21	36.96	40.57	10.60	31.35	0.62	57.46
3/18/93	0600	0.96	0.42	82.05	85.23	14.98	40.09	1.40	43.53
3/18/93	1200	0.90	0.56	18.77	20.80	24.52	69.42	1.15	4.90
3/18/93	1800	0.94	0.26	21.85	23.62	31.80	66.68	1.31	0.21
3/19/93	0000	0.87	0.53	23.42	31.23	40.03	59.11	0.90	N/A
3/19/93	1200	0.91	0.33	8.78	12.23	30.99	68.36	0.65	N/A
3/19/93	1800	0.91	0.36	6.78	8.08	28.96	64.85	N/A	6.06
3/20/93	1200	0.96	0.44	29.88	29.38	16.58	50.27	0.85	32.27
3/20/93	1800	0.97	0.27	41.78	45.24	13.95	62.95	0.77	22.30
3/21/93	0000	0.97	0.29	24.89	26.45	21.59	49.04	0.72	28.62
3/21/93	0600	0.94	0.37	10.03	11.06	23.69	48.37	0.81	27.22
3/21/93	1200	0.88	0.39	10.31	10.32	12.98	77.03	N/A	9.88
3/22/93	0000	0.93	0.27	12.52	14.52	36.43	60.26	0.62	2.55
3/22/93	0600	0.88	0.42	22.96	25.03	35.56	63.52	0.92	N/A
3/22/93	1800	0.88	0.56	26.53	30.93	11.06	83.32	0.65	4.95
3/23/93	0600	0.86	0.56	26.86	28.15	14.92	83.20	0.96	0.96
3/23/93	1800	0.85	0.70	12.37	27.05	31.13	68.17	0.67	N/A
3/24/93	0000	0.83	0.83	28.29	31.70	16.37	79.94	0.98	2.71
3/24/93	0600	0.87	0.65	20.73	29.82	19.95	78.03	0.77	1.24
*3/24/93	1200	0.85	0.67	3.23	13.24	11.93	83.23	0.98	3.85
3/24/93	1800	0.83	0.56	24.75	32.63	4.96	89.49	0.95	4.60
Average		0.95	0.37	24.53	27.47	19.04	59.08	1.13	20.75

* Measured mass is less than the calculated uncertainty

N/A = Source Profile was not used in the modeling.

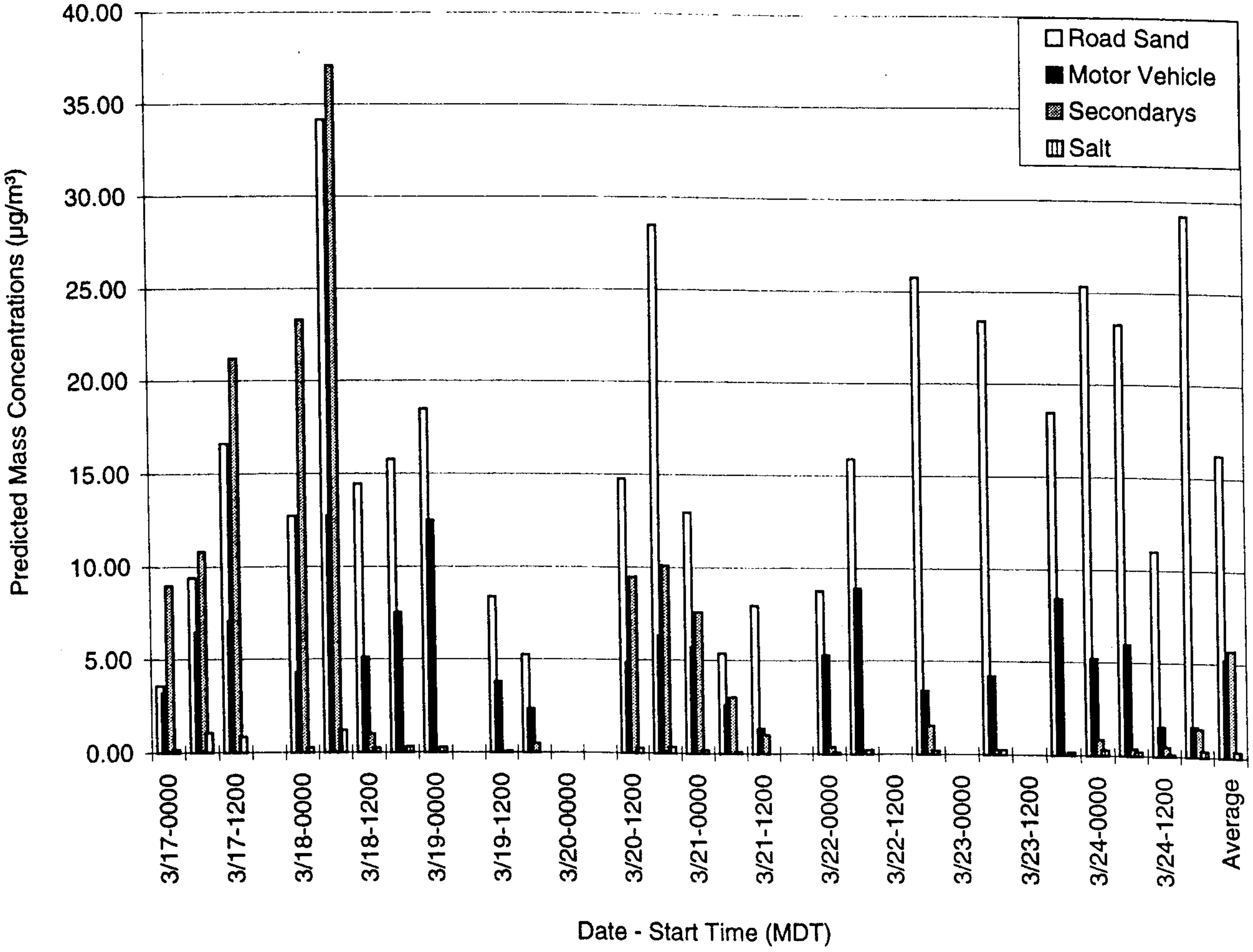

Figure 18. Predicted source contributions to ambient PM-10 at the Denver, CO site.

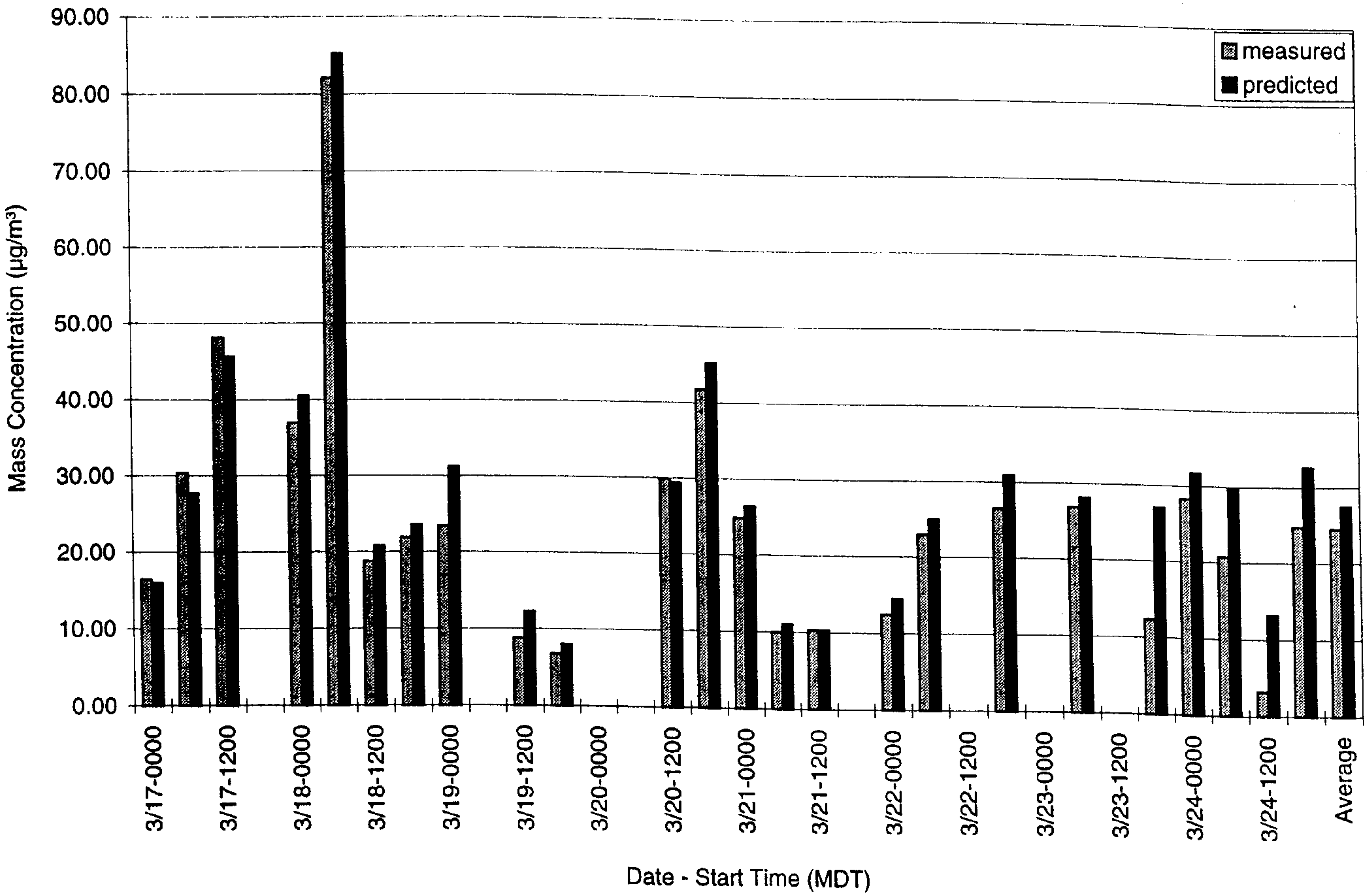

Figure 19. Predicted vs. measured mass at the Denver, CO site.

The second difficulty associated with the modeling of the Denver data was the unusually high amounts of organic carbon (OC) present in the ambient data. The unusually high (organic carbon)/(elemental carbon) ratio of 4.5 has been seen in previous studies (Watson et al., 1993) and can be explained by several possibilities. The excess may be due to secondary organic carbon formation in a relatively stagnant atmosphere. This does not seem to be the case in Denver, since the meteorological data shows that throughout the sampling period, the average wind speed was approximately 16 kh^{-1}. The second possibility resides with the quartz filter substrate used in the ambient monitoring. The quartz filters may have absorbed gaseous volatile organic carbon (VOC) species during the sampling. Therefore, the amount of organic carbon (OC) detected by TOR analysis would actually be greater than the particulate OC present. Examination of the OC temperature profiles showed higher than normal amounts of carbon detected during the initial temperature ramp to 120°C. This is a strong indicator of possible VOC contamination, but it is not conclusive. Therefore, since the source of excess OC cannot be confidently determined, the OC component was not used to model the Denver data.

For specific time periods, the contribution of sand ranged from ~23 percent to greater than 89 percent of the ambient PM-10 levels. On average, the sand contributed over 59 percent of the ambient PM-10 levels. Motor vehicle contributions were in general relatively low, ranging from 5 percent to just over 40 percent, with the average contribution of ~19 percent. Secondary (AMNIT and AMSUL) levels averaged >20 percent over the sampling periods, with values ranging from below quantification to greater than 57 percent with higher levels being present in the earlier sampling periods. The salt contributions were small, with values ranging from 0 to ~4 percent with an average of just over 1 percent.

Figures 20a and 20b show the apportionment's during the periods of maximum and minimum PM-10 mass. During the maximum PM-10 mass, the resuspended sanding material, the secondary material and the motor vehicle contributions account for 99 percent of the PM-10 level. The other 1 percent is the contribution from the salt. The minimum PM-10 period is dominated by contributions from the resuspended sanding material (65 percent) and the motor vehicle emissions (29 percent), with the remainder coming from secondary pollutants. The salt profile was not used to fit this data.

The average source contributions, shown in figure 20c, demonstrate a more evenly distributed apportionment than either the maximum or the minimum PM-10 results. Three sources, sanding material, secondary, and motor vehicles pollutants 99 percent of the PM-10 levels, while the salt portion only represents a small part of the makeup. On a per-species basis, the motor vehicle portion accounts for 19 percent, the secondary 21 percent, sanding material 59 percent, and salt 1 percent of the ambient PM-10 concentrations.

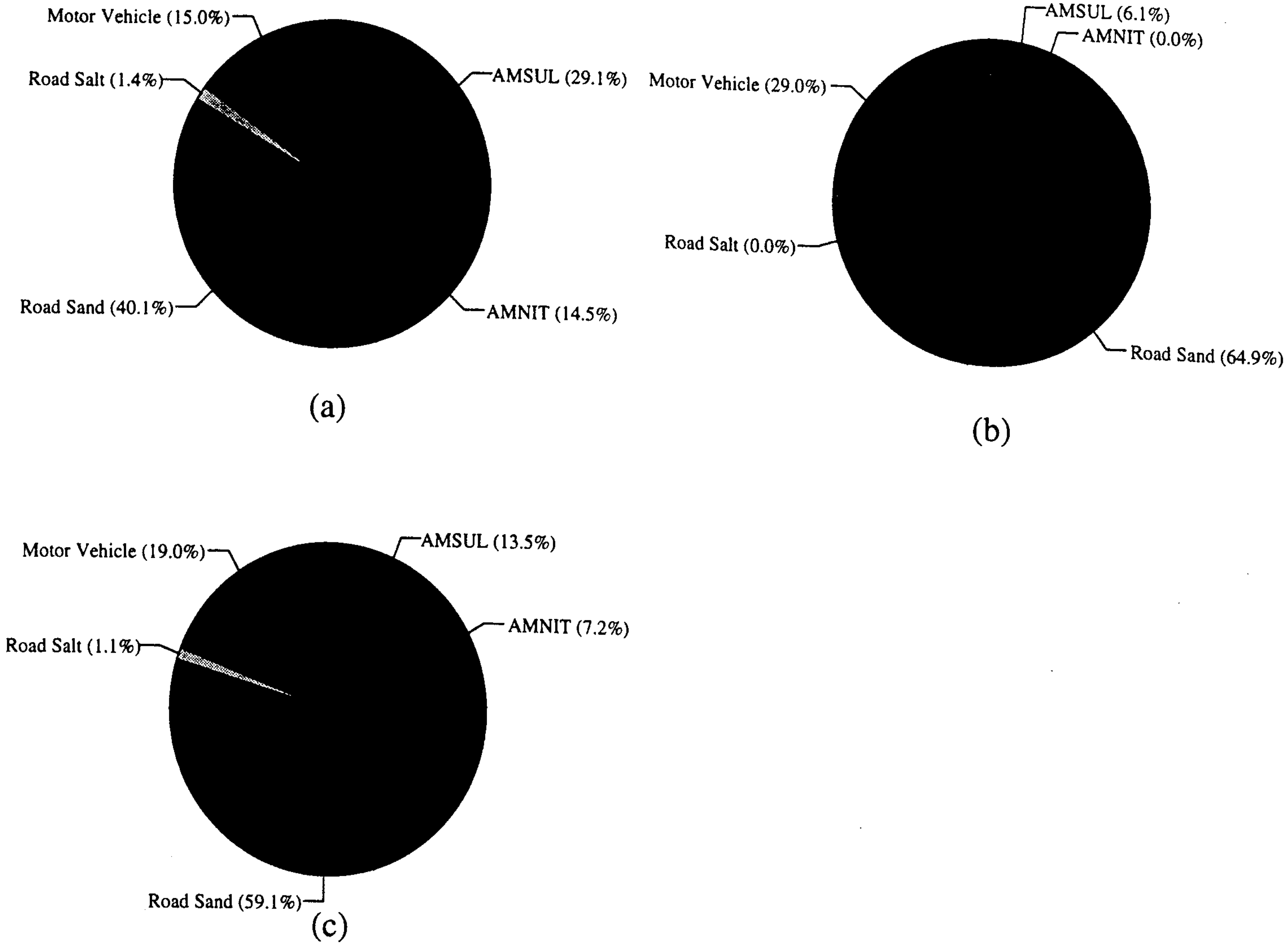

Figure 20. Percent contributions for PM-10 concentrations for the Denver, CO site.

(a) maximum (82.05 µg/m^3), (b) minimum (3.23 µg/m^3), and (c) average (24.53 µg/m^3)

RENO, NV SITE

The purpose of the sampling at Reno, Nevada was to observe PM-10 levels and to determine, by modeling, the source apportionment for an area which sporadically receives large quantities of snow over short periods of time. After these snow storms, large quantities of sanding material are dumped onto the area roads. Conditions in January of 1993 were optimum for this study. Sampling initially began on January 11, 1993, after the passage of a large storm which had dumped approximately 10 inches of snow on the local area. Sampling was suspended on January 13, 1993 as a series of storms entered the area. These storms dropped another 6 inches of snow over the next six days. Sampling resumed on January 19, 1993 after the passage of the storms and continued for the next nine days. When sampling resumed, there was approximately 12 inches of snow on the ground, while at the conclusion of the sampling, there was only a trace of snow present. During this time period, several small snow showers dropped up to half an inch of snow, but they were short lived.

Sampling was performed at the Reno site from January 11 to January 13, 1993 and from January 19 to January 28, 1993. Four 6-hour samples were taken daily during the time periods of 0000-0600, 0600-1200, 1200-1800, and 1800-0000 hours. Only 20 of the 54 samples taken were analyzed. The results of these analyses were then used to perform source apportionment's for the site. The summary of the results are shown in table 12.

The modeling of the data was performed using a motor vehicle profile (MVRENO), one of two resuspended road sanding material profiles (RNODRT, RNODST), a constructed salt profile (NACL), and AMNIT and AMSUL combined in table 12 under the secondary heading. The two sanding profiles used for the modeling are essentially the same (table 3b), with the major difference being that RNODRT profile contained salt, while the RNODST did not. The RNODRT profile is a composite of samples taken directly off the streets near the sampling sites, while the RNODST profile is a composite of samples taken from a street sweeper and the piles of sanding material used on the roads. The fitting of these profiles to the Reno site showed that the RNODRT over-predicted the amount of salt seen, whereas the RNODST sample under-predicted the salt present in the ambient samples. This leads us to believe that there is some combination of the two profiles being detected at the sampling site. Therefore, during the modeling the RNODST profile was used with the constructed salt profile (NACL) to accurately account for the salt present. Figure 21 graphically shows the results from the modeling.

The fitting parameters were excellent (table 12). The mass (predicted)/(measured) ratios were near optimum, ranging from 86 percent for the run on 1/28/93 from 1200 to 1800 to a high of 119 percent on 1/28/93 from 1800 to 0000. The average of all of the runs was 98 percent for the (predicted)/(measured) values. The predicted and measured values are shown graphically in figure 22.

Table 12. Summary of Results from the Reno, NV Site

Date	Start Time (PDT)	Fitting Parameters		Mass (μg/m^3)		Percent Contributions			
		r^2	c^2	Measured	Predicted	Motor Vehicle	Road Sand	Road Salt	Secondary
1/22/93	1800	0.99	0.15	62.40	57.32	16.29	80.11	1.19	2.41
1/23/93	0600	0.99	0.10	47.89	48.33	19.35	72.54	0.95	7.14
1/23/93	1200	0.99	0.18	36.84	36.64	10.43	73.55	1.91	14.08
1/23/93	1800	0.99	0.22	105.24	95.00	21.63	69.04	1.69	7.63
1/24/93	0600	0.99	0.22	102.08	88.99	18.08	64.85	1.37	15.70
1/24/93	1200	0.98	0.28	109.70	103.69	17.97	62.64	1.10	18.29
1/25/93	0000	0.98	0.29	58.45	60.23	24.39	57.88	1.38	16.67
1/25/93	1200	0.99	0.23	131.81	120.13	14.37	67.52	0.64	17.47
1/25/93	1800	0.99	0.25	128.02	120.74	20.27	61.59	1.15	17.00
1/26/93	0000	0.99	0.14	39.29	39.37	28.47	36.73	0.56	34.21
1/26/93	0600	0.99	0.17	47.76	48.03	27.69	36.21	0.42	35.67
1/26/93	1200	0.99	0.15	72.32	64.27	18.30	53.49	0.93	27.28
1/26/93	1800	0.99	0.15	63.03	59.79	28.80	40.93	0.47	29.80
1/27/93	0000	0.99	0.09	40.82	41.97	32.88	29.93	0.19	37.00
1/27/93	1800	0.99	0.18	67.00	71.00	24.46	40.27	0.69	34.56
1/28/93	0000	0.98	0.25	62.75	68.96	21.10	40.15	0.51	38.24
1/28/93	0600	0.99	0.14	80.50	77.34	20.42	49.24	0.52	29.84
1/28/93	1200	0.98	0.45	144.37	124.35	15.48	64.39	1.00	19.12
1/28/93	1800	0.99	0.26	90.36	107.03	21.98	61.95	1.27	14.80
1/29/93	0000	0.99	0.20	75.45	71.20	22.99	63.67	1.00	12.35
Average		0.99	0.16	78.30	76.59	21.80	57.34	0.94	19.90

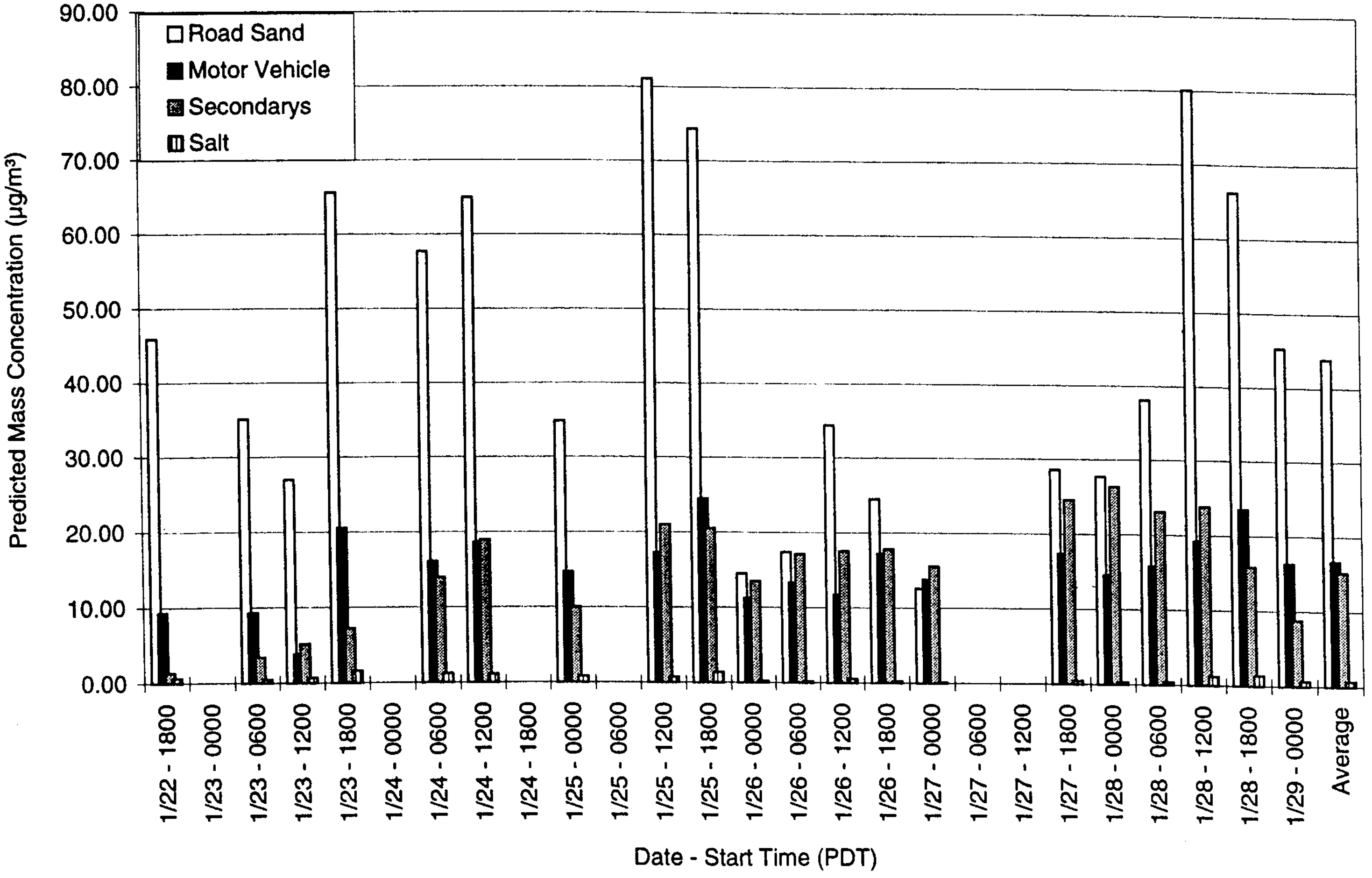

Figure 21. Predicted source contributions to ambient PM-10 at the Reno, NV site.

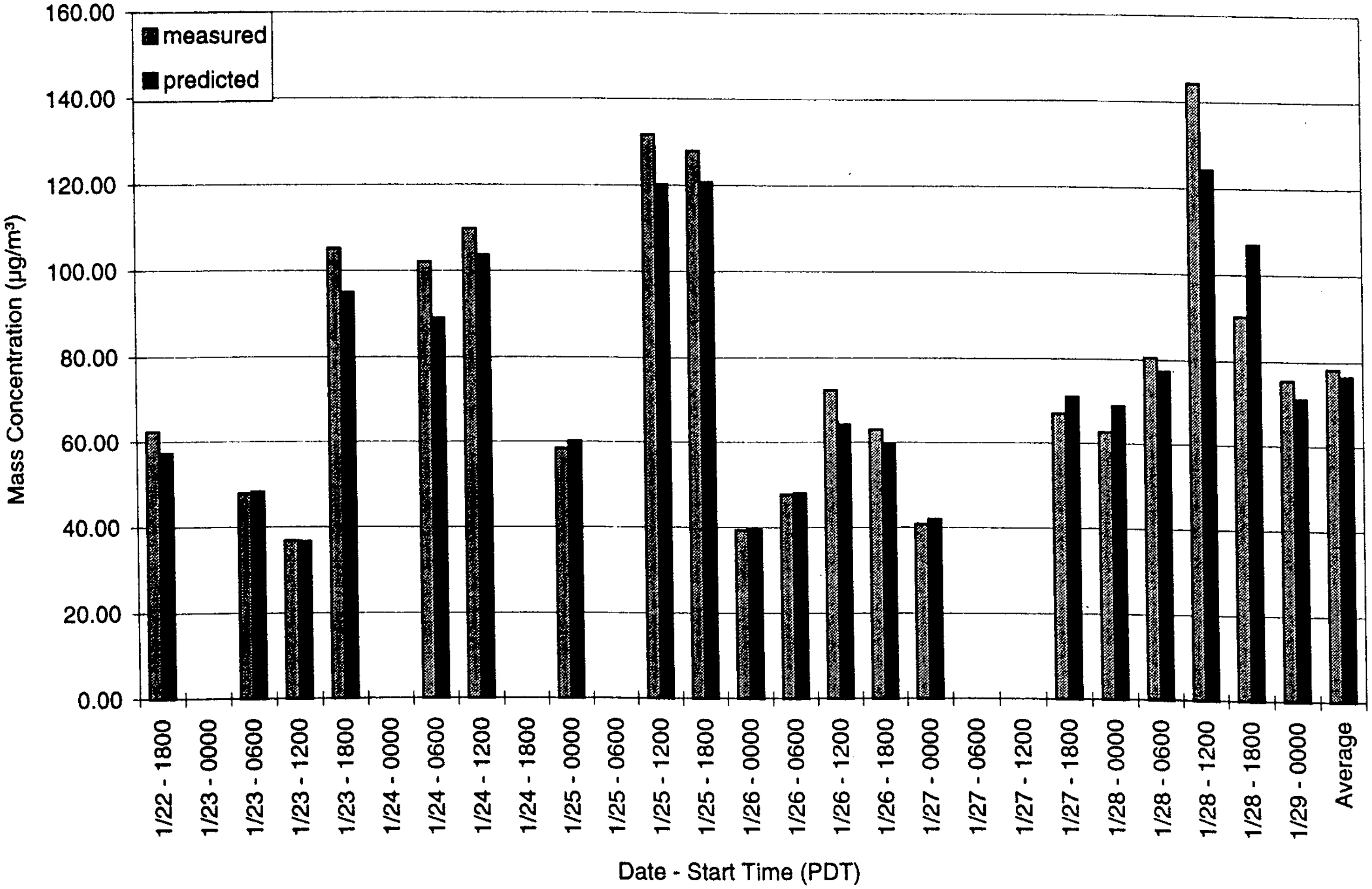

Figure 22. Predicted vs. measured mass at the Reno, NV site.

For specific time periods, the contribution of road sand ranged from ~30 percent to over 80 percent of the ambient PM-10 levels. On average, the road sand contributed over 57 percent of the ambient PM-10 levels, similar to that seen in Denver. Motor vehicle contributions ranged from ~10 percent to 33 percent, with the average contribution of ~22 percent. Secondary (AMNIT and AMSUL) levels averaged >19 percent over the sampling periods, with values ranging from >2 percent to a little over 38 percent. The contribution of salt to ambient PM-10 levels amounted to approximately 1 percent over all the sampling periods.

The time period from 1/24/93 to 1/28/93 shows a rise and fall in the amount of secondary pollutants present. During the same time period, the amount of road sand present decreased noticeably, with the values rising again as the secondary levels decreased. The reason for this trend is unclear at this time.

Figures 23a, b, and c show the apportionments for the periods of maximum and minimum PM-10 mass, and for the average PM-10 mass for all time periods, respectively. The values of 64 percent, 74 percent, and 57 percent for the maximum mass, minimum mass, and the average, respectively, demonstrate the dominance of the resuspended sanding material on ambient PM-10 levels.

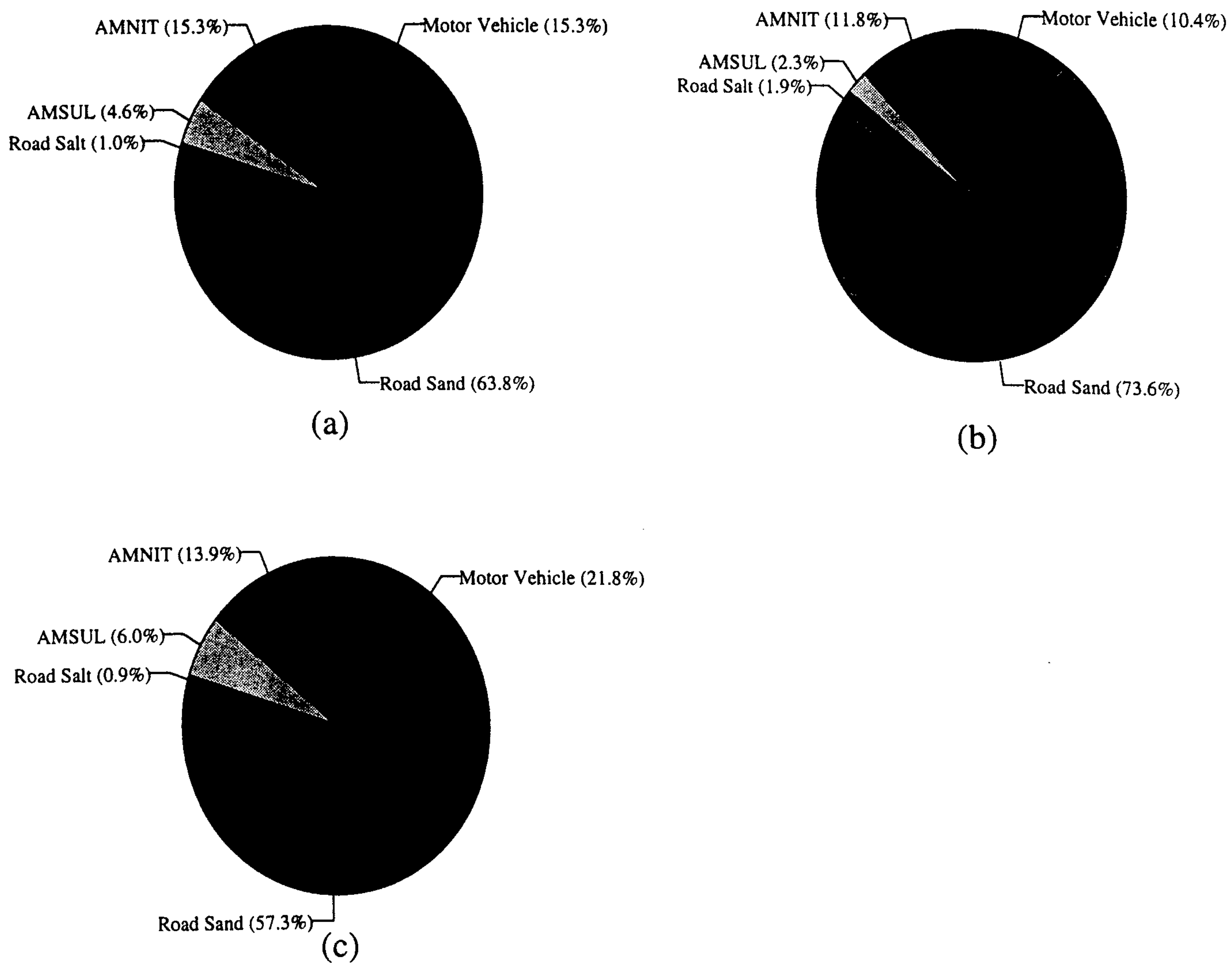

Figure 23. Percent contributions for PM-10 concentrations for the Reno, NV site.

(a) maximum (144.37 µg/m^3), (b) minimum (36.84 µg/m^3), and (c) average (78.30 µg/m^3)

SUMMARY OF ROAD SANDING AND SALTING STUDY

The purpose of this portion of the study was to seek a better understanding of the contributions of road sanding and salting material to ambient PM-10 levels. The three sites sampled (Albany, NY, Denver, CO, and Reno, NV) provided three different situations during the winter months. These sites represented, respectively, a worst case scenario for road salting material, a typical case for road sanding material, and a worst case scenario for road sanding material.

The site in Albany had an average PM-10 level of 37 $\mu g/m^3$ over the time periods analyzed. Of this, approximately 44 percent could be directly attributed to the resuspension of road sanding material left from previous sandings of the roads. The road salting material, although heavily used throughout the study, contributed only about 13 percent to the ambient PM-10 levels. The observed sand portion of the PM-10 is the result of sand left upon the road from road treatments previous to the sampling periods. This shows that even in a heavy road salting environment, any road sanding material present will contribute a greater amount to ambient PM-10 concentrations.

At the Denver site the average PM-10 concentration over the analyzed time periods was ~25 $\mu g/m^3$. Road sanding material contributed, on average, 59 percent of the observed levels. This demonstrates that for a typical winter setting, road sanding material is a significant source of the ambient PM-10, and that control of that source would lead to a marked decrease in observed PM-10 loadings.

The site at Reno saw significantly higher PM-10 levels over all of the sampling periods, with an average level of 78 $\mu g/m^3$. However, the contribution of sanding material to the observed PM-10 was approximately the same as seen in Denver (~57 percent). The difference here is that the high PM-10 level will contribute significantly toward to the annual geometric mean nonattainment limit of 50 $\mu g/m^3$, which is violated in Reno. During the sampling periods there were a total of six intervals in which PM-10 levels exceeded 100 $\mu g/m^3$. The highest observed level, 144 $\mu g/m^3$, occurred on January 28, 1993 from 1200-1800 hours. This is very close to the 24-hour ambient air quality standard of 150 $\mu g/m^3$. It should be noted that this was a 6-hour sample, and not a 24-hour average.

During 19 of the 20 time periods sampled at the Reno site, road sand was the major contributor to the ambient PM-10 levels. It is therefore clear that if the contributions of road sand were to be reduced, the ambient PM-10 concentrations would significantly decrease. One possibility for the control of resuspended road sand would be the application of less sanding material or increased utilization of road sweeping equipment to remove the material from the roads. It should be noted, however, that a previous study in Reno showed that road sweeping procedures used at the time of the study had no effect upon PM-10 levels (Chow, 1989).

CHAPTER 7: RESULTS OF RESUSPENDED ROAD DUST STUDY

PHOENIX, AZ SITE

CMB Analysis

A total of 54 active ambient samples were taken at the Phoenix, AZ site between May 28 and June 10, 1993. Sampling was performed between 1200 and 1800 hours (PDT) each day. The configuration of the samplers is described in chapter 4. Of the 54 total filters, only 14 had complete chemical analyses performed upon them. These filters were the ones sampled at the base of the sampling array on the downwind side of the road. Additionally, two dirt samples were obtained from the vicinity of the sampling sites, one from each side of the road. These were then combined to create a composite sample which was resuspended and used as a source profile for CMB analysis.

The summary of concentrations measured by the four different samplers are given in table 13. This data along with the wind speed and direction data were used as input for dispersion modeling. The results are discussed below.

The results from the CMB modeling are shown in table 14. The fitting parameters were good with r^2 values ranging from 0.85 to 0.98 and χ^2 values of 0.18 to 1.90. The (predicted)/(observed) mass ratios ranged from 100 percent to 152 percent, with an average of 119 percent for the ambient samples and 117 percent for the average profile. The predicted and measured values are shown graphically in figure 24. Overall, the fitting by the model was good.

The major problem experienced with the CMB modeling centered around the measured ratios of organic carbon (OC) to elemental carbon (EC). This is the same problem as seen in the ambient data at the Denver, CO site. Since neither of the two possible explanations presented in chapter 6 can be confirmed, the OC component was not used in the modeling.

The results of the CMB modeling are relatively one sided (figure 25). For specific time periods, the contribution of geological material ranged from 58 percent to over 92 percent of the ambient PM-10 levels, with an average of 70 percent. The motor vehicle profile constituted the next most prevalent source. The motor vehicle source contribution ranged from ~3 percent to over 36 percent with an average of ~22 percent of the ambient levels. The contribution of NACL and Secondary sources were minimal, with an average contributions of 2.6 percent and 5.5 percent, respectively.

Figures 26a, b, and c show the apportionments for the periods of maximum and minimum PM-10 mass, and for the average PM-10 mass for all time periods, respectively. The values of 71 percent, 59 percent, and 70 percent for the maximum mass, minimum mass, and the average, respectively, demonstrate the dominance of the resuspended road dust on ambient PM-10 levels.

Table 13. Concentration (µg/m³) from Individual Samplers at the Phoenix, AZ Site

Date	Upwind	Bottom	Middle	Top
5/28/93	43.98 ± 2.34	27.54 ± 1.75	21.82 ± 1.38	24.44 ± 1.65
5/29/93	22.64 ± 1.39	15.07 ± 1.13	15.12 ± 1.13	14.67 ± 1.12
5/30/93	5.96 ± 0.90	12.06 ± 1.04	12.78 ± 1.06	10.14 ± 0.98
5/31/93	17.38 ± 1.18	19.82 ± 1.31	17.60 ± 1.22	18.23 ± 1.24
6/1/93	12.71 ± 1.02	17.84 ± 1.23	16.14 ± 1.19	18.63 ± 1.27
6/2/93	18.05 ± 1.20	17.84 ± 1.23	17.71 ± 1.23	19.62 ± 1.30
6/3/93	17.01 ± 1.17	22.97 ± 1.42	25.29 ± 1.52	25.02 ± 1.51
6/4/93	17.95 ± 1.20	31.56 ± 1.78	31.89 ± 1.81	24.80 ± 1.50
6/5/93	23.47 ± 1.42	31.07 ± 1.77	32.65 ± 1.84	34.58 ± 1.94
6/6/93	10.73 ± 0.97	15.19 ± 1.13	16.05 ± 1.17	17.29 ± 1.23
6/7/93	20.28 ± 1.30	20.25 ± 1.32	22.79 ± 1.42	19.78 ± 1.30
6/8/93	13.31 ± 1.04	23.98 ± 1.47	23.70 ± 1.46	21.50 ± 1.37
6/9/93	9.49 ± 0.96	17.64 ± 1.22	24.23 ± 1.49	16.61 ± 1.21
6/10/93	12.78 ± 1.04	25.24 ± 1.51	18.40 ± 1.26	21.95 ± 1.39

Table 14. Summary of Results from Phoenix, AZ Site

		Fitting Parameters		Mass (μg/m^3)		Percent Contribution			
Date	Start Time	r^2	c^2	Measured	Predicted	PHMV	NACL	AMBSUL	PHGEO
5/28/93	1200	0.94	0.50	27.54	27.77	19.05	3.53	4.93	72.49
5/29/93	1200	0.95	0.39	15.07	17.63	27.17	4.65	5.39	62.79
5/30/93	1200	0.95	0.31	12.06	14.06	30.94	3.84	6.54	58.68
5/31/93	1200	0.96	0.38	18.82	22.31	21.52	3.32	6.28	68.89
6/1/93	1200	0.97	0.22	17.84	27.06	26.20	1.70	2.29	69.81
6/2/93	1200	0.96	0.25	17.84	20.03	3.16	1.95	2.50	92.40
6/3/93	1200	0.95	0.47	22.97	30.08	20.71	2.46	4.22	72.61
6/4/93	1200	0.85	1.90	31.56	35.48	12.12	2.76	13.73	71.39
6/5/93	1200	0.97	0.34	31.06	30.92	10.35	4.56	6.08	79.01
6/6/93	1200	0.97	0.23	15.19	18.03	17.30	5.27	4.33	73.10
6/7/93	1200	0.98	0.18	20.25	24.46	27.92	4.17	3.35	64.55
6/8/93	1200	0.97	0.19	23.98	28.57	35.35	2.35	3.29	59.01
6/9/93	1200	0.96	0.24	17.64	23.77	36.73	1.72	3.32	58.22
6/10/93	1200	0.96	0.26	25.24	28.05	33.16	1.35	3.21	62.28
Average		0.96	0.36	21.29	25.08	21.77	2.63	5.54	70.06

Sources Key:
PHMV = Phoenix Motor Vehicle Source Profile
NACL = Constructed Sodium Chloride Profile
AMBSUL = Ammonium bisulfate (NH_4HSO_4), indicative of pollution transport or stagnant atmosphere
PHGEO = Geological sample gathered near the sampling site

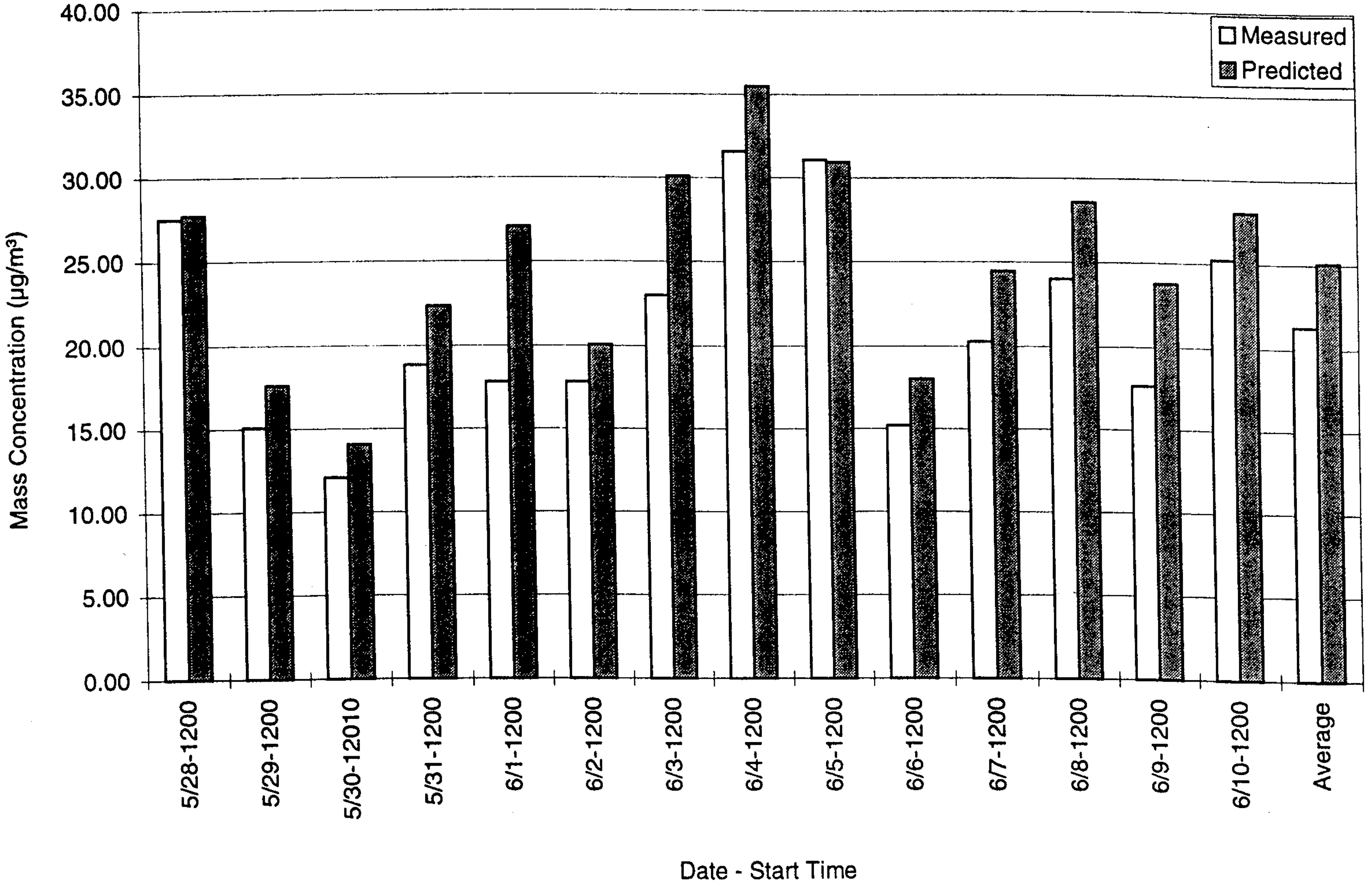

Figure 24. Predicted vs. measured mass at the Phoenix, AZ site.

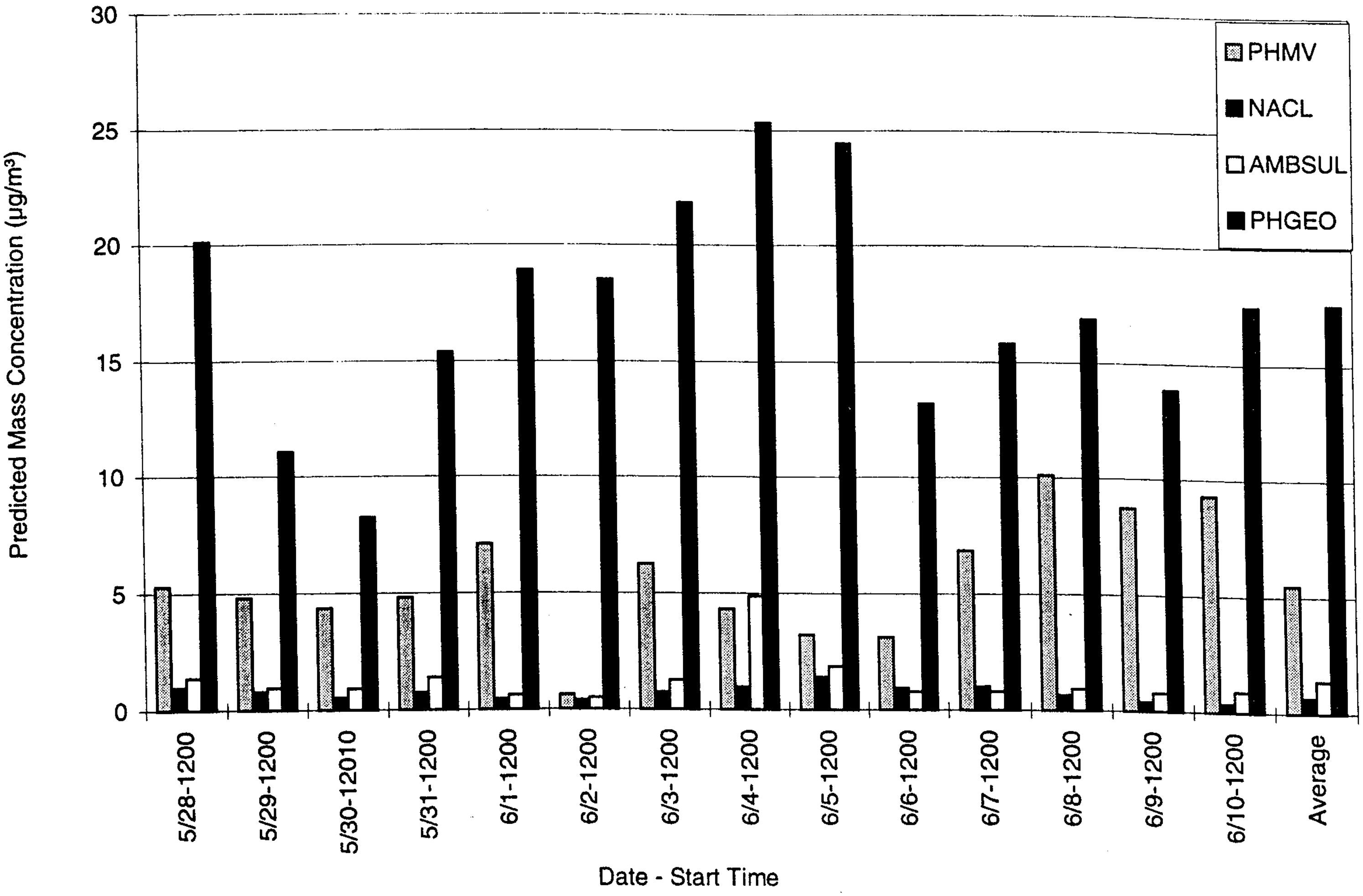

Figure 25. Predicted source contributions to ambient PM-10 at the Phoenix, AZ site.

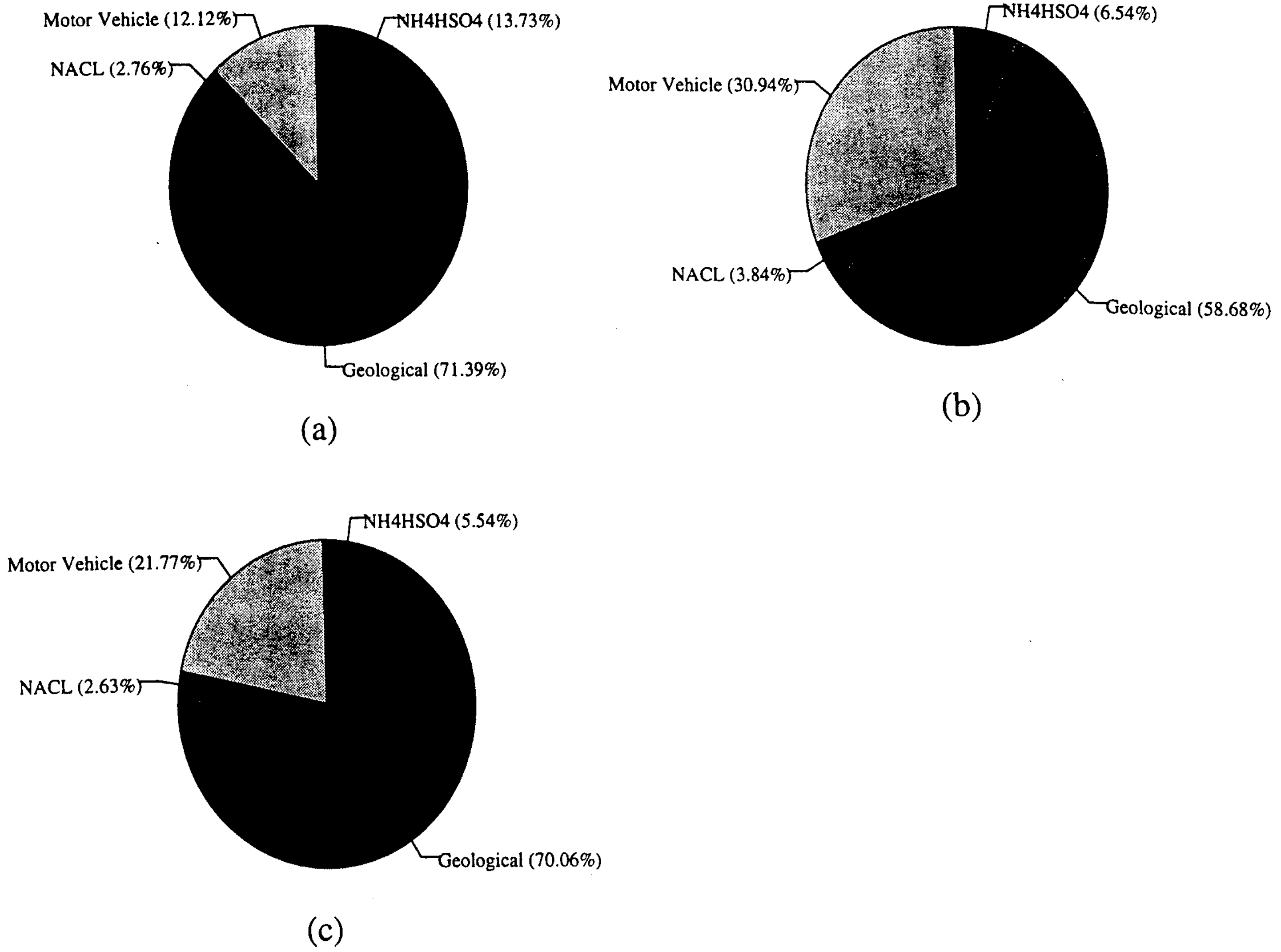

Figure 26. Percent contributions for PM-10 concentrations for the Phoenix, AZ site.

(a) maximum (31.56 μg/m^3), (b) minimum (12.06 μg/m^3), and (c) average (21.29 μg/m^3)

Emission Factor Determination via Dispersion Modeling Analysis

Although chemical composition analyses were only performed on 14 of the 54 samples obtained in Phoenix, the mass was determined on all filters. Wind speed and direction were also determined every fifteen minutes during the 6-hour sampling period.

In order to determine whether or not the filter samples were amenable for use in calculating emission factors using dispersion modeling techniques, the average wind direction had to be in the sector defined by ± 45° from perpendicular to the road. Since the road orientation was north/south, this meant that the average wind direction over the 6-hour sampling period needed to be between 225 and 315°, since the downwind samplers were located on the eastern side of the roadway. Figures 27 through 33 shows the wind direction for each of the 14 sampling days. The solid horizontal lines in each figure indicate the interval between 225 and 315°. As can be seen from these figures, only 1 day (June 6) had the wind direction entirely between the ± 45° criteria, although June 1 and 2 had all but the first 15 minute sampling period inside of the acceptable range. For the 6-hour filter sampling period, the average wind direction for May 30 and 31, as well as June 3, 4 and 5 were also found to be within the ± 45° criteria. Thus, samples from May 30 and 31, and June 1, 2, 3, 4, 5, and 6 were evaluated to determine emission factors using the dispersion modeling methodology outlined in Chapter 2. However, as table 13 indicates, on June 2, even though the wind direction was largely from the correct quadrant, the upwind concentration was larger than the downwind concentrations for all but the top sampler. As a consequence, June 2nd samples were eliminated from the evaluation.

Table 15 shows the results of the dispersion modeling analysis. For these analyses, an initial σ_z of 1.5 meters was assumed. In addition, although emissions from paved road resuspension originate at an initial height of zero (with no buoyancy affect from the emission source itself since the plume temperature is essentially equivalent to ambient temperatures), an initial plume centerline height of 0.5 meters was also assumed. Both of these assumptions were made in order to account for turbulent dispersion immediately behind the vehicles due to the vehicle wake. Similar assumptions have been utilized in other studies.

The results presented in table 15 indicate that, compared to the values determined using the U.S. EPA's AP-42 emission factor model for paved roads, the emission factors determined in this study were generally a factor of 10 to 100 less than those predicted by AP-42. The AP-42 emission factors calculated for the comparison in table 15 used a silt loading value that is much lower than that currently recommended in AP-42, however recent field studies have indicated that the silt loading on paved roads with average daily traffic values (ADTV) above 5000 vehicles may be much lower than the average values currently reported in AP-42. Even using the lower silt loading value, the emission factors calculated via dispersion modeling were significantly lower than those derived using AP-42.

Results of paved road experiments conducted in the Spokane area by Claiborne et al. (1995) indicate that for some types of paved roads emission factors determined using dispersion modeling based on tracer gas experiments were higher than those calculated from AP-42. However for higher ADTV roads, they found that AP-42 overpredicted the emission factors calculated by as much as 44 percent.

Table 15. Result of Emission Factor Calculations using Dispersion Modeling with the Phoenix Data

Date	Wind Direction	Wind Speed (mph)	Calculated emission factors (g/veh-mi)				AP-42 Emission factor/Calculated factor[a]			
			Bottom	Middle	Top	Average	Bottom	Middle	Top	Average
5/30/94	226.52	2.38	0.03	0.05	0.21	0.10	12.23	7.34	1.76	3.81
5/31/94	277.53	5.10	0.00	0.00	0.02	0.01	74.98	558.59	21.19	48.15
6/1/94	273.62	6.66	0.01	0.01	0.10	0.04	57.60	54.96	3.70	9.82
6/3/94	267.34	4.14	0.00	0.01	0.05	0.02	107.00	51.73	7.84	19.20
6/4/94	281.46	4.17	0.03	0.05	0.18	0.09	10.84	7.11	2.12	4.26
6/5/94	259.44	7.59	0.03	0.06	0.63	0.24	11.69	6.20	0.60	1.56
6/6/94	265.00	7.08	0.01	0.02	0.16	0.06	44.89	24.10	2.27	5.96

[a] AP-42 Emission factor values were calculated using a silt loading of 0.04 g/m^2, and a vehicle weight of 2.25 tons.

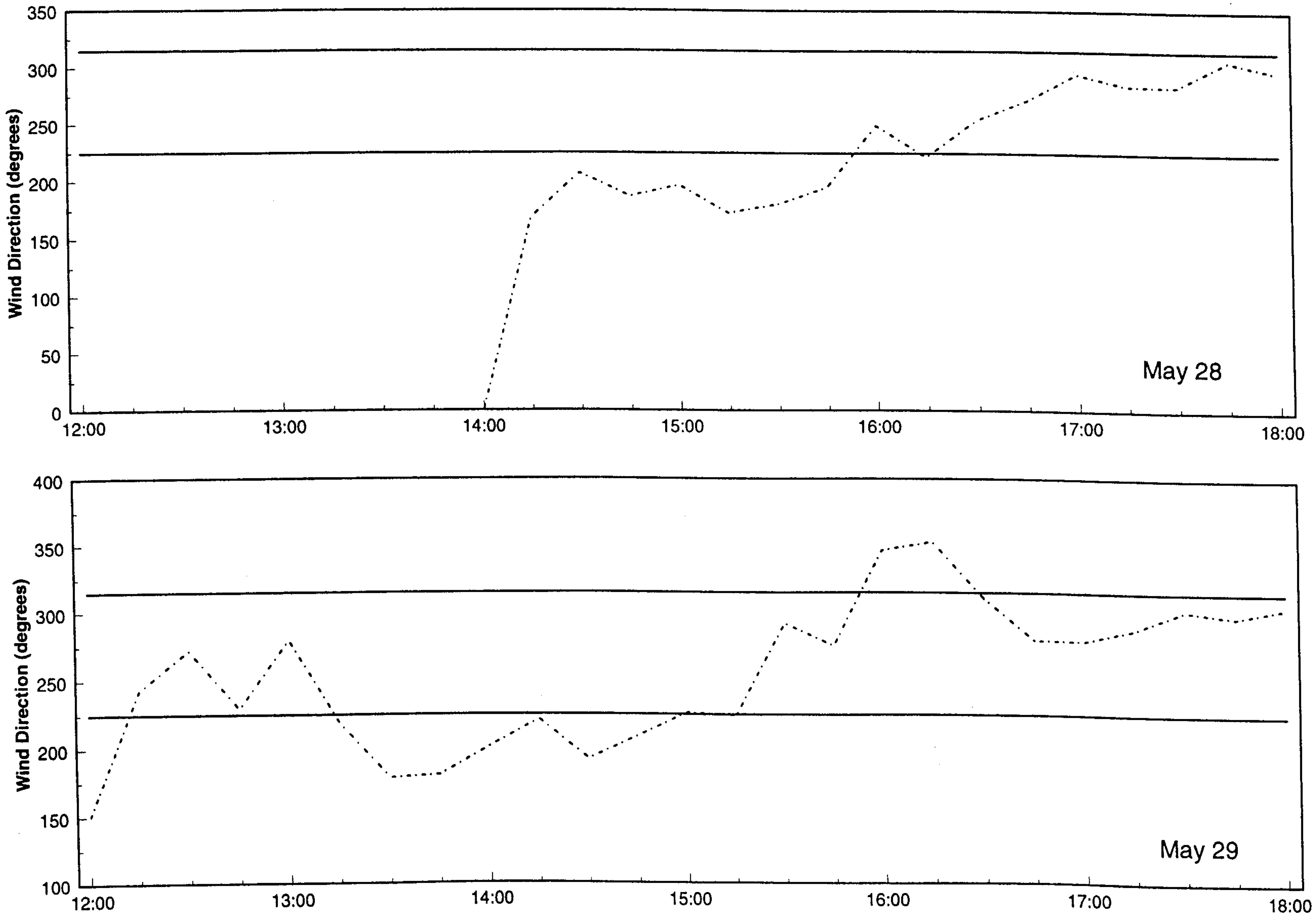

Figure 27. Wind direction on May 28 and 29, 1993.

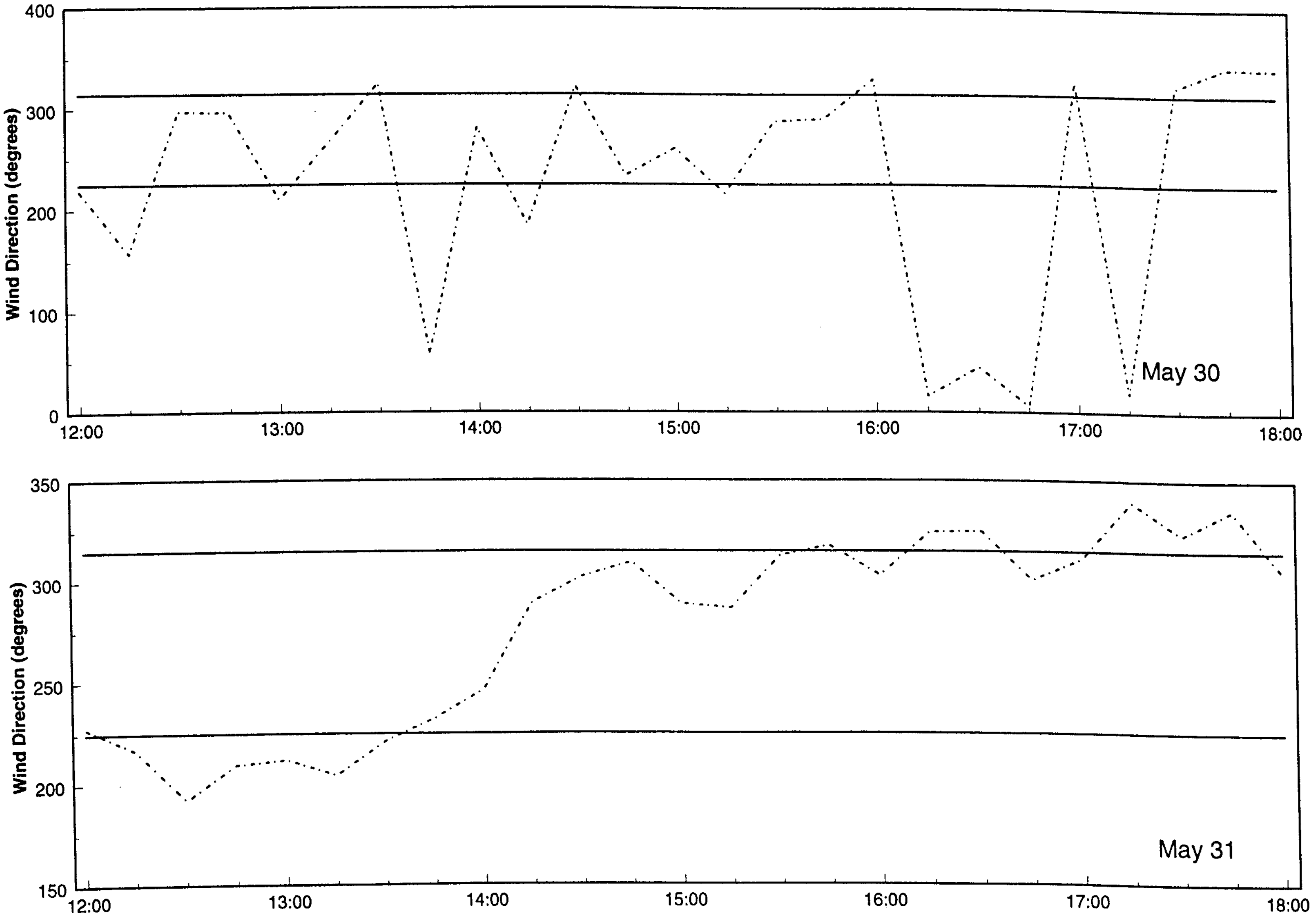

Figure 28. Wind direction on May 30 and 31, 1993.

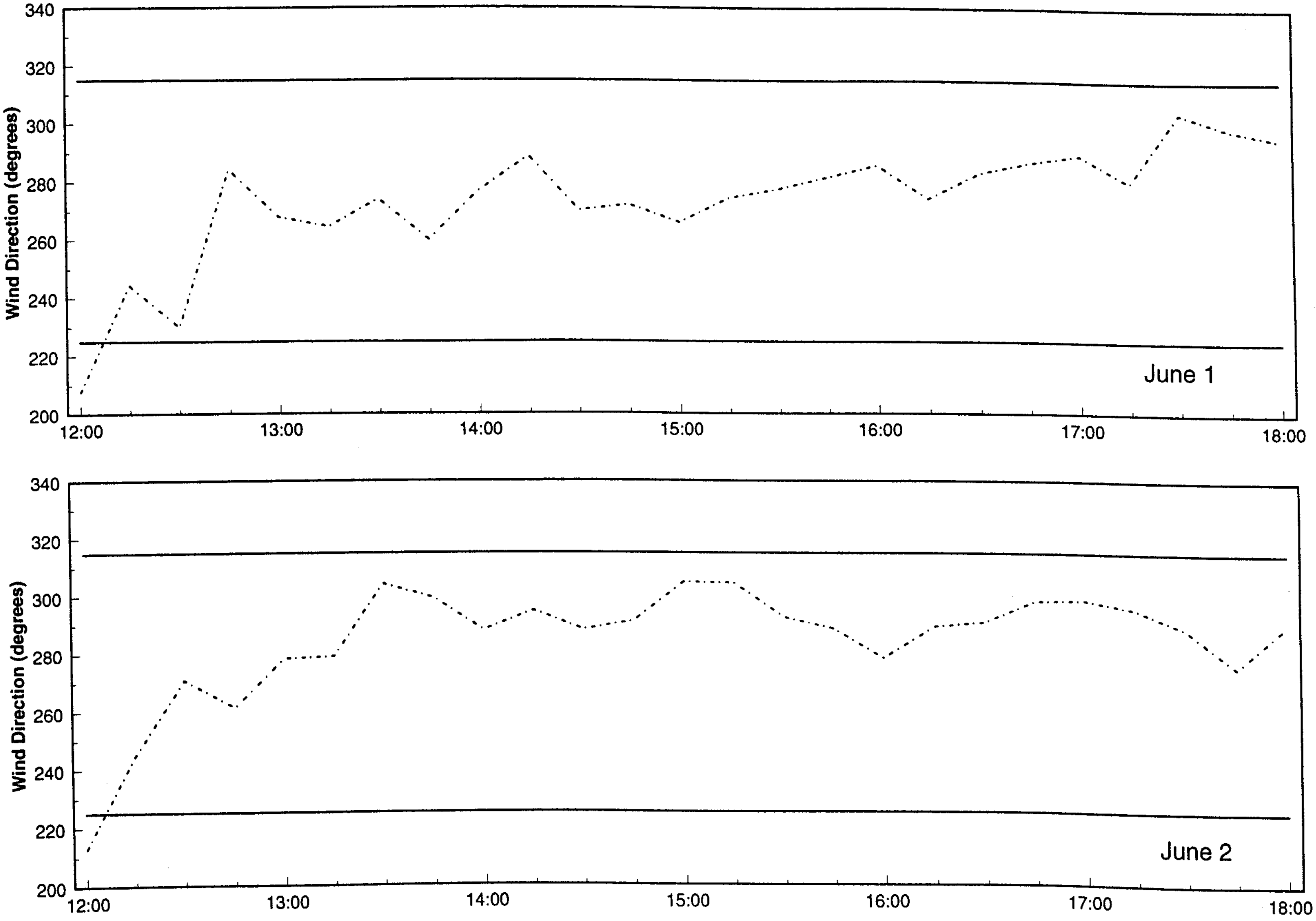

Figure 29. Wind direction on June 1 and 2, 1993.

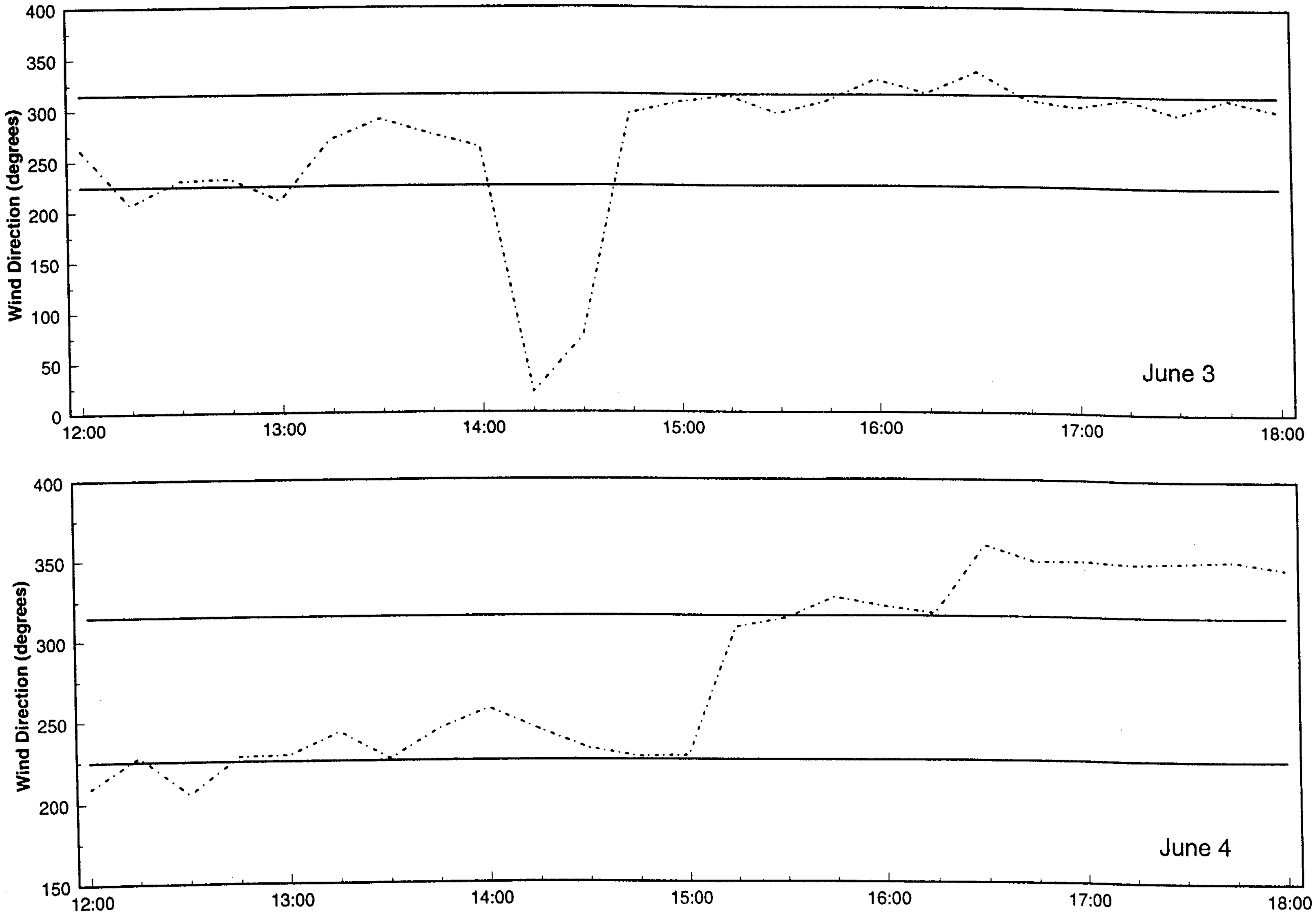

Figure 30. Wind direction on June 3 and 4, 1993.

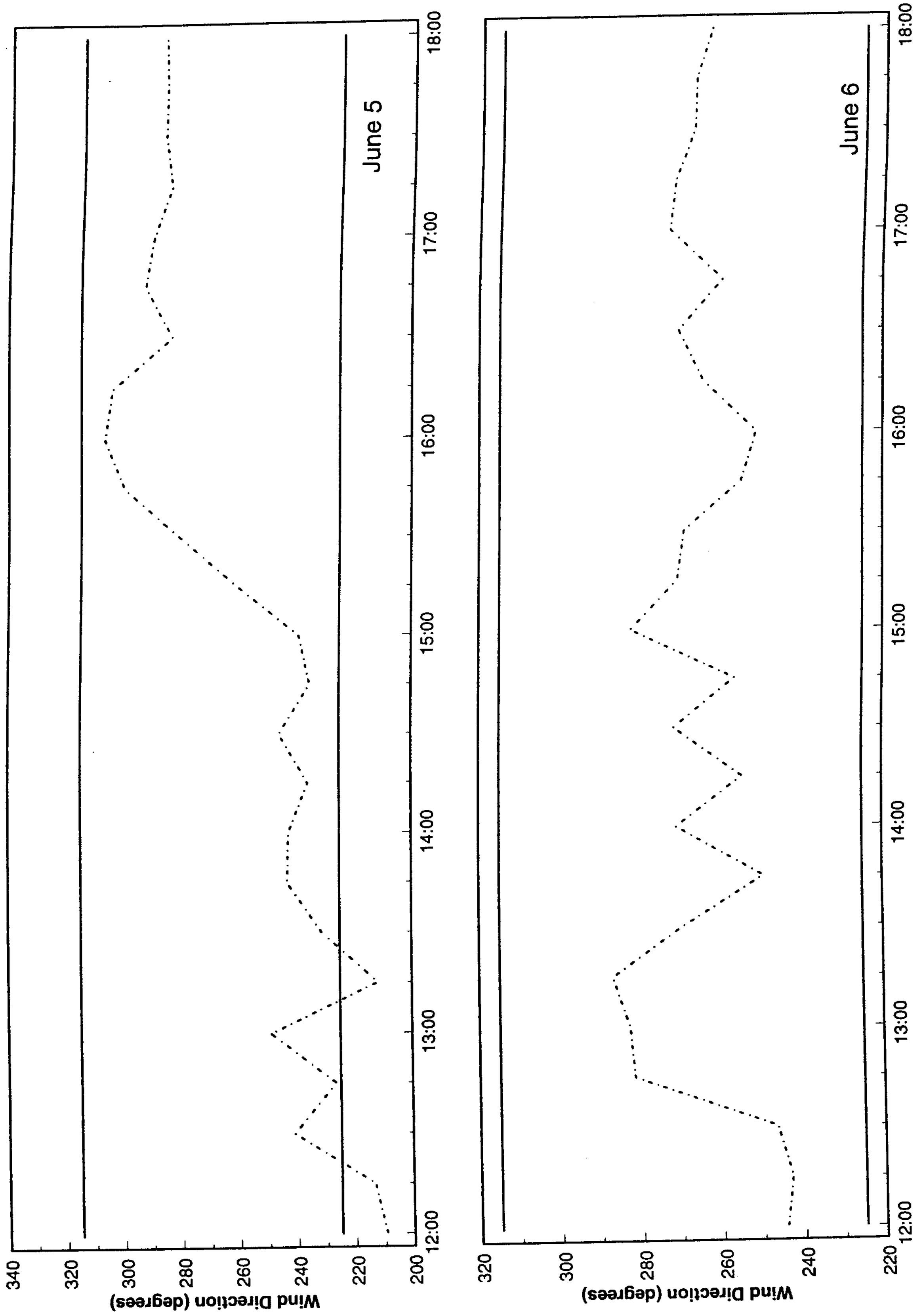

Figure 31. Wind direction on June 5 and 6, 1993.

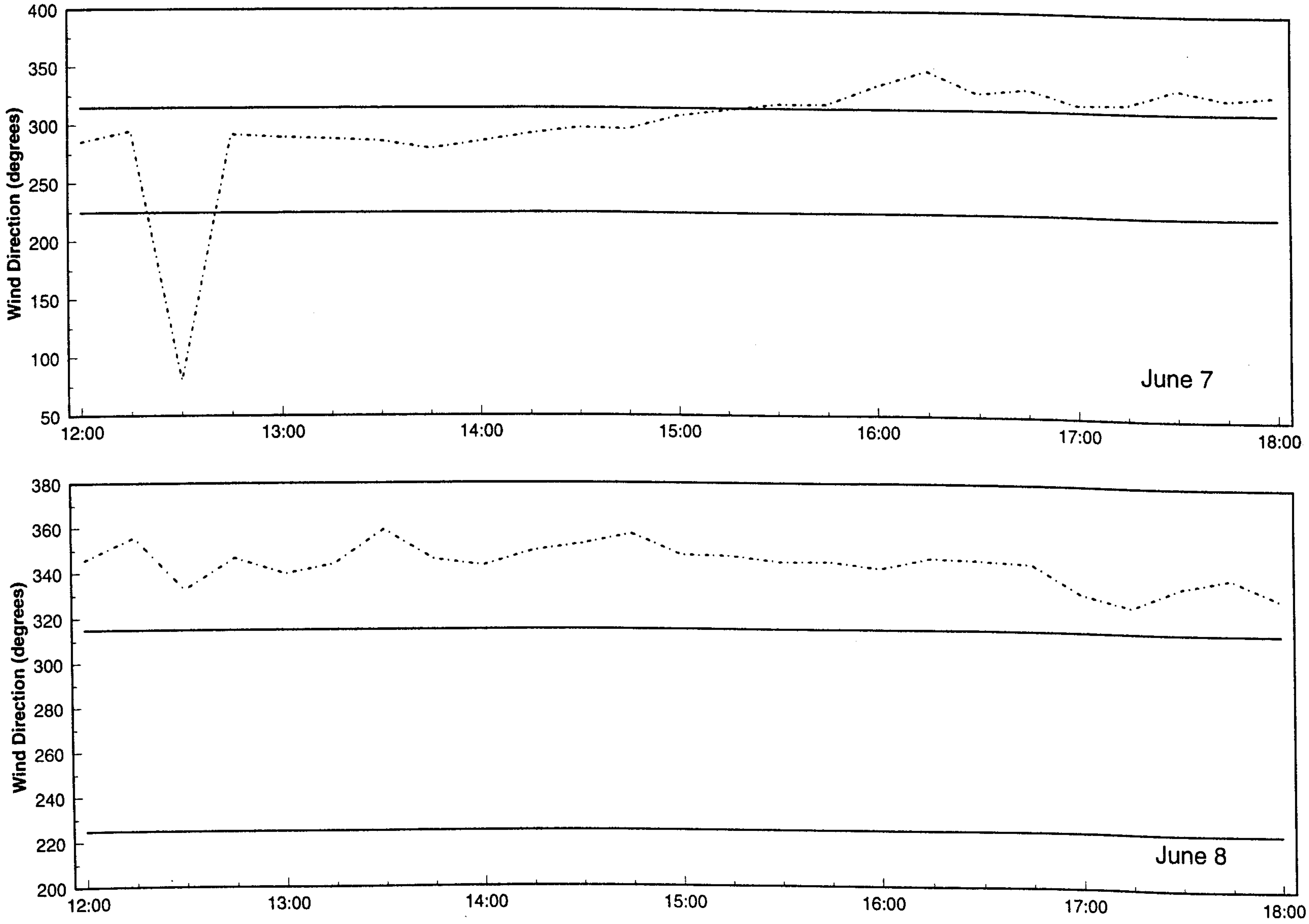

Figure 32. Wind direction on June 7 and 8, 1993.

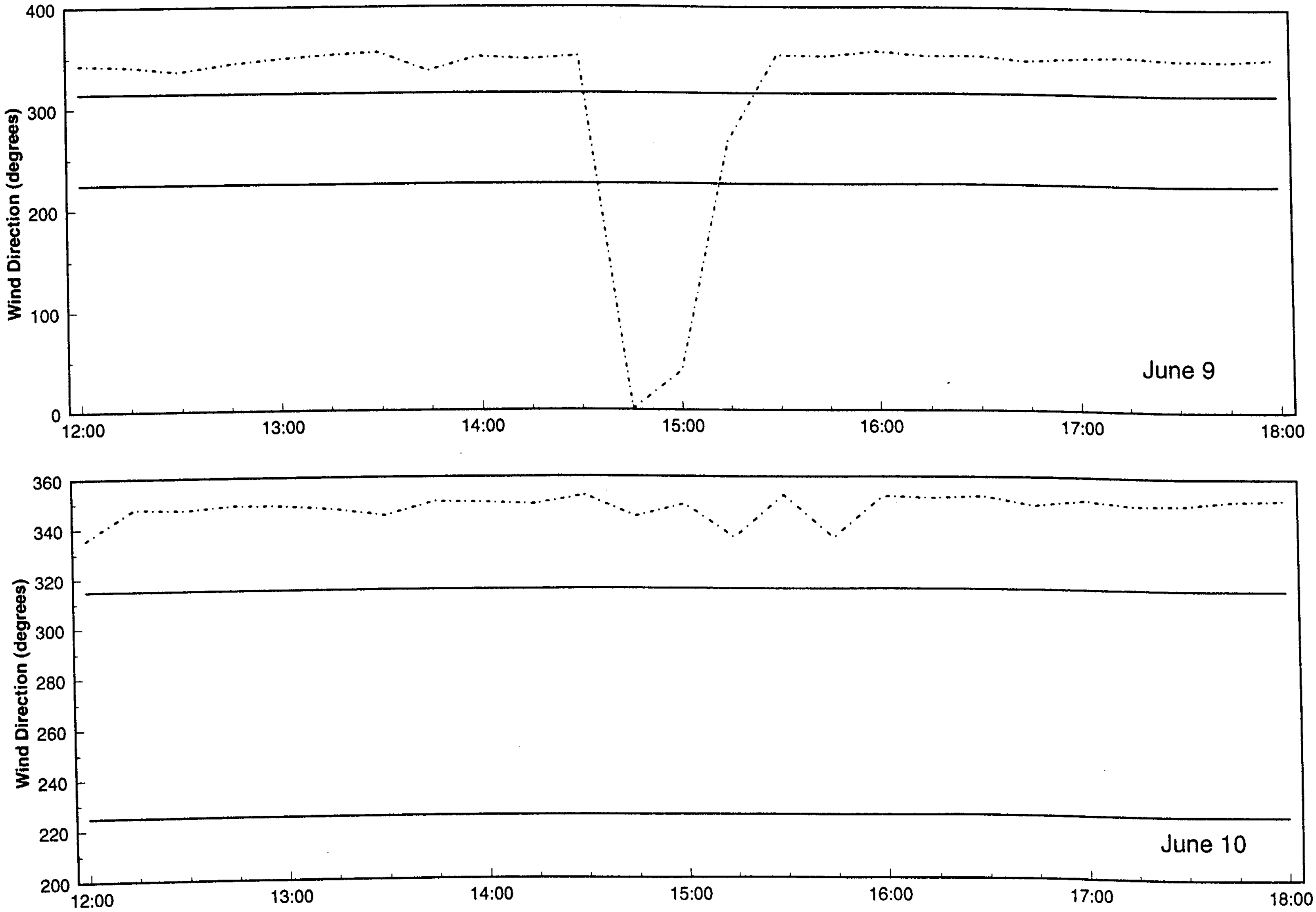

Figure 33. Wind direction on June 9 and 10, 1993.

SPOKANE, WA SITE

A total of three samples were taken at a Spokane, Washington site on November 16, 18, and 19, 1993 from the hours of 1200 to 1800 PDT. Sampling was performed by Washington State University personnel. The limited number of samples were then used as input for CMB modeling. Several dirt samples were gathered near the site and were then returned to the Desert Research Institute facilities in Reno, NV for resuspension and analysis (Chow *et al.*, 1994). The two samples obtained were combined to form a composite sample, Spokane road dirt, which was used to model the ambient samples.

The data from the three ambient samples are shown in table 16, along with an average ambient profile. These four profiles were used as input for CMB modeling.

The results from the CMB modeling are shown in table 17. The fitting parameters were excellent, with r^2 values from 0.96 to 0.98 and χ^2 values of 0.05 to 0.26. Optimum r^2 and χ^2 values should approach 1.00 and 0.00, respectively. The (predicted)/(observed) mass ratios ranged from 94.8 percent to 115.2 percent, with an average of 104 percent for the three ambient samples and 103 percent for the average profile. Overall, the fitting by the model was exceptional.

Once again, there were high organic carbon (OC) values in the ambient samples. Therefore, the OC component was not used in the modeling on the ambient data.

The results of the CMB modeling are significantly one sided. All three samples along with the average profile are shown in figures 34 to 37. The road dirt contributions were 67 percent (figure 34), 89 percent (figure 35), and 84 percent (figure 36) for the three samples, while the average profile, figure 37, had a road dirt contribution of 81 percent. The motor vehicle contribution ranged from 10 percent (November 18 sample) to 19 percent (November 16 sample). The average sample showed a motor vehicle contribution of 15 percent. The sodium chloride contribution varied from 1 percent (November 18 and 19) to 13 percent (November 16), with the average profile contributing 3 percent. The ammonium bisulfate contributed a minimal amount, approximately 1 percent. This shows that there is very little secondary aerosol present.

Table 16. Concentration (in $\mu g/m^3$) of Species Measured at the Spokane, WA Site*

	11/16/93	11/18/93	11/19/93	Average
Mass ($\mu g/m^3$)	27.017	44.138	54.905	42.020
Cl^-	2.133	0.344	0.274	0.917
NO_3^-	0.965	0.720	1.842	1.176
$SO_4^=$	0.626	0.501	0.969	0.699
NH_4^+	0.127	0.169	0.453	0.249
Na^+	1.376	0.231	0.284	0.630
K^+	0.088	0.078	0.109	0.092
OC	5.956	8.477	13.817	9.417
EC	1.940	2.555	3.722	2.739
Na	0.838	0.157	0.128	0.374
Mg	0.100	0.241	0.279	0.206
Al	1.299	3.307	3.585	2.730
Si	5.128	10.888	11.696	9.238
P	0.006	0.048	0.013	0.022
S	0.226	0.318	0.439	0.328
Cl	2.370	0.303	0.190	0.954
K	0.430	0.809	0.999	0.746
Ca	0.653	1.251	1.350	1.085
Ti	0.135	0.327	0.312	0.258
V	0.001	0.005	0.000	0.002
Cr	0.007	0.010	0.002	0.006
Mn	0.024	0.042	0.042	0.036
Fe	1.037	2.341	2.430	1.936
Co	0.000	0.000	0.000	0.000
Ni	0.001	0.000	0.001	0.001
Cu	0.008	0.010	0.010	0.010
Zn	0.053	0.081	0.209	0.114
Ga	0.001	0.001	0.000	0.001
As	0.000	0.000	0.000	0.000
Se	0.000	0.001	0.001	0.001
Br	0.004	0.005	0.007	0.005
Rb	0.001	0.004	0.004	0.003
Sr	0.007	0.011	0.013	0.010
Y	0.002	0.002	0.002	0.002
Zr	0.005	0.010	0.007	0.007
Mo	0.000	0.003	0.003	0.002
Pd	0.000	0.000	0.002	0.001
Ag	0.000	0.004	0.006	0.003
Cd	0.015	0.016	0.000	0.010
In	0.017	0.005	0.004	0.009
Sn	0.000	0.000	0.002	0.001
Sb	0.005	0.005	0.000	0.003
Ba	0.058	0.112	0.102	0.091
La	0.000	0.000	0.102	0.034
Au	0.004	0.003	0.000	0.002
Hg	0.000	0.000	0.001	0.000
Tl	0.000	0.000	0.000	0.000
Pb	0.021	0.025	0.027	0.025
U	0.000	0.000	0.002	0.001

*Nominal Uncertainty ± 10 percent

Table 17. Summary of modeling results from Spokane, WA study

Species	Average	11/16 - 1200	11/18 - 1200	11/19 - 1200
Motor Vehicle	6.486	5.138	5.268	7.342
Sodium Chloride (NaCl)	1.459	3.429	0.493	0.563
Ammonium bisulfate (NH_4HSO_4)	0.336	0.344	0.187	0.620
Spokane Road Dirt	34.512	18.506	44.882	43.515
Predicted Mass	42.793	27.417	50.830	52.040
Uncertainty (±)	5.369	2.256	3.870	4.261
Observed Mass	42.020	27.017	44.138	54.905
Pred./Obser. Mass	1.018	1.015	1.152	0.948
Fitting Parameters				
R-squared (r^2)	0.98	0.98	0.98	0.96
Chi-squared (χ^2)	0.05	0.12	0.10	0.26

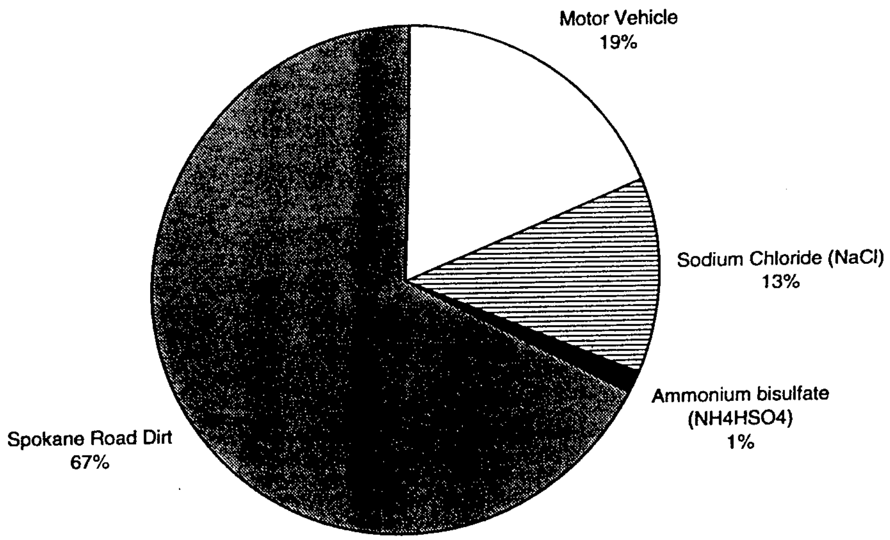

Figure 34. Predicted source contributions for 11/16/93 sample from the Spokane, WA site.

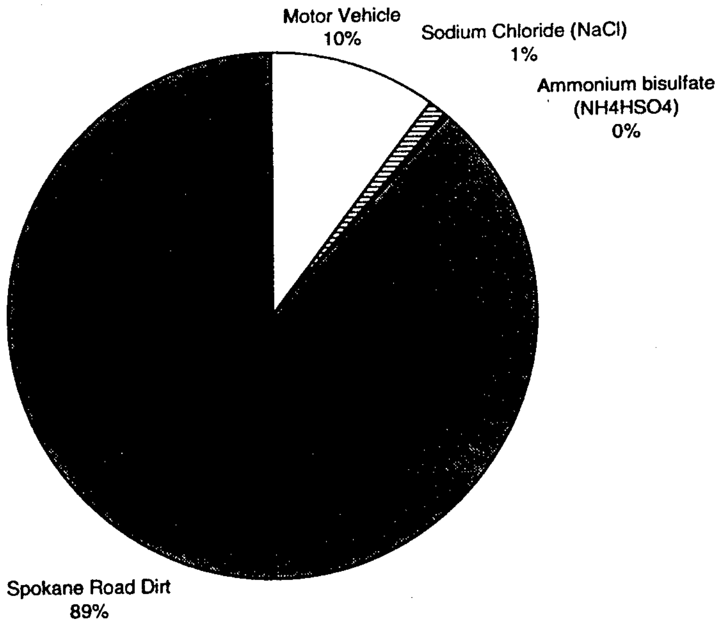

Figure 35. Predicted source contributions for 11/18/93 sample from the Spokane, WA site.

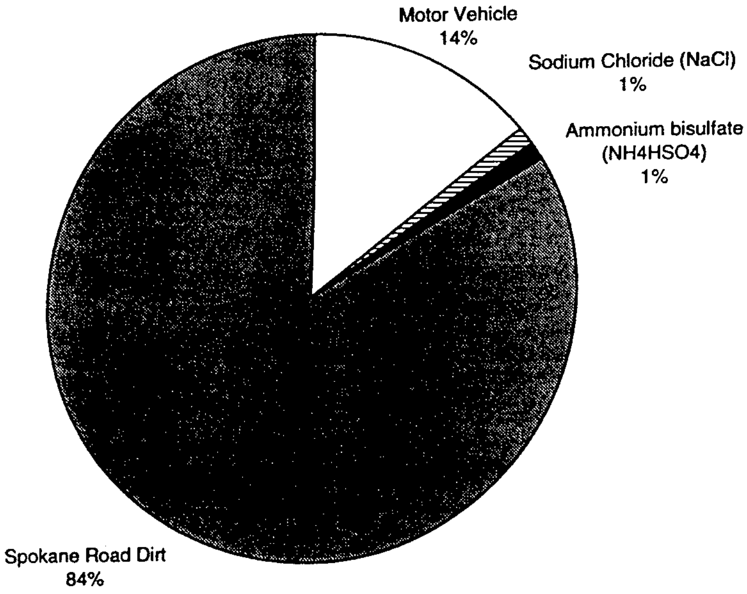

Figure 36. Predicted source contributions for 11/19/93 sample from the Spokane, WA site.

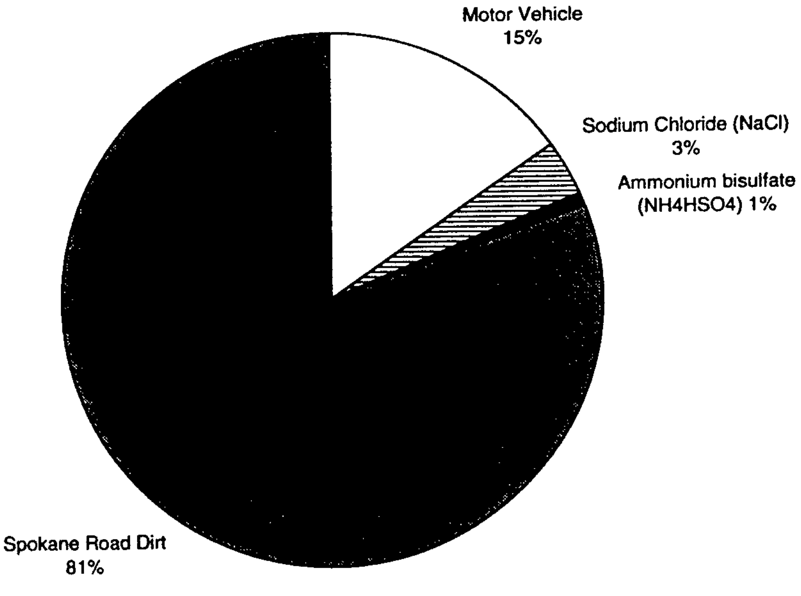

Figure 37. Source contributions for average Spokane, WA sample.

PARTICLE SIZE DISTRIBUTION INFORMATION

Roadway Surface Materials

Material available for resuspension from paved roadways was collected at Denver, Reno, Phoenix, and Spokane. The samples collected were sieved using standard sieving methods to remove particles larger than 106 µm (140 mesh sieve size). The remaining material was then submitted to Amherst Process Instruments, Inc. where the size distribution of the remaining material was determined using their Aerosizer instrument. The Aerosizer determines the particle size distribution of powdered, dry materials using a time-of-flight principle. Two analyses were made for each sample. Figure 38 shows the cumulative volume distribution by geometric diameter for the four sites (Denver, Phoenix, Reno, and Spokane). Each distribution curve represents the average of two sample analyses. Figure 39 provides an analysis for each site of the volume of material that would have been found on a standard sieve if the samples had been physically sieved. For example, approximately 10 percent of the material evaluated would have passed through a sieve with a pore size of 20 µm and ended up on a sieve with a pore size of 10 µm. Thus the percentages in figure 39 for the bars above the 10 µm diameter really represent particles less than 20 µm and greater than or equal to 10 µm.

Figure 40 indicates the PM-10/silt content ratio for the materials analyzed using the Aerosizer. This ratio is developed by determining the cumulative volume below 10 µm divided by the cumulative volume below 75 µm. The range of values is fairly small with the average value approximately 0.02. This clearly indicates that the amount of direct PM-10 material available from the road surface is exceptionally low relative particle size cutoff that is typically used in emission factor determinations. The cumulative distribution graphs in figure 38 clearly show that virtually all of the material less than 106 µm is in what would normally be considered the silt fraction (i.e., 75 µm). It is also important to note that no primary particles ≤ 2 µm were measured.

Fine Particle Size Distribution Measurements

Size-segregated particulate measurements in air affected primarily by mobile source emissions were taken in the course of this study, utilizing a cascade impactor designed specifically for fine particle aerosol research. The sampling venues included the Interstate 10 Deck Park Tunnel in Phoenix, AZ, and a Washoe County (Reno), NV, District Health Department Air Quality Monitoring site located adjacent to the intersection of the Interstate 80 and 395 freeways. The Phoenix measurements were taken in the eastbound tunnel bore, at locations near the tunnel entrance and exit. Average vehicle counts were between 4600 and 7400 vehicles per hour. The fleet composition was dominated by light-duty, spark ignition vehicles. Due to the labor-intensive nature of cascade impactor measurements, the total sampling runs were limited to nine, including six plus one blank set in Phoenix, and two runs in Reno.

The objectives of these measurements were as follows:

1) to characterize motor vehicle primary particulate sizes and,

2) to provide size distribution data that could be used as inputs to atmospheric transport, deposition, and health and risk effect estimates.

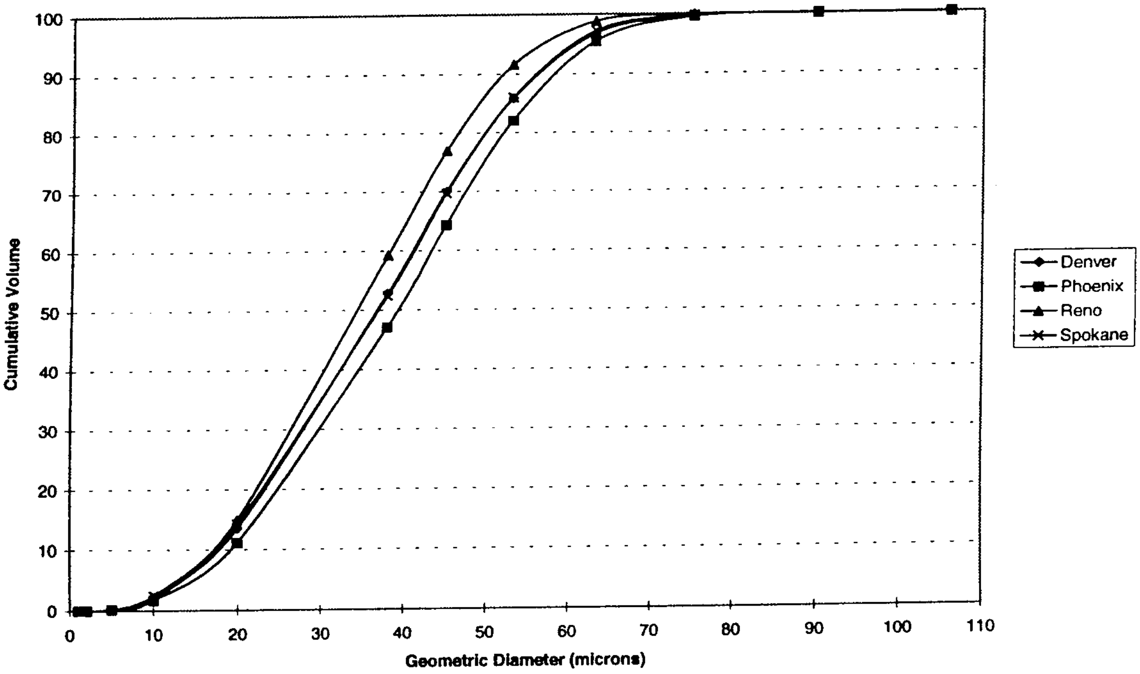

Figure 38. Cumulative particle size distribution from API particle size analyzer.

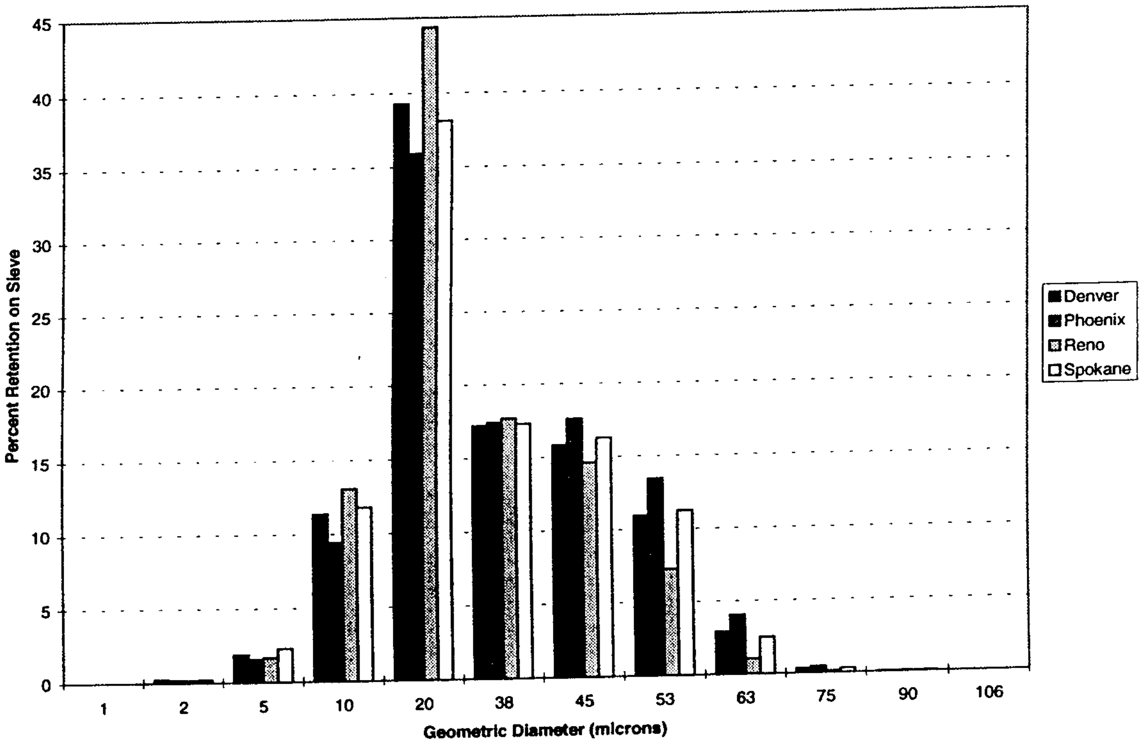

Figure 39. Percent of material retained on sieve.

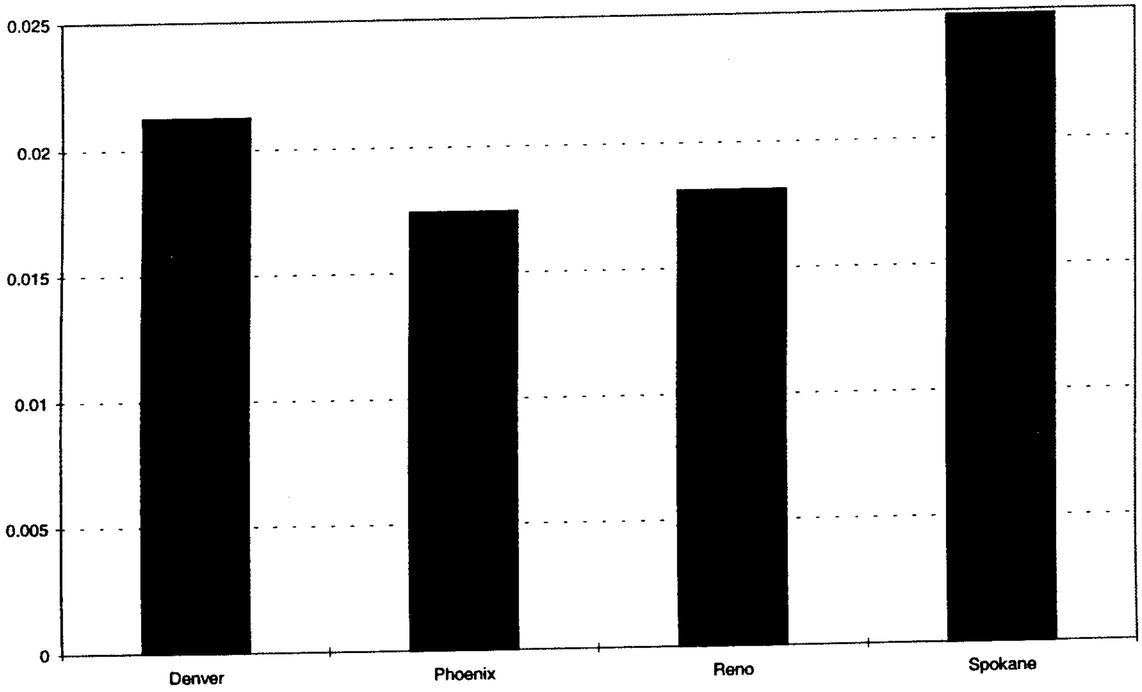

Figure 40. PM-10 to silt (75 µm) ratio.

Samples for the Phoenix and Reno fine particle size study were collected using the Microorifice Uniform Deposit Impactor (MOUDI) developed by Marple (Marple, et. al., 1991). The MOUDI is a nine-stage cascade impactor which contains several significant improvements over previous devices including 1) the flow rate is 30 l/m which is greater than most similar devices, allowing for the accumulation of greater mass deposits in shorter times, and 2) the smallest size stage in the MOUDI collects particles of 0.05 µm aerodynamic diameter with 50 percent efficiency, a particle size range and collection efficiency that are too small for efficient collection with other devices.

The MOUDI collects particulate matter samples on eight collection stages which are characterized by the particle equivalent aerodynamic diameter cutpoints as follows:

Stage 1	3.16 µm
Stage 2	1.78 µm
Stage 3	1.00 µm
Stage 4	0.54 µm
Stage 5	0.37 µm
Stage 6	0.15 µm
Stage 7	0.11 µm
Stage 8	0.05 µm

The stage cutpoints specify the aerodynamic diameters of particles collected with 50 percent efficiency. Small percentages of particles with cutpoints larger than the indicated stage size do penetrate down to the next stage, while roughly equal percentages of particles smaller than the stated cutpoint size are actually captured on the given sampling stage.

For this work, the particulate samples were captured on 47 mm Teflon film substrates mounted in each MOUDI collection stage. These substrates are appropriate for gravimetric and inorganic chemical analyses (if required). During the January 24-26, 1995 sampling period, a MOUDI unit was located first at the exit of the I-10 tunnel, and then at the entrance end of the eastbound bore. The sampler was located adjacent to the fast lane curb. The sampler intake was a 3-meter length of 1-cm diameter tubing. The nominal run time at the Phoenix site was designated as 4 hours, but small variations occurred due to logistical difficulties. The measurements were taken on workdays and were timed to separately sample morning and evening rush hour traffic. The Reno samples were obtained with the same intake, but the sampler was located adjacent to the northern margin of Interstate 80 at the Galletti Way sampling site operated by Washoe County. Both Reno runs were obtained on June 20, 1995.

The Phoenix exit and entrance and Reno measurements are presented in figures 41-43. The blank data indicate that a typical blank level is about 8 µg per stage, corresponding to about 1 µg/m^3 for these sampling conditions; therefore, the lower detection limit of the measurement is about 1 µg/m^3 in this data set. Two runs (6 and 9) are not presented in the figures, because in each case, the aerosol loadings were within the blank range. (Because the MOUDI is not a real-time instrument, it is sometimes difficult to forecast run times which will produce above-detection-limit loadings on the stages.)

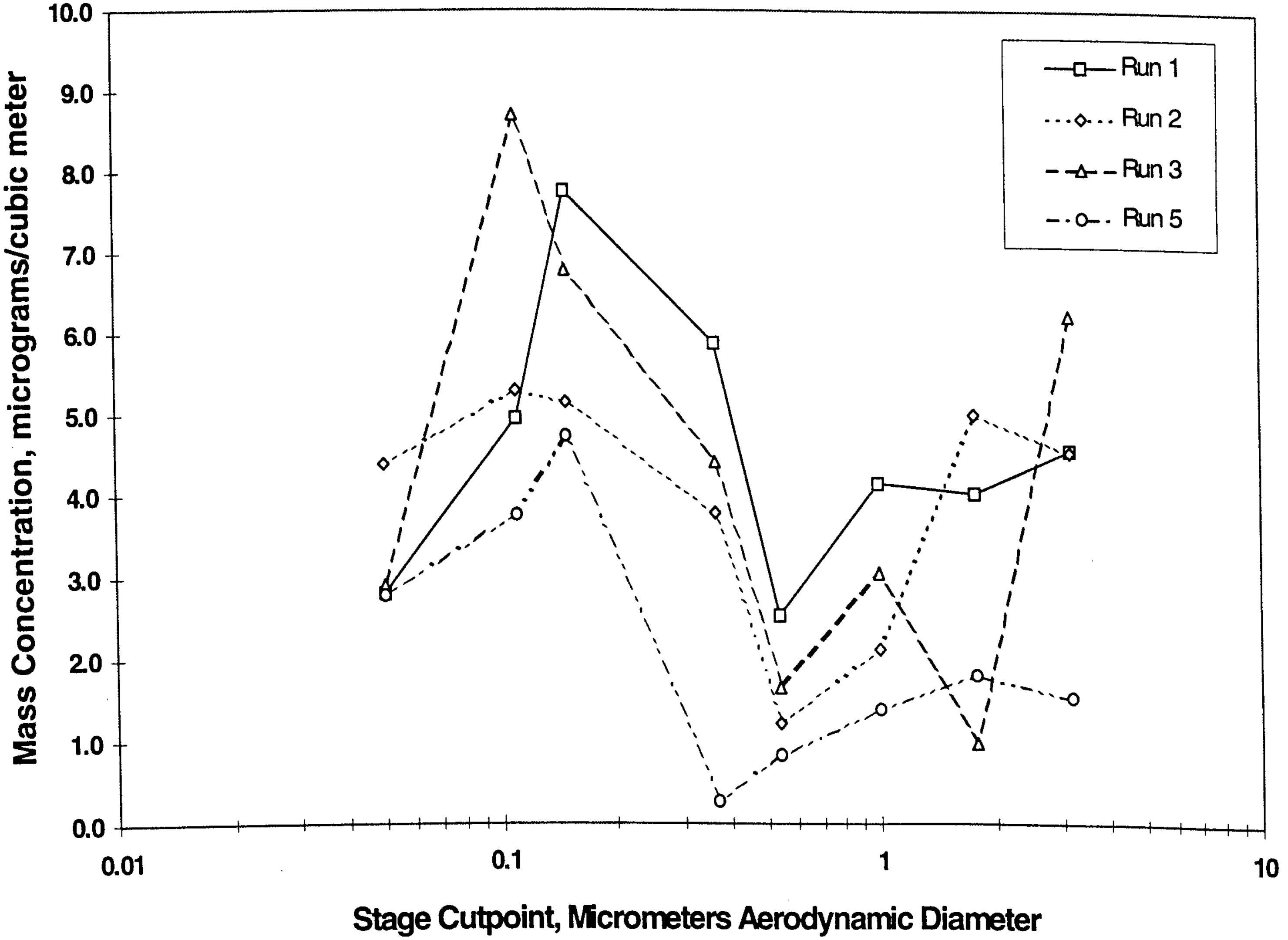

Figure 41. Phoenix Tunnel exit data from the MOUDI sampler.

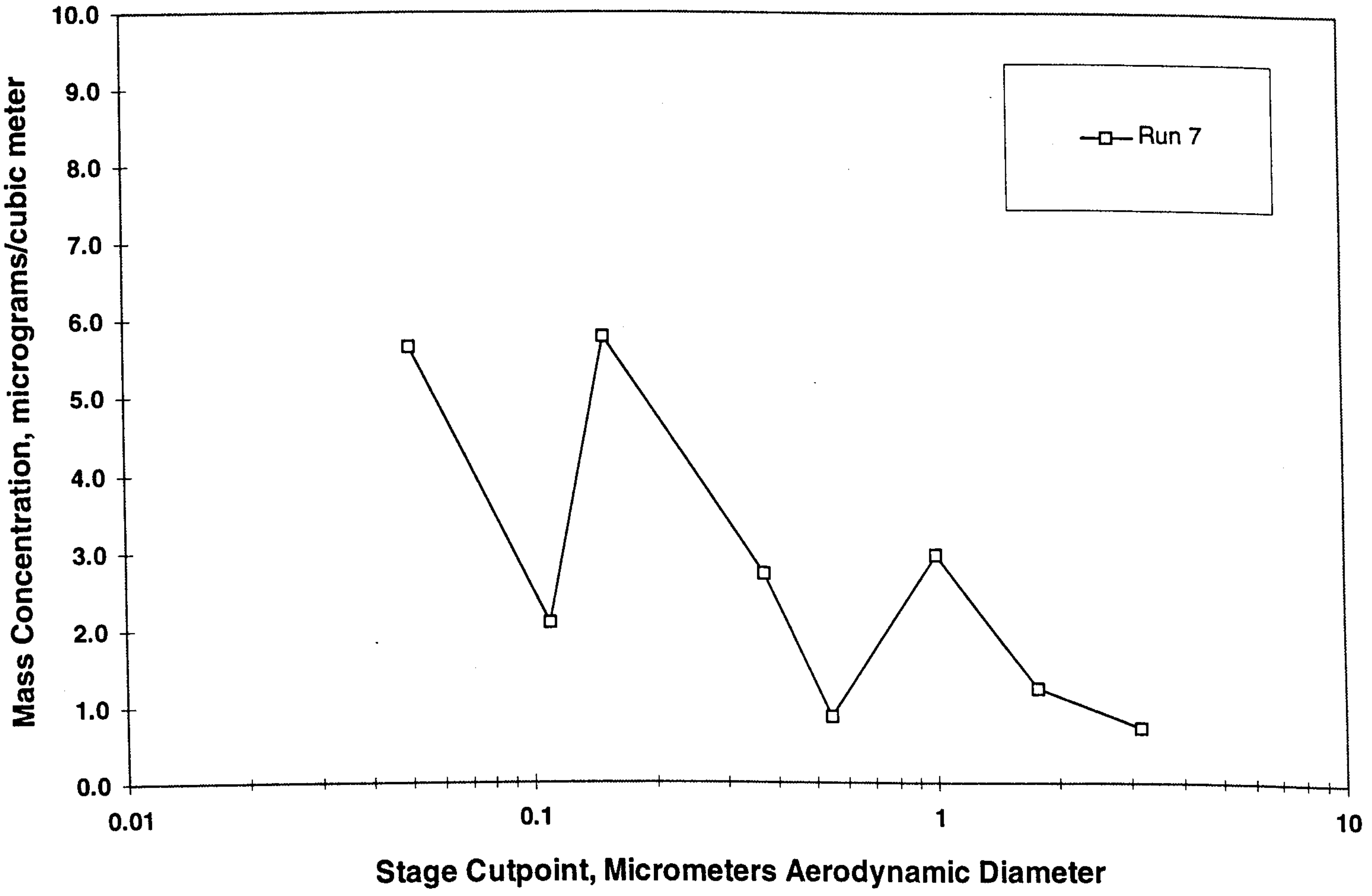

Figure 42. Phoenix Tunnel entrance data from the MOUDI sampler.

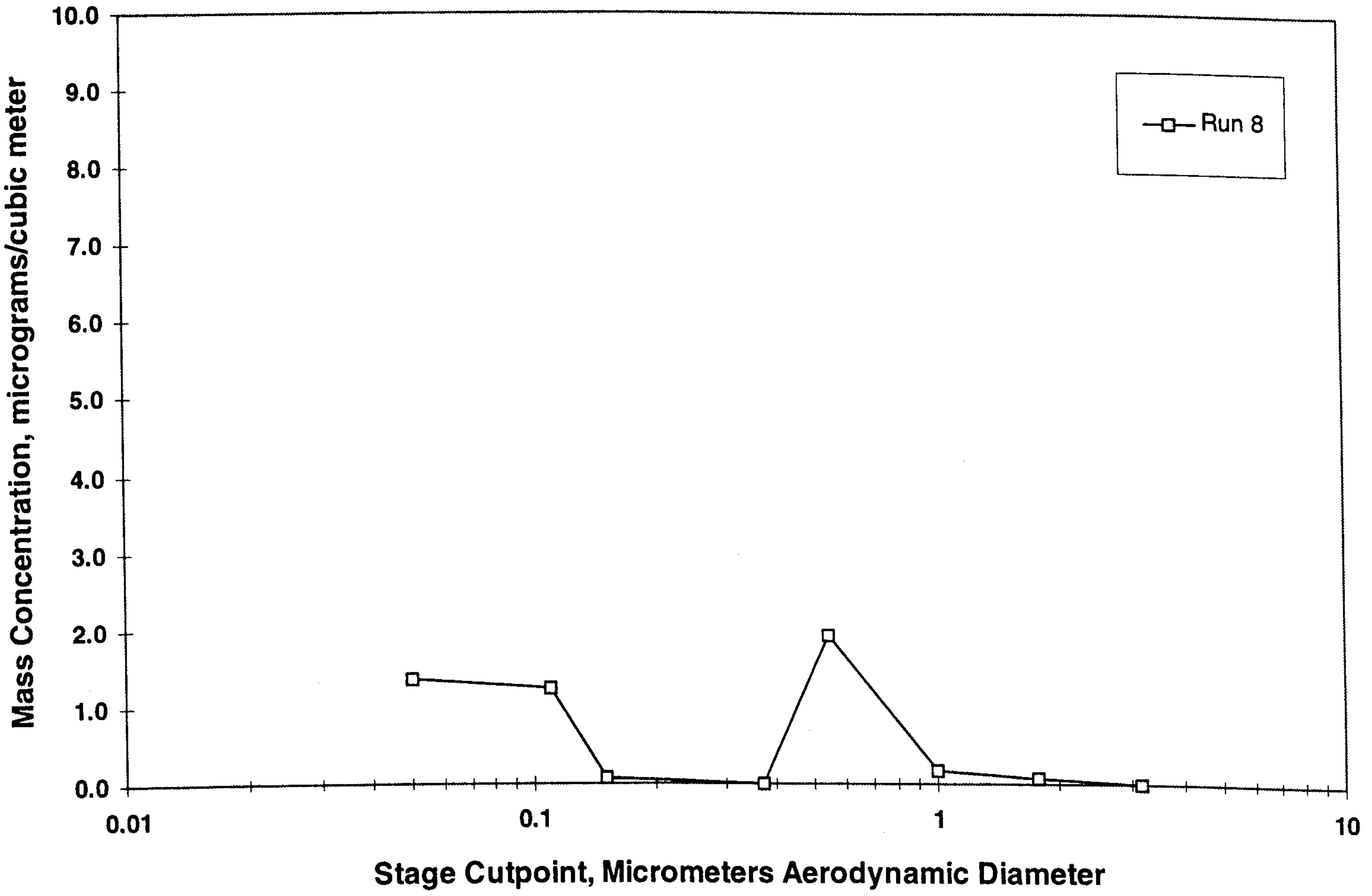

Figure 43. Reno data from the MOUDI sampler.

The Phoenix tunnel exit data (figure 41) indicate bimodal size distributions, with a fine mode peaking in the 0.1 to 0.2 µm interval, and apparently, the small-size tail of a coarse mode which peaks above 1.0 µm. The coarse mode in this arid location probably includes mineral dust, in addition to primary exhaust particles. Runs 1 and 3 were taken during the morning, while runs 2 and 5 were taken during the evening. The fine mode concentrations are greatest during the two morning runs, but systematic differences are not found in the coarse mode data.

The Phoenix tunnel entrance data (figure 42) show more stage-to-stage variability and are not as readily interpreted in terms of distinct modes. The coarse mode concentrations were less than or equal to their exit counterparts. If this finding were reproducible, it would indicate that coarse mode constituents are not dominated by sources external to the tunnel, but rather seem to be produced by vehicle traffic inside the tunnel.

The Reno results (figure 43) were obtained following a prolonged period of rain. The flow was essentially post-frontal, although weak. Road dust was probably minimized due to the recent rains, and vehicular emissions were diluted by ambient flow. The sampling site was upwind from the nearest segment of the freeway, but downwind from the main I-80/395 intersection. The data in figure 43 suggest a fine mode similar to the Phoenix tunnel exit data. There is an isolated peak at 0.54 µm which is difficult to attribute to a specific source without supporting chemical information.

Vehicle particulate emission size distribution data sets are not commonly available. However, studies such as Pierson and Brachaczek (1983) provide opportunities for comparisons to the Phoenix and Reno data. These investigators utilized a cascade impactor to measure size distributions and size-resolved particulate chemical compositions attributable to emissions from diesel and gasoline vehicles traversing the Allegheny Mountain Tunnel of the Pennsylvania Turnpike in August and September of 1979. The smallest cutpoint in the impactor in that study was 0.4 µm, and the largest-size cutpoint was approximately 9 µm, hence the coarse mode is better defined, and the fine mode not as clearly defined, compared to the MOUDI data collected in this study. The Allegheny Tunnel distributions are bimodal, peaking at aerodynamic diameters estimated as less than or equal to 0.4 µm, and at about 4 µm, by the investigators. Carbonaceous material is the major constituent, although size-resolved carbon data are not available. Zinc, bromide, and lead were found in the fine mode, while soil elements were found in the coarse mode. Presumably, the majority of the carbon particles were also in the fine mode. Although the Allegheny Tunnel study was performed in 1979, the resulting size data are consistent with those for Phoenix and Reno.

SUMMARY OF ROAD DUST STUDY

The results from the field work performed in Phoenix, AZ and Spokane, WA clearly indicate that geologic material is a major contributor to ambient filter loadings for samplers located in close proximity to paved roadways. The results from the CMB work showed that on average, 70 percent of the PM-10 contribution was geologic material. Motor vehicle exhaust was the next major contributor, averaging 22 percent. Total measured mass concentrations over the 6-hour sampling period were between 10 and 34 µg/m^3.

The Spokane CMB results were similar to those for Phoenix, although the geologic contribution was higher on average for the Spokane samples. Geologic contributions averaged 81 percent with the average vehicle exhaust component equal to 15 percent. Secondarily formed particulates contributed relatively low amounts in both Phoenix and Spokane. Total measured mass during the 6-hour sampling period in Spokane was slightly higher than that measured in Phoenix ranging from 27 to 55 $\mu g/m^3$.

The dispersion modeling for Phoenix provided extremely interesting results. The emission factors estimated using dispersion modeling indicated that values determined using EPA's AP-42 emission factor equation would over predict those derived using dispersion modeling by a factor of 10 to 100. This over prediction resulted even though very low silt loading values for the paved road were assumed in making the emission factor calculation from AP-42.

CHAPTER 8: SUMMARY OF HIGHWAY STUDY

Diesel emissions, resuspended road dust, and/or the resuspension of road sanding and salting material can, under certain conditions, greatly impact ambient PM-10. Understanding these sources will lead to revisions of area emissions inventories and possibly the eventual altering of SIPs in attempts to meet the current air quality standards

The Manhattan data were apportioned using the CMB and it was found that, on average, 53 percent of the measured particulate mass was emitted directly from diesel buses. The Fort McHenry data used the high percentage of diesel trucks in the tunnel to calculate diesel emission factors. The observed values were 0.015 ± 0.060 and 0.67 ± 0.13 g/veh-mi for spark ignition vehicles and heavy duty diesel emission vehicles, respectively. These updated emission factors will be used to help develop the State Implementation Plans (SIP's) in PM-10 nonattainment areas using EPA's AP-42 methodology (EPA, 1985).

Measurements to determine the impact of road salting were taken at a site in Albany, New York during the winter of 1993. The roads in the sampling area were regularly salted and sanded throughout the course of the sampling periods. On average, the salting material contributed almost 14 percent of the ambient PM-10 concentrations, while the greatest observed contribution of salt was 49 percent during the sampling periods.

The sanding portion of the study included two parts. The first part was to measure the impact of sanding material, in a typical setting, on ambient PM-10 concentrations. This was done in Denver, Colorado and it was found that, on average, over 59 percent of the ambient PM-10 concentration was attributable directly to the resuspension of road sanding material, while a maximum of 83 percent was observed during the sampling periods.

Part two of the sanding portion of the study was done in Reno, Nevada, at a site which received large amounts of snow, and thus large amounts of road sanding material, over a short period of time. This led to an average contribution of over 57 percent of the ambient PM-10 concentrations. The maximum observed contribution from sanding material at Reno was 81 percent of the observed PM-10.

The results from Albany, Denver, and Reno demonstrate that under certain conditions, road sanding and salting are important sources of ambient PM-10 concentrations.

The road dust portion of this study is primarily directed at modeling the dispersion of vehicle emissions across motor vehicle roadways. However, CMB modeling of the ambient data for the Phoenix, AZ site showed that as much as 92 percent of the ambient PM-10 was directly contributed to an on-site geological source, while on average, approximately 70 percent of ambient levels was found to be from the geological source. Throughout the entire Phoenix portion of the study, motor vehicle contributions only reached a maximum of 36 percent of the ambient PM-10 levels. Similar results were seen at the Spokane, WA site. The average contribution of on-site resuspended road dust was 80 percent with a maximum of 88 percent. The maximum contribution of motor vehicle emissions was 18 percent. Clearly, these two sites show that in fair weather conditions, resuspended road dust and geological material can contribute significant amounts to ambient PM-10 levels.

Although the Phoenix and Spokane sites both indicated that the relative contribution of geologic material on ambient filters can be very high, the dispersion modeling results for Phoenix indicated that normal methods of assessing the magnitude of these emissions could result in serious overestimation of the emission levels from paved roads. Emission factors calculated using dispersion modeling and compared to emission factors calculated using EPA's AP-42 showed that the AP-42 emission factors were a factor of 10 to 100 higher than those determined using dispersion modeling.

Finally, particle size distribution information developed for paved road surface material samples and the fine particle component of ambient aerosols directly related to highway sources indicate that 1) the amount of actual material in the ≤ 10 μm fraction of paved road materials is extremely small, and 2) the particle size distribution for the fine particle mode seems to indicate that there is a bimodal distribution with a peak around the 1 μm range. The fine particle data seem to indicate that there is a tail from a coarse particle mode, however the samplers used to collect this information had an upper size cutpoint of approximately 3 μm and the peak is probably in the 4-10 μm range.

CHAPTER 9: RECOMMENDATIONS

The work performed in this study indicated that while highway sources can contribute significantly (on a percentage basis) to ambient particulate levels, the levels of the contributions from the various components of highway sources varies. In areas where the source is important, resuspension of materials (whether derived natively via windblown deposition or via road sanding and salting operations for snow and ice removal) can contribute a significant portion to ambient particulate loadings. However, dispersion modeling indicates that the contributions from this component of highway particulate sources is substantially less than that predicted via typical emissions models. As a consequence additional work is need to improve the way that emissions from this source category are estimated.

This work also showed that tunnel studies offer an excellent method for characterizing particulate emissions from highway sources, particularly direct tailpipe emissions. These studies need to be expanded so that a wider range of conditions is evaluated to produce emission factors that include information concerning load, idling, etc.

Finally, new techniques are now available that enable investigators to evaluate the actual fraction of fine particle material on the road surface. New emission factor models should evaluate whether or not this direct measure of particles ≤ 10 µm can be utilized to develop better emission factor models.

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