MEASUREMENT AND SOURCE APPORTIONMENT OF PM10 ROADWAY EMISSIONS

WA-RD 303.1

Final Report
April 1994

Washington State Department of Transportation

Washington State Transportation Commission
Transit, Research, and Intermodal Planning (TRIP) Division
in cooperation with the U.S. Department of Transportation
Federal Highway Administration

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
WA-RD 303.1		

4. TITLE AND SUBTITLE	5. REPORT DATE
Measurement and Source Apportionment of PM_{10} Roadway Emissions	April 1994
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Candis Claiborn, Arundhati Mitra, Hal Westberg, Brian Lamb	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center (TRAC) Civil and Environmental Engineering; Sloan Hall, Room 101 Washington State University Pullman, Washington 99164	10. WORK UNIT NO.
	11. CONTRACT OR GRANT NO. T9234-03
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation Transportation Building, MS 7370 Olympia, Washington 98504-7370	13. TYPE OF REPORT AND PERIOD COVERED Final Report
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

The objectives of this research are to develop a methodology for assessing PM_{10} emissions from roads, and to compare emission factors developed from this method to those published factors currently in use by regulatory agencies.

Upwind and downwind concentrations of PM_{10} were monitored at several paved and unpaved roadway sites in eastern Washington and northern Idaho. A novel method for measuring PM_{10} emission rates that used an inert, atmospheric tracer to simulate the road sources of PM_{10} was developed. Using this methodology, PM_{10} emission rates were measured from paved and unpaved roads.

The results of this study demonstrate that the use of an inert tracer in a line source to simulate roadway PM_{10} emissions can provide a tool for improving the existing emission inventories for fugitive PM_{10} emissions from roads. The emission factors calculated for unpaved roads were similar in magnitude to those currently used by the Department of Ecology. The factors for paved roads were nearly an order of magnitude higher than those currently in use. PM_{10} emission rates for paved roads were found to be highly variable. depending on parameters that include wind speed, the variability in the wind direction, and traffic and roadway conditions.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
Key words: Air pollution, Particulate matter, PM_{10}, Fugitive emissions, Emission factors, Dispersion models.	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None	85	

Final Report
for
Research Project T9234-03
"PM_{10} Emissions Measurement & Source Apportionment"

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Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

April 1994

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SUMMARY

The overall goal for this work was to improve our understanding of source strengths of airborne particulate matter with aerodynamic diameter smaller than 10 microns (PM_{10}), particularly those associated with roadways. Specific objectives included the following:

1) to compile a thorough literature review dealing with PM_{10} source characterization, ambient measurements, and analytical methods;

2) to measure PM_{10} concentrations near roadways during a variety of conditions; and

3) to test a novel tracer technique in a series of roadway dispersion studies as a method for estimating PM_{10} source strengths as a function of traffic, roadway, and meteorological conditions.

This report describes the results of PM_{10} monitoring and dispersion studies completed during 1992. Included is a data base of the PM_{10} monitoring results as well as a description of the emission estimates and dispersion modeling results developed from the project. The immediate benefit from this research program is a better understanding of PM_{10} emission rates and ambient concentrations near roadways. This work lays the foundation for refining PM_{10} emissions estimates from roads which, in turn, are necessary for the development of an air quality model of PM_{10} impact from roadways. In a broader sense, the methods demonstrated in this work will

also lead to a better understanding of the relative contributions of various nonpoint sources to ambient PM_{10} and will facilitate the development of PM_{10} models which, in the long term, will provide guidance for improving air quality.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

PM_{10} concentrations near paved and unpaved roads were measured, for a variety of traffic, meteorological, and road conditions. Emission rates from both paved and unpaved roads were also measured, using a novel tracer technique. The results from these measurements are compared to published emission rates.

Emission factors calculated as part of this work for unpaved roads appear to be similar in magnitude to the published values. The emission factor calculated for paved roads appears to be higher than the currently used factors, although there is a high degree of variability in the published factors, due to variables such as traffic speed, meteorological conditions, and traffic conditions including the amount of traction sand or the presence of mud trackout from construction sites, etc., on the road.

The technique used in this study to determine emission factors was found to be suitable for measuring PM_{10} emission factors from roads and can be used to eliminate some of the uncertainty that is introduced in modeling local dispersion.

RECOMMENDATIONS

The recommendations from this study are as follows:

(1) The published emission factors were determined via methods that are highly uncertain and, in some cases, inaccurate; thus, the currently used factors are applied with a high degree of uncertainty. To determine the impacts of paved and unpaved roads on air quality for the purpose of implementing control strategies, the published emission factors should be improved through direct measurements.

(2) The emission factors for paved roads currently used in EPA models are particularly subject to uncertainty, and should be refined if they are to be used as the basis for implementing control strategies to reduce ambient PM_{10}. Several issues, such as the effects of traction materials on PM_{10} emission factors from paved roads should be examined in detail.

(3) The contribution of PM_{10} from paved and unpaved roads during episodic conditions should be evaluated. Reconciliation of dispersion modeling results using improved emission factors with receptor modeling based on matching chemical analyses of collected samples with the chemical "fingerprints" of the various sources is required to determine the effects of highway traffic on episodic levels of PM_{10}.

(4) The tracer technique used in this study was found to be a suitable method for measuring PM_{10} emission rates from

roads, and it has the benefit of eliminating some of the uncertainties associated with previous methods. A data base of PM_{10} emissions from various roads should be developed using this method. Such a data base would serve to improve the emission inventories that are widely recognized as needing additional research.

INTRODUCTION

Transportation engineers and planners are required by law to address the air quality impact of new transportation projects. This requires prediction of atmospheric concentrations of criteria pollutants including nitrogen oxides, carbon monoxide, sulfur dioxide, and fine particulate matter with a diameter equal to or less than 10 micrometers (referred to as PM_{10}) in the vicinity of the project. The current methods for predicting PM_{10} concentrations from traffic-related activities are based on emission factors that are applied with a large degree of uncertainty. State Implementation Plans (SIPs) for improving air quality rely heavily on these highly uncertain emission factors.

This research is aimed at reviewing the existing methods for determining the contribution of ambient PM_{10} that is due to transportation activities, and developing a methodology for assessing emissions from roads. This is to be accomplished by measuring PM_{10} concentrations downwind of a roadway and developing a method for deriving the source

strength of total emissions as a function of traffic density, type of traffic, roadway, and meteorological conditions. Several different measurement schemes and associated modeling analyses were investigated for developing a method which could be applied at other locations. These included upwind-downwind PM_{10} concentration measurements along both paved and unpaved roads, and simulation of PM_{10} emissions using an inert atmospheric tracer where the ratio of PM_{10} to tracer concentrations measured downwind of a road is used to calculate the PM_{10} emission rate from the road.

BACKGROUND

The Clean Air Act specifies maximum acceptable pollutant levels, or National Ambient Air Quality Standards (NAAQS), for all criteria pollutants, including PM_{10}. According to these standards, the annually-averaged ambient PM_{10} level cannot exceed 50 micrograms per cubic meter ($\mu g/m^3$). Moreover, the ambient concentration cannot exceed 150 $\mu g/m^3$ averaged over a 24-hour period, more than once per year. Table 1, from a review of receptor modeling for PM_{10} control (Watson et al., 1989), shows PM_{10} concentrations in various western U.S. cities ranging from 9 $\mu g/m^3$ in Las Vegas, NV to 208 $\mu g/m^3$ in Telluride, CO.

Spokane is one of the two regions in eastern and central Washington State that are currently classified as PM_{10} "nonattainment" areas (NAA); i.e., in violation of

Table 1. Summary of average source contributions to PM10 concentrations in U.S. cities (Watson et al., 1989).

City	Primary Geological	Secondary Geological	Primary Motor Vehicle	Primary Vegetation Burning	Secondary Sulfate & Nitrate	Msc. Source 1	Msc. Source 2	Msc. Source 3	Measured PM10
Fresno, CA	17.1	0.7	4.0	9.2	1.3	0.1	0.0	0.0	48.1
Bakersfield, CA	27.4	3.0	5.5	9.6	4.1	0.5	0.0	0.0	67.6
Burbank, CA	21.3	0.0	6.1	0.0	17.2	0.1	0.9	9.8	56.6
Upland, CA	25.4	0.4	4.1	0.0	20.9	0.6	0.6	7.8	58.0
Los Angeles, CA	23.8	0.0	6.4	0.0	18.8	0.0	1.3	7.9	60.2
Rubidox, CA	43.1	4.0	6.6	0.0	27.7	0.3	1.0	5.9	87.4
Lennox, CA	16.0	0.1	4.6	0.0	15.5	0.2	3.1	7.6	46.9
Long Beach, CA	20.7	0.0	5.1	0.0	17.2	0.1	2.0	6.4	51.9
Anaheim, CA	21.2	0.0	4.1	0.0	16.8	0.4	1.4	8.2	52.1
Chula Vista, CA	6.7	0.0	0.8	0.0	7.5	0.4	2.7	2.0	28.8
Sparks, NV	15.1	0.0	11.6	13.4	3.6	0.0	0.0	0.2	41.0
Reno, NV	14.9	0.0	10.0	1.9	1.9	0.0	0.0	0.0	30.0
Verdi, NV	7.8	0.0	4.0	1.1	1.0	0.0	0.0	0.0	15.0
Las Vegas, NV	0.0	0.0	8.9	0.1	0.0	0.0	0.0	0.0	8.7
Hayden, AZ1	5.0	2.0	0.0	0.0	4.0	74.0	5.0	1.0	105.0
Hayden, AZ2	21.0	4.0	0.0	0.0	4.0	28.0	0.0	1.0	59.0
Telluride, CO 1	32.0	0.0	0.0	98.7	0.0	61.3	0.0	0.0	208.0
Telluride, CO 2	12.1	0.0	0.0	7.3	0.0	7.3	0.0	0.0	27.0
S. Chicago, IL	27.2	2.4	2.8	0.0	15.4	15.1	2.2	0.0	80.1
Mean	18.8	0.9	4.5	7.4	9.3	9.9	1.1	3.0	59.5
Std. Dev. (%)	53.0	160.0	75.0	294.0	92.0	212.0	128.0	119.0	71.0
Percent Contribution	32.0	1.0	7.0	12.0	16.0	17.0	2.0	5.0	100.0

either or both of the above standards. Yakima is currently the other official NAA in eastern Washington; the TriCities area is proposed as an NAA but is not yet designated. Four exceedances of the 24-hour PM_{10} standard were observed in Spokane in 1989 (2/6, 2/8, 2/9, and 9/25). In 1990, six exceedances were recorded (2/28, 3/2, 9/8, 10/4, 11/9 and 11/23). Some of these exceedances (particularly those in late summer or early autumn) are thought to be due to windblown dust from agricultural areas (Spokane Area Chamber of Commerce, 1993).

Road dust from paved and unpaved roads is also thought to be a major source of PM_{10} in Spokane. As shown in Figure 1, when natural sources such as windblown dust are neglected, paved and unpaved roads and unpaved parking lots are thought to contribute approximately 74% of Spokane's PM_{10}, based on the 1993 PM_{10} inventory for Spokane (WSDOE, personal communication, 1993). As the state develops its SIP for reducing ambient PM_{10} levels in Spokane, requirements for measuring and modeling PM_{10} concentrations will increase. Economic and efficient control strategies cannot be developed without a clear understanding of the relative importance of different sources.

In addition to emissions inventories, much of our current understanding of source apportionment for PM_{10} has been derived from receptor modeling where the relative amounts of different chemical species in PM_{10} samples are matched to source fingerprints of PM_{10}. For example, the

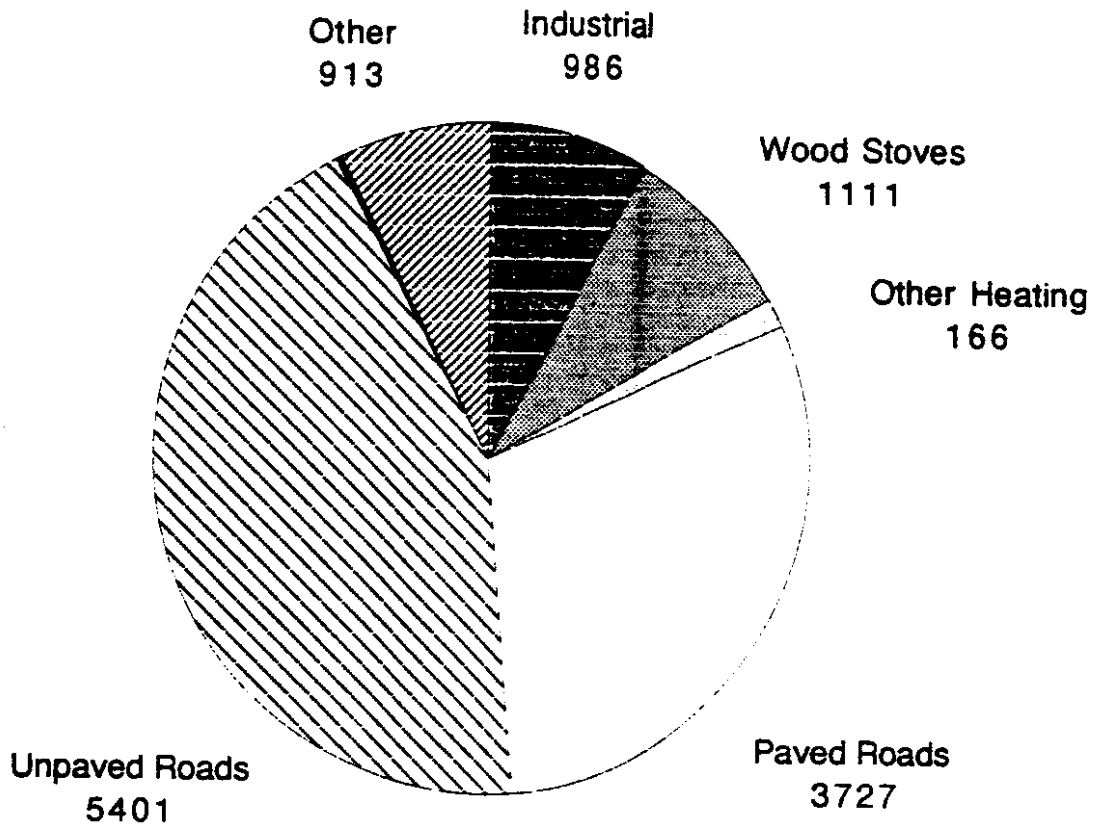

Figure 1: Sources of Ambient PM_{10} in Spokane, based upon the 1993 emissions inventory (WSDOE, 1993). All values are in tons per year.

types of sources for PM_{10} in those cities listed in Table 1 (Watson et al. 1989) were classified in terms of geological, construction, motor vehicle exhaust, and vegetative burning sources, and in terms of secondary sulfate, nitrate, and other miscellaneous sources. On average, geological sources (which include unpaved and paved road dust) and motor vehicle exhaust contributed nearly 40% of the total PM_{10}. The formation of secondary particles contributed 16% of the total, and other sources combined for the balance.

An important result of the development of source receptor modeling is the compilation of detailed source profiles. Watson et al. (1989) reported the existence of several PM_{10} source profiles including the California Air Resources Board (CARB) source characterization program (Ahuja et al., 1989) and the Pacific Northwest Source Profile Library Development Program (Core, 1989). In the CARB program, the following sources are chemically characterized in four size fractions: paved roads, unpaved roads, agricultural tilling, sand and gravel processing, road sanding, agricultural burning, forest fires, oilfield steam generators, heavy duty diesels, and woodburning in California. In the Pacific Northwest program, sources are chemically characterized in two size fractions for paved road dust, slash burning, wood burning, veneer driers, hog fuel boilers, fiber board driers, phosphate fertilizer, residual oil combustion, kraft recovery furnaces, lime kilns, and motor vehicle exhaust.

In a similar effort, Scheff et al. (1989) derived volatile organic compound (VOC) profiles for motor vehicles, fugitive gasoline vapors, petroleum refineries, architectural coatings, graphic arts, wastewater treatment, vapor degreasing, dry cleaning, auto painting, and polyethylene production. Zweidinger et al. (1990) have investigated the linkage between organic PM_{10} and VOC sources and identified a suite of VOC which can be used as tracers for mobile source emissions of fine particulate organics.

The development of the source chemical profiles provides a basis for fingerprinting different sources and identifying the relative importance of those sources in ambient concentrations. However, these profiles only provide a relative indicator of source strength. Estimation of the magnitude of the emission rate of PM_{10} from a specific source, required for modeling its impact on air quality, requires additional information. To derive source strengths, either direct source emission measurements must be made or ambient concentrations of PM_{10} must be made and the data used with methods to account for the effects of atmospheric dilution upon the emissions. In the latter case this implies the use of a dispersion model or simulation of the source with the release of an atmospheric tracer. To our knowledge, a tracer technique has not previously been employed to determine PM_{10} emission rates.

Direct source sampling and other data were used to develop an emissions inventory of organic fine aerosol for

Table 2. Emission inventory of fine aerosol organic material in the Los Angeles basin (from Hildemann et al., 1991).

Source Type	OC emitted, * Kg/day	% of OC emissions	source to be tested	notes
(1) paved road dust	5114	18.6	X	**
(2) charcoal broilers	4389	15.9	X	***
(3) noncatalyst gasoline vehicles	3710	13.5	X	***
(4) diesel vehicles	2100	7.6	X	***
(5) brake lining	1480	5.4	X	**
(6) surface coating	1433	5.2		****
(7) cigarettes	1336	4.9	X	***
(8) fireplaces	1270	4.6	X	***
(9) forest fires	877	3.2		*****
(10) roofing tar pots	752	2.7	X	***
(11) natural gas combustion	692	2.5		***
(12) organic chemical processes	692	2.5	X	****
(130 tire wear	671	2.4		**
(14) misc industrial point sources	393	1.4		****
(15) catalyst-equipped gasoline vehicles	335	1.2		***
(16) misc petroleum industry processes	278	1.0		
(17) primary metallugical processes	228	0.8		
(18) railroad (diesel oil)	211	0.8		
(19) residual oil stationary sources	206	0.7		
(20) refinery gas combustion	195	0.7		
(21) secondary metallurgical processes	167	0.6		
(22) mineral industrial processes	158	0.6		
(23) other organic solvent use	106	0.4		
(24) jet aircraft	92	0.3		
(25) asphal roofing manufacturing	81	0.3		
(26) coal buring	76	0.3		
(27) wood processing	74	0.3		
(28) residual oil-fired ships	66	0.2		
(29) structural fires	63	0.2		
(30) distillate oil stationary sources	61	0.2	X	***
other sources	226	0.8		
total	27532			

* Annual average emission stated at a daily rate. ** tested by grab sampling and then resuspension of the collected particulate matter. *** tested via dilution sampling. **** This category represents a collection of many small dissimilar sources for which a small number of tests cannot be used to represent the emissions from the group as a whole. ***** Forest fires are an occasional emission source that does not affect ambient samples on a routine basis.
a routine basis.

the Los Angeles basin (Hildeman et al., 1991). The results from this work are shown in Table 2. Paved road dust accounts for 19% of the total organic carbon, but the combined emissions from vehicle tailpipe, brake linings, and tire wear account for 31.1% of the total. Published emission factors for roads have been developed using upwind-downwind monitoring (U.S. Environmental Protection Agency, 1985), with the effects of atmospheric mixing addressed by applying vertical, dispersion modeling in EPA-approved models (e.g., CALINE3, HIWAY).

Esplin (1988) outlined a vertical profiling method in which the mass flow rate of pollutant through a vertical plane downwind of an isolated source was obtained. This approach requires the measurement of the vertical profiles of wind speed and concentration at the downwind edge of the source and integrated over the crosswind horizontal extent of the source. For a roadway, this method would be directly applicable, but the need for integrating in the crosswind horizontal direction is eliminated since the roadway source effectively provides the crosswind integration. Micrometeorological gradient methods have been widely used to measure the flux of pollutant to or from a homogeneous surface. In this approach, the vertical gradients of temperature, wind speed, and/or moisture are used with surface layer similarity theory and the measured mean concentration gradient to estimate the pollutant vertical flux. This method is not viable for estimating PM_{10}

emissions from roadways because the roadway is an isolated source and does not meet the requirement for an extended homogeneous source area. Roadside vertical concentration gradients could be used with a line source dispersion model to back-calculate the emission rate. However, this requires careful evaluation of the accuracy of the line source model for the conditions of interest.

Published PM_{10} Emission Factors from Roads

The published factors currently used to estimate fugitive dust emission rates from roadways were developed using a combination of upwind-downwind measurements and vertical profile measurements. The results of these various emission factor estimates are highly variable, and in some cases the variability may be orders of magnitude in difference. An intercomparison study in which 5 groups participated was conducted within a steel complex (McCain et al., 1985). Each group independently measured PM_{10} emissions from unpaved roads, and all five groups used vertical, isokinetic sampling. The resulting factors calculated by these groups ranged from 1.2 to 2.6 kg/VKT, and the average error was $\pm$ 40%.

Because of the high variability in these estimates, the EPA specifies a rating system for emissions factors, as described in the AP-42 document (U.S. EPA, 1985). To get an "excellent" rating requires that the emission factor be based on a broad spectrum of facilities, using approved methods.

In addition, to apply the emission algorithm thus developed also requires site-specific information.

As an example, based on the vertical profiling method, the following emission estimate algorithm for unpaved roads was developed (Fitzpatrick, 1987):

$$E = k(1.7)(s/12)(S/48)(W/2.7)^{0.7}(w/4)^{0.5}((365-p)/365) \quad (1)$$

where E is the emission rate, in kg/vehicle-kilometer traveled (VKT), k is 0.36 for PM_{10}, s is a factor that takes into account the road surface (s=5 for gravel roads, 28.5 for dirt, and 9.6 for limestone), S is the average vehicle speed (km/h), W is the average vehicle weight, in tons, w is the average number of wheels per vehicle, and P is the average number of precipitation days per year. For a gravel road, average vehicle speed 20 km/h, average vehicle with 4 wheels and weighing 1 ton, and 90 precipitation days/year, the emission factor predicted from this expression would be 0.04 kg/VKT.

Other emission algorithms for unpaved roads are also available (Fitzpatrick, 1987). Most include factors taking into account vehicle type (vehicle weight, number of wheels, and/or speed), road surface conditions (e.g., silt volume and/or surface type), and moisture or humidity factors.

PM_{10} emissions from paved roads are due largely to re-entrained road dust. Sources of dust on paved roads that can be re-entrained as PM_{10} include vehicular trackout from construction areas, water or wind erosion from nearby areas,

oil leaks and spills, street repairs, traction sands or salts, and atmospheric deposition. Relatively few emissions estimates for paved roads are available and, as might be expected, estimates vary greatly. Earlier studies examined total suspended solids (TSP) from roads (Cowherd and Englehart, 1984). The results of one study conducted in Seattle estimated a TSP emission rate of 230 g/VKT, at an average speed of 20 mph. Most other estimates are much lower; at the other end of the spectrum, another study that was based on an upwind-downwind measurement scheme estimated 3.7 g/VKT. The emission factors for PM_{10} from paved roads range from 1-15 g/VKT (Cowherd and Englehart, 1984).

Airborne particulate emissions from paved roads are related to traffic volume and surface silt volume, which in turn is related to the average traffic speed and volume. For predicting PM_{10} from paved roads, the following algorithm has been used:

$$e = A(sL/B)^C \qquad (2)$$

where e is the emission rate (g/VKT), sL is the silt volume (g/m^2), which is dependent on type of street, number of lanes and traffic volume. A, B and C are empirically derived factors that depend on particle size (U.S. EPA, 1985). For example, for "collector" streets (two-lane roads on which the average traffic volume is between 500 and 10,000 vehicles per day) sL is approximately 0.9 g/m^2. For the urban paved road model, A is 2.28, B is 0.5, and C is 0.8. The predicted PM_{10}

emission factor for this type of paved road would be 3.7 g/VKT (Cowherd, 1989). Similarly, for major streets or highways, the predicted emission factor is 1.8 g/VKT.

In a recent specialty conference on PM_{10} standards and nontraditional particulate source controls (Chow et al., 1993), a panel of experts concluded that the emissions estimation methods for nonpoint sources of PM_{10} are uncertain and often even inaccurate. They recommended that additional research is needed to improve particulate emissions inventories, particularly for "fugitive" (nonpoint) sources.

Tracer Techniques

The need for vertical profile measurements or meteorological measurements is reduced if an atmospheric tracer is released to simulate the source emissions. In the case where the tracer release is deployed to completely simulate the source, the emission rate of the pollutant (Q_p) can be obtained directly from measurements of the pollutant and tracer concentrations (C_p and C_t) downwind (with any background concentration subtracted):

$$Q_p = Q_t \cdot C_p/C_t \qquad (3)$$

where Q_t is the measured tracer release rate. Lamb et al. (1986) employed this method to determine the emission rate of biogenic hydrocarbon released from a grove of oak trees. This type of tracer flux measurement has been used recently to measure methane emissions from natural gas facilities (McManus et al., 1991; Lamb et al., 1992) and to measure

volatile organic emissions from a wastewater treatment basin (Howard et al., 1992). Okamoto et al. (1990) employed a line source of sulfur hexafluoride (SF_6) tracer gas along a roadway and obtained NO_x emission rates for comparison to emission rates from vehicle dynamometer and traffic density data. These authors concluded that both approaches were in good agreement.

In summary, published emission factors are available for both paved and unpaved roads, however both (particularly the paved road factors) are highly variable and are applied with a large uncertainty. These factors have been determined using upwind-downwind measurements and vertical profile methods to provide information on atmospheric mixing. The use of a tracer release to account for atmospheric dilution is an established method for determining emission rates of trace gases from point, line and area sources, and may provide a powerful way to obtain direct measurements of roadway PM_{10} emission rates. In this research we investigate the use of a tracer method for determining PM_{10} emission rates from roads, and apply these approaches to the development of an emission algorithm for modeling PM_{10} emission rates from roadways.

EXPERIMENTAL PROCEDURES

The objectives of the experimental program were to develop and demonstrate a method for measuring PM_{10} emission rates from roads, and to obtain direct emission measurements

for comparison to published emission rates. The field program was conducted in two phases: 1) preliminary roadside PM_{10} concentration measurements at several paved road sites, and 2) an intensive PM_{10} and tracer field study conducted at sites in Spokane, Washington. In the following section, each of these experiments is described.

ROADSIDE MEASUREMENTS ON PAVED ROADS

Roadside experiments were conducted on paved roads during the months of July, August, and September of 1992 on several Washington and Idaho highways. During a roadside experiment, portable PM_{10} samplers were deployed on each side of the road to measure upwind (background) and downwind PM_{10} concentrations. The major objectives of the roadside measurements were to determine whether a concentration difference across various roadways could be determined and to check the reliability of the samplers. Ideally, if the wind direction remains constant for the duration of the experiment, the downwind side should show a higher concentration than the upwind, and this concentration increment should be proportional to the emission rate of PM_{10}. These concentration increments, when used in dispersion modeling, can also be used for back-calculating emission factors. Multiple samplers were set up on each side of the road, within three feet of each other at a distance of approximately 8m from the road edge, to determine the reproducibility of the samplers.

Site Selection

The main criteria for site selection included prevailing winds across the road, moderate traffic volume, some distance removed from intersections, adequate space along the roadways to safely set up samplers, and absence of structures (e.g., buildings) or other objects that might interfere with wind. The monitoring sites included Highway 270 (the Moscow-Pullman highway), the Highway 12 bridge over the Clearwater River in Lewiston, and Highway 395 (North Division Street) in Spokane. Roadside measurements were also attempted on the Pullman-Colfax highway; however, due to inadequate traffic volume, this site was determined to be unsuitable for our studies. On the Moscow-Pullman highway, the samplers were set 3m from the edge (white line) of the road. At the Clearwater bridge site, the samplers were set on the levee, which was approximately 3m below the roadway height. The samplers were set at a distance of approximately 7m from the edge of the bridge. At the N. Division site, for the experiments during July and August the samplers were installed 10m from the centerline of the road on the east side, and 9m from the centerline on the west side (the road was 6m wide). For the experiments conducted in September, one sampler was installed on each side of the road, at a distance of approximately 20m from the centerline.

Experimental Methods

Programmable, battery-operated PM_{10} samplers (Lane Regional Air Pollution Authority, Springfield, OR) were used

to collect filter samples for PM_{10}. It should be noted that, although this particular PM_{10} sampler is not designated as a "reference method" by the EPA (i.e., conforming completely to NAAQS protocol), the device nevertheless has been extensively studied by the EPA and is an EPA-sanctioned method; in other words, the EPA has deemed this method a useful supplement to the PM_{10} NAAQS refence method (U.S. EPA, 1992). In the sampling mode, air is drawn through a size-selective separator and then through a filter medium. Particle separation is achieved by impaction. An actual flow rate of 5 lpm, necessary to obtain a 10 micrometer size cutoff, is set by an internal rotameter and maintained by a pressure transducer. Samples were collected on 47mm Teflon PTFE membrane and quartz-microfiber membrane filters (Gelman Sciences Inc.).

For all experiments, the filters were weighed on a microbalance with a capacity of 250 mg and sensitivity of 1.0 µg (Cahn Model 33). The balance was calibrated and at least two laboratory blanks were weighed prior to each weighing session. All filters were equilibrated at 40% relative humidity (RH) in a equilibrator for at least 24 hours before and after sampling. Potassium carbonate solution was used in the equilibrator to maintain 40% RH (Federal Register, 40 CFR, 1987). Two measures of precision were conducted. The first, a measure of analytical precision, was determined by examining the reproducibility of control filter weighing. The mean standard deviation was 18 µg or less for filters

weighing approximately 130 mg (Table 3). Sampling precision, measured as repeatability between the samplers, varied from 0.3% to 20% except for two cases where the differences were 44% and 62% (Table 4). The reason for these two outliers is not known. The overall precision of the instrument as measured from the average percent difference between co-located samplers is ± 17% for all cases and ± 9% excluding the two outliers. The EPA specifies that the precision for these samplers based on co-located samplers should be ± 15% or better (U.S. EPA, 1992).

For a 12-hour test, this means that the minimum detectable increment across a road will be 5 $\mu g/m^3$ based on the reproducibility of control filter weighings. Based on the average sampling precision of 17.3%, at ambient levels of approximately 40 $\mu g/m^3$, the minimum detectable increment will be 7 $\mu g/m^3$.

Equilibrated filters were pre-weighed, placed in filter-holders and carried to the sites in sealed plastic bags. The rotameter readings were recorded at the start and finish of every sampling event to ensure that filters were not leaking and to determine that filter clogging had not occurred. Samplers were mounted on fence posts at a height of approximately 2m above the ground.

A portable anemometer continuously recorded ambient temperature and wind speed for all three wind components (u,v, and w) during the roadside measurements. The wind vector is reported in polar coordinates, with the wind speed

Table 3. Summary of control filter weighings for PM10.

Filter No.	Location	Type of Blank	Number of weighings	Average Filter wt. (mg)	Standard Deviation (mg)
C1	WSU	LAB	3	145.407	0.013
C2	WSU	LAB	3	138.759	0.003
C3	WSU	LAB	9	136.553	0.078
C1	SCAPCA	LAB	5	132.182	0.005
C2	SCAPCA	LAB	4	144.811	0.015
C3	SCAPCA	LAB	8	123.795	0.007
C4	SCAPCA	LAB	6	148.291	0.007
C5	SCAPCA	LAB	6	146.783	0.011
C6	SCAPCA	LAB	2	141.073	0.014
F1	SCAPCA	FIELD	5	133.194	0.014
F2	SCAPCA	FIELD	7	124.796	0.011
F3	SCAPCA	FIELD	4	149.241	0.035
				Average	0.018

Table 4. Reproducibility of co-located samples for PM10 near roadways.

	PM10 concentrations (ug/m3)			
Dates	Sampler1	Sampler2	Sampler3	% Difference*
07/09/92	25.2	28.9		13.7
	10.0	9.0		10.5
07/07/92	26.4	16.8		44.4
	26.0	31.4		18.8
08/05/92	37.4	35.2	32.7	6.8**
08/10/92	33.3	33.1		0.5
08/12/92	32.4	17.0		62.3
08/30/92	49.4	57.1		14.5
08/31/92	34.3	36.4		5.9
09/17/92	68.6	60.6		12.3
09/18/92	75.3	75.1		0.3
		Average		17.3
		AdjustedAverage***		9.3

* Calculated as (S1-S2)/AVE(S1,S2)*100%.

** Largest difference among the samplers is shown.

*** Adjusted Average is calculated excluding 44.4% and 62.3% differences.

in units of m/s, and wind direction expressed as the angle with true north. Meteorological data were stored as 10-minute averages in a datalogger. Traffic counts were obtained using DOT-supplied counters.

At the end of an experiment, the filter holder attachments were transported back to the Laboratory for Atmospheric Research (LAR), WSU. In the lab the filters were retrieved from the holder, placed in clean petri dishes, and equilibrated for at least 24 hours before weighing. After weighing, the filters were immediately refrigerated in their respective air-tight petri dishes.

ROADSIDE MEASUREMENTS ON UNPAVED ROADS

An intensive field study was conducted in Spokane during the period of September 16 through September 28, 1992. Roadside measurements were conducted at three unpaved road sites during this time. The major objective of the intensive experiment was to examine the contribution of PM_{10} due to unpaved roads. This experiment was also conducted in cooperation with WSDOE, the Spokane County Air Pollution Control Authority, and EPA Region X.

These sites were divided into two primary sites (located at 55th street near the Freya street intersection and on Abbott road) and one secondary site (Austin road). At the primary sites, three samplers were set up on each side of the road. The samplers were located 20m from the centerline of the road and spaced 20m apart, parallel to the road. Co-located samplers were deployed for quality assurance

purposes. At the secondary site, a single sampler was located 20m from the road centerline on each side. Samplers were mounted at a height of approximately 2m on aluminum poles. Additional samplers for the intensive field study were supplied by the Spokane County Air Pollution Control Authority and by EPA Region 10.

At each primary site a 10m meteorological tower was erected. Tower-mounted instruments measured wind speed, wind direction, temperatures at 2m and 10m above the surface, relative humidity, precipitation, solar radiation, and barometric pressure. Data were stored as 15-minute averages. Traffic volume during the intensive field study was measured using DOT-supplied traffic counters. At the primary sites, counters that logged both the number of vehicles and vehicle speeds were deployed. The experimental duration was 12 hours, from 0700 to 1900 hours. This allowed the sampling period to capture the peak traffic periods, and to avoid shifts in wind direction that often occurred in the evening.

TRACER FLUX EXPERIMENTS

Tracer releases were conducted during two days at the 55th Street unpaved road site and during two days at the North Division Street paved road location. During each test, sulfur hexafluoride (SF_6) tracer was released at a steady, measured rate from a 100m line source deployed along the edge of the road. The objective of these tests was to simulate the generation of PM_{10} from the road with the tracer and to investigate the dilution rate of tracer (and PM_{10}) downwind

of the road. If the tracer release accurately simulates the source of PM_{10} on the road, then the ratio of PM_{10} to tracer concentrations (after subtraction of the background levels) will be equal to the ratio of the PM_{10} to tracer source strengths. In this way, the emission rate of PM_{10} can be calculated directly from the measured tracer release rate and the measured ratios of PM_{10} to tracer using Equation 3. The simulation of PM_{10} emissions with a tracer release also provides a basis for evaluation and application of a line source, roadway dispersion model. In this case, the tracer data are used to optimize the model parameters and then the model can be used with measured PM_{10} concentrations to back-calculate PM_{10} emission rates. If the model appears to be reasonably accurate based upon comparison with the tracer data, then we have some confidence that the model can be used to estimate PM_{10} concentrations for measurement periods where there are no tracer data. In this way, emissions can be estimated from a larger set of data.

Tracer Release

The tracer gas was released from a gas cylinder through a pressure regulator and rotameter into the 100m line source. The release period was approximately 6 hours. The line source was positioned at approximately 1m above the ground and approximately 5m from the edge (white line) of the road. The line source consists of segments of copper tubing (0.64 cm OD) connected with brass unions every 4m. Each union contains a stainless steel capillary vent (nominally 0.03 cm

bore x 30 cm length) to the atmosphere. When the copper line is pressurized at approximately 10 psig, the capillary vents provide a very uniform release rate of tracer along the length of the line.

The total release rate was monitored with a calibrated rotameter and individual capillary flow rates were measured periodically during each test day. The average release rate ranged from 45 mg/m/s to 55 mg/m/s among the four test periods. The variability in release rate during a particular test varied from ± 17% to ± 24%. The sum of the flow rates from the individual capillaries varied from 69 to 84 mg/m/s during the four test periods. The tracer release rate data are summarized in Table 5. There is a difference of approximately 35% between the total flow measured with the rotameter and the sum of the individual capillary flows. In previous experiments where a mass flowmeter was used in place of the rotameter, these differences did not exist. In the present case, it is not obvious why there is a difference and it is not obvious which set of measurements are in error. For the calculation of emission factors (equation 3) we used capillary flowrates since they are a direct measure of the rate of release of the tracer to the atmosphere and do not require a pressure correction as with the rotameter. Also the variation in the flowrates along the line of the release for any particular test was less than ± 10%.

Table 5. Summary of tracer release rate measurements during the roadway tracer experiments in Spokane, WA.

Dates	Rotometer Flow Rate		Capillary Flow Rate		% Difference
	Average	Standard Deviation	Average	Standard Deviation	
	ug/m/s	ug/m/s	ug/m/s	ug/m/s	
9/21/92	53	9	76	7	35.65
09/22/92	51	10	71	1	32.78
09/23/92	47	8	70	-	39.31
09/26/92	55	13	79	4	35.82

Tracer Sampling Methods

During each tracer test, sequential hourly average SF_6 samples were collected for six hours at one upwind and four downwind sampling points using automated syringe samplers (Krasnec et al., 1984). Each sampler is designed to collect as many as nine sequential syringe samples beginning at a pre-selected start time and with a pre-selected averaging time ranging from 5 min to 75 min. The samplers were co-located with PM_{10} samplers on fence posts deployed along a line extending away from the roadway along the direction of the prevailing wind direction. The release and sampling deployment for the 55th Street site (Tracer Tests 1 and 2) and the North Division site (Tracer Tests 3 and 4) are shown in Figures 2 through 4. During Test 2 at 55th Street, the wind was from the opposite direction and the sampling array was moved to the opposite side of the road. During the second test, two syringe samplers were co-located as a quality control check. The average difference between the two sets of samples was 17.2% (Table 6).

Tracer Sample Analysis

Tracer syringe samples were analyzed using a custom-built electron capture gas chromatograph equipped with a 5A 80/100 mesh molecular sieve stainless steel column (1/8 OD x 8 ft), a gas sampling valve fitted with a 1 cm^3 sampling loop, and a 200 mCi tritium foil electron capture detector. Pre-purified nitrogen was used as a carrier gas. The tracer peak areas were integrated with an electronic integrator (HP-

Table 6. Comparison of tracer concentrations obtained with co-located hourly average samplers during the roadside tracer experiment.

Sequence of hours	SF6 concentrations (ug/m3)		% Difference
	Sampler1	Sampler2	
1	18.1	17.0	6.3
2	18.0	15.3	16.2
3	12.3	19.9	47.2
4	19.3	19.0	1.6
5	23.4	18.7	22.3
6	20.2	22.2	9.4
		Average	17.2

Table 7. Calibration results for tracer analyses during the Spokane roadside tracer experiments.

Tracer Concentrations (ppt) Assigned	Calculated	Error (%)	Event	
70	74.6	6.6	With voltage divider	
70	77.3	10.4		
70	57.4	17.9		
70	61.3	12.3		
70	67.9	2.9		
Mean	67.7	10.0		C = aP^b
Standard Deviation	7.6			a = 2.1
				b = 1.13
% Deviation	11.2			r2 = 0.997
995	1005.7	1.1		
995	1143.0	14.8		
995	1025.7	3.1		
995	1047.6	5.3		
995	1049.4	5.5		
Mean	1054.3	6.0		
Standard Deviation	47.2			
% Deviation	4.5			
3040	2935.0	3.4		
3040	2820.0	7.2		
3040	2908.0	4.3		
3040	2896.0	4.7		
3040	2828.0	6.9		
3040	2912.0	4.2		
3040	3061.0	1.0		

Table 7. (cont.)

Tracer Concentration (ppt) Assigned	Calculated	Error (%)	Event
3040	3003.0	1.2	
3040	2790.0	8.2	
3040	2802.0	7.8	
3040	2982.0	1.8	
3040	2939.0	3.3	
3040	2740.0	9.8	
Mean	2906.3	4.5	
Standard Deviation	81.2		
% Deviation	2.8		
995	953.0	4.3	Without voltage divider
995	965.0	3.0	
995	979.0	1.6	
995	987.0	1.0	
995	991.0	1.0	C = aP^b
995	1012.0	1.6	a = 1.4
995	1010.0	1.5	b = 1.3
			r2 = 0.998
Mean	985.3	2.0	
Standard Deviation	20.2		
% Deviation	2.0		
3040	2990.0	1.6	
3040	2905.0	4.4	
3040	3100.0	2.0	
Mean	2998.3	2.7	
Standard Deviation	79.8		
% Deviation	2.7		

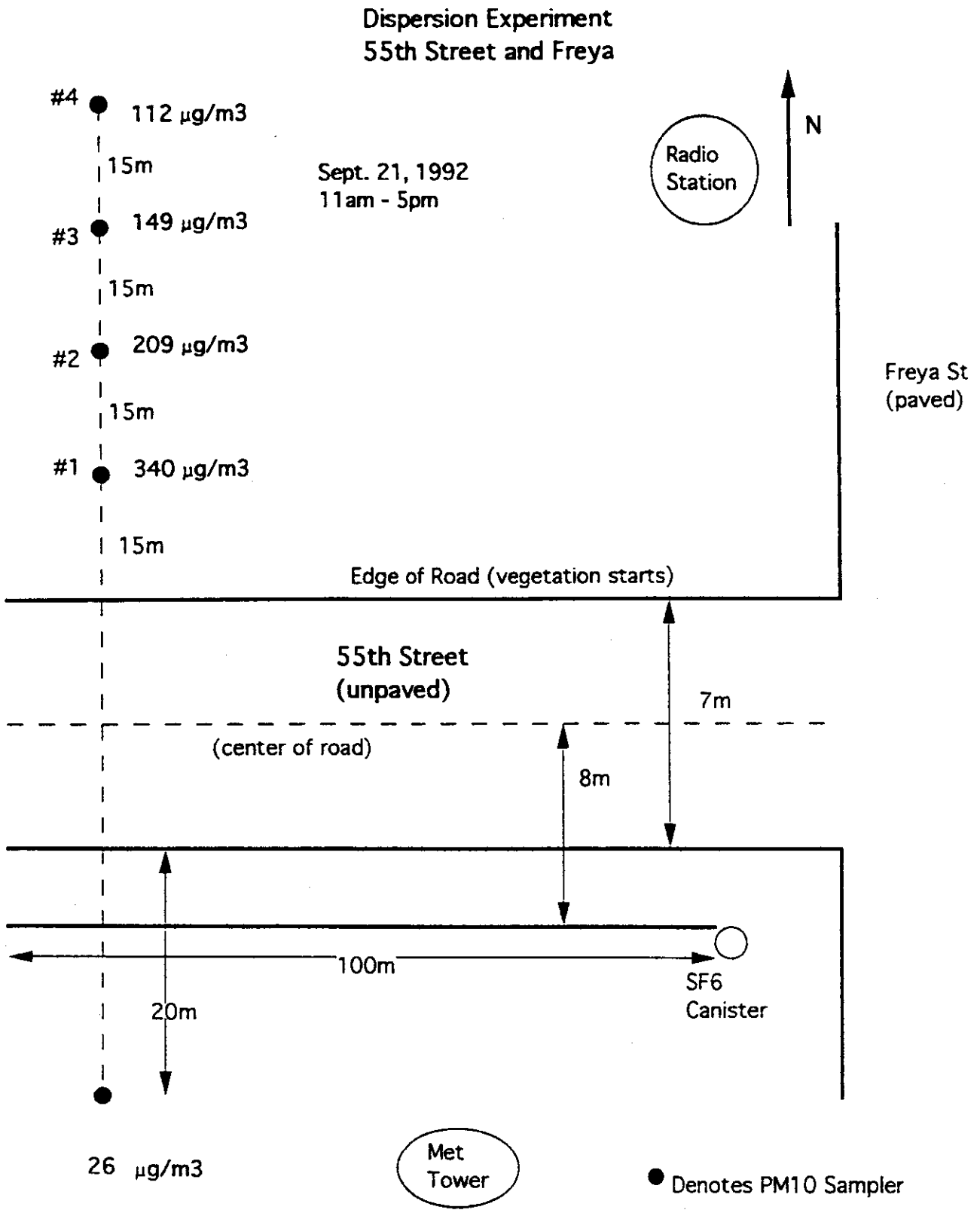

Figure 2: Experimental Configuration for Tracer Test for 55th Street and Freya Location, September 21, 1992.

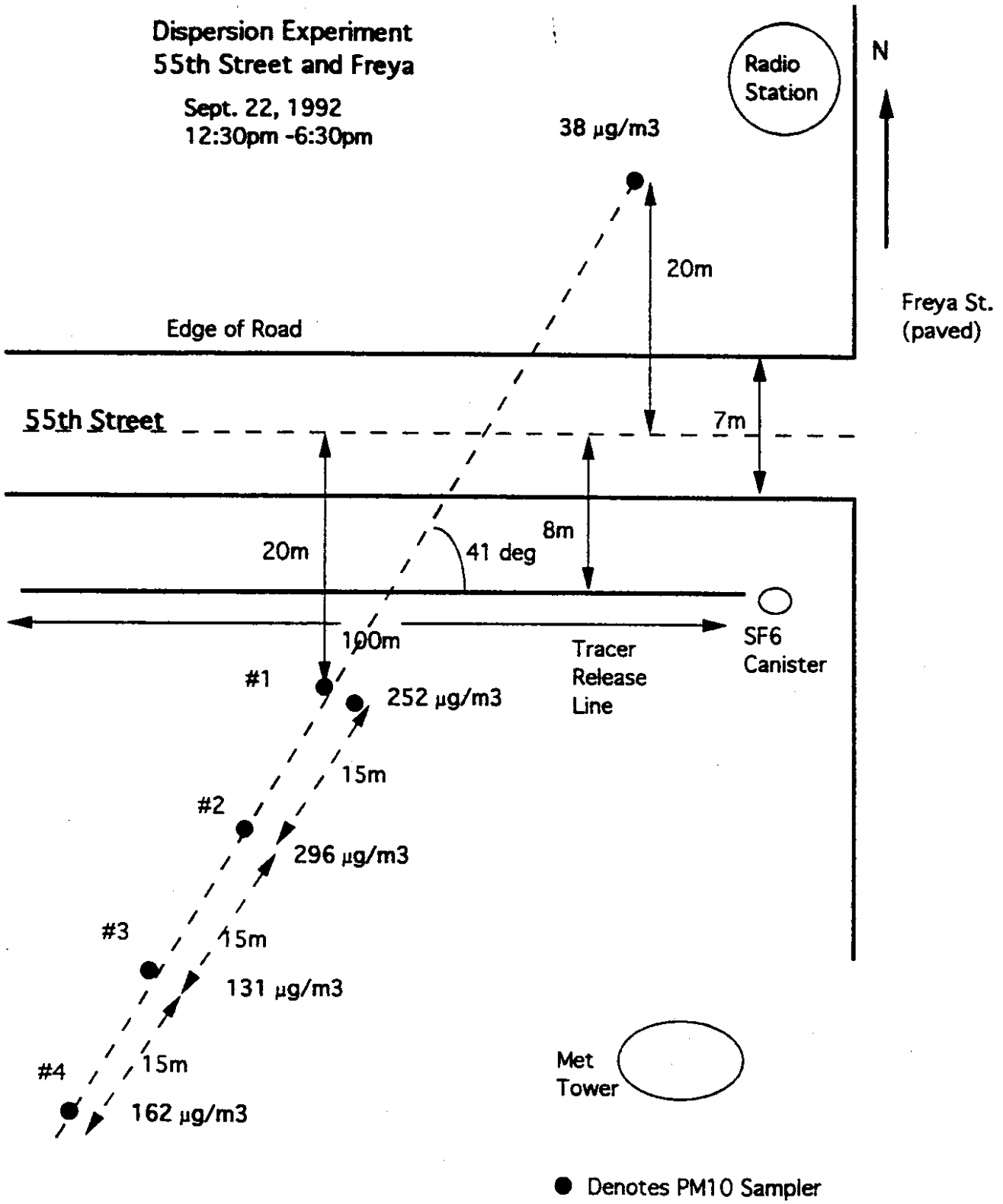

Figure 3: Experimental Configuration for Tracer Test for 55th Street and Freya Location, September 22, 1992.

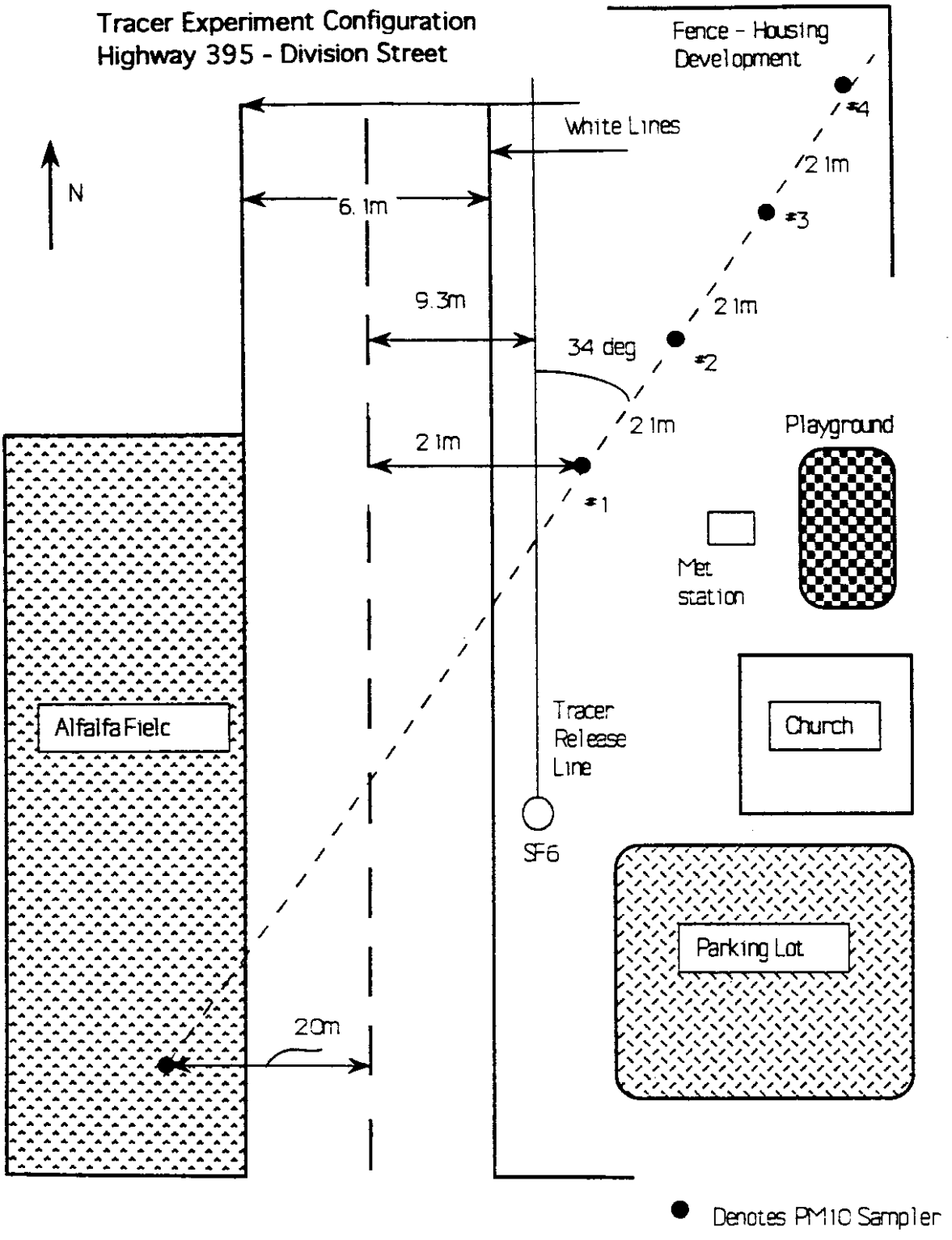

Figure 4: Experimental Configuration for Tracer Test for North Division Street (Highway 395) Location, September 23, 1992.

3392). The instrument was calibrated using a series of SF_6/air certified standards (Scott-Marin, Inc., ± 5% accuracy) over the range 70 to 3040 parts per trillion (ppt). Calibration results are summarized in Table 7. The reproducibility of standard analyses was better than ± 5%, and the error in the best-fit power law calibration curve was less than 6% as indicated in Table 7, except for the 70 ppt standard analyses where the reproducibility was 11% and the error in the best-fit power law was ± 10%.

DISCUSSION OF RESULTS

ROADSIDE MEASUREMENTS

During the roadside experiments periodic problems associated with battery failure were observed. Regardless of the period of operation of each individual sampler, unless otherwise noted, mean roadside concentrations were obtained by calculating concentrations for each sampler and averaging all concentrations. Meteorological data from the Potlatch Corp. paper mill at Lewiston, Idaho were obtained for experiments conducted at the Clearwater bridge site. Traffic counts were not available for each experiment but were obtained for at least one experiment at each site. Table 8 shows the average meteorological conditions and the PM_{10} data for all roadside measurements on paved roads described below.

MOSCOW-PULLMAN HIGHWAY SITE

The east-west orientation of the Moscow-Pullman highway (State Route 270) is shown in Figure 5. Roadside experiments

were conducted at this site on July 7, July 9, and July 14, 1992. Traffic volume obtained on 7/14 is assumed to be representative for this site.

On July 7, two samplers were operated on each side of the road from 0930 to 1830 hours. No wind data were available on this day, however hand-held anemometer measurements indicated that the wind speed fluctuated around 2 to 3 m/s. The wind direction was variable, fluctuating from SW to NE during the course of the experiment. Since the road is oriented E-W, the wind direction changed from one side of the road to the other, so that one might expect that the net PM_{10} increment across the road would be reduced. The average concentration measured on the north and south sides of the road was 21.6 $\pm$ 4.8 $\mu g/m^3$ and 28.7 $\pm$ 2.7 $\mu g/m^3$ respectively. The difference in concentration across the road was 7.1 $\mu g/m^3$ (assuming that the north side is the upwind side). The approximate per vehicle increment was 0.0017 $\mu g/m^3$ for an overall traffic volume of 4260 vehicles.

On July 9, two samplers were operated on each side of the highway from 0730 to 1730. The average wind speed and direction were 2.2 m/s and 268 $\pm$ 46 deg N, respectively, between 0742 and 1526 hours. The average downwind (north side) PM_{10} concentration measured during this experiment was 27.1 $\pm$ 1.9 $\mu g/m^3$, and the upwind concentration was 9.5 $\pm$ 0.5 $\mu g/m^3$. The increment in roadside PM_{10} concentration across the highway was 17.6 $\mu g/m^3$. Using the traffic volume from 7/14 (4330 vehicles over the sampling period), the PM_{10}

Table 8. Summary of paved roadside PM10 measurements at sites in Washington and Idaho.

Date	Start Time	Stop Time	Wind Direction	Wind Speed	Traffic Count	Upwind Concentration	%Standard Deviation	Downwind Concentration	%Standard Deviation	(Downwind -upwind) Concentration	Increment/ Vehicle(#)
			(Deg. N)	(m/s)	(no.)	(ug/m3)		(ug/m3)		(ug/m3)	(ug/m3/vehicle)
Moscow-Pullman Highway # 270											
07/07/92	0930	1830		2.0*	4260!	28.7	9.4	21.6	22.2	7.1	0.0017
07/09/92	0730	1730	268	2.2	4330!	9.5	5.2	27.1	6.8	17.6	0.0041
07/14-15/92	0630	0630		4.0*	5725	12.8	52.3	38.2	16.6	25.4	0.0044
Clearwater Bridge, Highway # 12, Lewiston, ID.											
08/09-10/92	2000	2000	186	3.2	13333	16.3	52.3	35.1	5.5	18.8	0.0014
08/12-13/92	1400	1400	150	3.2	12969	10.4	40.6	31.0	10.6	20.6	0.0016
08/30-31/92	1400	1400			13312	30.0		30.5	21.4	0.5	0.0000
08/31-09/1/92	2215	1710	167	5.1	9350	32.5		53.4	6.0	21.0	0.0022
North Division, Highway # 395, Spokane, WA.											
07/27/92	0700	1900	NE &		6080						
& 07/28/92	0600	1800	SW *	1.5*	5670	11.4	32.0	7.2	15.0	4.2	0.0004
08/05/92	0600	1800			6316						
&08/06/92	0600	1800	SW*	3.5*	6015	15.0	45.0	31.0	20.0	16.0	0.0013
09/16/92	0600	1800			5890!!	26.7		33.3		6.6	0.0011
09/17/92	0715	2200	151	1.3	6785	13.6		49.0		35.4	0.0052
09/18/92	0700	1900			6515	30.2		31.6		1.4	0.0002
09/21/92	0700	1900	200!	1.4	5915	28.0		9.4		-18.6	-0.0030
09/23/92	0700	1800	207	3.4	5550	21.4		24.0		2.6	0.0005
09/25/92	0700	1900	237	2.9	6045	35.0		36.0		1.0	0.0002
09/26/92	0700	1700	217	3.0	3885	9.7		46.5		36.9	0.0090

* Data obtained using a hand-held anemometer.

** Data estimated from 55th Street site.

! Data estimated from the data obtained on 07/14-15/92.

!! Data calculated from the data obtained on 09/23/92.

Delta C is the PM10 concentration difference across the road per vehicle , calculated as the downwind concentration minus the upwind concentration divided by the total number of vehicles.

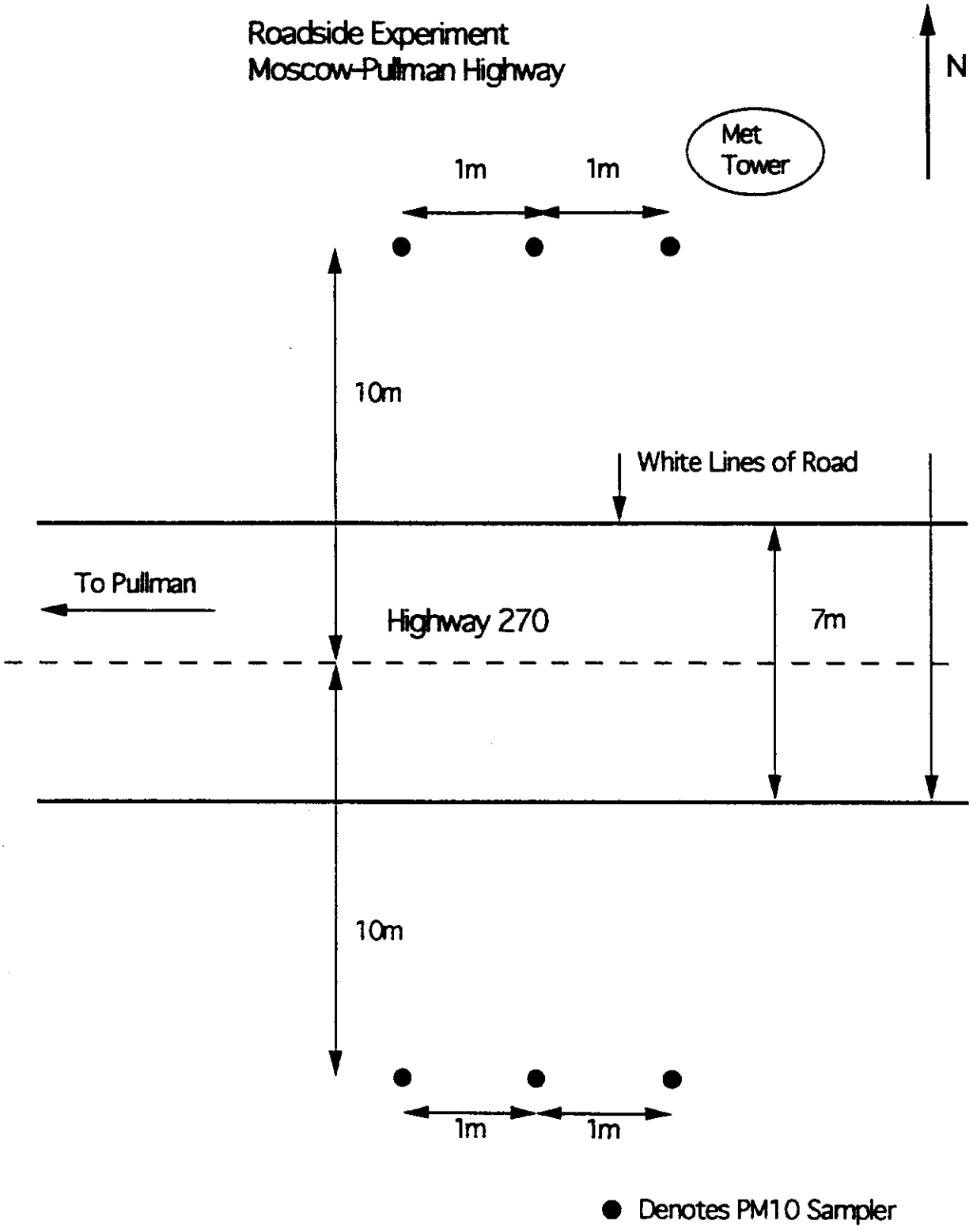

Figure 5: Experimental configuration for Roadside Experiments on Moscow-Pullman Highway (State Route 270)

increment per vehicle was approximately 0.0041 $\mu g/m^3$/vehicle.

Three samplers were operated on each side of the highway from 0830 hours on July 14, 1992 through 0630 hours on July 15, 1992. No meteorological data were available for this period; however, frequent checks indicated that SW winds at 4 to 5 m/s prevailed from 0800 until sunset and after sunset winds from the NE prevailed. The total number of vehicles counted during this 22 hour period was approximately 5725. The average PM_{10} concentration measured on the north (downwind) side of the road was 38.2 $\pm$ 6.4 $\mu g/m^3$. Battery failures were experienced during this experiment, resulting in a high variability between samplers on the south side of the road. The average PM_{10} concentration on the south side of the road was 12.8 $\pm$ 8.9 ug/m^3, or 52.3% variability, the highest variability observed at this site. The PM_{10} concentration increment across the road was 25.4 $\mu g/m^3$ over this 22 hour period, or 0.0044 $\mu g/m^3$/vehicle.

LEWISTON SITE

The orientation of the Highway 12 bridge over the Clearwater river at Lewiston is north - south (Figure 6). Roadside experiments were conducted at this site on August 9, August 12, August 30, and August 31, 1992 (Table 8).

The first roadside experiment at this site was performed from 2000 hours on August 9, 1992 through 2000 hours on August 10, 1992. Three samplers were set up on each side of the bridge as shown in Figure 6. Meteorological data

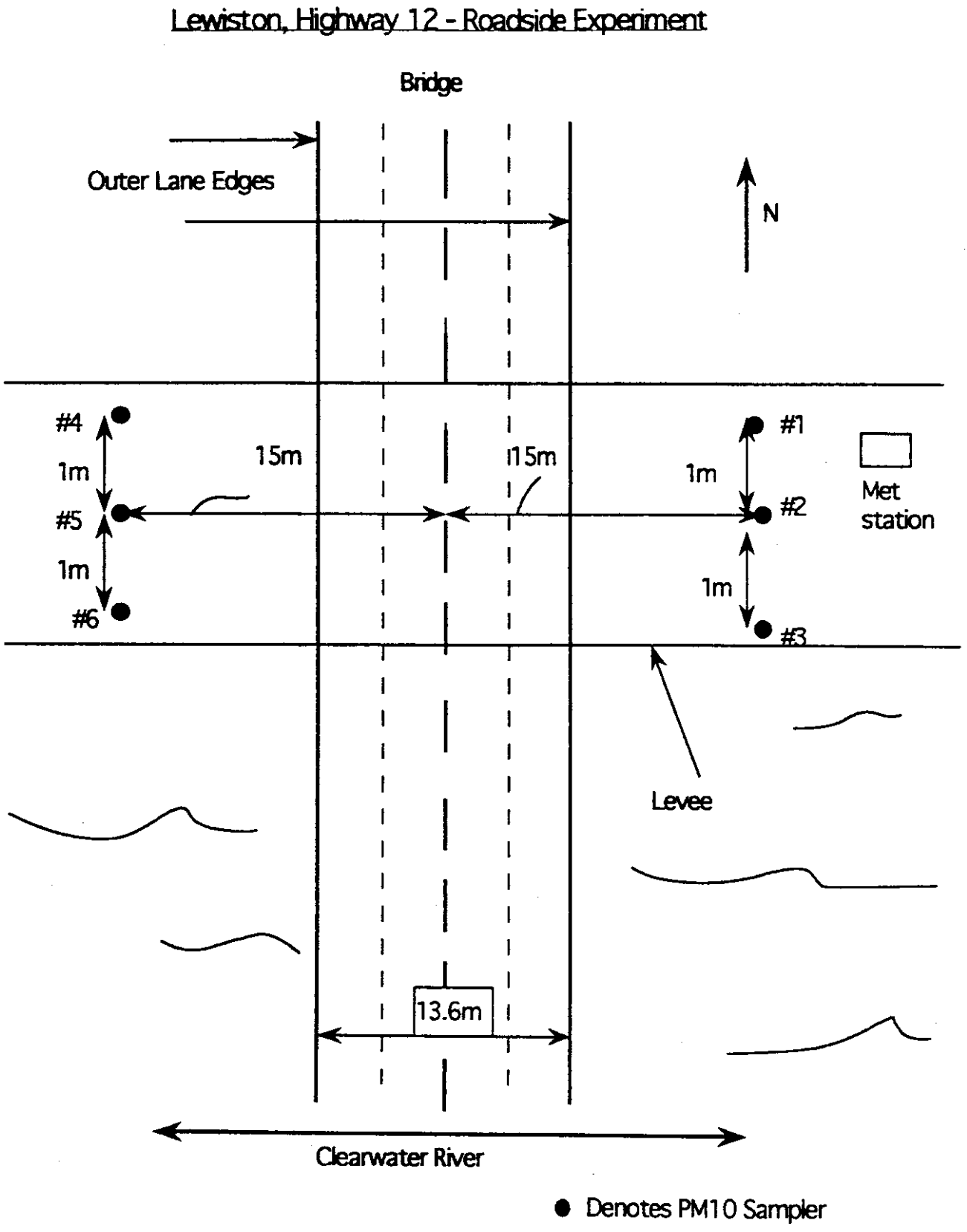

Figure 6: Experimental configuration for roadside experiments on Highway 12 Bridge, Clearwater River, Lewiston, Idaho.

obtained from the Potlatch Corporation facility approximately 1 km east of the bridge indicated an average wind direction from 186 ± 89 deg N and wind speed of 3.2 m/s for this period. However, the prevailing wind direction changed from SW to NE over this period. The 24 hour averaged downwind (east side) and upwind PM_{10} concentrations were 35.1 ± 1.9 $\mu g/m^3$ and 16.3 ± 8.5 $\mu g/m^3$ (52.3%) respectively. Battery failure occurred on the first and third samplers on the upwind side within 6.0 hours. The concentration increment across the road was 18.8 $\mu g/m^3$ with an overall traffic count of 13,333 vehicles. This yields an average PM_{10} increment of 0.0014 $\mu g/m^3$/vehicle.

Three samplers were operated on each side of the bridge from 1400 hours on August 12 through 1400 hours on August 13, 1992. The wind direction was from 150 ± 82 deg N at 3.2 m/s over this 24 hour period. The total traffic volume during the 24 hour period was 12,969 vehicles. The 24 hour PM_{10} concentration on the downwind side of the bridge was 31 ± 3.3 $\mu g/m^3$ and on the upwind side the PM_{10} concentration was 10.4 ± 4.2 $\mu g/m^3$ (40.6%). The PM_{10} increment across the road was 20.6 $\mu g/m^3$, and the average increment was 0.0016 $\mu g/m^3$/vehicle.

Three samplers on the east side of the bridge and one sampler on the west side of the bridge were operated from 1400 on August 30, 1992 to 1400 hours on August 31, 1992. No meteorological data were available for this day. The total traffic volume for this period was 13,312. The 24 hour

average PM_{10} concentrations measured on the east and west sides of the bridge were 30.5 and 30 $\mu g/m^3$ respectively. One of the samplers on the east side of the bridge measured only 17.0 $\mu g/m^3$ over a 24-hour sampling period. The PM_{10} increment across the road was negligible.

During August 31, 1992, three samplers on the east (downwind) side of the road and one sampler on the west side of the road were operated from 2215 to 1710 hours, September 1, 1992. The average wind direction was 167 $\pm$ 90 deg N at 5.1 m/s for this 19 hour period. The traffic volume during this 19 hour sampling period was 9350 vehicles. The average downwind PM_{10} concentration was 53.4 $\pm$ 3.2 $\mu g/m^3$ and the upwind PM_{10} concentration was 32.5 $\mu g/m^3$. The increment of roadside PM_{10} across the bridge was 21.0 $\mu g/m^3$, or 0.0022 $\mu g/m^3$/vehicle.

NORTH DIVISION SITE

The North Division (Highway 395) site is oriented 10 degrees off true North (Figure 7). Preliminary roadside experiments were conducted at this site on July 27 and August 5, 1992 (Table 8). Results from roadside experiments conducted at this site as part of the intensive field study performed in September are also presented in this section.

Beginning July 27, 1992, upwind and downwind PM_{10} samples were composited for 24 hours over two days. The samplers were operated from 0700 to 1900 hours on July 27, and from 0600 to 1800 hours on July 28. Continuous wind data

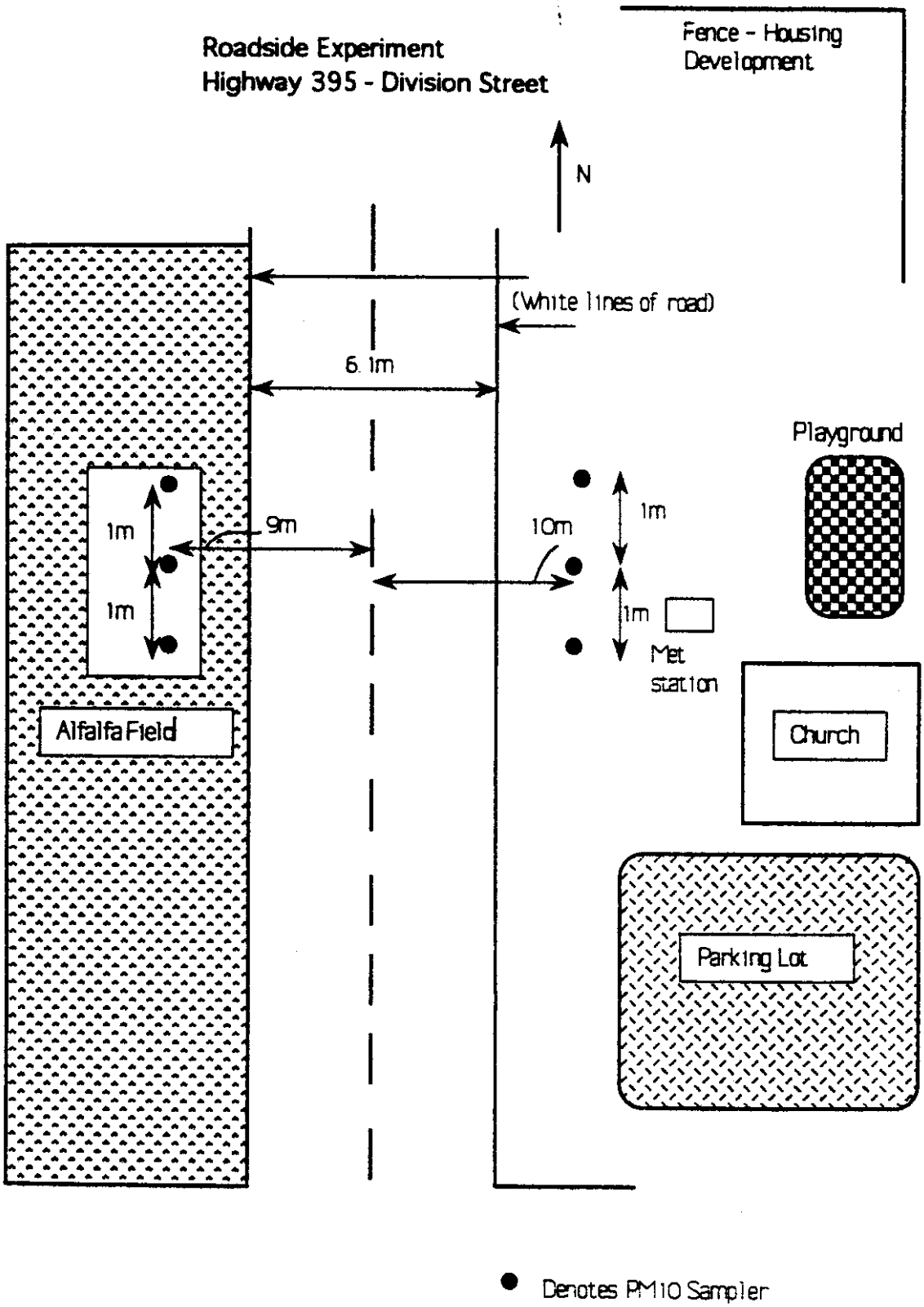

Figure 7: Experimental configuration for roadside experiments North Division Street (Highway 395).

were not collected, however checks with a handheld anemometer indicated that until noon the wind was from NE and after noon the prevailing wind was from SW at approximately 1.5 m/s. The total numbers of vehicles on July 27 and 28 during the sampling periods were 6080 and 5670, respectively. The average east and west roadside PM_{10} concentrations were 7.2 and 11.4 $\mu g/m^3$, respectively. The PM_{10} concentration increment was 4.2 $\mu g/m^3$, or 0.0004 $\mu g/m^3$/vehicle and the direction of the increment implies that the net transport occurred from the east side.

Roadside PM_{10} concentrations were again composited from 0600 to 1800 hours on August 5 and 6, 1992. Periodic checks indicated that the winds were from the SE in the earlier part of the day and became southwesterly in the afternoon on August 5. On August 6, the prevailing winds were from the SW at 3.5 m/s. The traffic volume during the two sampling periods were 6316 and 6015 vehicles, respectively. The average PM_{10} concentrations on the east (downwind) and west sides of the highway were 31 and 15 $\mu g/m^3$, respectively. Only two sampler results were considered in calculating the average concentration for the west side of the road. The remaining sampler measured only 0.8 $\mu g/m^3$ over this 24 hour sampling period. The difference in roadside PM_{10} concentration across the road was 16 $\mu g/m^3$, or 0.0013 $\mu g/m^3$/vehicle.

Sampler configuration during the September measurements at N. Division is illustrated in Figure 8. Samplers were

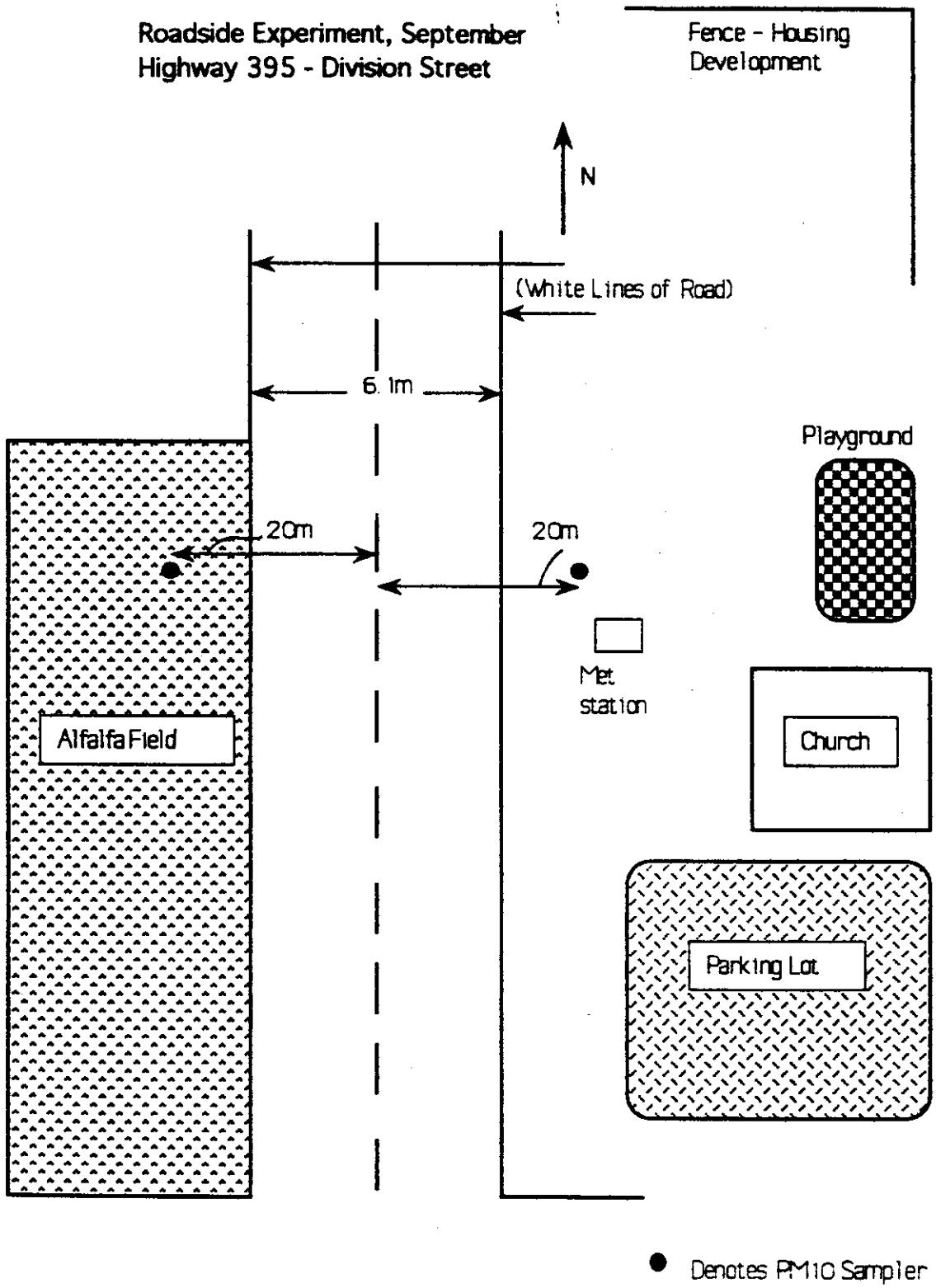

Figure 8: Experimental Configuration for Roadside Experiments on North Division Street (Highway 395) Conducted During September Intensive field study.

operated on each side of the road for 12 hours, from 0600 to 1800 hours on September 16, 1992. No wind data were available on this day, however data from other Spokane sites suggest that the average local wind direction in Spokane was from the SW. The concentrations on the east (downwind) and west sides of the road were 33.3 $\mu g/m^3$ and 26.7 $\mu g/m^3$, respectively. The increment across the road for this day was 6.6 $\mu g/m^3$. Traffic volume was not measured on this day, however using the hourly traffic volume obtained for the following Wednesday (September 23), the per vehicle increment was 0.0011 $\mu g/m^3$/vehicle for an overall traffic volume of 5890 vehicles.

On September 17, 1992, the concentrations on the east and west sides of the road were 13.6 $\mu g/m^3$ and 49.0 $\mu g/m^3$, respectively over a sampling period of 14.7 hours (from 0715 to 2200 hours). The average wind speed and direction over the sampling period were 1.3 m/s and 151 $\pm$ 119 deg N, respectively. The increment across the road is 35.4 $\mu g/m^3$, or 0.0052 $\mu g/m^3$/vehicle for the traffic volume from Thursday, September 24, of 6785 vehicles.

Two samplers were operated from 0700 to 1900 hours on September 18, 1992. No wind data were available at this site on this day. Meteorological data from 55th indicated that the wind direction was from the SW, while the Abbott site instrument showed that the wind was from the SE. The traffic volume over the 12 hours sampling period was 6515 vehicles. The PM_{10} concentrations on the east and west (downwind) sides

of the road were 30.2 and 31.6 $\mu g/m^3$, respectively, so that the increment was 1.4 $\mu g/m^3$, or 0.00021 $\mu g/m^3$/vehicle.

On September 21, 1992, the PM_{10} concentrations on the east and west sides of the road were 9.7 and 28.0 $\mu g/m^3$, respectively. No meteorological data were collected for this day, however, if we assume that the wind direction at the N. Division street corresponds to that at 55th street (approximately 1 m/s and 200 deg N), then the upwind side (west side) showed a higher concentration than the downwind side, and the difference across the road was -18.6 $\mu g/m^3$, or -0.0031 $\mu g/m^3$/vehicle for a total traffic volume of 5915 vehicles. We recognize that this apparent negative increment is not consistent with increasing PM_{10} concentration across the road, however, to be consistent we have retained our upwind-downwind designation.

The PM_{10} concentration on the east and west sides of the road were 24.0 and 21.4 $\mu g/m^3$ over an 11 hour period on September 23, 1992. The average wind was from 207 $\pm$ 33 deg. N at 3.41 $\pm$ 0.7 for the sampling period. The increment of PM_{10} concentration across the road on this day was 2.6 $\mu g/m^3$ for an overall traffic volume of 5550 vehicles, or 0.0005 $\mu g/m^3$/vehicle.

The PM_{10} concentration on the east and west sides of the road on September 25, 1992 were 35.0 and 36.0 $\mu g/m^3$, respectively. The average winds were from 237 $\pm$ 38 deg N at 2.9 $\pm$ 0.5 m/s for this period. The difference in PM_{10}

concentration across the road was 1.0 $\mu g/m^3$, or 0.0002 $\mu g/m^3$/vehicle.

On September 26, 1992, the samplers were operated from 0700 to 1700 hours. The west side sampler stopped after 2.4 hours and measured a concentration of 9.7 $\mu g/m^3$. The PM_{10} concentration on the east side of the road was 46.5 $\mu g/m^3$. A dust storm was observed during approximately the last hour of sampling. Because of the assumed increase in background PM_{10} from the dust storm that would have occurred after the west-side sampler quit, the increment was not calculated for this day.

INTENSIVE FIELD STUDY

55th Street

The orientation of 55th street near the Freya street intersection is east-west (Figure 9). The prevailing wind direction is from the southwest, so that the north side of the road is generally the downwind side. During the intensive field study, the samplers were operated for approximately 12 hours, from 0700 to 1900 hours. Recurring battery failures were experienced throughout the experiments, so that some samplers failed to run for the full 12 hours. PM_{12} sampling heads were occasionally inadvertently used instead of PM_{10} heads; these occurrences were recorded. Table 9 shows the average meteorological conditions and the PM_{10} data for this and other unpaved road sites. On September 17, 1992, samplers were operated from 8000 to 1900 hours. The average wind speed and wind direction were 1.8 $\pm$ 0.6 m/s and

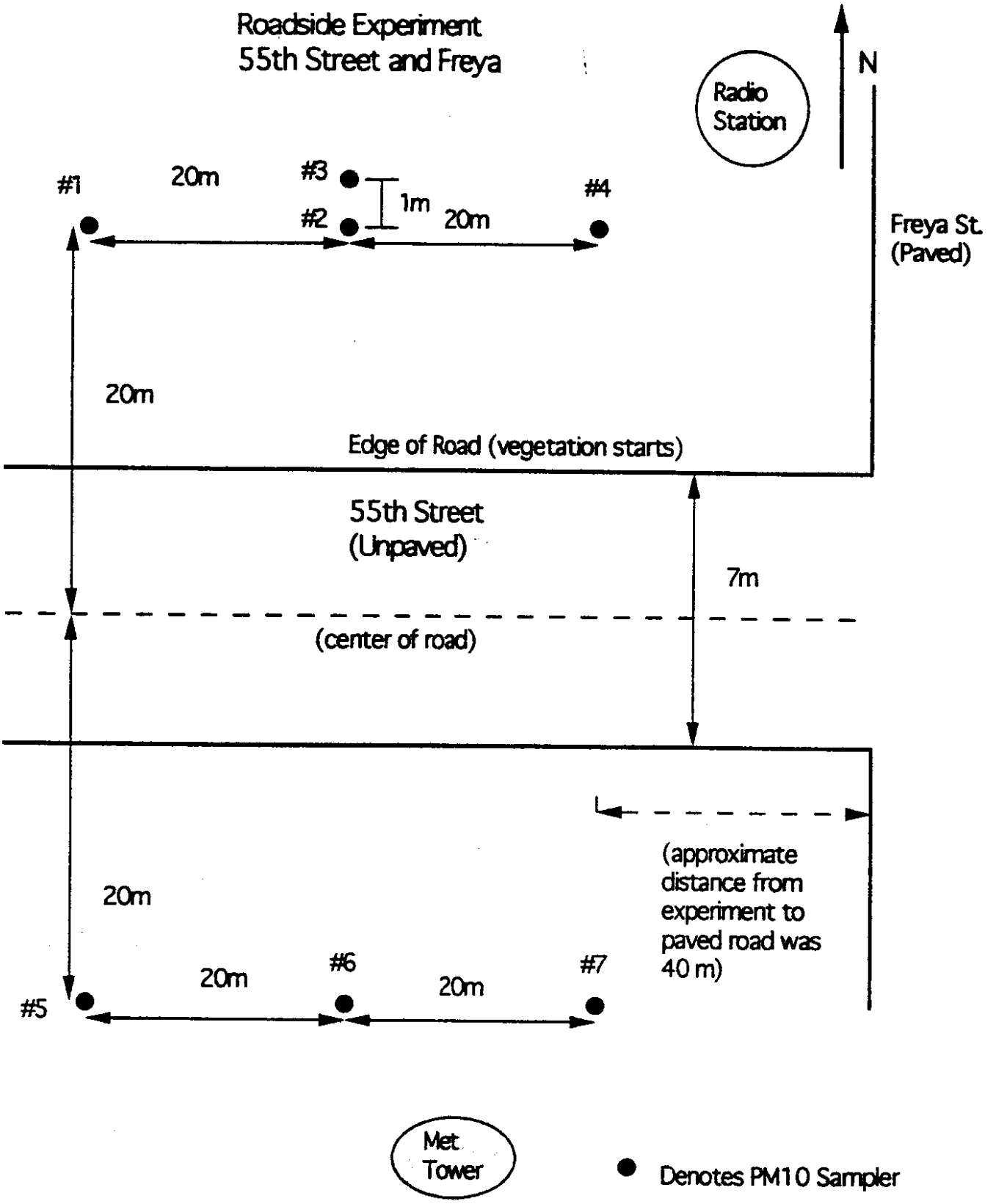

Figure 9: Experimental configuration for Roadside Experiments on 55th Street, near Freya, conducted during September intensive field study.

192 ± 142 deg, respectively. Traffic counters were not yet deployed, however the traffic pattern for September 23, 1992 suggests a traffic volume of 555 vehicles for the duration of the experiment. The average concentration of PM_{10} on the downwind (north) side was 146 $\mu g/m^3$ which was lower than the south side (average concentration was 366 $\mu g/m^3$). The concentration on the north side ranged from 51 $\mu g/m^3$ (position 4) to 199 $\mu g/m^3$ (position 2) and that on the south side from 316 $\mu g/m3$ (position # 5) to 443 $\mu g/m^3$ (position #6). The PM_{10} concentration increment across the road was -220 $\mu g/m^3$, or -0.39 $\mu g/m^3$/vehicle.

On September 18, 1992, the samplers were operated from 0800 to 2000 hours. The average wind speed and direction over this 12 hour period were 1.7 ± 0.6 m/s and 205 ± 62.7 deg N respectively. No traffic data were available on this day, so the traffic volume was assumed to be the same as that for the following Friday (September 25, 1992), or approximately 545 vehicles over the 12 hour sampling period. The average concentration on the downwind and upwind sides of the road were 560 and 123 $\mu g/m^3$. The filter from sampler at position number 6 on the upwind side was damaged and was thus discarded. The increment across the road was 437 $\mu g/m^3$, or 0.80 $\mu g/m^3$/vehicle.

The samplers were operated from 0720 to 1900 hours on September 21, 1992. The average winds for this sampling period were from 186 ± 26 deg N at 2.65 ± 0.8 m/s. The total number of vehicles from 0900 to 1900 hours was 400, and the

traffic volume from 0720 to 0900 was estimated from the data of September 22. The PM_{10} concentration on the downwind side (north side) ranged from 97 $\mu g/m^3$ (position # 4) to 540 $\mu g/m^3$ (position # 1) and the average was 271 $\pm$ 193 $\mu g/m^3$ (or $\pm$ 71%, which was the highest variability observed at this site during the intensive field study). The average concentration on the upwind side was 50.0 $\pm$ 6.9 $\mu g/m^3$ (13.4%). The PM_{10} concentration increment was 221 $\mu g/m^3$, or 0.41 $\mu g/m^3$/vehicle, for an overall traffic volume of 545 vehicles.

Three samplers on the north side and two samplers on the south side of the road were operated on September 22, 1992 from 0700 to 1900 hours. The average wind speed and direction was 3.0 $\pm$ 0.9 m/s and 60 $\pm$ 27 degrees N. The total traffic volume for this 12-hour period was 580 vehicles. On the downwind (south) side the concentrations ranged from 206 $\mu g/m^3$ (position # 6) to 418 $\mu g/m^3$ (position # 5). The average concentration was 313 $\pm$ 106 $\mu g/m^3$ (33.89%). The average upwind concentration was 93.0 $\pm$ 37.2 $\mu g/m^3$, and the increment is 220 $\mu g/m^3$, or 0.37 $\mu g/m^3$/vehicle.

On September 23, 1992, PM_{12} inlet heads were inadvertently installed on position 1 (north, or downwind, side), and on position 7 (south side). The average PM_{10} concentration over this 12 hr period on the north (downwind) side of the road was 189 $\pm$ 44.6 $\mu g/m^3$ (23.6%). The maximum concentration was 233 $\mu g/m^3$ and was recorded by the sampler at position 4. The lowest concentration was 144.1 $\mu g/m^3$ at position 2. On the south side of the road the only sampler

that recorded PM_{10} was at position 6 and the concentration recorded was 34.8 $\mu g/m^3$. The average wind speed over this 11.6 hour period was 5.8 $\pm$ 0.5 m/s. The average wind direction was 201 $\pm$ 16 deg N. The total traffic volume during the sampling period was 570. The PM_{10} concentration increment was 154 $\mu g/m^3$ while increment per car was 0.27 $\mu g/m^3$/vehicle.

Three samplers on the north side, and two on the south side of the road, collected PM_{10} on September 25, 1992 from 0745 to 1900 hours. The average wind speed and direction were 5.1 $\pm$ 0.5 m/s and 220 $\pm$ 20.4 deg N, respectively. The overall traffic volume during this period was 520 vehicles. Samplers at positions 2 and 3 were co-located. The average downwind PM_{10} concentration, including the concentration measured at position 3, was 183.0 $\pm$ 79.1 $\mu g/m^3$ (variability 43.0%). The average upwind PM_{10} concentration was 65.0 $\mu g/m^3$. The PM_{10} concentration increment was 118 $\mu g/m^3$, or 0.23 $\mu g/m^3$/vehicle.

On September 26, five samplers collected PM_{10}, operating from 0745 to 1650 hours. The average winds were from 187 $\pm$ 17 deg N at 6.8 $\pm$ 1.3 m/s. The total traffic volume until 1445 hours was 305 hours. The average PM_{10} concentration on the north side (downwind) of the road was 73.4 $\pm$ 4.9 $\mu g/m^3$ ($\pm$ 6.6%). The south side (upwind) of the road recorded an average concentration of 64.1 $\pm$ 20.9 $\mu g/m^3$ (variability 32.6%). The PM_{10} increment across the road was, at a maximum, 9.3 $\mu g/m^3$ or 0.03 $\mu g/m^3$/vehicle, based on the 305 vehicles

counted until 1445. The actual increment will be lower, due to the uncounted vehicles from 1445 to 1650 hours.

Abbott Road

At the Abbott Road site the road is oriented north-south and the prevailing wind direction is SW, so that the east side of the road is typically the downwind side. Four samplers (positions 1,2,3,4) were set up at the east side of the road with those at positions 2 and 3 co-located (Figure 10). On the west side of the road three samplers (positions 5,6,7) were set up. Table 9 shows the average meteorological conditions and the PM_{10} data for this site.

On September 17, 1992, samplers were set up at all seven positions on the road. The average wind speed during the 10 hour experiment was 1.8 ± 0.8 m/s. The wind direction was highly variable and nearly parallel to the road, with an average direction of 186 ± 135 deg N. An unusually high concentration of 310 $\mu g/m^3$ was observed at position #4. The concentrations measured at the co-located samplers were within 12% of each other (60 and 68 $\mu g/m^3$). Taking all the samplers into consideration the average concentration on the east (downwind) side of the road was 129 ± 105 $\mu g/m^3$ (variability 81%). The average concentration on the west side of the road was 105 ± 14.1 $\mu g/m^3$ (variability of 13.4%). If we do not take into consideration the 4th sampler on the east side the average downwind concentration is 67.7 $\mu g/m^3$, which is lower than the average upwind concentration. It is interesting to note that, on this day at the 55th Street

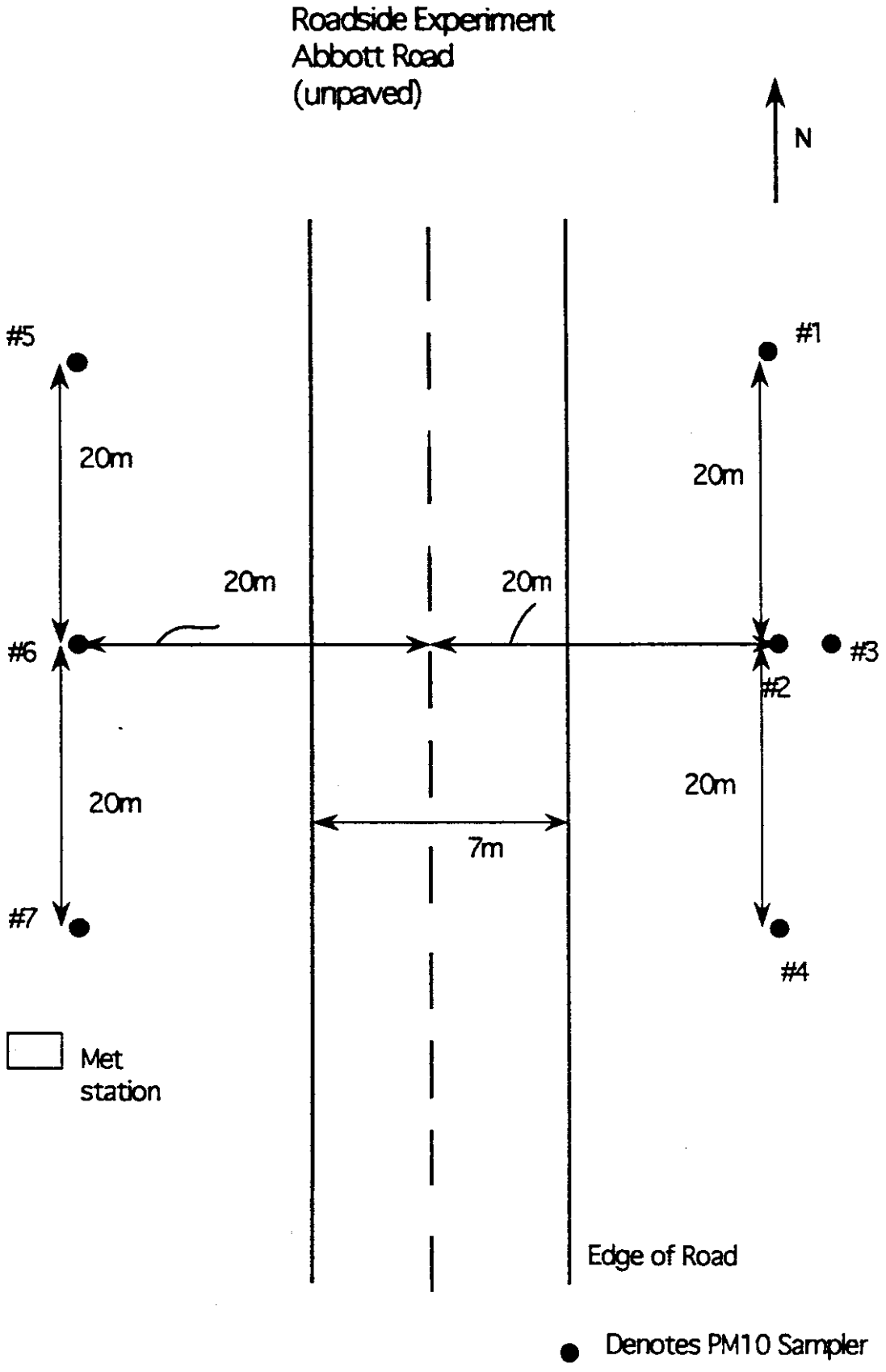

Figure 10: Experimental configuration for roadside experiments on Abbott Road, conducted during September intensive field study.

Table 9. Summary of unpaved roadside PM10 measurements at sites in Spokane, WA.

Date	Start Time	Stop Time	Wind Direction	Wind Speed	Traffic Count	Upwind Concentration	%Standard Deviation	Downwind Concentration	%Standard Deviation	(Downwind -upwind) Concentration	Increment/ Vehicle
	(hr)	(hr)	(Deg. N)	(m/s)	(no.)	(ug/m3)		(ug/m3)		(ug/m3)	(ug/m3/vehicle)
55th. Street											
09/17/92	0800	2000	192	1.8	555*	366	15.0	146	45.7	-220	-0.39
09/18/92	0800	2000	205	1.7	545*	123	54.7	560	9.1	437	0.80
09/21/92	0720	1900	186	2.6	545	50	13.4	271	71.2	221	0.40
09/22/92	0700	1900	60	3.0	560	93	40.0	313	33.8	220	0.37
09/23/92	0725	1900	198	6.2	570	35	0.0	189	23.6	154	0.27
09/25/92	0745	1900	220	5.1	520	65	3.1	183	43.2	118	0.23
09/26/92	0745	1645	187	6.8	305	64	32.6	73	6.6	9	0.03
Abbott Road											
09/17/92	0900	1900	186	1.8	41*	105.4	13.4	128.4	82.0	23	0.56
09/18/92	0855	1900	166	1.8	48	46.4	10.0	78.6	10.2	32.2	0.67
09/21/92	0745	1900			41	28.8	23.5	42.7	5.7	13.9	0.34
09/22/92	0700	1720			65	30.5	15.6	66.3	53.0	35.8	0.55
09/23/92	0700	1900	202	5.4	60	59.3	5.4	64.2	2.3	4.9	0.08
09/26/92	0730	1750	190	6.2	51*	41.2	8.7	85.5	8.4	44.3	0.87
Austin Road **											
09/18/92	0720	1900				5.4		5.9		0.5	
09/21/92	0715	1917				26.3		33.9		7.6	
09/22/92	0720	1911				21.1		46.8		25.6	
09/23/92	0720	1915				3.4		44.7		41.3	
09/28/92	0745	2055				40.1		53.6		13.5	

* For these days traffic volumes are estimated from the corresponding weekdays, either from the following or the previous week.

** At this site upwind and downwinde concentrations actually represent concentrations on the west and east side of the road, respectively. No traffic or meteorological data were available for this site.

site, the downwind concentration was also observed to be lower than the upwind concentration. The anomalies observed on this day at these two sites are probably due to the variable wind direction. The increment across the road was 23 $\mu g/m^3$, or 0.56 $\mu g/m^3$/vehicle.

Samplers were again set up at all seven positions on September 18, 1992. The average wind direction over this sampling period was 166 $\pm$ 66 deg N; therefore, the wind was again nearly parallel to the road. A concentration of 75 $\mu g/m^3$ was calculated for both of the co-located samplers. The average concentration on the east side of the road was 78.6 $\pm$ 8.0 $\mu g/m^3$ (variability of 10.2%). The average concentration on the west side of the road was 46.4 $\pm$ 4.7 $\mu g/m^3$ (variability of 10.0%). The east side recorded a higher concentration than the west side, with a PM_{10} concentration increment of 32.2 $\mu g/m^3$, or 0.67 $\mu g/m^3$/vehicle for a traffic volume of 48 vehicles.

On September 21, samplers were set up at positions 1,2, and 4 on the east side of the road. The traffic volume was 41 vehicles. A battery failure on the meteorological tower occurred on this day, so that no wind data were available; however, data from 55th street suggest that on this day the winds were strong and steady from the south to southwest, or nearly parallel to the road. (At 55th street the average wind speed and direction were approximately 3 m/s and 190 $\pm$ 30 deg N, respectively.) The average concentration on this side of the road was 42.8 $\pm$ 2.4 $\mu g/m^3$ (variability 5.6%). On the west

side of the road, the average concentration was 28.8 ± 6.8 $\mu g/m^3$ (variability of 23.5%). The increment across the road was 13.9 $\mu g/m^3$, or 0.34 $\mu g/m^3$/vehicle.

Samplers were set up on September 22 at the same positions as the previous day. Traffic volume during this experiment was 65 vehicles. The average wind direction and wind speed from 55th street, assumed to apply to this site as well, were 60 deg N and 3.0 m/s respectively. The average concentration on the west side (downwind) was 66.3 ± 35.0 $\mu g/m^3$ (or 52% variability), and the average on the east side was 30.5 $\mu g/m^3$. The high variability on the west side is due to the sampler at position 6, which gave a concentration of 115 $\mu g/m^3$. Without this sampler the average concentration on the west side reduces to 41.6 ± 3.5 $\mu g/m^3$ (8.3% variability). The PM_{10} concentration increment was 35.8 $\mu g/m^3$, or 0.55 $\mu g/m^3$/vehicle.

Only two samplers were set up on each side of the road on September 23, 1992. The average wind speed and direction for this site were 5.4 ± 1.6 m/s and 202 ± 13.4 deg N. The average concentration on the east (downwind) side of the road was 64.2 ± 1.5 $\mu g/m^3$ (variability of 2.4%). The average on the west side was 59.3 ± 3.2 $\mu g/m^3$ (variability of 5.5%). The PM_{10} increment across the road was 4.9 $\mu g/m^3$, or 0.08 $\mu g/m^3$/vehicle, for a traffic volume of 60 vehicles.

On September 26, 1992, three samplers on the east side and two samplers on the west side of the road were operated. The average wind speed and direction were 6.2 m/s and 190 ±

10 deg N, respectively. Total traffic volume extrapolated from data of September 19 was estimated to be 51 vehicles. The average concentration on the east side of the road was 85.5 $\pm$ 8.0 $\mu g/m^3$ ($\pm$ 8.4%). The average concentration on the west side of the road was 41.2 $\pm$ 3.6 $\mu g/m^3$ (8.7% variability). For this day, the PM_{10} concentration increment was 44.3 $\mu g/m^3$, or 0.87 $\mu g/m^3$/vehicle.

Austin Road

The orientation of the third unpaved road site is North-South. Two samplers were set up at this site; one on each side of the road, 20m from the centerline. No wind data were available from this site. The traffic counter failed during the intensive field study so that the traffic volume was not accurately recorded, however the number of cars on this road period. The PM_{10} data collected from this site are summarized in Table 9. In general, the background PM_{10} concentrations at this site (average 19 $\mu g/m^3$) are lower than those observed at the Abbott Road site (average 41 $\mu g/m^3$ for 9/18-9/26). The traffic volume, PM_{10} concentration increments, and downwind concentrations are also lower.

TRACER FLUX EXPERIMENTS

Two tracer tests were conducted at an unpaved road site and two tests were conducted at a paved highway site. In each case, the samplers were deployed in a straight line along the prevailing wind direction. The six-hour average meteorological conditions and traffic volumes during the tracer test periods are listed in Table 10. The measured PM_{10}

Table 10. Summary of six hour average meteorological and traffic data for the intensive tracer experiments.

Test No.	Wind Speed	Standard Deviation	Wind Direction	Standard Deviation	dT/dZ	Sigma Theta	Bulk Ri(b)	Stability Class	Traffic Vol.
	(m/s)	(m/s)	(deg)	(deg)	(C/m)	(deg)			(cars/hr)
1	2.6	0.27	199	27.00	-0.24	28.43	-0.02	B	44
2	3.3	0.73	53	15.53	-0.22	19.20	-0.01	B	50
3	3.4	0.55	211	33.42	-0.21	14.64	-0.01	C	470
4	4.1	1.00	214	16.00	-0.18	13.70	-0.00	C	529

Table 11. Tracer and PM10 concentrations measured during the tracer flux experiments in Spokane, WA.

Test	Date	Start Time	Background PM10 Concentration (ug/m3)	Downwind Position	Tracer Average** (ug/m3)	Concentration Standard Deviation (ug/m3)	Delta PM10 Concentration (ug/m3)	Delta PM10/ Tracer	Average Ratio	% Deviation
1	09/21/92	1100	26	#1	6.8	1.94	314	46.3	54.0*	17.00
				#2	2.7	1.00	183	66.8		
				#3	1.2	0.64	123	106.9		
				#4	1.7	0.65	86	49.4		
2	09/22/92	1230	38	#1	10.0	7.85	214	21.4	27.0	15.84
				#2	7.9	2.80	258	32.8		
				#3	3.7	3.73	93	25.3		
				#4	4.3	2.98	124	28.6		
3	09/23/92	1100	44	#1	-	-	39	-	-	-
				#2	-	-	32	-		
4	09/26/92	1100	43	#1	5.5	1.92	123	22.2	24.4	9.00
				#2	2.1	0.96	57	26.6		
				#3	1.7	0.62	-	-		
				#4	1.4	0.50	-	-		

* The average ratio is calculated excluding the ratio at position #3.

** Average tracer concentrations are calculated after subtracting the background/contamination.

and tracer concentrations are summarized in Table 11. Details of the individual tests follow.

Test 1

The first tracer test was conducted from 1100 to 1700 on September 21, 1992, at the 55th Street location (Figure 2). The average wind direction was from 199 deg N at 2.6 m/s for the 6-hour duration of the test. Winds were generally from the southeast or approximately perpendicular to the road. Traffic volume increased from approximately 30 vehicles/hr to almost 90 vehicles/hr in mid-afternoon and then decreased back to 30 vehicles/hr by 1700 at the end of the test. The 6 hr average traffic volume was 44 vehicles/hr.

The upwind PM_{10} concentration measured during this test was 26 $\mu g/m^3$. Downwind concentrations decreased from 340 $\mu g/m^3$ next to the road to 112 $\mu g/m^3$ approximately 50m downwind. It was obvious from observations at the site that vehicular movement produced substantial dust plumes which were carried downwind of the road past the sampling array. SF_6 concentrations showed good agreement with the pattern in the PM_{10} concentrations and decreased from 6.8 $\pm$ 1.9 $\mu g/m^3$ next to the road to 1.7 $\pm$ 0.7 $\mu g/m^3$ away from the road. The concentration ratios of PM_{10} less the background level, to SF_6 tracer, are shown in Table 11 and Figure 11 for this test. The average ratio was 53.8 $\pm$ 9.2 ($\pm$ 17%) over the four sampling locations. At position #3 the tracer concentration had a high variability (53%) and therefore was not considered

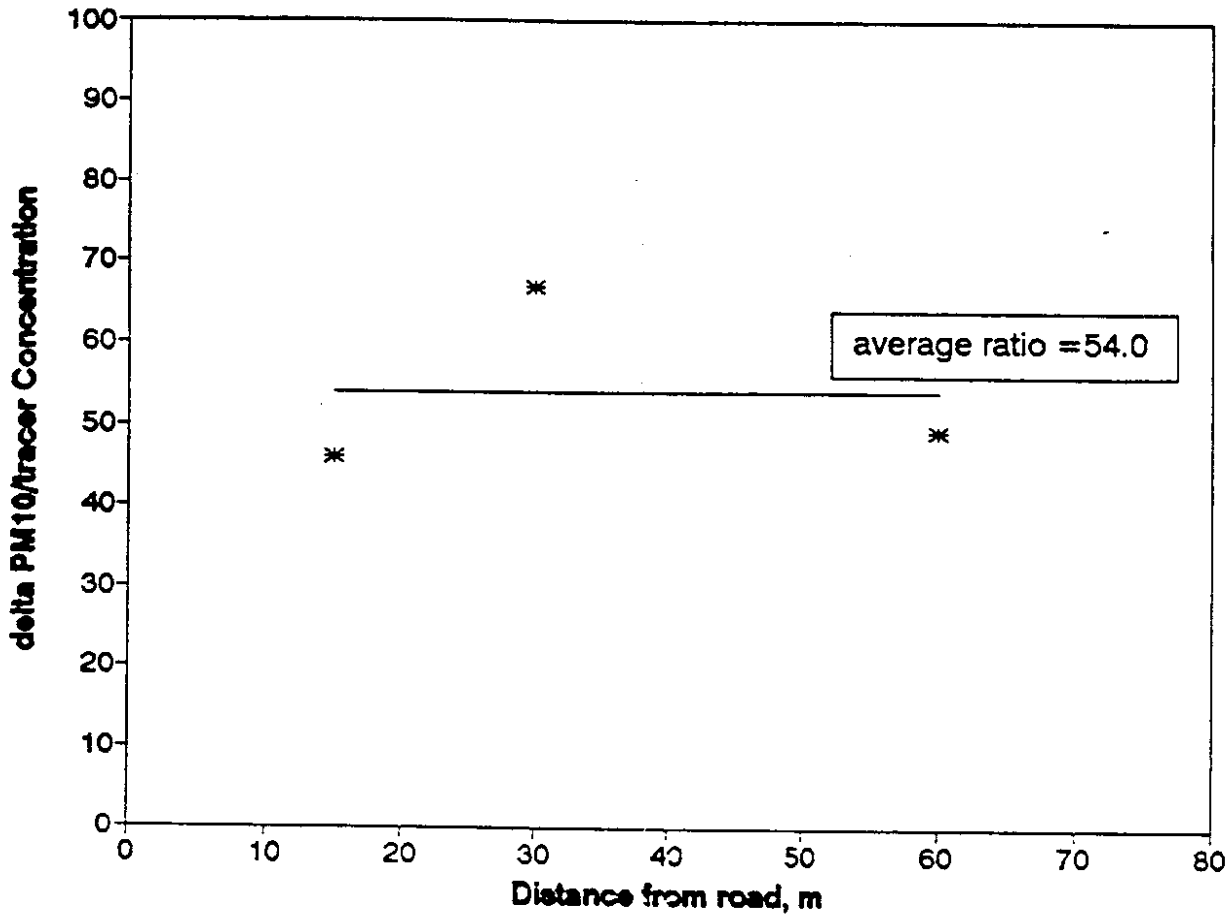

Figure 11: Concentration Ratios of PM_{10} to SF_6 for Tracer Test 1 at 55th Street, September 21, 1992.

for calculating the average ratio. This is a reasonably constant value of the ratio and indicates that the tracer release was a reasonable simulation of the PM_{10} emissions. With a measured tracer release rate of 76 µg/m/s, the average ratio of concentrations yielded an estimated PM_{10} emission rate equal to approximately 4104 µg/m/s. With the average vehicle density, this converts to 533 g/VMT, or 0.33 kg/VKT on an unpaved road.

Test 2

The second tracer study was conducted from 1230 to 1830 on September 22, 1992, at the 55th Street location (Figure 3). The average wind direction was from 53 deg N at 3.2 m/s. on a 6 hour basis. Prevailing wind direction was from the northeast, making an angle of approximately 41 degrees with the road. The traffic density increased from approximately 45 vehicles/hr at noon to 70 vehicles/hr at 1700 and then decreased back to approximately 45 vehicles/hr at 1900. The 6-hour average traffic volume was 50 vehicles/hr on this day.

The upwind PM_{10} concentration measured during this test was 38 µg/m^3. Downwind of the road, the PM_{10} concentration exhibited considerable variability and did not decrease evenly as a function of downwind distances (Table 11). The maximum concentration of 292 µg/m^3 occurred at the second downwind location, while the minimum concentration, 131 µg/m^3, occurred at the third sampling location. The upwind tracer concentration measured during this test was 8.6 $\pm$ 3.9 µg/m^3 which is an unreasonably high background concentration.

It appears that contamination of the syringe samplers probably occurred during handling for this test. The downwind tracer concentration distribution also showed an irregular pattern and decreased from approximately 18.6 ± 3.3 $\mu g/m^3$ next to the road (position #1) to 12.9 ± 2.9 $\mu g/m^3$ at position #4, as shown in Figure 3. Because of the high upwind tracer concentration and the elevated downwind tracer concentrations, we assume that all of samplers were contaminated for this test. To account for this the upwind concentration of SF_6 was deducted from the downwind tracer concentrations. The average ratio was 27 ± 4.2 (± 15.5%) over the four sampling positions (Table 11). This is a reasonably constant value of the ratio in spite of the contamination problem and agrees with the first test to indicate that the tracer release was a good simulation of the emission of PM_{10} from the roadway. The average ratio of concentrations, with a measured tracer release rate of 71 µg/m/s, yields an estimated emission rate of PM_{10} approximately equal to 1917 µg/m/s. On a per vehicle basis, this corresponds to 226 g/VMT, or 0.14 kg/VKT.

Test 3

The third tracer test was conducted from 1100 to 1700 on September 23, 1992, at the North Division site location. The average wind direction was from 211 deg N at 3.4 m/s over a 6-hour period. The winds were predominantly from the south and southwest at an angle of approximately 200 degrees with

the road. The 6-hour average traffic volume was 470 vehicles/hr.

The upwind PM_{10} concentration measured during this test was 58 $\mu g/m^3$. Downwind concentrations decreased from 83 $\mu g/m^3$ immediately downwind of the road to 45 $\mu g/m^3$ at the fourth sampling position as shown in Figure 4 and Table 11. The similar concentrations at the third and fourth sampling positions downwind of the road suggest that emission from the roadway does not affect the ambient roadside PM_{10} level beyond these distances. The lowest downwind concentration was 43 $\mu g/m^3$ and was considered as the background level for this particular day. The upwind tracer concentration measured on this day was 28.1 $\pm$ 11.2 $\mu g/m^3$ which indicates a contamination problem. Downwind tracer concentrations were in poor agreement with the pattern in the PM_{10} concentrations and exhibited an irregular distribution of concentrations along the downwind to the road. No ratio calculation was possible for this test data.

Test 4

The fourth tracer test was conducted from 1100 to 1700 on September 26, 1992, at the North Division location. The average wind direction was from 214 deg N at 4.1 m/s on a 6-hour basis. Winds were from the southwest making an angle of 206 degrees with the road. The average hourly traffic volume for the 6-hour period of this test was 529 vehicles/hr.

The upwind PM_{10} concentration measured during this test was 88 $\mu g/m^3$. The downwind concentrations decreased from 166

$\mu g/m^3$ next to the road to 41 $\mu g/m^3$ at the end of the sampling array as shown in the Figure 4. Tracer concentrations showed good agreement with the pattern in the PM_{10} concentrations and decreased from 5.5 $\pm$ 1.9 $\mu g/m^3$ next to the road to 1.4 $\pm$ 0.5 $\mu g/m^3$ away from the road. The background PM_{10} concentration for this day was assumed to be 43 $\mu g/m^3$ and was subtracted from roadside concentrations to calculate the increment across the road. The average ratio was 24.4 $\pm$ 2.2 ($\pm$ 9.0%) over the first two sampling positions. The low variability in the ratios confirms that the tracer release was a reasonable simulation of the PM_{10} emission from the highway. With the tracer release rate of 79 $\mu g/m/s$, the average ratio of concentrations yields an estimated PM_{10} emission rate equal to approximately 1896 $\mu g/m/s$, or 13 g/VKT on the paved highway.

DISCUSSION

Roadside Measurements.

As can be seen from Table 9, the PM_{10} concentration increment across the road for paved roads is highly variable (average value 0.0011 $\pm$ 0.0022 $\mu g/m^3$, or $\pm$ 200%). While less so than those for paved roads, the increments calculated for unpaved roads are also quite variable (average 0.40 $\pm$ 0.22 $\mu g/m^3$/vehicle, or $\pm$ 55%). This variability is expected, and is due to a number of meteorological conditions. For example, the wind speed will have an impact on the increment. Other factors that would be expected to impact the PM_{10}

increment would include the degree to which the wind direction shifts relative to the road orientation. If the angle between wind direction and the road is relatively small, and/or the standard deviation in the wind direction is large, the effect should be to reduce the increment across the road.

Comparison to Published Factors.

Using the SF_6 tracer technique, we calculated emission factors for both paved and unpaved roads. For unpaved roads, the factor calculated ranged from 0.14 to 0.33 kg/VKT (Table 12). Currently, WSDOE uses a factor of 0.28 kg/VKT for unpaved roads. This factor was derived from emission factor algorithms published in AP-42. For comparison, the factor that is predicted from equation (1) for a gravel road, average vehicle speed of 20 kph, in Spokane, would be roughly 0.2 kg/VKT. The emission factors calculated in the present study via this tracer technique are of the same order of magnitude as those given in AP-42 and used by WSDOE. It is interesting to note that, during a recent study conducted on dirt roads in rural Arizona (Muleski and Stevens, 1992), the PM_{10} emission factor was also estimated to be of the same order of magnitude as those published in AP-42, corroborating the results of this study. By contrast, the emission factors for paved roads appear to be much more variable and uncertain. Factors given in AP-42 range from 1 to 4 g/VKT. For re-entrained road dust from paved roads with average traffic speed of 35 mph, the PM_{10} emission factor used by

WSDOE is 1.2 g/VKT. At higher speeds, this factor decreases. Other PM_{10} factors due to tailpipe emissions, tire and brake wear, and sanding materials are also tabulated, but are 1 to 2 orders of magnitude smaller than the factor for resuspended road dust. From the present work, an emission factor of nearly 13g/VKT (Table 12), or nearly an order of magnitude higher than that used by DOE, was calculated. In a recent study conducted in Denver (Zimmer et al., 1992), emission factors for paved roads were found to be on the order of 4 to 5 times greater than those given in AP-42, again corroborating the results of the present work.

Dispersion Modeling.

The tracer data can be used to calibrate an existing line source model, SIMFLUX, which then can be used in predicting downwind PM_{10} concentrations from roadways as a function of wind speed and direction. SIMFLUX is a Gaussian plume dispersion model that simulates a line source as a dense array of point sources (Howard et al., 1992). Pasquill-Gifford diffusion curves are used in the model to specify dispersion coefficients. To treat the initial mixing due to vehicular turbulence, initial horizontal and vertical dispersion coefficients can be specified in a virtual point source approach. The initial horizontal and vertical dispersion coefficients s_{yo} and s_{zo} are calculated as:

$$s_{yo} = L/4.3 \quad (4)$$

$$s_{zo} = h/2.15 \quad (5)$$

Table 12. Estimated PM10 emission rates based upon PM10/tracer concentation ratios.

Test	Date	Location	PM10/tracer Concentration Ratio	%Standard Deviation	Tracer Emission Rate (ug/m/s)	Traffic Volume (cars/hr)	Estimated PM10 Emission Rate (ug/m/s)	PM10 Emission Rate (g/VKT)	Published Factors (g/VKT)	Type of Road
1	09/21/92	55th. Street	54.0	17.0	76	44	4104	336	283	Unpaved
2	09/22/92	55th. Street	27.0	15.5	71	50	1917	140	283	Unpaved
4	09/26/92	N.Division	24.4	9.00	79	529	1896	13.0	3.71	Paved

where L and h are the horizontal and vertical dimensions of the source, respectively. The meteorological data needed as input parameters include average wind direction (with respect to North), wind speed, and atmospheric stability class during the sampling period.

If the average sampling time (avet) is different from 10 minutes (default value), s_y can be corrected to the actual sampling period using

$$s_{new} = (avet/10)^{1.7} \qquad (6)$$

For application to the tracer test periods, stability classes were determined using the vertical temperature gradient (dT/dz), the standard deviation in the wind direction (σ_o), and bulk Richardson Number (R_{ib}) as listed in Table 10. Stability classes specified by the temperature gradient yielded Class A stability for all four tracer flux experiment days. According to the (standard deviation in horizontal wind direction) method Class A conditions existed during Test 1 and Class B conditions existed during Test 2, while class C conditions occurred during Tests 3 and 4. Stability class based upon R_{ib} were Class B for Test 1, class B/C (border value) for Test 2, and class C for Tests 3 and 4. The stability class determined by the bulk Richardson number is assumed to be the most representative as it takes into account both the wind speed and the vertical temperature gradient. Using the range of stability class predicted by the bulk Richardson number, the model was tested versus the observed tracer concentrations for tests 1, 2 and 4. Figure

12 shows the comparison between observed and predicted concentrations of SF_6 for the first tracer experiment. Optimal results were obtained with the initial width (L_o) and height (h_o) set at 5m and 3m respectively for the first and fourth tracer tests. For the second test an initial width of 3m and initial height of 1m gave the best results. The change in the initial dispersion coefficients between the first and second tests might be due to the less unstable conditions during the second test day. Table 10 lists the results of model optimization calculations and the respective parameters used.

The predicted and observed concentrations were used to calculate model performance statistics including the fractional bias (FB), the normalized mean square error (NMSE), slope (s), intercept (I) and correlation coefficient (r^2). The statistical measures of model evaluation are listed in Table 13. The NMSE in no case exceeded 1 for this experiment. NMSE is an overall indicator of the model performance,

$$NMSE = \overline{(C_o - C_p)^2} / \overline{C_o}.\overline{C_p} \qquad (4)$$

where C_o is the observed concentration, C_p is the predicted concentration, and the bars indicate mean values. A perfect model should have a zero NMSE value. Hanna et al., (1985) concluded that a good model will have a NMSE near 0.4 , while a poor model will have a NMSE greater than 4. Thus the model has a good potential to predict the downwind concentrations

as indicated by the low NMSE scores. The fractional bias is calculated as

$$FB = 2.(\overline{C_o} - \overline{C_p})/(\overline{C_o} + \overline{C_p}) \quad (5)$$

The ability of the model to predict average concentration is determined by the bias of the average predicted and observed values. The observed and predicted concentrations agreed within a factor of 2 (|FB|<0.67) (Cox, 1988) in all cases. However, the negative FB values indicate that the model has a tendency to overpredict. This might be rectified by assuming less restrictive initial horizontal and vertical dispersion coefficients for very unstable conditions and for urban paved roads. The initial dispersion coefficients that take into account the effect of mechanical mixing due to the traffic wake on the urban highways should be a function of the volume of traffic and traffic speed on any particular road.

This comparison between the tracer data and the model predictions suggests that it is feasible to use SIMFLUX to model roadway emissions. It should be recognized, however, that PM_{10} emission rates back-calculated with the model will have associated uncertainties in the range of a factor of two. Even so, it is worthwhile to use the model with measured PM_{10} concentrations from the roadside experiments to estimate PM10 emission rates. The model was tested versus

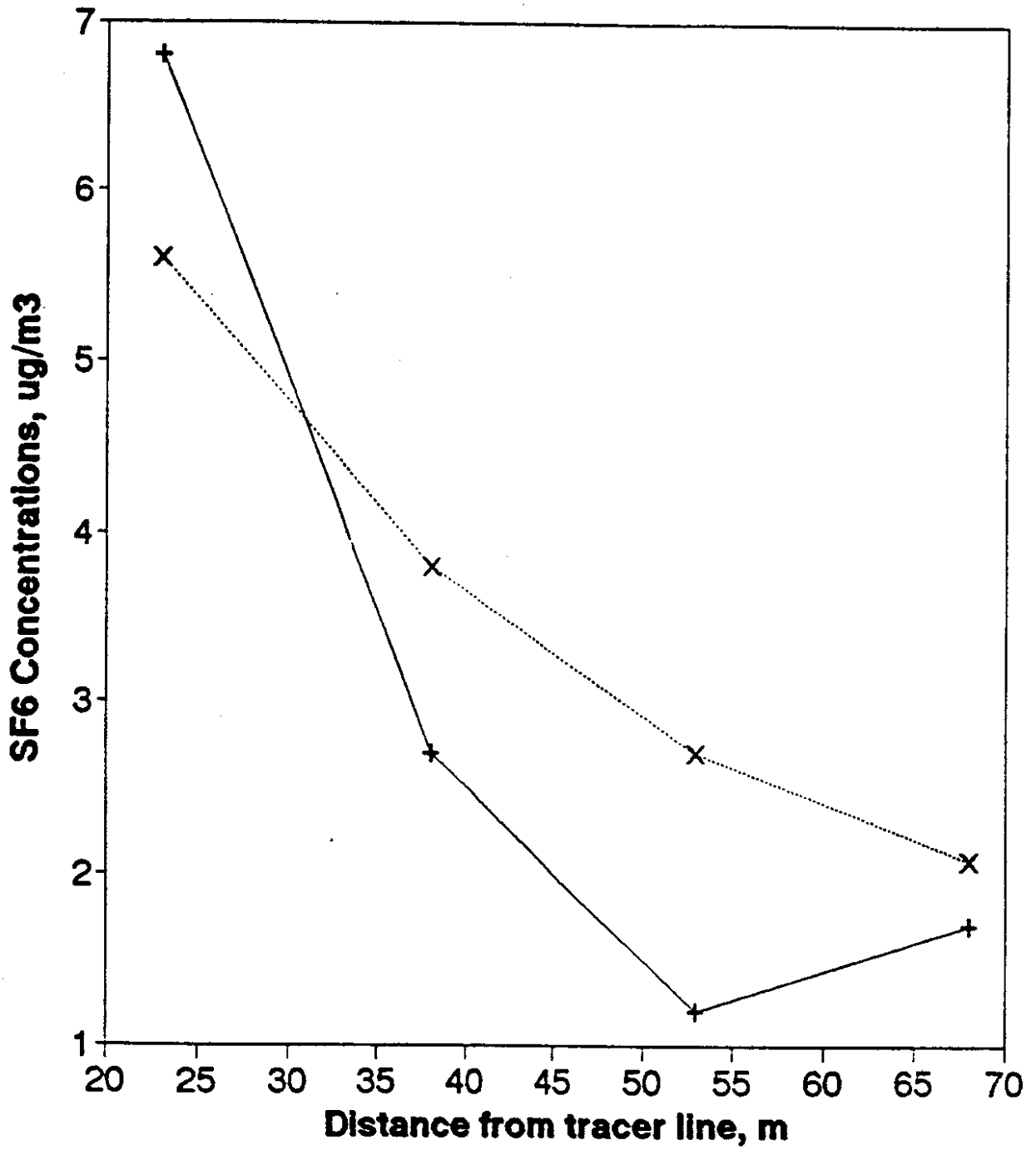

Figure 12: Observed and Predicted Concentrations of SF_6 as a Function of Distance from the Road, for Tracer Test 1, 55th Street, September 21, 1992. The x's refer to predicted concentrations, and the +'s refer to the observed.

Table 13. Observed and predicted tracer concentrations using the modified SIMFLUX line source model.

Test	Stability Class	Yo,Ho	Average Observed tracer Concentration (Co)avg	Average Predicted tracer Concentration (Cp)avg	FB	NMSE	I	S	r2
		(m,m)	(ug/m3)	(ug/m3)					
1	3	5,3	3.10	3.54	-0.13	0.11	1.76	0.60	0.89
2	4	3,1	6.47	5.10	0.24	0.08	0.35	0.73	0.89
4	3	5,3	2.67	4.25	-0.45	0.24	1.15	1.15	0.94

FB = Fractional Bias = 2(Co(avg)-Cp(avg))/(Co(avg)+Cp(avg))
NMSE = Normalized Mean Square Error =(((Co)i-(Cp)i) ^ 2)avg/((Co(avg)*Cp(avg))

Yo, Ho, = Initial plume dimensions to account for vehicle turbulance.
I : intercept, S : slope, r2 : correlation coefficient

the observed tracer concentrations for each test.

Determination of emission factors from roadside measurements and comparison with published factors

PM_{10} emission factors were determined by back-calculation (upwind/downwind method of emission factor calculation) using the roadside measurements and the optimized SIMFLUX line source dispersion model. Table 14 summarizes the PM_{10} and meteorological data used for the model calculations and results obtained. The PM_{10} data obtained during the tracer tests were also used to back-calculate emission factors and to compare with the corresponding emission factors calculated by the tracer ratio method.

Table 15 summarizes the emission factors calculated by the upwind/downwind method (also shown in Table 14) for each site. The table also shows the comparison between the emission factors calculated in the present study and the emission factors derived from the algorithms in AP-42. In order to obtain average values for emission factors the two unusually high emission factors obtained for the Abbott road (3000 g/VKT) and Lewiston (34 g/VKT) sites were not included because the variability associated with the average emission factors exceeded 100% if these two values were considered. The average PM_{10} emission factors calculated by the upwind/downwind method for 55th Street and for Abbott road are 242 g/VKT (variability ± 26%) and 120 g/VKT (variability ± 45%), respectively. When emission factors are calculated

only on the basis of the data obtained during the tracer tests the emission factors for the 55th Street were 260 and 250 g/VKT for the first and second test day, respectively. These values are comparable to the values obtained by the tracer ratio method (336 g/VKT and 140 g/VKT) and the predicted values (283 g/VKT). The low emission factor on the second day might be due to the tracer contamination problem discussed before.

The North Division Site and the Moscow-Pullman site (two lanes with average daily traffic more than 500) fall into the category of collector streets and have a predicted PM_{10} emission factor of 3.71 g/VKT (US EPA, 1985). The average emission factor calculated by the upwind/downwind method for these sites is 3.80 g/VKT (variability $\pm$ 98%). The Lewiston site falls into the highway category (four lane with daily average traffic volume more than 10,000) and has a predicted emission factor of 1.80 g/VKT (US EPA, 1985). Dispersion modeling of the upwind/downwind experiment yielded an emission factor of 4.20 g/VKT (variability $\pm$ 35%). Dispersion modeling of the third and fourth tracer test data yielded emission factors of 5.1 and 9.3 g/VKT for the North Division site, while the tracer ratio method calculated a factor of 13.0 g/VKT. The variability in emission factors is attributed to the uncertainties associated with the actual measurements and the model performance.

Table 14. Emission Factor Calculation by Upwind/Downwind Method.

Place	Date	Downwind Concentration (obs) (ug/m3)	Upwind Concentration (obs) (ug/m3)	Downwind Concentration (pr) (ug/m3)	Upwind Concentration (pr) (ug/m3)	Emission Factor g/VKT	wind Speed m/s	std.dev m/s	Wind Direction Deg N	Angle with road Deg	std.dev Deg N	Traffic Volume vehicles/hr
Paved Roads												
Lewiston (Highway)	08/09-10/92	35	22	169	110	3.15	3.20	1.13	186	6	89	555
	08/12-13/92	32	10	150	144	34.18	3.20	1.40	150	30	82	540
	08/31-1/92	53	32	91	51	5.22	5.10	3.20	167	13	90	492
N.Division (Collector Street)	09/23/92	24	21	141	82	0.44	3.25	0.89	207	17	32	505
	09/25/92	36	35	158	102	0.18	2.90	0.52	237	47	21	504
	Test III	83	58	146	97	5.07	3.40	0.55	214	24	32	470
	Test IV	166	88	138	65	9.32	4.26	0.40	211	40	16	529
Mos Pullman (Collector Street)	07/09/92	27	10	162	119	4.16	2.20	1.11	268	2	46	433
Unpaved Roads												
Abbott Road	09/17/93	128	105	87	49	164.70	2.54	0.79	207	27	132	4
	09/23/93	31	13	64	59	74.58	5.40	1.28	202	22	12	5
	09/26/93	86	41	23	19	3000.62	6.20	1.92	190	10	18	5
55th Street	09/21/93	271	50	456	17	136.11	2.60	0.75	192	88	25	48
	09/22/93	313	93	326	106	267.25	3.00	0.94	60	30	25	48
	09/23/93	189	35	220	80	298.32	5.75	1.33	201	82	18	49
	Test I	340	26	360	32	259.17	2.60	0.44	199	71	27	50
	Test II	251	38	318	87	249.84	3.30	0.73	53	37	15	44

Table 15. Comparison of Emission Factors in the Present Study to the published Factors.

Site	Type of Road	Emission Factors (g/VKT) Published	Tracer Ratio Method	Upwind/Downwind Average	Method %Deviation
55th Street	Unpaved	283	336	242	26
Abbott	Unpaved	283	-	120	45
N.Divison & Moscow/ Pullman	Collector Street	3.71	13.0	3.80	98
Lewiston	Highway	1.80	-	4.20	35
Test 1	Unpaved	283	336	260	-
Test2	Unpaved	283	140	250	-
Test3	paved	3.71	-	5.10	-
Test4	paved	3.71	13.0	9.30	-

APPLICATIONS AND IMPLEMENTATION

The results of this study demonstrate that the use of an inert tracer in a line source to simulate roadway PM_{10} emissions can provide a powerful tool for improving the existing emissions inventories for fugitive PM_{10} emissions from roads. This is particularly important given the uncertainties and inaccuracies inherent in the emission rate estimation methods that were utilized to develop the current emission factors.

The emission factors estimated for unpaved roads were similar in magnitude to those currently used by WSDOE. For unpaved roads, based on empirical equations given in the EPA document AP-42, the emission rate used by WSDOE is 0.25 kg/VKT. We calculated factors of 0.10 and 0.28 kg/VKT in the tracer experiments conducted as part of this research. It is interesting to note that one other, current field study that estimated PM_{10} emission rates from unpaved rural roads in Arizona also calculated factors that are similar in magnitude to those given in AP-42 (Chow et al., 1993, and references therein).

The emission factor estimated for paved roads (1.0 kg/VKT) was much higher than those currently used by WSDOE (0.12 kg/VKT). This result is consistent with another, recent study, in which PM_{10} emission factors from paved roads in Denver were estimated that are 4 to 5 times higher than those given in AP-42 (Chow et al., 1993). The current algorithm for estimating PM_{10} emissions from paved roads are not

reliable, particularly if the silt volume on the road is beyond the range of silt volumes used to develop the algorithm. A much larger data base is needed to develop the paved road algorithm.

Currently for lack of better information these existing algorithms are used to develop the state implementation plan to bring the Spokane area into compliance with the National Ambient Air Quality Standard for PM_{10}. The results of this study demonstrate the need for careful interpretation of the results of dispersion modeling in which these algorithms provide emission estimates especially for paved roads. Regulatory officials should conduct sensitivity analyses to determine how sensitive the dispersion model is to the accuracy of the paved road emission factor estimate.

ACKNOWLEDGMENT

The authors acknowledge the support of the Washington State Department of Transportation (WSDOT) for this research. In particular, we wish to express our thanks to Art Lemke, Pat LaViollette, and Peter Downey, all of WSDOT, for their support and guidance through this work. We also wish to thank Clint Bowman of the Washington State Department of Ecology (WSDOE) for numerous discussions on PM_{10} and for his assistance in determining and setting up the various sites operated during the intensive field experiment. We wish to thank Mr. Ron Edgar of the Spokane County Air Pollution Control Authority (SCAPCA) for the use of laboratory facilities in Spokane and for providing additional samplers and technical assistance during the intensive field experiment. We also appreciate help provided by WSDOE personnel in Spokane for their help in setting up the Spokane sites for the intensive field study, and to Rob Wilson of the U.S. Environmental Protection Agency, Region X, for providing additional meteorological masts. The contact person for WSDOT was Mr. Art Lemke.

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