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# Project Summary

# Philadelphia Roadway Study

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**The primary objective of this study was to collect particulate mass concentration data to define vertical and horizontal distances from roadways required for inhalable particulate (IP) monitor siting. Secondary objectives were to compare the particulate mass measurements to a simple model which considers both dilution and settling of particulate matter and to determine if the siting criteria for inhalable particulate matter (<15 μm) applies to lead (Pb) measurements made with an IP sampler.**

*This Project Summary was developed by EPA's Environmental Monitoring Systems Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).*

## Introduction

Existing guidelines for siting TSP samplers near roadways are contained in Federal Register Methods Vol. 44, No. 92, May 10, 1979. For ambient 24-hour general population exposure and surveillance monitoring a sampler set too close to any localized source such as a heavily traveled roadway would overestimate the level of TSP for the general surrounding area. The guidelines restrict sampling closer to the roadway than 25 m at a two m height and five m at a 15 m height. A straight line connecting these two points defines the restricted boundary.

The development and implementation of a size-specific ambient particulate standard instead of the current Total Suspended Particulate standard will require additional information on how the various size fractions of particles disperse in the area surrounding a major roadway. The information would be used to replace the criteria for TSP sampling.

Since the rate of deposition and vertical diffusion depends upon particle size, the criteria for TSP cannot be assumed to apply to both the larger coarse (2.5 up to 10 or 15 μm) particles and the smaller fine (<2.5 μm) fraction. Smaller particles are assumed to deposit from the atmosphere much slower than the larger ones, with the very small submicron size particles behaving nearly as a gas. Assuming no reaction, pollutant gases tend to decrease in concentration away from the source because of dilution. Suspended particles are reduced in concentration by both dilution and deposition.

## Experimental Procedures

### *Approach*

The approach was to collect the fine and coarse particulate mass fractions at one point upwind, one point in the center, and nine points directly downwind of a major roadway when the wind direction was within a 90 degree sector centered about the perpendicular to the road. Horizontal distances are referenced from the edges of the 60 m wide roadway unless otherwise noted. Likewise, vertical distances are referenced from ground level. These data could then be used to construct concentration isopleths. The upwind sampling site was used for estimating the background concentrations. A sampling site was located in the roadway median on the perpendicular to verify the maximum concentrations extrapolated from the roadside measurements. Sierra Model 244E Dichotomous Samplers with 15 μm inlets were used for collecting the fine and coarse fractions on 37 mm teflon filters. The dichotomous samplers were operated in accordance with procedures of the Inhalable Particulate Network (IPN). The particle separation characteristics of the sampler are based on aerodynamic particle size which transforms the actual diameter to the equivalent diameter of a unit density sphere having the same settling velocity as the particle in question of whatever shape and density. All particle sizes referred to in the report are aerodynamic diameter. Sampling was initially performed (Phase I) at ground level two m height above the doorway to determine at what point downwind the concentration had been reduced by upwind diffusion and particle deposition to approximately the background level. Sampling in the vertical direction was then conducted using two towers -- one located at roadside five m downwind, and the other approximately half-way downwind from roadside to the point at which the roadway particulate mass concentrations had dropped to within 10% of background level. The half-way point was found to be approximately 25 m downwind.

Meteorological measurements for wind speed, wind direction, temperature and humidity were made from a 15 m height at the monitoring site located 5 m downwind of the roadway. A Climatronics electronic weather station was used to acquire the data on strip chart recordings.

Based on historical meteorological data for the area, particle sampling was initiated in March, 1982, to obtain the downwind particle concentration gradient under wind direction conditions that were expected to be primarily perpendicular within ±45° of the roadway. In order to minimize variations in wind speed and direction during particle sampling, sampling periods of "acceptable" meteorology were limited to a 14 hour (7:00 AM - 9:00 PM) daytime sampling period. With this schedule the early morning inversions, wind instability and the night time low traffic count were eliminated.

Based on data from an earlier study, sampling was only conducted when wind speeds were above two mph and wind directions within ±45° of the freeway perpendicular. Wind speeds below two mph do not provide adequate transport to define a profile. Wind directions perpendicular within ±45° were expected to provide ratios of downwind to upwind concentrations exceeding at least a factor of two.

A Climatronics Wind Controller (Model WMIII - PN100864) activated by wind speed and direction sensors limited sampling to periods when parameters were within preset specifications. The statistical study design recommended at least 10 valid sample runs for the horizontal configuration and 10 for the vertical configuration. A sample run was required to last for at least four hours in order to have adequate mass collection on each dichotomous sample filter.

The number of vehicles operating on the roadway during the study was very important. Any large fluctuations in traffic count would affect the particle concentration levels (and hence the isopleths) around the study site. Mechanical car counters were used to obtain real time hourly traffic counts. Daily traffic flows ranged from 2119 to 3906 vehicles/hour during sampling periods (average = 3177 + 460). The 7:00 AM - 9:00 PM sampling period had a reasonably constant traffic density during this time period.

## Site Location and Description

The study was conducted in Northeast Philadelphia at Roosevelt Boulevard between South Hampton and Woodhaven Roads. Roosevelt Boulevard serves as one of the two major north-south traffic arterials for the city. Preliminary meteorological monitoring and review of historical data indicated that winds could be expected to flow across the roadway into the sampling cross-section at least 80% of the days allotted for the study. The sampling cross-sections were located on the grounds of the Pennsylvania State Hospital where the upwind and downwind sites were on open grass covered fields extending more than 1200 meters from the roadway in both the upwind and downwind directions. The sampling site reach was without interfering buildings and service roads for approximately 3500 m along the roadway. The location was within two miles of an EPA Inhalable Particulate (IP) Network site which averaged 33 $\mu g/m^3$ for IP mass during the period March, 1980 through May, 1981.

## Sampling Scheme

Particulate sampling points on the roadway perpendicular were located 220 m upwind, the roadway median, five, 25, 75, 125, and 175 m downwind during Phase I sampling. After 12 sample runs were completed for Phase I, the dichotomous samplers were relocated for vertical, Phase II sampling. Towers were used for elevating the dichotomous samplers to seven and 15 m heights. Samplers were located at 220 m upwind (two m elevation), the roadway median (two m elevation), five m downwind (two, seven, 15 m elevations), and 25 m (two, seven, 15 m elevations). Sampling was begun simultaneously at each of the seven points located on the roadway perpendicular if the wind speed and direction were within acceptable limits. A collocated sampler at the 25 m downwind, two m height sampling site was operated throughout the study to obtain precision data. Sampler flow checks were made daily, and a performance audit completed to verify that the calibrations had not changed during the study.

## Sample Analysis

The dichotomous coarse and fine fraction samples were analyzed gravimetrically for mass concentration. Lead and bromine concentrations were determined by energy dispersive X-Ray Fluorescence. The analysis procedures used for the IP Network, Standard Operating Procedures for the X-Ray Fluorescence Analysis of Multielements on Dichotomous Sample Filters,EMSL-RTP-SOP-EMD-010, November, 1981, were followed.

## Results and Discussion

Twenty-four sample runs were completed between March 5, 1982 and May 7, 1982 with an average sample time of 10.3 hours. Eight horizontal and ten vertical sets of samples (complete at all sampling points) were used for defining the horizontal and vertical particulate mass concentration gradients. In addition, horizontal profiles were obtained on two days immediately following "salting" of the roadway to prevent icing. These data were not included in the general statistical analysis but are described separately.

## Horizontal Profile

Average downwind concentrations ($\mu g/m^3$) of fine, coarse, and total (coarse + fine) particles for mass and lead mass were examined as a function of distance (m) from the highway. Concentrations measured at ground level (two m height) were averaged over eight days of sampling at each of six downwind and one upwind sites. The sampling days cover a range of hourly traffic densities from 2160 to 3906 vehicles with wind speeds ranging from 5.8 to 18.5 mph. Based on the concentration measured five m downwind of the roadway edge, the average maximum increases above background (at two m height) in particulate mass and lead concentration downwind of the roadway were:

| | Phase I ($\mu g/m^3$) | Phase II ($\mu g/m^3$) |
|---|---|---|
| Coarse mass | 4.6 | 8.5 |
| Fine mass | 2.6 | 4.8 |
| Total mass | 7.2 | 13.3 |
| Fine lead | 0.47 | 0.48 |
| Coarse lead | 0.08 | 0.11 |
| Total lead | 0.55 | 0.59 |
| Wind speed (mph) | 11.2 | 8.4 |

The coarse particulate mass concentration at the two m elevation increases from the roadway centerline to five meters downwind and then decreases with distance while the fine particulate mass decreases with distance immediately from the centerline. The total mass decreases with distance from the centerline. A significant contribution is made to the coarse fraction from pavement wear and particle re-entrainment, which contribute little to the fine fraction. This fact and the effect of atmospheric turbulence probably account for the difference in concentration profiles for the different size fractions of the mass.

Logarithmic equations fitted by least squares methods were used to empirically describe (for distances between five m and 175 m downwind of the roadway edge) the relationship between the horizontal two m mass concentration (C) in $\mu g/m^3$ and distance (D) in meters downwind as follows:

| Fraction | Equation | Correlation Coefficient | Standard error of estimate ($\mu g/m^3$) |
|---|---|---|---|
| Coarse mass | C = 17.56 - 1.71 ln D | 0.990 | 0.40 |
| Fine mass | C = 18.82 - .99 ln D | 0.964 | 0.53 |
| Total mass | C = 36.378 - 2.71 ln D | 0.990 | 0.66 |

The coefficients show good correlation of C and ln D. Setting the equations equal to background concentration and solving for distance, the downwind point at which levels reach background were determined. These distances are *74 m (coarse), 87 m (fine),* and *77 m (total).*

Correlation coefficients between traffic density and mass concentration for each particulate size fraction (fine and coarse) were calculated for each of the six downwind ground level sampling stations. Statistically significant correlation at the 90% probability level occurred for fine mass and traffic at 5 m downwind and at the roadway. No other correlations between particulate mass fractions and traffic density were found at the 90% probability level apparently due to the limited range of traffic densities present during the study. Correlations between wind speed and fine particulate mass were statistically significant at the 90% probability level for all sites. In the case of the coarse fractions none of the sites correlated with wind speed except for the site five m downwind at a height of seven m. Total mass correlated with wind speed at the 90% probability level for all sites except at 175 m downwind.

Lead mass concentration averages also were plotted versus horizontal distance downwind. The lead concentrations decrease with distance from the roadway with the highest concentrations occurring at the center of the roadway (0.17 $\mu g/m^3$ coarse, 0.60 $\mu g/m^3$ fine, and 0.78 $\mu g/m^3$ total). The concentrations for total and fine fractions remain significantly above background for at least 175 m downwind. The lead concentration apparently does not dilute vertically at the same rate as the fine mass mode. Logarithmic equations fit by least squares to empirically describe the deposition and vertical diffusion are given as follows (for distances between five m and 175 m downwind of the roadway edge):

(C = mass concentration, $\mu g/m^3$; D = distance downwind, m)

| Fraction | Equation | Correlation Coefficient | Standard error of estimate ($\mu g/m^3$) |
|---|---|---|---|
| Coarse Pb | C = .187 - .029 ln D | 0.985 | .095 |
| Fine Pb | C = .715 - .106 ln D | 0.990 | .032 |
| Total Pb | C = .903 - .135 ln D | 0.990 | .032 |

The correlation between traffic density and lead concentrations for the fine size fraction were significant at the 90% probability level for all ground level sites except 175 m downwind. Correlations between fine lead and wind speed were found for all sites at the 90% probability level. The correlation between coarse lead and traffic density was significant at the 90% probability level only for sites at five m, 25 m, and 75 m downwind. Coarse lead and wind speed correlations were significant at the 90% probability level at all downwind sites except for five m and 25 m at a height of seven m. Wind speed was a more dominant factor than traffic density in determining both mass and lead concentration levels over the range of conditions encountered.

## Vertical Profile

Vertical profiles for mass and lead in each particle size fraction were first examined by plotting the average concentration for 10 sample runs versus heights of two m, seven m, and 15 m based on measurements from towers located at five m and 25 m downwind. Background measurements were made at the two m height.

Mass concentrations measured at the two tower locations and upwind at a two m height were averaged over 10 days of sampling at each of the six tower locations. The coarse particle concentrations were statistically different from two m background (95% probability level) only at the ground level locations. Fine particulate mass was significantly different from two m background for at least 15 m vertically at the 25 m downwind site and at least seven m vertically at the five m downwind site. Total particulate mass measured at heights above ground level (two m) were found to be significantly different from two m background for only the seven m vertical at the five m downwind location. The vertical gradient mass data was not fit to empirical equations since it was at background level at some of the elevated measuring points.

In the vertical profiles, lead concentrations for fine and total particles were significantly different from background up to 15 m vertically for both downwind towers. Coarse lead was significantly above background for at least seven m vertically at both downwind towers.

No significant correlations were found between composite mass fractions and traffic density at the elevated sites. The same was true for the lead fractions. Wind speed correlated with fine mass at the 99% probability level for all sites except the five m downwind, 15 m height site. Coarse particle mass fractions correlated significantly with wind only at the five and 25 m downwind sites at the seven m height. Coarse lead fractions correlated significantly only at the 15 m height at five m and 25 m downwind. Fine lead showed a significant correlation with wind speed at all sites.

Since fine and total lead concentrations were above background up to a 15 m height, logarithmic equations as follows, were fitted by least squares to empirically describe the vertical dilution, (C = mass concentration, $\mu g/m^3$; H = distance above ground, meters):

| Fraction | Equation | Correlation Coefficient | Standard error of estimate ($\mu g/m^3$) |
|---|---|---|---|
| Fine lead (5m dw) | $C = 0.674 - 0.222 \ln H$ | 0.990 | 0.030 |
| Total lead (5m dw) | $C = 0.833 - 0.273 \ln H$ | 0.990 | 0.057 |
| Fine lead (25m dw) | $C = 0.498 - 0.145 \ln H$ | 0.998 | 0.013 |
| Total lead (25m dw) | $C = 0.609 - 0.177 \ln H$ | 0.998 | 0.008 |

### *Bromine/Lead Ratios*

The Br/Pb ratios found to exist in the downwind roadway particulate matter were consistent with ratios reported in the literature. As described by Harrison and Sturges, the major particulate species of exhaust lead and bromine in the United States is PbBrCl and should give a Br/Pb mass ratio of 0.386 in the exhaust. The average Br/Pb ratio for all ten downwind monitoring locations was $0.36 \pm .06$ in the fine fraction and $0.55 \pm .26$ in the coarse fraction. Eighty percent of the lead mass was found in the fine fraction.

### *Development of Empirical Model for Roadway Generated Particulate Levels*

Rodes and Holland developed an expression in the Los Angeles Catalyst Study which predicts (for two m height) the exponential horizontal decrease of an initial concentration of an inert gas measured at a given point downwind of the centerline of a roadway. This approach was used to develop an equation for computing particulate and lead mass concentration at heights up to 15 m above ground level and distances between five m and 175 m downwind of roadway edge for cross-wind cases at wind speeds between three and six mph. Rodes and Holland's equation is

$$C = C_{26}\left(\frac{26}{X}\right)^{B_1} + C_b$$

Where C = mass conc. at distance downwind ($\mu g/m^3$)

$C_{26}$ = mass conc. at initial point downwind 26 m from roadway centerline ($\mu g/m^3$)

$B_1$ = "vertical" dilution parameter

X = distance downwind from centerline (m) where $26M < X < 414m$

C = background conc. ($\mu g/m^3$)

It was modified to account for the vertical gradient. The term $(2/H)B_2$, which describes the vertical gradient at a given height H from the initial height of two meters is added to the Rodes equation to give:

$$C = C_{31}\left(\frac{31}{D}\right)^{B_1} \times \left(\frac{2}{H}\right)^{B_2} + C_b$$

Where $C_{31}$ = mass conc. at initial five m downwind point, 31 m from centerline of road and two m above ground ($\mu g/m^3$)

D = distance downwind from centerline (m) where $31M < D < 206M$

$B_1$ = Horizontal gradient coefficient

H = vertical height (m) where $2M < H < 15M$

$B_2$ = vertical gradient coefficient

C = background upwind concentration ($\mu g/m^3$)

At any downwind two m sampling height, the third term becomes unity $[(2/2)\ B_2 = 1]$ and the equation reduces to the same form as Rodes and Holland equation. Least square regressions were used to determine the value of $B_1$ and $B_2$ based on measurements made during the study. Data acquired from the horizontal and vertical downwind mass and lead measurements (above background) were combined to determine siting constraints in both the horizontal and vertical direction. Average wind speed and traffic density of 11.0 mph and 3304 veh/hr during horizontal profiling compared to an average of 9.4 mph and 3129 veh/hr during vertical profiling providing similar mass loading, mixing and resulting downwind mass concentrations for the two sampling configurations (Phase I and Phase II).

Results of the regressions are as follows:

(a) Total mass (<15 microns)

$$\text{Conc } (\mu g/m^3) = 15.91\left(\frac{31}{D}\right)^{1.28}\left(\frac{2}{H}\right)^{1.67} + C_b;\ R^2 = .83$$

(b) Coarse Mass (2.5-15 microns)

$$\text{Conc } (\mu g/m^3) = 11.09\left(\frac{31}{D}\right)^{1.99}\left(\frac{2}{H}\right)^{2.24} + C_b;\ R^2 = .88$$

(c) Fine Mass (0-2.5 microns)

$$\text{Conc } (\mu g/m^3) = 4.56\left(\frac{31}{D}\right)^{.82}\left(\frac{2}{H}\right)^{.35} + C_b;\ R^2 = .67$$

(d) Fine Lead (0-2.5 microns)

$$\text{Conc } (\mu g/m^3) = .46\left(\frac{31}{D}\right)^{1.24}\left(\frac{2}{H}\right)^{1.50} + C_b;\ R^2 = .96$$

These equations, based on the average of site differences between upwind and downwind concentration levels, were used to construct contour maps. For fine, coarse, total mass and fine lead, isolines describe percentages of mass (above background) at given heights and distances downwind of the roadway.

As shown by the models, the fine and coarse mass fractions exhibit contrasting patterns downwind of the roadway. At two m height, a 25% above background mass level extends downwind from roadway centerline 47 m for fine and 65 m for coarse.

Fine lead shows a distance of 75 m downwind is required for the concentration to drop to 250% above background at the two m height. Above the six m height, lead concentration falls very rapidly with height (the 250% level at 15 m height = eight m downwind). The isopleths show the majority of coarse mass and fine lead to be concentrated below the six m height, while the fine mass is more evenly distributed throughout the two-15 m vertical. This can be explained by the fact that above background fine lead was elevated ~800% and coarse mass ~45% in comparison to only ~ 18% for fine mass, making fine mass downwind more equally distributed in the vertical. These statistical models are not valid for distances less than five m of the roadway edge.

## Conclusions and Recommendations

Significant differences at the 95% confidence level were found to exist between downwind (including roadway) and upwind background mass concentrations of fine, coarse, and total particulate matter. Significant differences at the 95%

confidence level also were found for the lead component of the mass fractions.

Within wind speed and traffic density boundaries of the study, the downwind mass gradients in the vertical and horizontal directions were predictable from an empirical relationship. Therefore, zoning graphs for use in developing siting constraints were obtainable for the mass and lead fractions. The bromine/lead ratio was found to be consistent with other studies indicating that the increased lead mass levels were generated from the roadway. The criteria for siting TSP samplers (presently in the Federal Register) cannot be used for siting IP samplers since the constricted area is not bounded by a straight line as given in the TSP criteria. The area is bound by an exponential function with respect to height and distance. The downwind mass and lead concentration profiles for each size fraction measured are similar in shape but extinction rates vary considerably for the different fractions measured.

The particulate mass settling rate (deposition) downwind to a distance of 175 m is not significant. The downwind horizontal decrease in particulate concentration at a height of two m is due mostly to the upward diffusion of the particles. Only 1.2% of the fine mass is lost between five m and 25 m downwind at a height up to 15 m. The coarse mass decreased 9.7% at the same height and over the same distance. One cannot assume that correct siting can be accomplished by placing the sampler at a greater height, since the plume rises with distance downwind. The downwind dilution rate of lead associated with the fine fraction is different from that of the fine or coarse mass fraction. Most of the lead remains below a height of seven m vertically, and is significantly above zero at a distance of 175 m downwind.

It was possible to empirically derive two dimensional exponential equations describing dilution of mass and lead content in both the horizontal and vertical directions downwind which account for greater than 90% of the variability in the data. The equations are of the form used to describe dilution of an inert gas. However, the exponents in the fitted equations are not in agreement with the values found previously. The dilution rate is highly influenced by the difference in concentration upwind and that directly downwind of the source.

*R. **Burton** (also the EPA Project Officer, see below) and **J. Suggs** are with Environmental Monitoring Systems Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC 27711.*
*The complete report, entitled "Philadelphia Roadway Study," (Order No. PB 84-226 927; Cost: $8.50, subject to change) will be available only from:*
*National Technical Information Service*
*5285 Port Royal Road*
*Springfield, VA 22161*
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