FINAL REPORT

0297

AN EMPIRICAL RELATIONSHIP BETWEEN MESOSCALE CARBON MONOXIDE CONCENTRATIONS AND VEHICULAR EMISSION RATES

by

Gerardo G. Clemeña
Materials Research Analyst

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

July 1979
VHTRC 80-R2

ENVIRONMENTAL RESEARCH ADVISORY COMMITTEE

MR. E. T. ROBB, Chairman, Assist. Environmental Quality Engr., VDH&T

MR. M. C. ANDAY, Assistant Head, VH&TRC

MR. R. E. BLASER, Univ. Distinguished Prof., VPI & SU

MR. L. E. BRETT, JR., District Engineer, VDH&T

MR. R. E. CAMPBELL, Assist. Transp. Planning Engineer, VDH&T

MR. A. R. CLINE, Dist. Environmental Coordinator, VDH&T

MR. R. V. FIELDING, Materials Engineer, VDH&T

MR. R. L. HUNDLEY, Environmental Quality Engineer, VDH&T

MR. D. D. MCGEEHAN, Hwy. Research Scientist, VH&TRC

DR. TOM STEPHENS, Assoc. Prof. of Civil Engineering, VPI & SU

MR. W. P. TUCKER, Right-of-Way Engineer, VDH&T

MR. R. G. WARNER, Assist. Construction Engineer, VDH&T

MR. R. B. WELTON, Environmental Coordinator, FHWA

MR. J. E. YEATTS, Assist. Location & Design Engineer, VDH&T

ABSTRACT

Presented is a relatively simple empirical equation that reasonably approximates the relationship between mesoscale carbon monoxide (CO) concentrations, areal vehicular CO emission rates, and the meteorological factors of wind speed and mixing height. The approximation is an extension of rollback modeling and was derived from aerometric data measured at a major urban area in Virginia. A similar equation has been found valid for data measured at another major urban area.

Transportation planners can use such an approximation in conjunction with a grid inventory of areal vehicular CO emissions to obtain an areal profile of mesoscale CO concentrations. Such an approximation would be preferable to the complex and potentially more accurate diffusion models when reliable input data are not available, which is often the case. It can be used by air quality planners involved in the project-level analyses to estimate the existing worst-case background levels of CO at a proposed urban highway site. This estimation can then be combined with the predicted worst-case CO contribution from the proposed highway project to determine if expensive air monitoring is necessary.

03[illegible]

FINAL REPORT

AN EMPIRICAL RELATIONSHIP BETWEEN MESOSCALE CARBON MONOXIDE CONCENTRATIONS AND VEHICULAR EMISSION RATES

by

Gerardo G. Clemeña
Materials Research Analyst

INTRODUCTION

The analysis of mesoscale carbon monoxide (CO) emissions has become an important part of the assessment of potential effects on air quality that may arise from changes in the traffic network. In the analysis, using such emission models as the SAPPOLUT[1] or the emission module in the APRAC-2,[2] the total CO emission in each grid square is estimated to obtain a gridded inventory of emissions corresponding to a given traffic alternative. After the analysis has been repeated for all available alternatives, transportation planners can decide which alternative is favorable from the standpoint of air quality by comparing the emissions corresponding to the various alternatives.

This report documents an attempt to derive a simple empirical relationship between the CO emission in each grid square, the mesoscale CO concentration, and meteorological variables from measurements made in two major urban areas in Virginia — the metropolitan Richmond and the Tidewater areas.

EXPERIMENTAL APPROACH

The general approach used in the study consisted of the following steps: 1) preparation of a gridded inventory of vehicle kilometers traveled (VKT) in one of the urban study areas; 2) selection, from the inventory, of several grid squares representing a wide range of VKTs; 3) in each grid square, location of a CO measurement site; 4) simultaneous measurements of hourly CO concentrations at all the sites, supplemented by measurements of meteorological variables; 5) calculation of the corresponding hourly CO emissions for each of the selected grid squares; and 6) correlation of the hourly CO emissions, mesoscale CO concentrations, and meteorological variables. A detailed description of some of these steps and pertinent information are presented herein.

Grid Inventory of Vehicle Kilometers Traveled

The first area utilized in this study was metropolitan Richmond, which is located in the middle of the eastern half of Virginia. Since the area is on the fall line dividing the Piedmont and the Coastal Plains, its topography varies from 3 to 64 m above mean sea level. A 484-km^2 area consisting of the city of Richmond in the middle and surrounded by part of Henrico County on the north and part of Chesterfield County on the south was gridded into squares 2.0 km by 2.0 km in dimension (Figure 1). Then the total daily VKT in each grid square was calculated by

$$TDV = \sum_{\ell} (\text{Length})_{\ell} \times (\text{ADT})_{\ell}, \qquad (1)$$

where TDV = the total daily VKT, in vehicle-kilometers, in a grid square;

(Length) = the segment length, in kilometers of the primary traffic link ℓ in the square; and

(ADT) = the average daily traffic on the primary link ℓ.

The 1976 traffic data provided by the Virginia Department of Highways and Transportation were used.[3] To evaluate the possible effect of using different grid sizes on the correlation being sought, an additional inventory was performed on the same study area using a grid of 1.4 x 1.4 km squares (Figure 1). In this inventory, the second grid was laid over the study area in such a manner that many of the smaller squares were almost completely contained in, or overlapped by, as many of the larger squares when the first grid was also laid over the area. Then, by selecting CO measurement sites from some of the overlapping pairs of different sized squares, the measured CO concentrations at these sites could be correlated with CO emissions estimated on the basis of both grid sizes.

The second study area was in the Tidewater area of Virginia. It consisted of the city of Norfolk at the western half and the city of Virginia Beach at the eastern half. The study area of 448 km^2 was gridded into 2.0 x 2.0 km squares only for the inventory of the daily VKT using recorded 1977 traffic data.[4,5]

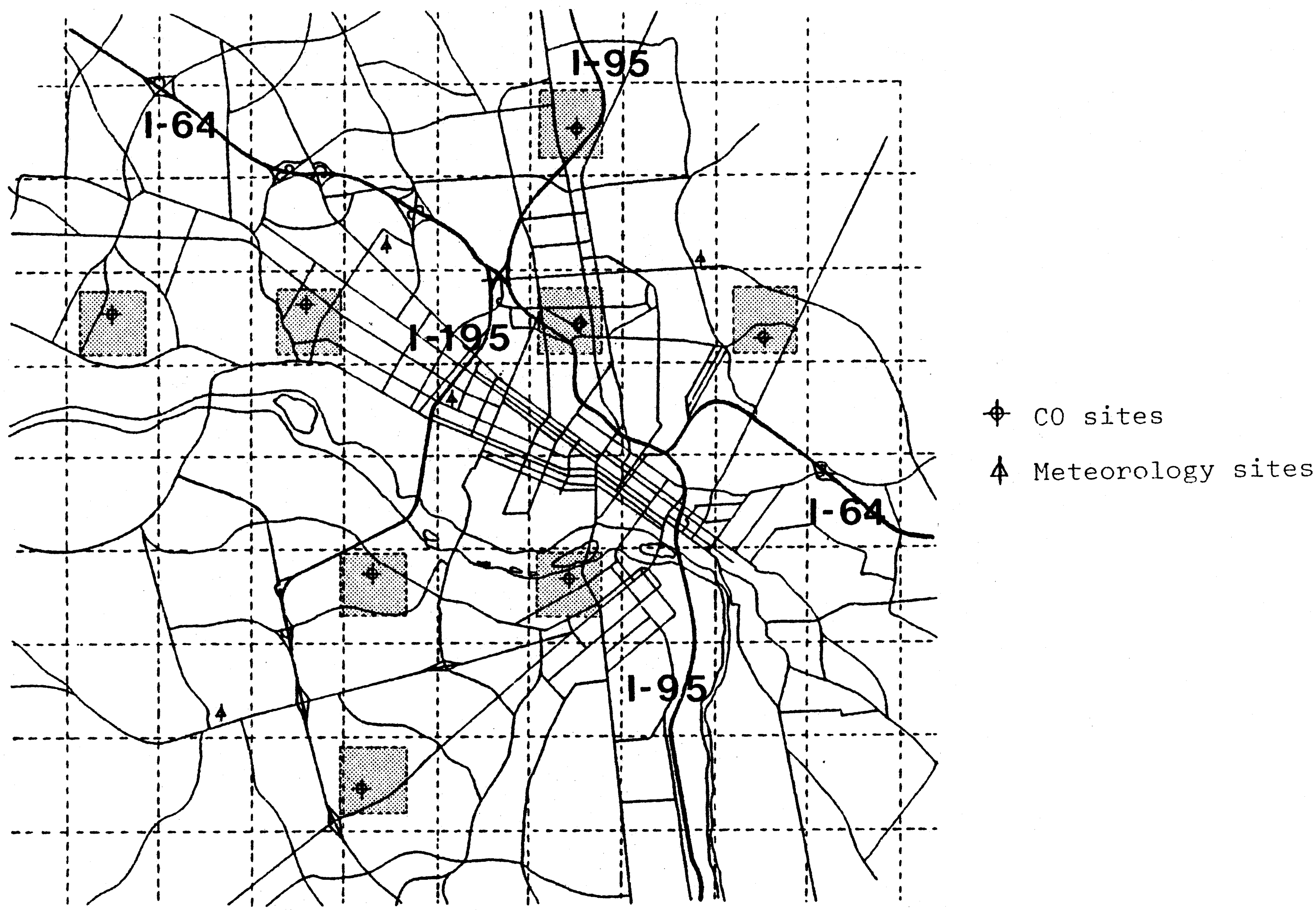


Figure 1. Metropolitan Richmond area gridded into 2.0 x 2.0 km squares. The shaded 1.4 x 1.4 km squares are portions of the second grid used.

CO Measurement Sites

Metropolitan Richmond

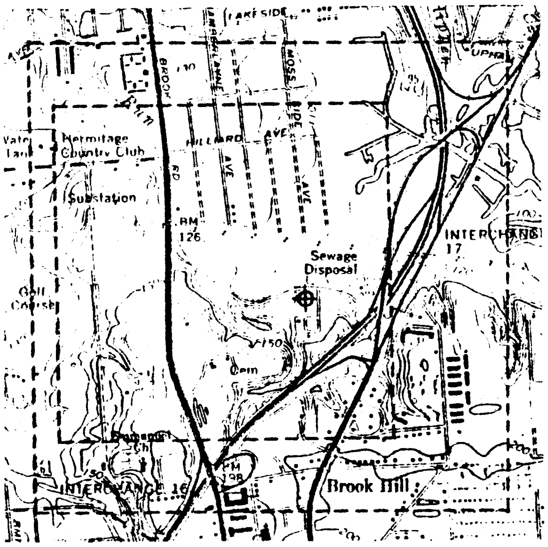
From the two emission inventories for metropolitan Richmond, eight pairs of overlapping grid squares were selected (Figure 1). Based on 1976 traffic data collected by the Virginia Department of Highways and Transportation,[3] these squares represented ranges of 15,000 - 206,000 and 11,000 - 144,000 daily VKT in the 2.0-kilometer-square and the 1.4-kilometer-square grids, respectively. Then, in each pair a CO measurement site was located that was 1) beyond the microscale effect of any primary link; 2) accessible to personnel and air sampling devices; and 3) fairly safe from vandalism. Figure 2 presents topographic maps showing the grid squares wherein sites 1 through 8 were located. The exact locations of these sites and the land uses surrounding them are given in Table 1.

Site 1 had appreciable traffic surrounding it, as shown in Table 2. To the east of the site were Interstate 95 and Route 369, to the west was Brook Road, or Route 1, and to the north was Hilliard Road.

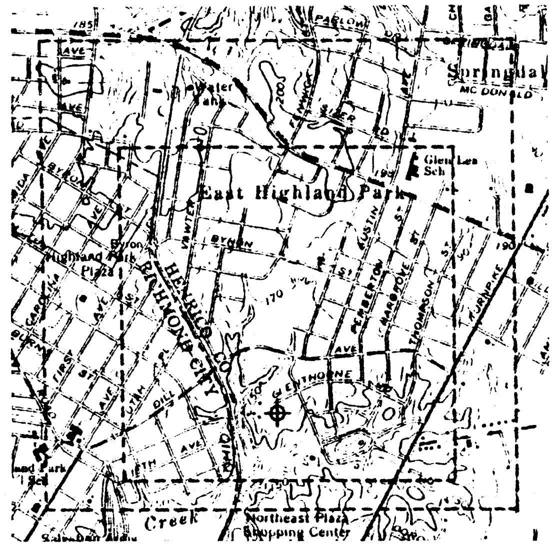
Site 2 had considerably less traffic and ranked in the lower four of the eight sites. The contributing primary links were Laburnum Avenue to the northeast and the Mechanicsville Turnpike to the east. The small number of industrial and commercial enterprises in the area are scattered along the two primary links.

Site 3 had the highest total daily VKT among the eight sites, as shown in Table 2. This was contributed by Laburnum Avenue to the north, Brook Road and Chamberlayne Avenue to the east, Brookland Park Boulevard to the south, and Interstate 95, Brookland Parkway, Hermitage Road and the Boulevard to the southwest and west. This site, which was located on the grounds of the Union Theological Seminary, was surrounded by more institutions than were the other sites. Included among the institutions were hospitals, schools, and a nursing home. All industrial and commercial enterprises were concentrated along Hermitage Road and the Boulevard south of Interstate 95.

The total daily VKT surrounding Site 4 was intermediate. Most traffic was carried by Patterson and Monument Avenues to the north, Libbie Avenue to the east, Grove Avenue, Cary Street and River Road to the south, and Three Chopt Road to the west of the site, which was located on the grounds of a relatively large private school. Most commercial enterprises, including a large shopping center not shown in Figure 2, were located along Patterson Avenue and the northern portion of Libbie Avenue.

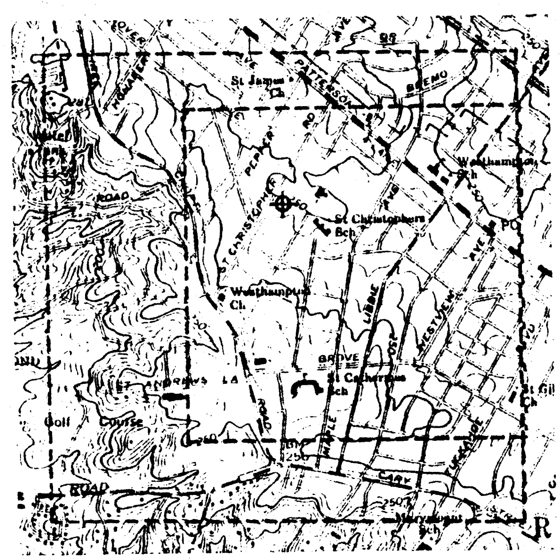


Site 1



Site 2

Site 3

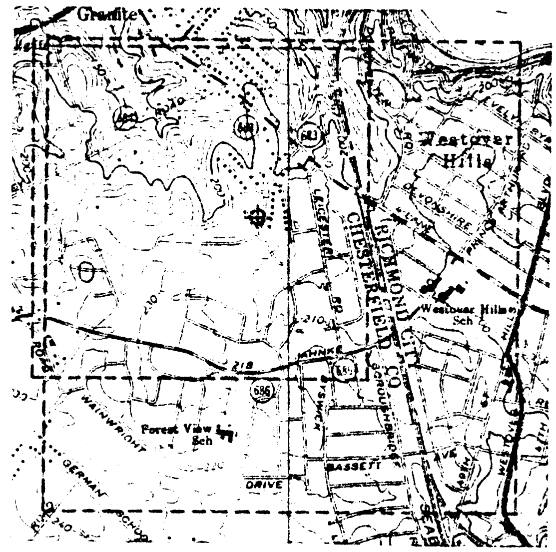


Site 4

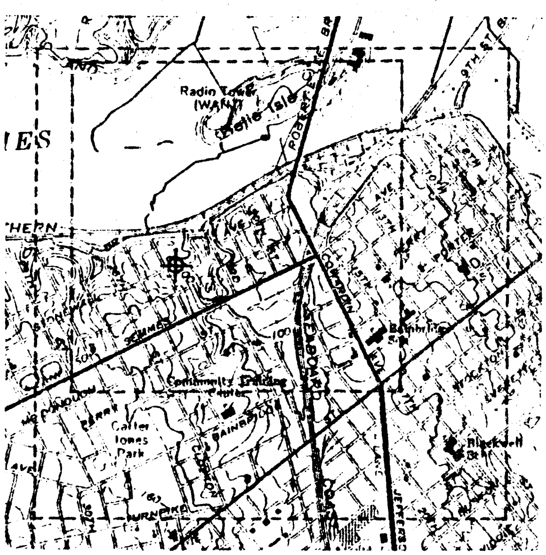
Figure 2. CO measurement sites in metropolitan Richmond.
(These are marked by ⊕.)

03

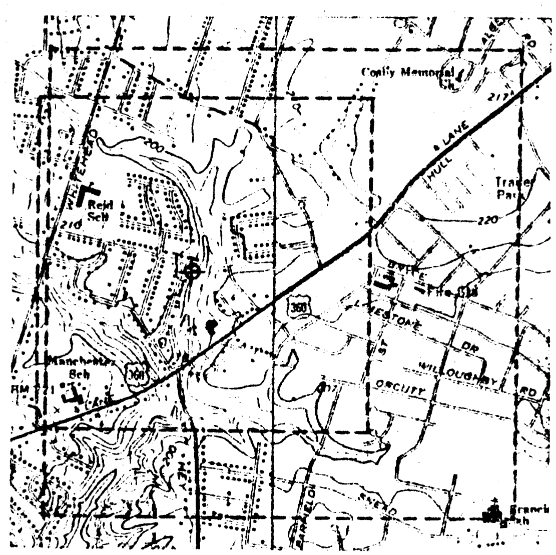
Site 5



Site 6



Site 7



Site 8

Figure 2. Continued.

Table 1

CO Measurement Sites Used in Metropolitan Richmond

Site No.	Location	UTM Coordinate	City/County	Land Use
1	East of Brook Rd; bt. Hilliard Road and Interstate 95	E 283.667 N 4165.464	Henrico Co.	60% open space; 30% residential; 5% multifamily; 5% commercial
2	Barrington Rd. and Glenthorne Rd.	E 287.476 N 4160.619	Henrico Co.	90% residential 10% open space, commercial and industrial
3	West of Brook Rd; bt. Westwood Ave. and Rennie Ave.	E 284.000 N 4161.274	Richmond	80% residential; 10% institutional; 5% multifamily 5% industrial and commercial
4	St. Christopher Rd; bt. Wesley Rd. and Henri Rd.	E 277.464 N 4161.928	Richmond	75% residential; 20% open space; 5% commercial
5	North of River Rd. and east of Parham Rd.	E 273.119 N 4161.928	Henrico Co.	100% residential and open space
6	Kildare Dr. and Westower Dr.	E 278.798 N 4155.786	Richmond	90% residential; 8% multifamily; 2% commercial
7	24th Ave. and Stonewall Ave.	E 282.630 N 4155.571	Richmond	50% residential; 20% river; 10% open space; 10% commercial; 5% multifamily; 5% industrial
8	Stansburg Dr. and Daytona Dr.	E 278.643 N 4151.512	Richmond	55% residential; 20% commercial; 15% open space; 5% multifamily; 5% institutional

Table 2

Estimated 1976 Total Daily VKT Surrounding the CO Measurement Sites in Metropolitan Richmond

Site No.	Total Daily VKT	
	2.0-km-square grid	1.4-km-square grid
1	167,000	90,000
2	89,000	35,000
3	206,000	144,000
4	111,000	46,000
5	15,000	11,000
6	77,000	31,000
7	175,000	79,000
8	53,000	35,000

Site 5 was surrounded by the least traffic, as shown by Table 2; with River Road to the south and Parham Road to the west. The surrounding area was all low density, single-family residences and open spaces.

Site 6 had relatively little traffic near it. This is contributed by Forest Hill Avenue to the north and northeast, Westower Hills Boulevard to the east, and Jahnke Road to the south. Commercial enterprises are concentrated along Westower Hills Boulevard.

Site 7 had a relatively large amount of traffic near it. This came mostly from Cowardin Avenue and Jefferson Davis Highway on the east, and Semmes Avenue, Bainbridge Street, the Midlothian Turnpike, and Hull Street to the south. The land surrounding this site was put to varied uses as compared to the other sites (Table 1).

Site 8 had one of the lowest traffic densities. This came from Hull Street on the southwest and Whitehead Road at the west. All the commercial establishments were located along Hull Street.

Tidewater Area

From the only VKT inventory for this second study area, six grid squares were selected (Figure 3). As indicated in Table 3, these squares provided a range of 60,000 - 386,000 daily VKT based on 1977 traffic data.[4,5] Then, using the previously mentioned criteria, a CO measurement site was located in each grid square.

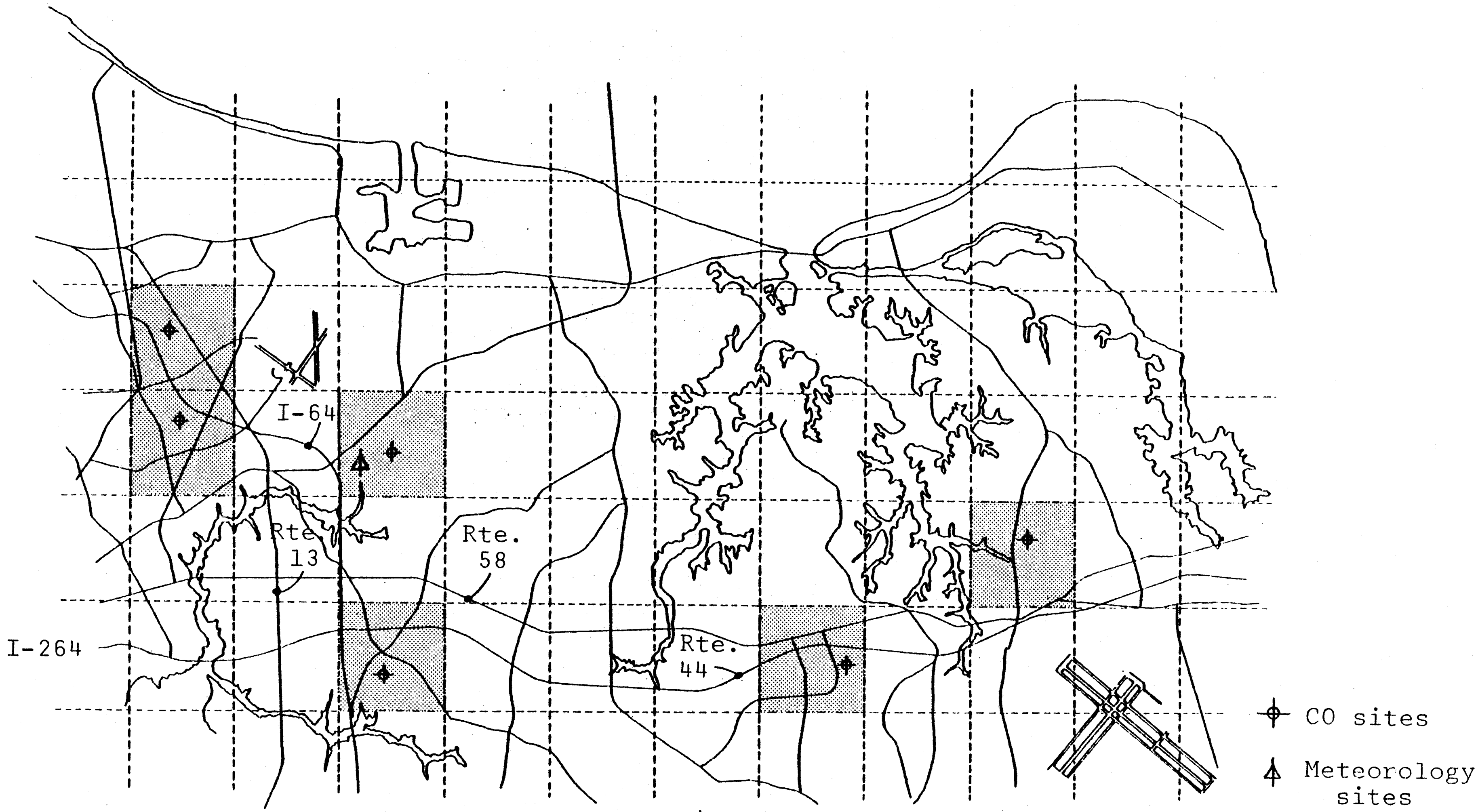


Figure 3. Tidewater area gridded into 2.0 x 2.0 km squares.

Table 3

Estimated 1977 Total Daily VKT Surrounding the CO Measurement Sites in Tidewater Area

Site No.	Total Daily VKT
1	260,000*
2	171,000
3	113,000
4	386,000
5	204,000
6	60,000

*Based on 2.0-km-square grid.

Table 4 gives the locations of the six sites and the existing land uses in their respective squares. Figure 4 presents topographic maps of the grid squares.

Site 1 had the second highest traffic surrounding it, according to Table 3. Figure 4 shows that this traffic came from the Military Highway to the east of the site, Norview Avenue to the south, and Interstate 64 and Chesapeake Boulevard to the west. Among the six sites, this had the most commercial establishments.

Site 2 had less traffic surrounding it than did site 1. Figure 4 shows that this traffic was contributed by Interstate 64 and the Military Highway to the northeast, Azalea Garden Road to the east and southeast, Robin Hood Road, Caravan Drive, and Princess Anne Road to the south, and Sewell's Point Road to the west. This site had the least open space of any of the sites.

Site 3 had light traffic. This traffic came from Baker Road on the east, Interstate 64 and Wesleyan Drive on the west, and Northampton Boulevard to the north. Traffic counts for Wesleyan Drive and Baker Road were both less than 10,000 ADT. Among the six grid squares in the Tidewater area, the square associated with Site 3 had the most open spaces, which included farmland, woodland, lakes, two campuses, and part of a golf course.

Site 4 had the highest traffic, as indicated in Table 3. This traffic is contributed by Princess Anne Road to the general northeast of the site, Newton Road and Interstate 64 on the west, and the Norfolk-Virginia Beach Expressway on the north. As Table 4 shows, use of the land around the site is varied, with appreciable commercial activities.

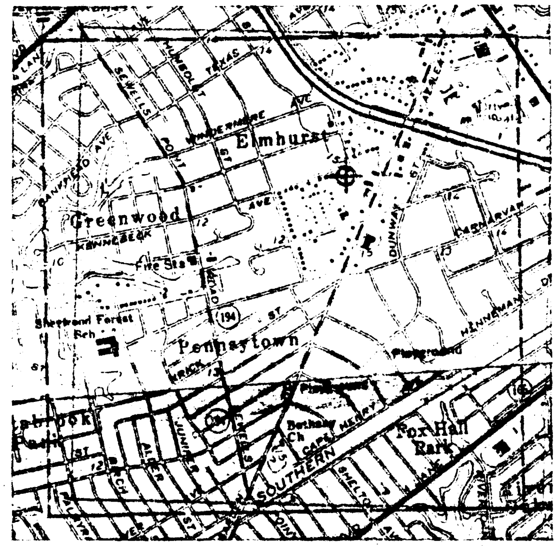
Table 4

CO Measurement Sites Used in Tidewater Area

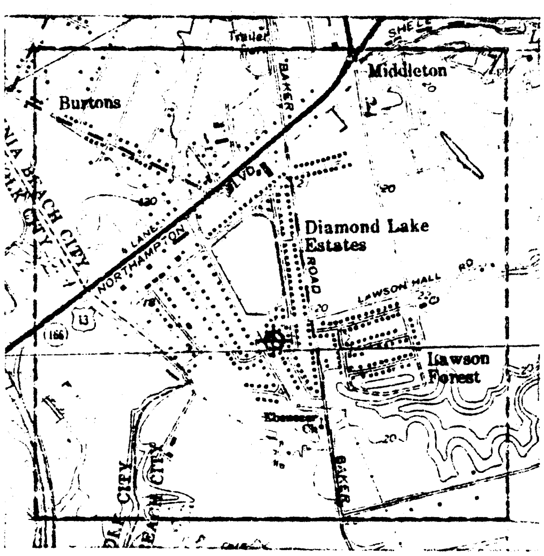
Site	Location	UTM Coordinate	City	Land Use
1	On E. Tanner Creek Dr. in the Rosemont Area east of Int. 64	E 390.180 N 4084.301	Norfolk	50% residential; 20% multifamily; 20% commercial; 5% institutional; 5% open space
2	At 5171 Kennebeck Ave. in the Elmhurst Area south of Int. 64	E 390.704 N 4082.419	Norfolk	70% residential; 15% multifamily; 10% commercial; 5% institutional
3	At 1029 Anoka Ave. in the Diamond Lake Estate south of Rte. 13	E 394.426 N 4081.594	Virginia Beach	72% open space; 20% residential; 5% institutional; 3% commercial
4	At 5606 Colter Court in the Arrowhead Area south of Rte. 44	E 394.286 N 4077.398	Virginia Beach	40% open space; 35% residential; 15% commercial; 8% multifamily; 2% institutional
5	At Lynnhaven School on Dillon Dr.	E 403.349 N 4075.896	Virginia Beach	55% residential; 27% open space; 11% commercial; 5% multifamily; 2% institutional
6	At 701 Earl of Warwick Ct. in the Wolfsnare Plantation east of Great Neck	E 406.674 N 4079.077	Virginia Beach	50% open space; 37% residential; 12% multifamily; 1% commercial

0312

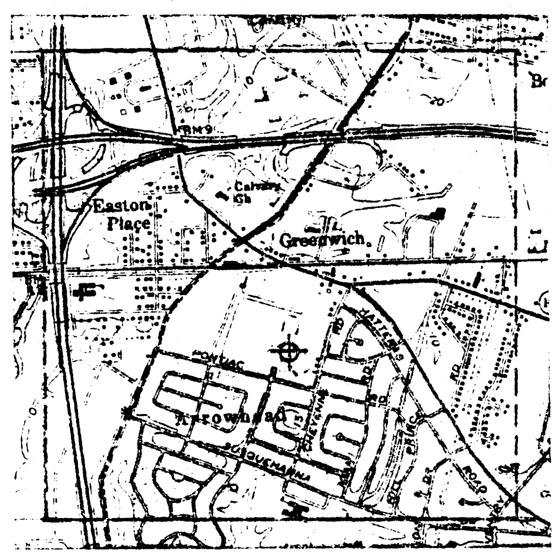
Site 1



Site 2



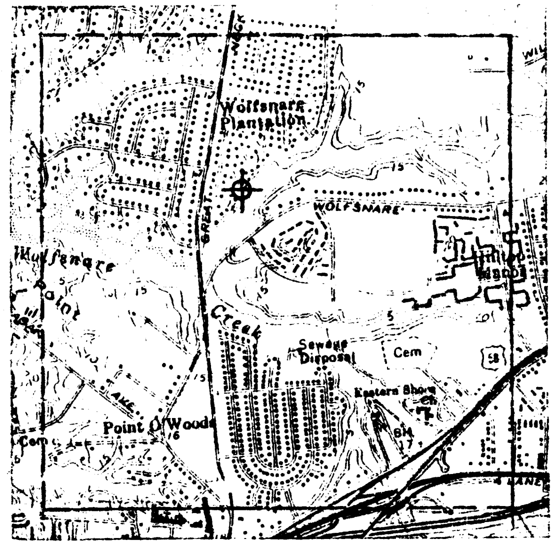
Site 3



Site 4

Figure 4. CO measurement sites in Tidewater area. (These are marked by -⊕-.)

Site 5



Site 6

Figure 4. Continued.

Traffic around Site 5 was intermediate. It came mainly from Plaza Trail Drive and Rosemont Road to the west of the site, and the Norfolk-Virginia Beach Expressway and Virginia Beach Boulevard to the north. Except for the Norfolk-Virginia Beach Expressway, these roads were flanked by business establishments.

Site 6 had the least amount of traffic. It came mostly from Great Neck at the west of the site, and from a portion of Virginia Beach Boulevard on the south. The land is predominantly open space, but there are dwellings.

As it is usually extremely difficult to find a measurement site in a central business district that is beyond the microscale air quality effect of a nearby street, none of the sites in the study were located in a central business district.

Measurement of CO Concentrations and Meteorological Variables

CO Concentrations

Hourly average CO concentrations at all measurement sites in a study area were simultaneously measured with the aid of sequential air samplers, each designed to collect hourly air samples into separate Tedlar air bags at some preset sequence. Air samplers were located at all sites and programmed to collect air samples at the same hours. Each collected air sample was then analyzed for its CO concentration with a gas chromatograph equipped with a flame-ionization detector and calibrated daily with span gases.

In the first study area, i.e. metropolitan Richmond, the measurements were made for five consecutive days on December 12-16, 1977. During each day, hourly air samples were collected from each of the eight sites from 0500 to 2100 hours EST. This yielded a total of 640 air samples (Appendix A).

In the Tidewater area, similar measurements were made for only two consecutive days on January 9-10, 1979, at the six selected sites. A total of 192 air samples were collected and analyzed (Appendix A).

Meteorological Variables

Concurrent measurement of meteorological variables such as wind speed and direction and ambient temperature was also made in each study area at some selected spots.

In metropolitan Richmond, these variables were measured at a recreational park located along Interstate 195. This station was more or less central to all eight CO measurement sites (Figure 1). A second station was established at the edge of a small airport owned by the State Police at the southwest quadrant in the study area to measure only wind speed and direction. The two anemometers used were set up at a standard height of 10 m and with proper exposure. In addition to the data taken at these stations, concurrent data on wind speed and direction being continuously collected by the Virginia State Air Pollution Control Board at two locations in the area were also obtained. The anemometer at one location, which is a CAMP station at the northeast quadrant, was calibrated against one of the two previously mentioned anemometers for purposes of standardization. The wind speed data (Appendix B) collected at these four stations were averaged for use in the correlation.

In the Tidewater area, measurements of wind speed and direction and ambient temperature were made on the grounds of the Norfolk Academy, which is located in the western half of the study area. The collected wind data are listed in Appendix C.

Concurrent hourly mixing heights at the study areas were calculated from morning radiosonde data recorded at the nearest National Weather Service (NWS) upper air station and hourly averaged ambient temperatures observed at the study area using methods described by Ludwig et al.[2] Radiosonde observations at NWS upper air stations in Sterling (Station 72403) and Wallops Island (Station 72402) were used for the metropolitan Richmond and Tidewater areas, respectively.

Calculation of CO Emission Rates

For each measurement hour in a study area, a set of CO emission rates for all the selected grid squares were calculated. The CO emission rate in a square was calculated as the sum of emission rates from all individual primary links in that square, i.e.,

$$E_{ih} = \frac{1}{1,000} \sum (ADT)_{\ell} \cdot (Length)_{\ell} \cdot F_{\ell h} \cdot e_{\ell mstwm}, \quad (2)$$

where

E_{ih} = CO emission rate in kg/hr for grid square (i), during hour (h);

$F_{\ell h}$ = fraction of ADT on link (ℓ) during hour (h); and

$e_{\ell mstwm}$ = composite emission factor in g/km for link (ℓ), calendar year (m), average traffic speed (s), ambient temperature (t), percentage cold operation (w), and vehicle miles traveled mix (m) by vehicle type.

The remaining variables, (ADT) and (Length), were previously defined.

The $F_{\ell h}$ for each link occurring during the hour of interest cannot be practically measured. Instead, an average diurnal distribution (Figure 5) derived from recorded diurnal distributions for some typical downtown streets, city arterials, suburban arterials and suburban expressways was used for all the links of interest in metropolitan Richmond, and a similarly derived distribution was used in the Tidewater area.

The composite emission factors were computed by a method described by Kircher and Williams.[6] A nationwide vehicle-miles-traveled mix consisting of 80% by automobiles, 12% by light trucks, 5% by heavy gasoline trucks, and 3% by heavy diesel trucks was used for both study areas. These figures are close to the vehicle count average of 84% automobiles, 11% light trucks, and 5% heavy trucks observed on some major arterials in the Richmond area in 1975.

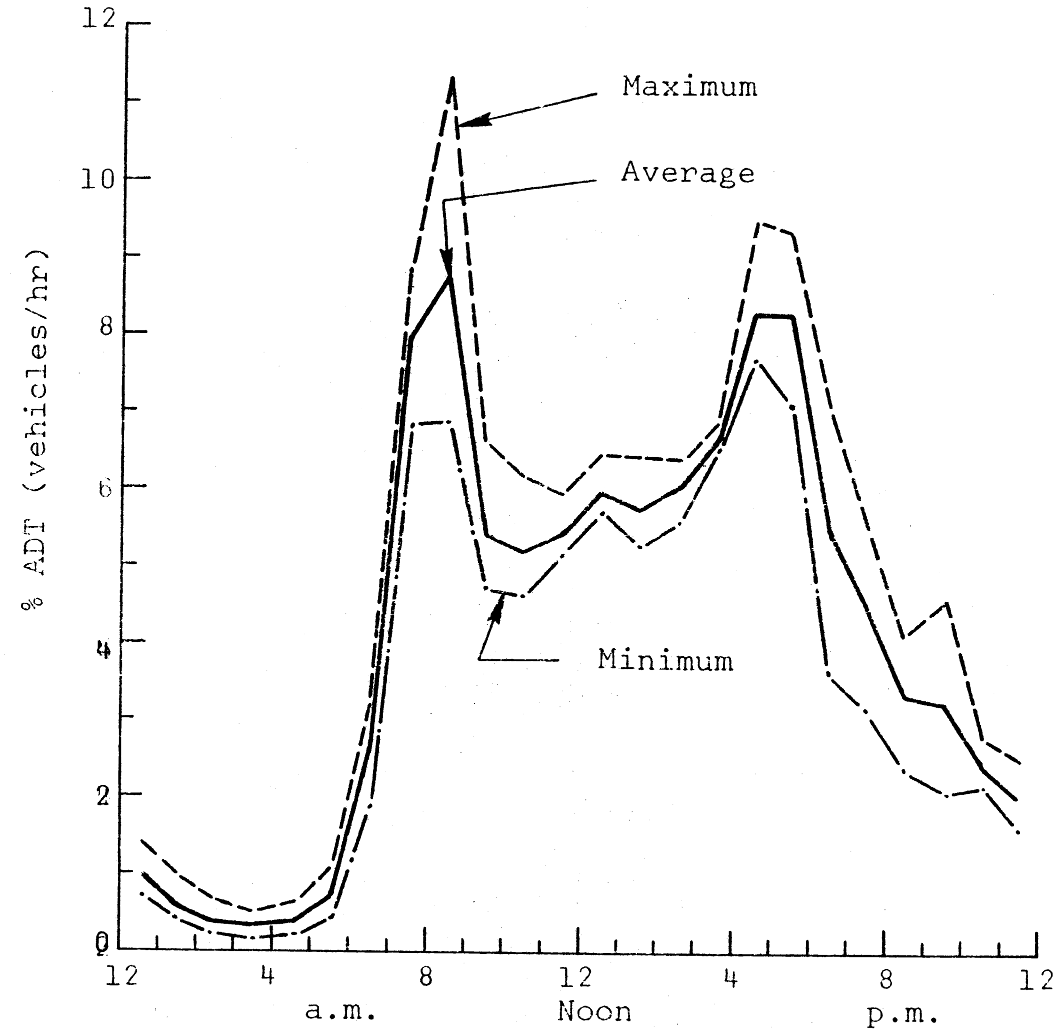


Figure 5. The average diurnal traffic distribution used for metropolitan Richmond.

Because reliable values for the percentages of vehicles operating in cold and hot transient were not available, the author elected to use 0% cold operation and 0% hot transient for expressways and rural arterials, and 20% cold operation and 27% hot transient for all other roads and for all hours of the day and both study areas. These figures were suggested as best estimates.[7]

The average traffic speeds for the links were provided by the Virginia Department of Highways & Transportation and were assumed to be uniform throughout each day in the absence of detailed estimates.

RESULTS AND DISCUSSION

In deriving an empirical relationship between the mesoscale CO concentration, vehicular CO emission in each grid square, and the meteorological variables some assumptions were made. These assumptions were: 1) motor vehicles were by far the largest contributor of the pollutant in question so that one could ignore the effect of other sources of CO; 2) the hourly mesoscale CO concentration in a grid square of a finite size was reasonably uniform; and 3) this concentration was linearly proportional to the hourly vehicular CO emission rate in the grid square, i.e.

$$[CO]_{ih} = m_h E_{ih} + b_h, \qquad (3)$$

where

$[CO]_{ih}$ = the hourly mesoscale CO concentration, in ppm, in grid square i during h th hour;

E_{ih} = the vehicular CO emission rate, in kg/hr, in the grid square i during h th hour; and

m_h, b_h = the constants for h th hour, which may be related to meteorological variables.

The last cited assumption is similar to that made in simple and practical rollback modeling.[8,9,10] Under the above assumptions, each set of hourly CO concentrations measured at the sites in Richmond were correlated, through regression analysis, with the calculated concurrent hourly CO emission rates to yield the best linear relationship between the variables for a given hour. An example of such an analysis is shown in Figure 6, where the correlation is extremely good. An examination of all the resulting correlations corresponding to the Richmond data for rush hours only revealed an average correlation coefficient of 0.66 and an average standard error of estimate of 0.4 ppm, using emissions calculated with the grid of 4 km^2-squares. For emissions calculated with the grids of 2 km^2-squares, an average correlation coefficient of 0.61 and an average standard error of estimate of 0.4 ppm were obtained. These statistics indicated that the assumed linear relationship between the mesoscale CO concentration and vehicular CO emission rate was reasonably valid.

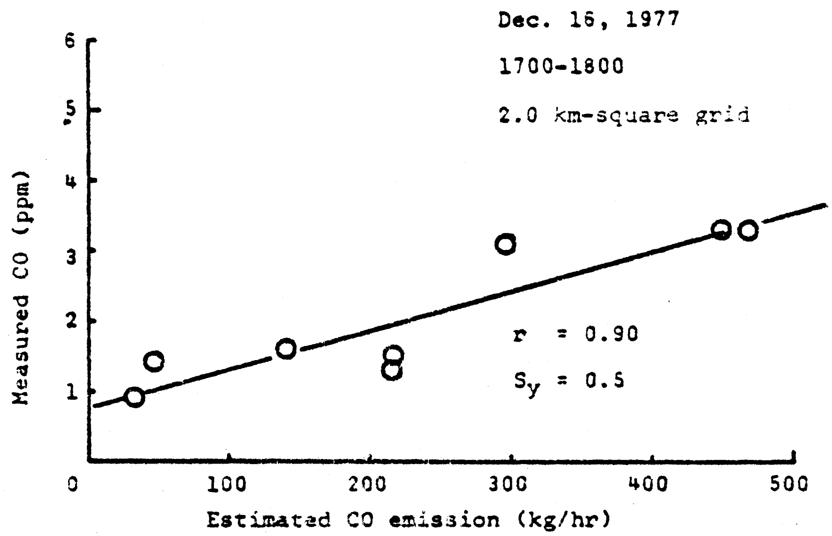


Figure 6. Relationship between measured mesoscale CO concentrations and estimated emissions. The best-fit straightline is displayed.

The set of proportionality factors, m_h, resulting from the above linear regression analyses were subsequently correlated with the meteorological variables such as wind speed and mixing height. It was found that the proportionality factor is best correlated to wind speed by

$$\log m_h = a_2 + a_1 \log \left(\frac{1}{\mu}\right) h , \qquad (4)$$

or

$$m_h = 10^{\{a_2 + a_1 \log \left(\frac{1}{\mu}\right) h\}} , \qquad (5)$$

where

μ_h = the hourly average wind speed, in km/hr, for h th hour; and

a_1, a_2 = constants.

The set of factors b_h may be viewed as "residual" pollutant concentrations from previous hours and uninfluenced by concurrent emission and meteorology, since it was found to correlate best with the previous hour's wind speed and mixing height. That is,

$$b_h = b_2 + b_1 \left(\frac{1}{\mu H}\right)_{h-1}, \tag{6}$$

where

μ_{h-1} = windspeed, in km/hr, during (h-1) th hour;

H_{h-1} = mixing height, in km, during (h-1) th hour; and

b_1, b_2 = constants.

Substituting equations 5 and 6 into equation 3 yields the relationship

$$[CO]_{ih} = kE_{ih} \cdot 10^{\{a_2 + a_1 \log \left(\frac{1}{\mu}\right)_h\}} + b_1 \left(\frac{1}{\mu H}\right)_{h-1} + b_2, \tag{7}$$

where all the variables and constants, except k, are as previously defined. The adjustment factor k is introduced to optimize the agreement between the measured CO concentrations, [CO] measured, and those calculated, $[CO]_{ih}$, with equation 7, i.e. to let $[CO]_{ih}$ = $[CO]_{measured}$. The optimum values for the various factors or constants, as derived from regression analyses, are given in Table 5 for the two grid systems used in metropolitan Richmond.

Table 5

Optimum Constants Based on the Richmond Data

Grid	k	a_1	a_2	b_1	b_2
2.0-km-square	2.11	1.31	-1.75	0.38	0.28
1.4-km-square	2.18	1.17	-1.56	0.46	0.24

A sensitivity analysis of equation 7 was conducted to assess how each of the input variables affect the calculated CO concentrations, using the following conditions as the base case:

CO emission rate	=	100 kg/hr,
concurrent wind speed	=	10 km/hr,
previous hour's wind speed	=	10 km/hr,
previous hour's mixing height	=	1 km,

and the constants listed in Table 5. Figures 7, 8, 9, and 10 illustrate that with the exception of the CO emission rate, all parameters inversely affect the calculated CO concentrations. The estimated relative importance of each input parameter is shown in Table 6. As expected from the assumptions used to derive the relationship, the CO emission rate is the most important input, then the concurrent wind speed; the least are the previous hour's wind speed and mixing height. This, of course, means that improvement in the estimation of the emission rate, which involved CO emission factors and various traffic data (especially those for the traffic rush hours), would provide the most improvement to the accuracy of the calculated CO concentrations. The same situation applies to the concurrent wind speed, although to a slightly less extent. It is interesting to note that there are not significant differences in the relative rankings of the input parameters in both grids, except for the emission rate. This parameter, apparently, affects the calculated CO concentrations that are based on the 1.4-km-square grid significantly more than those based on the other grid. This suggests that a grid consisting of large squares,but still of reasonable size so as not to lose spatial resolution, would be preferable since reliable or accurate traffic data are extremely scarce.

Using equation 7 and the above listed constants, the hourly mesoscale CO concentrations at each of the eight Richmond sites during the measurement period were calculated from emission rates estimated with the 2.0-km-square and the 1.4-km-square inventory grids. Figures 11 and 12 separately show comparisons of the measured and calculated mesoscale CO concentrations corresponding to the two grid systems. As is evident in the overall agreement between the measured and calculated concentrations, the empirically derived equation 7 reasonably relates the area vehicular CO emission rate and meteorology to mesoscale CO concentrations.

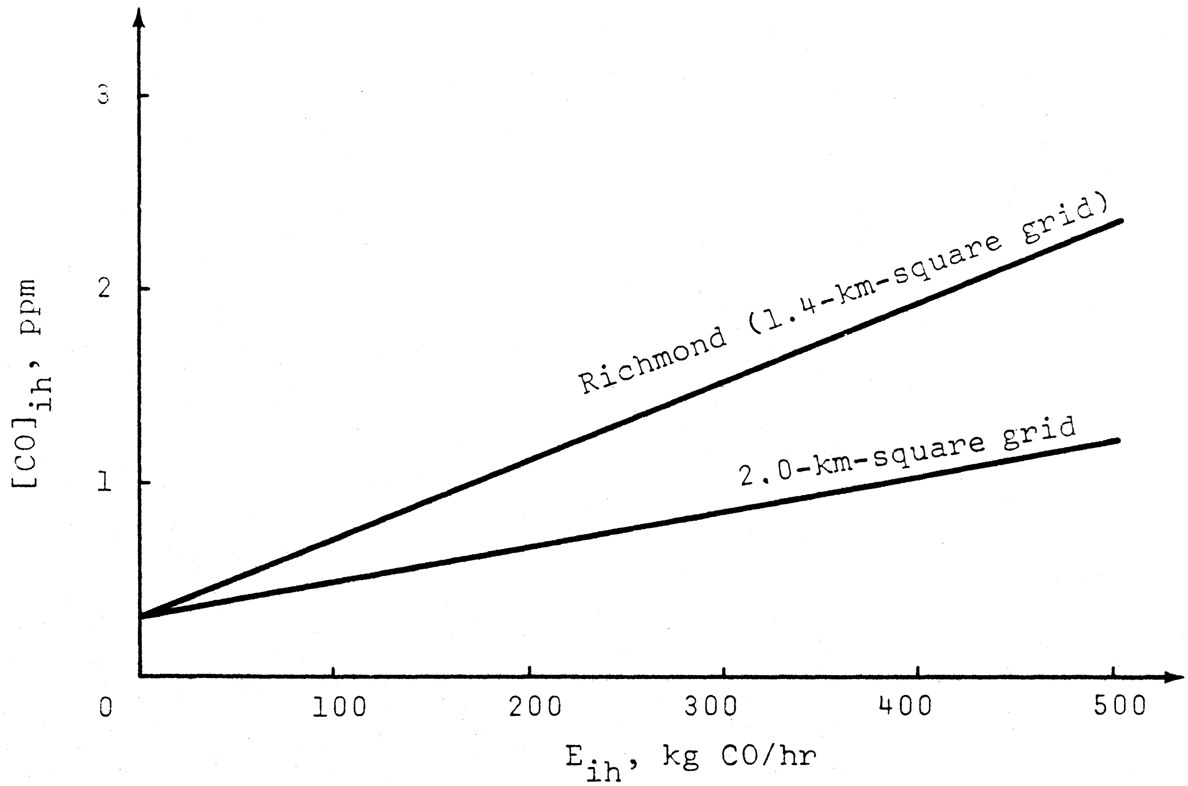


Figure 7. CO emission rate versus concentration.

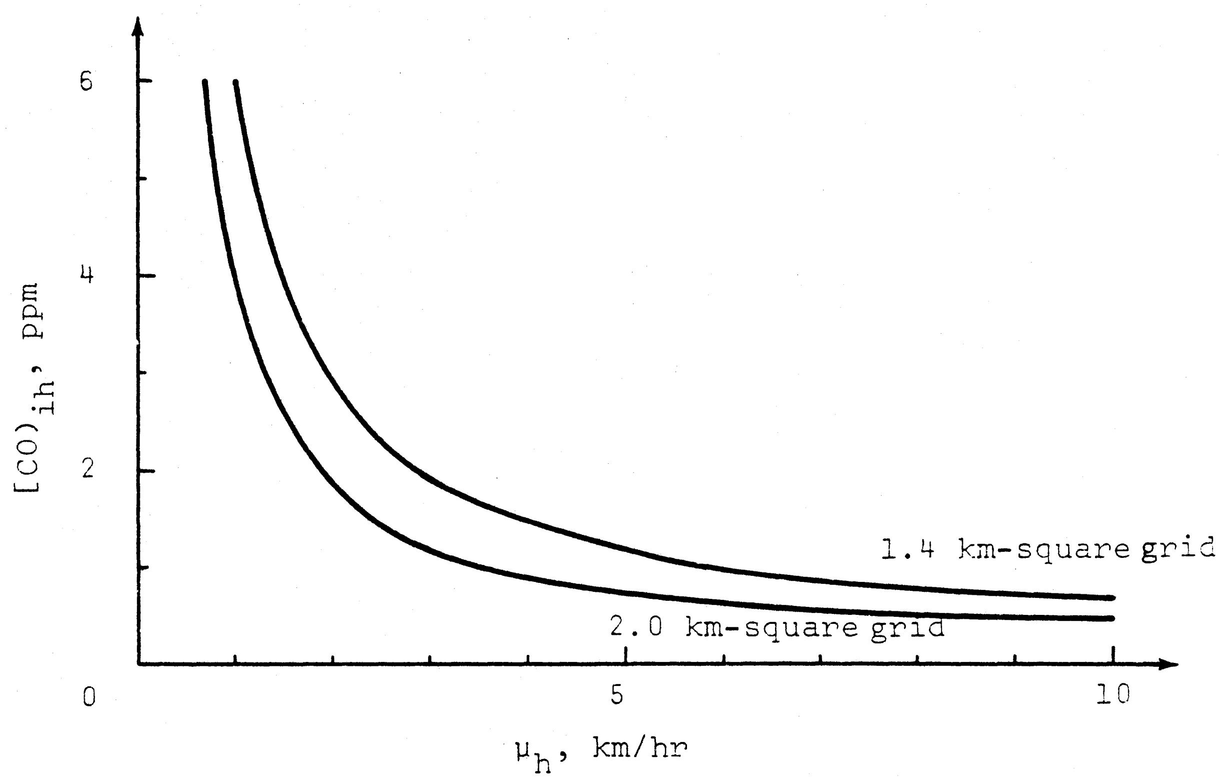


Figure 8. Concurrent wind speed versus CO concentration.

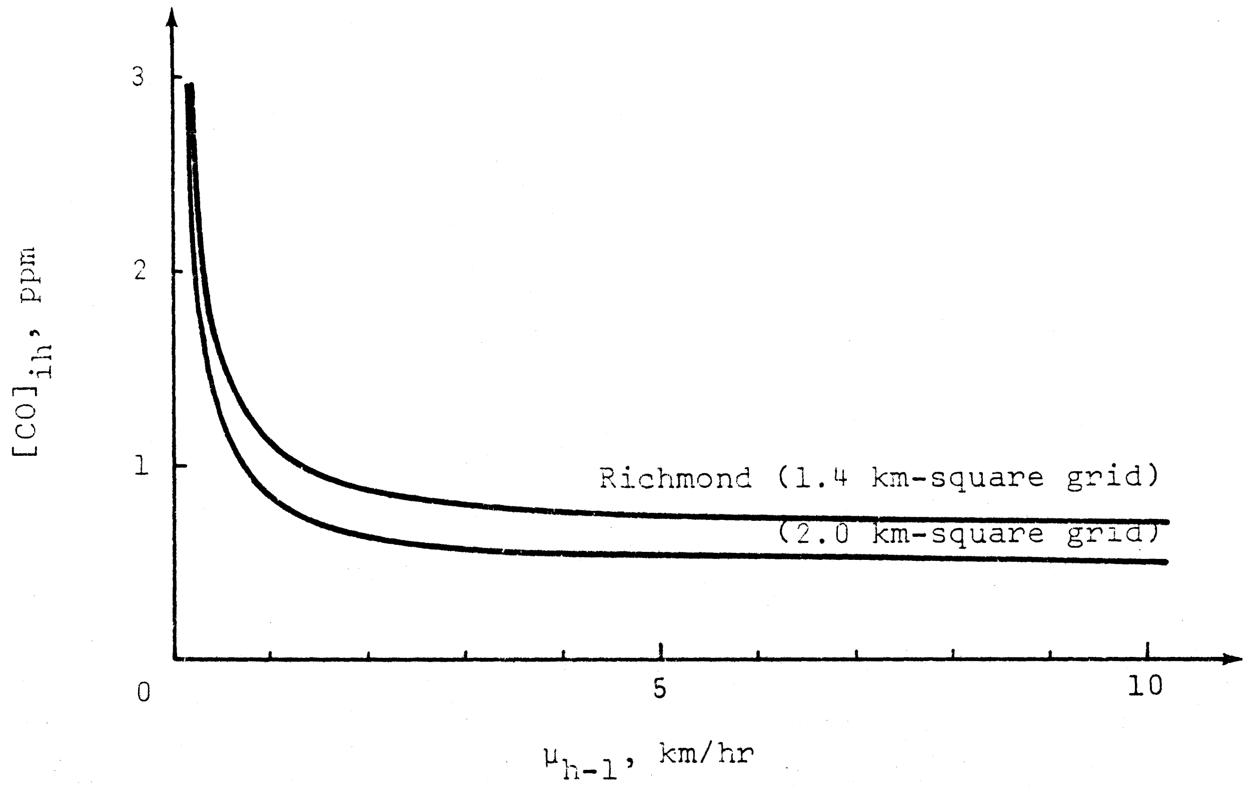


Figure 9. Previous hour wind speed versus CO concentration.

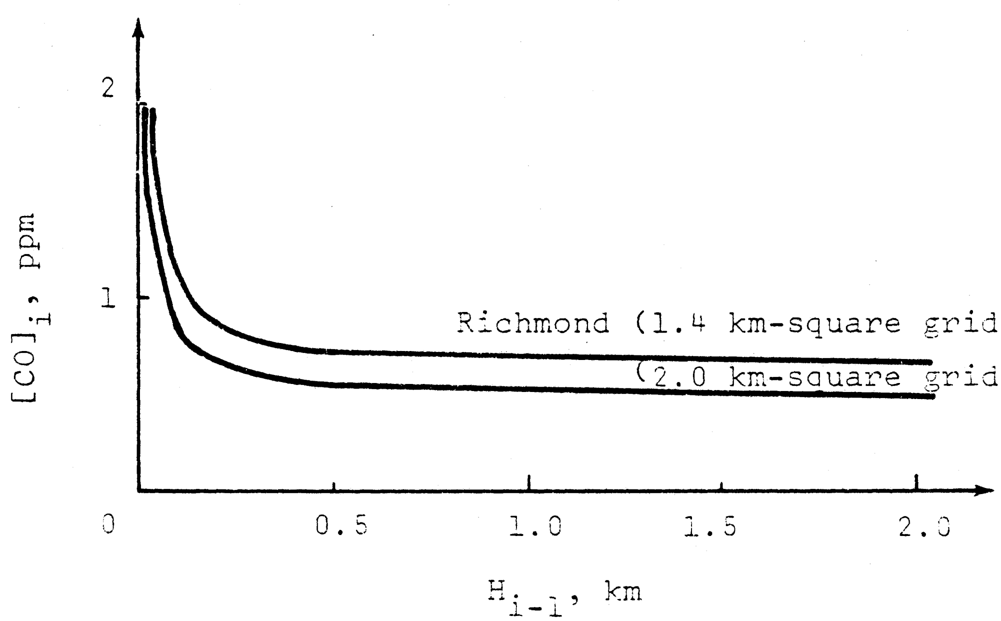


Figure 10. Previous hour mixing height versus CO concentrations.

Table 6

Sensitivity Rankings of Input Parameters

Input Parameter	Rate of Change in		% Change in		Abs. Sensitivity |C/IP|
	Input Parameter	CO Concentration (ppm)	Input (IP)	CO Conc. (C)	
E_{ih}	100-500 kg/hr	0.50 - 1.22 (0.70 - 2.34)*	+400	+144 (+234)	0.36 (0.58)
u_h	4-20 km/hr	0.93 - 0.39 (1.48 - 0.47)	+400	- 58 (- 68)	0.14 (0.17)
u_{h-1}	4-20 km/hr	0.55 - 0.48 (0.75 - 0.66)	+400	- 13 (- 12)	0.03 (0.03)
H_{h-1}	0.4-1.5 km/hr	0.56 - 0.48 (0.76 - 0.67)	+275	- 14 (- 12)	0.05 (0.04)

*Enclosed numbers correspond to the 1.4-km-square grid, while the unenclosed numbers are for the 2.0-km-square grid.

0324

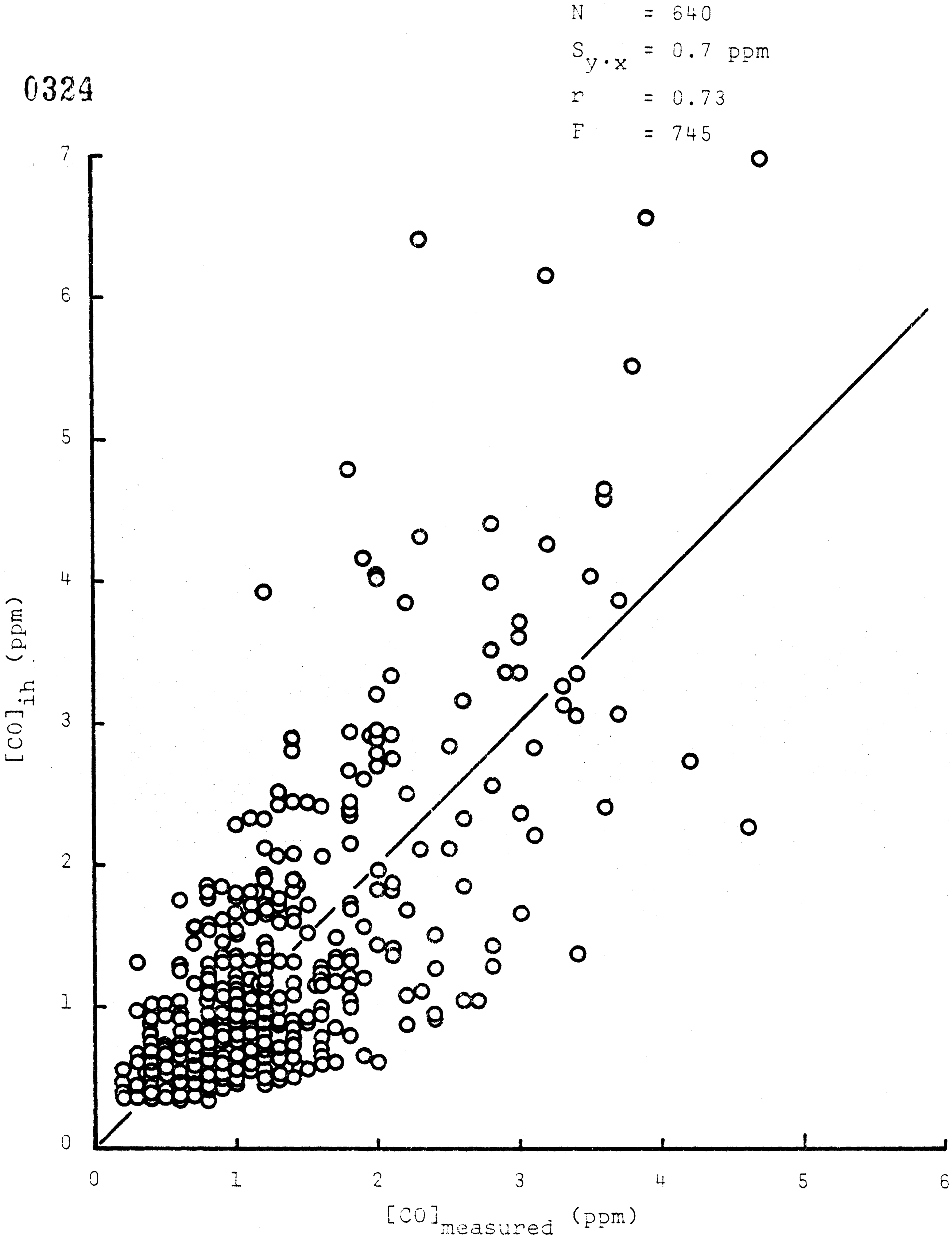


Figure 11. A plot of measured versus calculated CO concentrations for Richmond using a 2.0-km-square emission inventory grid.

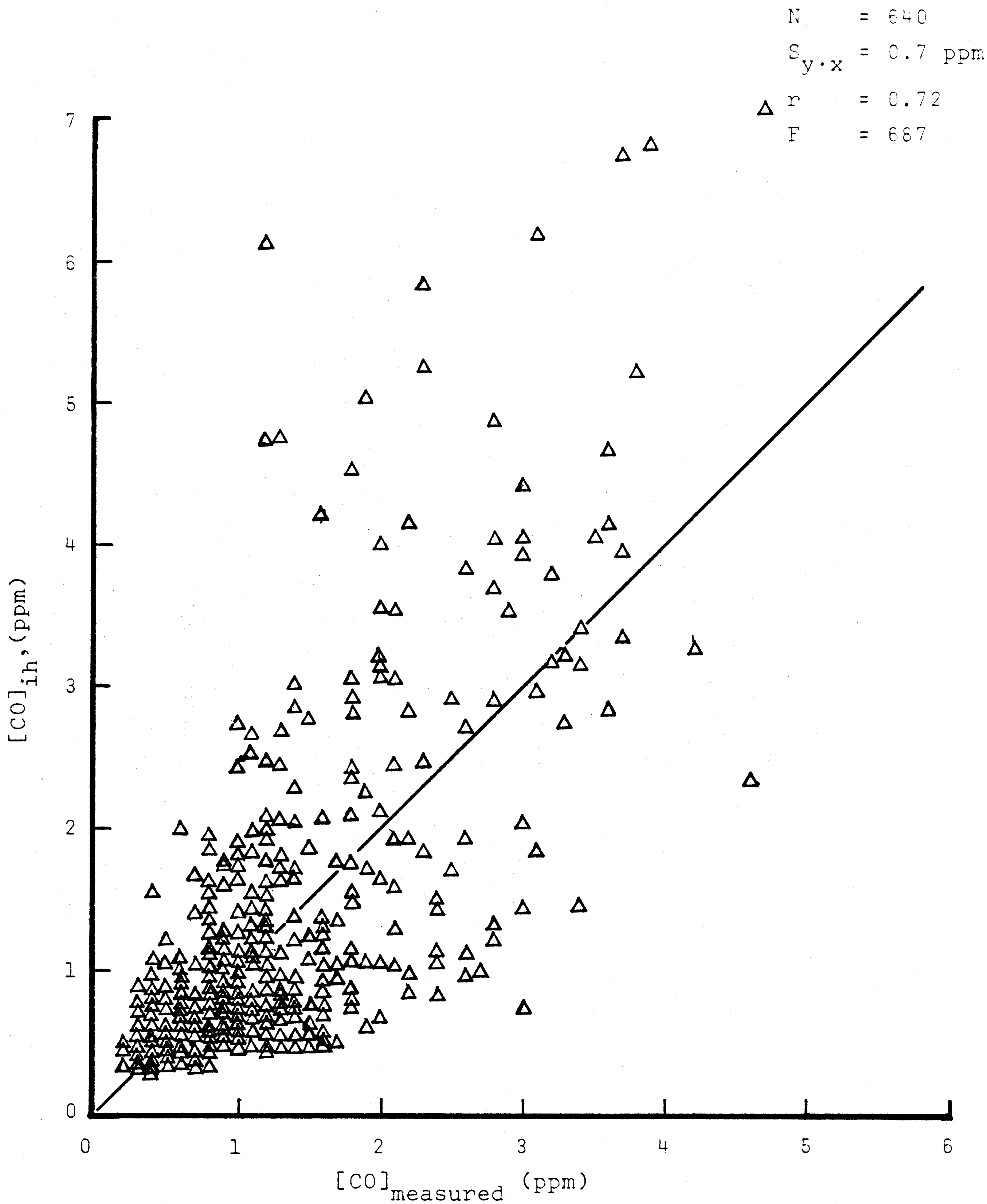


Figure 12. A plot of measured versus calculated CO concentrations for Richmond using a 1.4-km-square emission inventory grid.

Considering only the overall agreement shown in the above comparison, no discernible difference is found between the estimated emission rates from the two inventory grids. However, when consideration is given to the performance of equation 7 for the eight individual measurement sites (Table 7) the grid with the larger squares may be slightly preferable. As shown in Table 7, when the 2.0-km-square grid was used, the differences between the $Sy\text{-}x/\overline{C}_O$, i.e. standard error of estimate per unit of average CO concentration measured at a site, for the different sites were smaller, or more uniform. As Figure 2 shows, this slight difference between the two grids probably arose from the 2-km^2 squares being so small that, with the way the inventory grid was laid over the study areas, the CO emissions from some primary links that contributed to the mesoscale CO concentrations at some of the sites were not as sufficiently "covered" or included in the estimates of total emission rates as with the larger 4-km^2 squares.

Table 7 also indicates that some sites seemed to have consistently better results (i.e. relatively lower $Sy\text{-}x/\overline{C}_O$) using equation 7 than the other sites, in both grid systems. Specifically, sites 2, 6, and 8 appeared to have better results than sites 1 and 4. These differences between sites are to a certain extent illustrated in Figure 13. An examination of Table 1 does not reveal any discernible relationship between regression characteristics and land use.

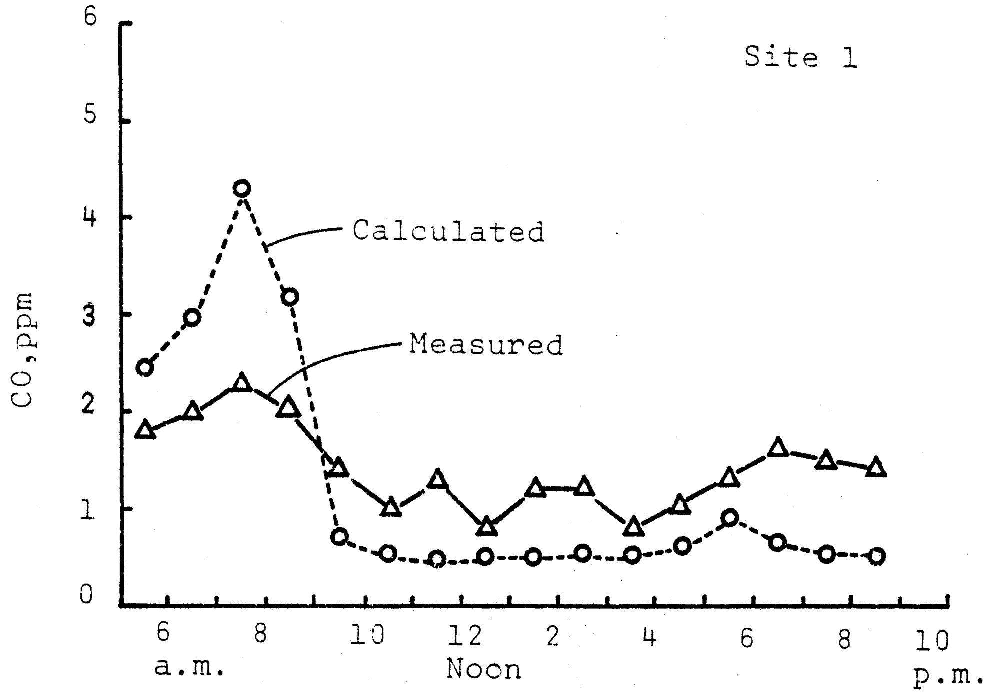
A similar analysis of the Tidewater data indicated that the relationship expressed in equation 7 is reasonably valid, as illustrated in Figure 14. Although it does not compare favorably with the Richmond results, the agreement between the measured and calculated CO concentrations for the Tidewater area is nevertheless reasonable, considering that the Tidewater data are relatively limited. The optimum constants, for equation 7, corresponding to the Tidewater data are given in Table 8.

Table 7

Linear Regression Characteristics for Individual Richmond Sites

Grid	Site	Corr. Coeff.	Sy-x (ppm)	$Sy\text{-}x/\overline{C}_o$
2.0-km-square	1	0.48	0.7	0.6 (3)*
	2	0.74	0.5	0.5 (2)
	3	0.77	0.8	0.6 (3)
	4	0.68	0.7	0.6 (3)
	5	0.66	0.4	0.5 (2)
	6	0.83	0.5	0.4 (1)
	7	0.83	0.8	0.6 (3)
	8	0.77	0.4	0.4 (1)
1.4-km-square	1	0.48	0.9	0.8 (5)
	2	0.73	0.5	0.5 (2)
	3	0.77	0.8	0.6 (3)
	4	0.58	0.9	0.8 (5)
	5	0.66	0.5	0.7 (4)
	6	0.83	0.4	0.4 (1)
	7	0.83	0.7	0.6 (3)
	8	0.77	0.5	0.5 (2)

*Enclosed numbers indicate the orders of increasing ratio of $Sy\text{-}x/\overline{C}_o$, where $\overline{C}_o$ is the average measured CO concentration for each site.



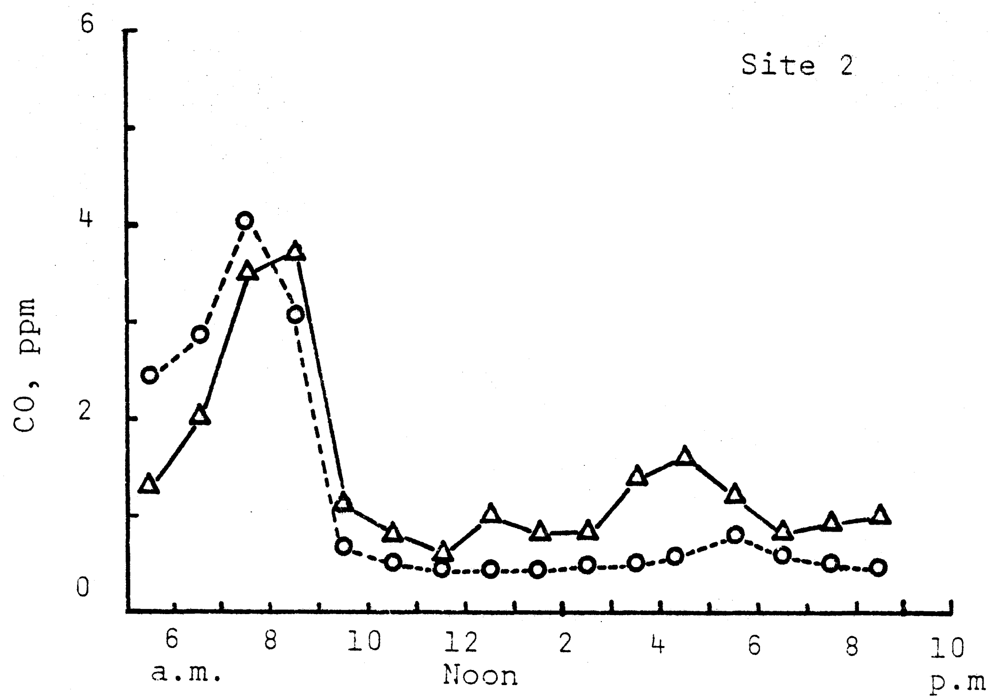
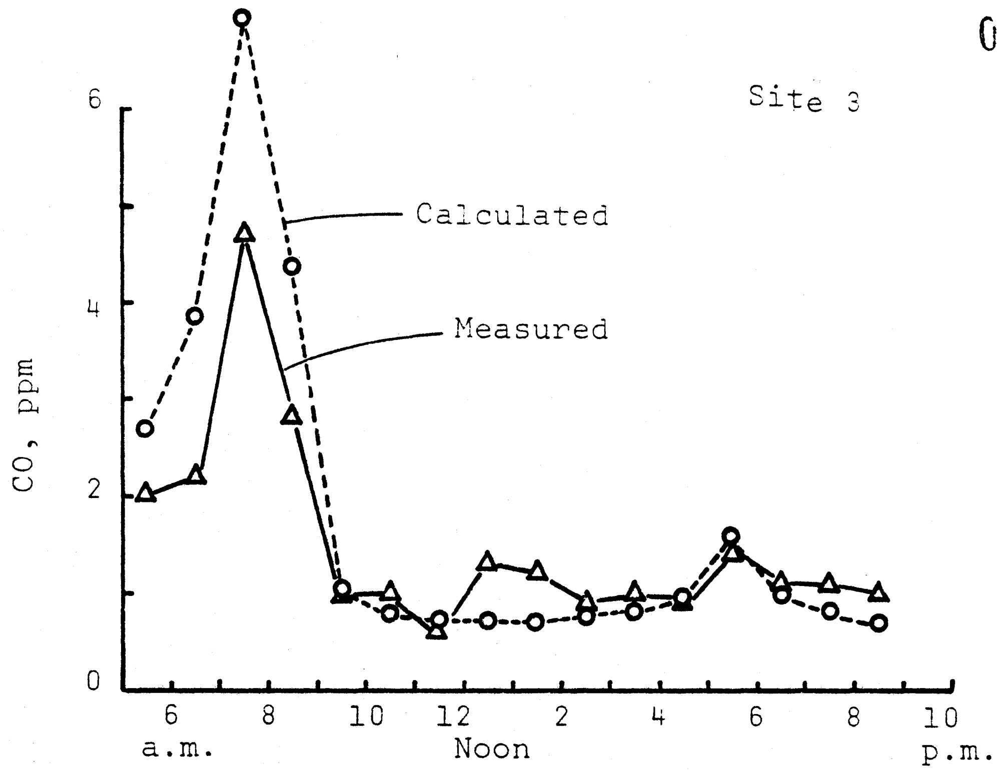


Figure 13. Comparison between measured and calculated CO concentrations for Richmond on December 12, 1977.



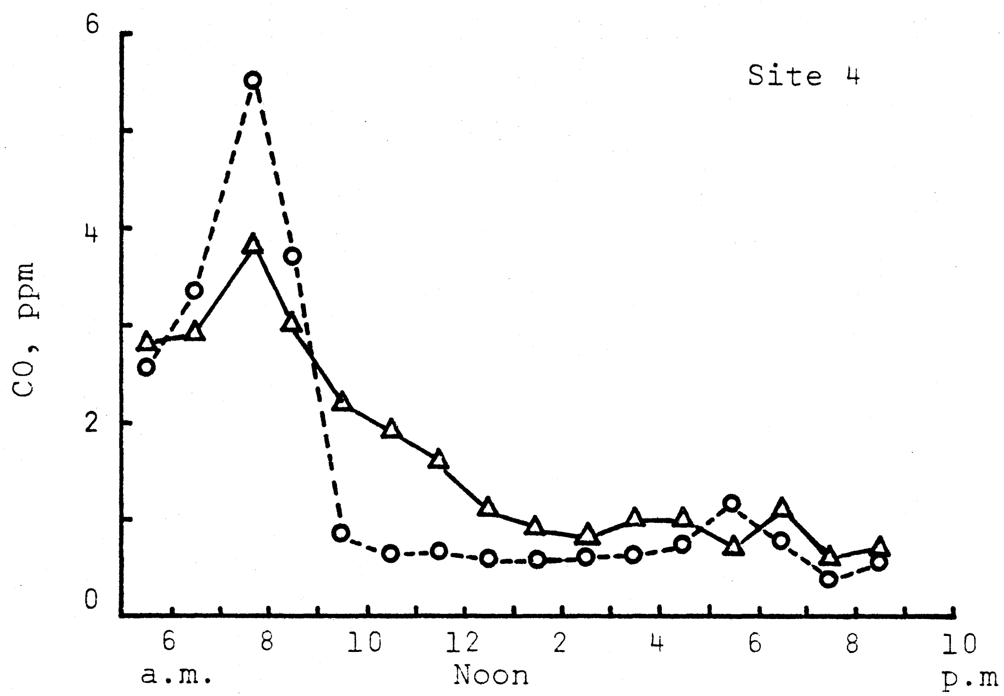
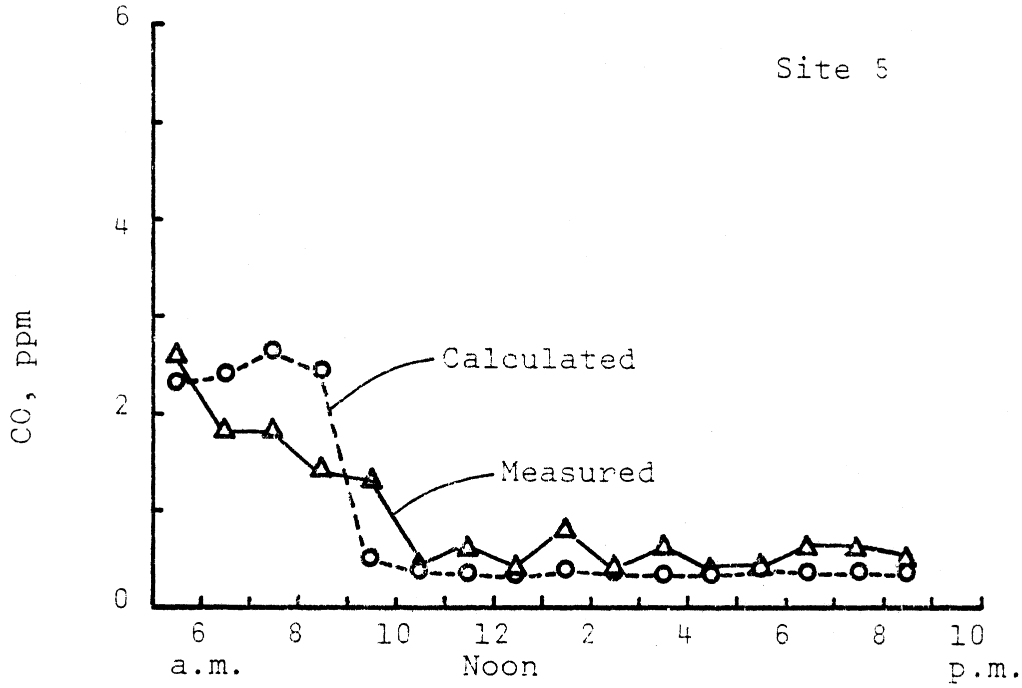


Figure 13. Continued.



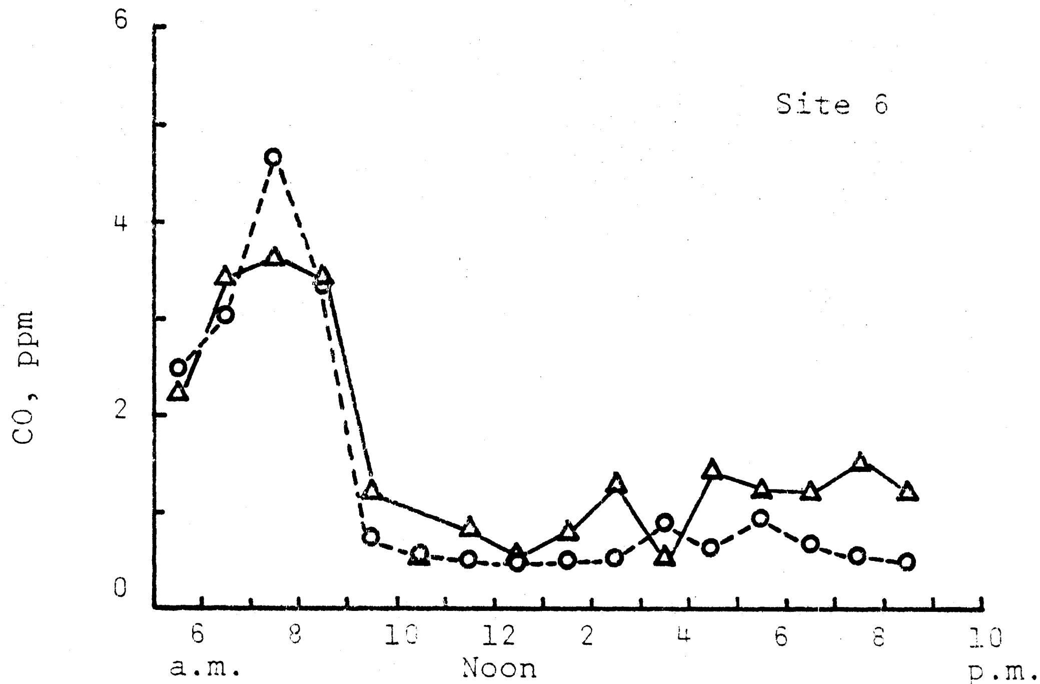
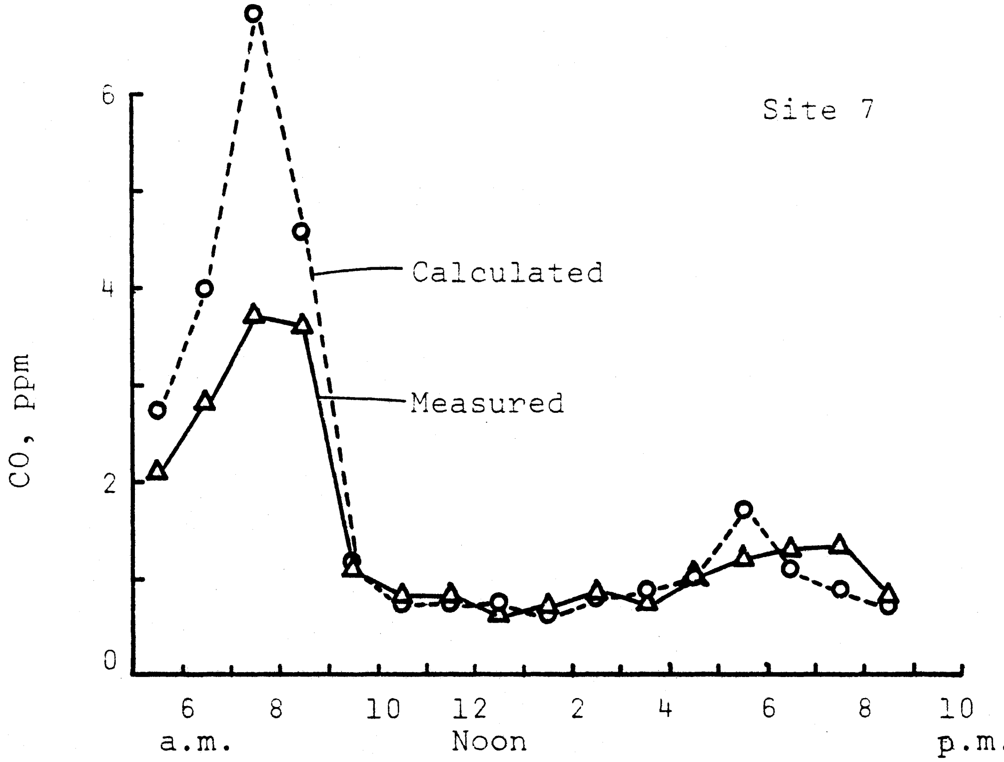


Figure 13. Continued.



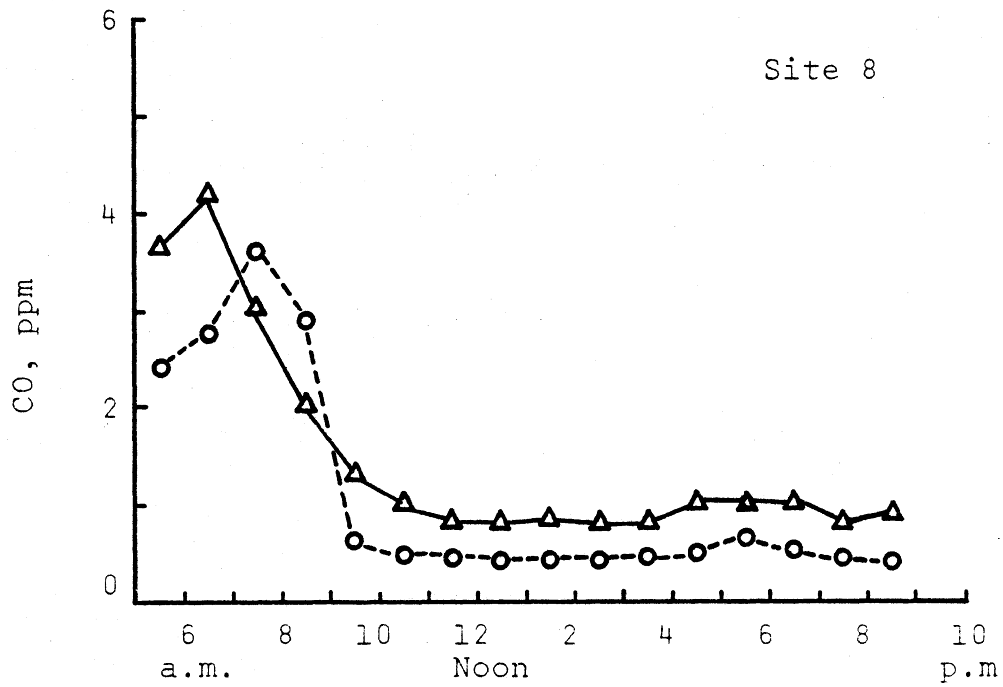


Figure 13. Continued.

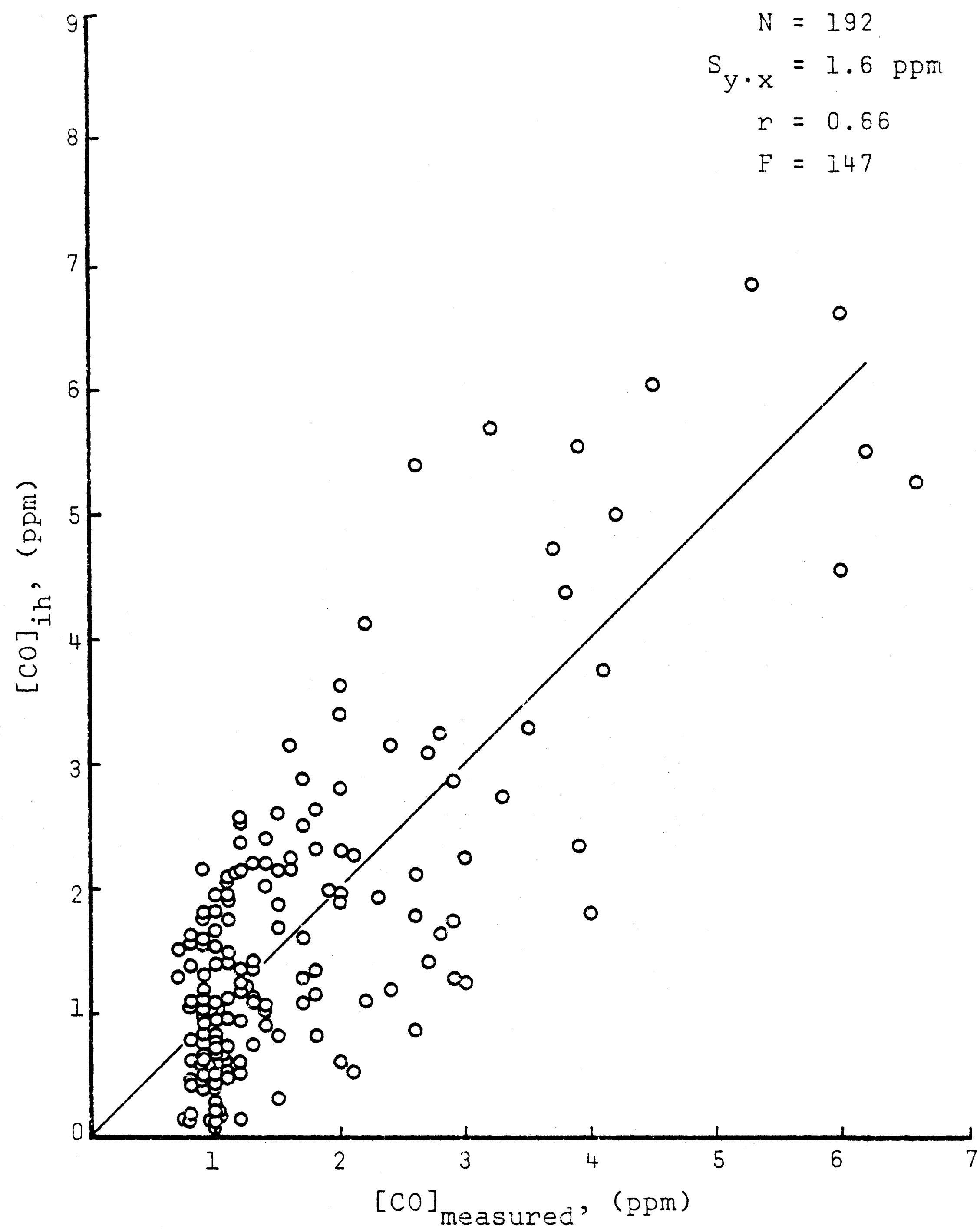


Figure 14. A plot of measured versus calculated CO concentrations for Tidewater using a 2.0-km-square emission inventory grid.

Table 8

Optimum Constants Based on the Tidewater Data and Using a 2.0-km-square Emission Inventory Grid

k	a_1	a_2	b_1	b_2
3.16	0.48	-2.34	5.74	-1.08

Without the adjustment factor k, equation 7 predicted lower CO concentrations for both urban areas when compared to observations, especially when the measured concentrations were greater than 2 ppm. This discrepancy is believed to have been caused by an underestimation of the areal emission rates — especially for the traffic rush hours — because of the lack of reliable data (or in some cases, none at all) on primary and secondary traffic volumes and speeds, the diurnal traffic distribution at each link, vehicle mixes, and percentage of cold operation.

CONCLUSION

As indicated by the agreement between the measured and calculated mesoscale CO concentrations for two Virginia urban areas, the relationship between the mesoscale CO concentrations and areal vehicular CO emission rates is reasonably approximated by

$$[CO]_{ih} = kE_{ih} \cdot 10^{\{a_2 + a_1 \log \left(\frac{1}{\mu}\right)_h\}} + b_1 \left(\frac{1}{\mu H}\right)_{h-1} + b_2. \quad (7)$$

When reliable data necessary for the estimation of emission rates are not available, the use of such an approximation may be preferable to the use of the more complex diffusion models.

Between the two emission inventory grids tested, the 2.0-km-square grid (with the larger squares) is probably preferable from two standpoints. First, a sensitivity analysis showed that the calculated CO concentration was relatively less sensitive to an error in emission rates estimated with the grid consisting of the larger squares. Second, an examination of the performance of equation 7 for the eight individual measurement sites in Richmond also favored that grid.

The correlations made in the study indicated that the various constants a_1, a_2, b_1, b_2, and k are fairly site-specific; i.e., their values differed for different urban areas. This specificity may be due to differences in topography and other factors unaccounted for in the present study.

ACKNOWLEDGEMENTS

The author expresses gratitude to the parties who allowed use of their properties as measurement sites in the study. Appreciation is extended W. Medlock of the Virginia State Air Pollution Control Board's Region 5 Office for some of the Richmond wind data, and the personnel of the National Weather Service at Sterling, Wallops Island, and Norfolk for radiosonde and wind data.

Acknowledgment is made of the assistance of S. F. Curling, Jr. of the Environmental Quality Division of the Virginia Department of Highways & Transportation in providing the emission factors, and to G. C. Campbell of the Traffic & Safety Division and F. M. Dunn, Jr. of the Transportation Planning Division in furnishing the traffic data. Appreciation is also expressed to M. O. Harris, G. Deavers, R. Millar, and P. Harris of the Research Council staff, and G. T. Gilbert, J. W. Reynolds, and S. Pillow, formerly of the Council, for their valuable assistance. Thanks go to F. H. Boehling, Jr. of the Department's Equipment Division for the powerline needed for one of the remote monitoring labs set up in Richmond for the measurements.

Appreciation is expressed to A. Fewell for typing assistance, and to members of the Council's report unit for editing and reproducing the report.

Acknowledgment is due Dr. N. T. Stephens of the Virginia Polytechnic Institute and State University for reviewing the report and making helpful suggestions.

The study was conducted with HPR funds administered through the Federal Highway Administration.

0336

REFERENCES

1. Federal Highway Administration, "Final Manual — Special Area Analysis", Washington, D. C., August 1973.

2. Ludwig, F. L., P. B. Simmon, R. C. Sandys, J. C. Bobick, L. R. Seiders, and R. L. Mancuso, "User's Manual for the APRAC-2 Emissions and Diffusion Model", Stanford Research Institute, Menlo Park, California, June 1977.

3. Virginia Department of Highways & Transportation, "Richmond Area Transportation Study — 1976 24-Hour Traffic Volumes", Richmond, Virginia, 1976.

4. _______, "City of Norfolk — 1977 24-Hour Traffic Volumes", Richmond, Virginia, 1977.

5. _______, "City of Virginia Beach — 24 Hour Traffic Volumes", Richmond, Virginia, 1977.

6. Kircher, D. S., and M. E. Williams, "Supplement No. 5 for Compilation of Air Pollutant Emission Factors (AP-42), Chapter 3, 2nd ed.," U. S. Environmental Protection Agency, Office of Air Quality Planning and Standards, 1975.

7. Communication with S. F. Curling , Jr., Environmental Quality Division, Virginia Department of Highways & Transportation, Richmond, Virginia.

8. Larsen, R. I., "Calculating Air Quality and Its Control," J. Air Poll. Control Assoc., 15:565 (1965).

9. Larsen, R. I., "Determining Reduced-Emission Goals Needed to Achieve Air Quality Goals — A Hypothetical". J. Air Poll. Control Assoc., 17:829,(1967).

10. Hanna, S. R., "A Simple Method of Calculating Dispersion from Urban Area Sources", J. Air Poll. Control Assoc., 21:774 (1971).

0338

APPENDIX A

MEASURED CO CONCENTRATIONS IN PPM

RICHMOND, VA.
DEC. 12, 1977

	SITE							
HOUR	1	2	3	4	5	6	7	8
0500 -0600	1.8	1.3	2.0	2.8	2.6	2.2	2.1	3.6
0600 -0700	2.0	2.0	2.2	2.9	1.8	3.4	2.8	4.2
0700 -0800	2.3	3.5	4.7	3.8	1.8	3.6	3.7	3.0
0800 -0900	2.0	3.7	2.8	3.0	1.4	3.4	3.6	2.0
0900 -1000	1.4	1.1	1.0	2.2	1.3	1.2	1.0	1.3
1000 - 1100	1.0	.8	1.0	1.9	.4	.5	.8	1.0
1100 - 1200	1.3	.6	.6	1.6	.6	.8	.8	.8
1200 - 1300	.8	1.0	1.3	1.1	.4	.5	.6	.8
1300 - 1400	1.2	.8	1.2	.9	.8	.8	.7	.8
1400 - 1500	1.2	.8	.9	.8	.4	1.3	.8	.8
1500 - 1600	.8	1.4	1.0	1.0	.6	.9	.7	.8
1600 - 1700	1.0	1.6	.9	1.0	.4	1.4	1.0	1.0
1700 - 1800	1.3	1.2	1.4	.7	.4	1.2	1.2	1.0
1800 - 1900	1.6	.8	1.1	1.1	.6	1.2	1.3	1.0
1900 - 2000	1.5	.9	1.1	.6	.6	1.5	1.3	.8
2000 - 2100	1.4	1.0	1.0	.7	.5	1.2	.8	.9

APPENDIX A (cont.)

RICHMOND, VA.
DEC. 13, 1977

HOUR	SITE 1	2	3	4	5	6	7	8
0500 -0600	.7	.9	1.1	.8	.8	.9	1.0	1.0
0600 -0700	.6	1.8	.9	.6	.7	.8	1.1	.9
0700 -0800	1.0	2.7	1.1	1.2	1.2	.8	1.2	.9
0800 -0900	1.0	1.2	1.2	1.2	.8	1.2	1.0	.8
0900 - 1000	1.1	1.1	1.2	1.0	1.4	.8	.9	.9
1000 - 1100	1.0	1.0	1.0	1.0	.8	.8	.8	.7
1100 - 1200	.9	1.0	1.2	1.3	.7	.8	.8	.8
1200 - 1300	1.4	1.0	1.0	1.1	.8	.7	.6	.6
1300 - 1400	.8	1.2	.6	1.2	.3	.8	.7	.7
1400 - 1500	.7	.6	.8	.6	.7	.8	.8	.7
1500 - 1600	.9	.7	.9	.7	.4	.5	.7	.7
1600 - 1700	.7	1.2	.8	.5	.4	.5	.9	.6
1700 - 1800	1.3	1.6	1.0	.8	.4	1.1	1.9	1.1
1800 - 1900	1.6	1.2	1.1	.9	.5	.8	1.4	1.2
1900 - 2000	1.5	.7	.8	.6	.5	.9	.8	.6
2000 - 2100	.9	.9	.9	.5	.6	.7	1.0	.8

RICHMOND, VA.
DEC. 14, 1977

HOUR	SITE 1	2	3	4	5	6	7	8
0500 -0600	.5	.7	.6	.4	.6	.5	.6	.7
0600 -0700	.8	.8	.6	.5	.7	.6	1.0	.6
0700 -0800	1.4	.9	1.2	.6	.6	.7	1.0	.7
0800 -0900	1.6	.6	1.6	.8	.7	.6	.6	.7
0900 - 1000	.8	.5	.7	.8	.5	.5	.8	.5
1000 - 1100	.6	.5	.6	.4	.3	.4	.7	.4
1100 - 1200	.8	.5	1.2	.4	.3	.5	.6	.4
1200 - 1300	.9	.5	1.1	.5	.4	.5	.7	.3
1300 - 1400	1.0	.5	.8	.4	.3	.5	.5	.5
1400 - 1500	1.0	.4	.8	.5	.2	.5	.5	.3
1500 - 1600	2.0	1.0	1.0	.5	.3	.5	.6	.4
1600 - 1700	2.4	1.6	1.9	.8	.3	.6	1.1	.5
1700 - 1800	2.3	1.1	3.7	2.0	.4	1.6	2.0	1.1
1800 - 1900	2.2	.9	2.5	2.5	.5	1.4	1.6	1.6
1900 - 2000	1.7	1.0	2.6	2.8	1.1	1.6	1.4	1.0
2000 - 2100	1.2	.9	2.1	2.0	1.5	1.8	1.2	1.7

APPENDIX A (cont.)

RICHMOND, VA.
DEC. 15, 1977

	SITE							
HOUR	1	2	3	4	5	6	7	8
0500 -0600	.4	.2	.3	.3	.3	.7	.5	.3
0600 -0700	.3	.4	.4	.5	.3	1.7	.8	1.2
0700 -0800	.4	.8	1.0	1.2	.4	1.4	2.1	1.5
0800 -0900	.9	1.1	1.3	2.1	.9	1.2	1.9	.5
0900 - 1000	.6	.6	.6	1.4	.5	.9	1.0	.6
1000 - 1100	.4	.3	.4	.4	.3	.5	.5	.4
1100 - 1200	.4	.2	.4	.3	.3	.4	.5	.4
1200 - 1300	.3	.4	.4	.4	.3	.4	.4	.4
1300 - 1400	.3	.2	.4	.4	.3	.5	.6	.4
1400 - 1500	.9	.3	.4	.4	.3	.4	.5	.3
1500 - 1600	.4	.4	.5	.5	.3	.5	.3	.4
1600 - 1700	.9	.6	.6	.6	.3	.4	1.1	.6
1700 - 1800	.8	1.6	3.1	2.0	.5	1.5	2.1	1.1
1800 - 1900	1.2	1.4	1.8	1.8	1.1	1.8	1.8	1.6
1900 - 2000	.8	1.2	1.4	1.0	1.0	.9	.9	1.2
2000 - 2100	1.1	1.0	2.3	1.2	.9	1.6	1.3	1.2

RICHMOND, VA.
DEC. 16, 1977

	SITE							
HOUR	1	2	3	4	5	6	7	8
0500 -0600	1.3	1.0	1.2	1.0	.7	.9	.8	1.2
0600 -0700	1.3	1.4	1.4	2.8	.8	1.2	1.6	2.0
0700 -0800	1.2	3.1	3.2	1.8	1.1	2.0	2.3	2.6
0800 -0900	1.9	3.8	3.9	1.3	1.5	3.2	3.1	3.0
0900 -1000	1.7	1.2	1.4	1.3	1.8	2.4	1.8	2.4
1000 - 1100	1.0	.6	.8	1.3	1.4	1.4	1.0	1.0
1100 - 1200	.8	.8	.8	1.2	.9	1.0	.6	.7
1200 - 1300	.8	.6	1.0	.9	.8	.9	.7	.7
1300 - 1400	.9	.6	1.1	.8	.6	1.0	.8	.6
1400 - 1500	.8	.7	1.0	.8	.7	.8	.8	.8
1500 - 1600	.8	.6	1.2	1.2	1.0	1.1	.8	.6
1600 - 1700	1.3	1.6	1.2	1.2	1.0	1.7	1.6	.9
1700 - 1800	1.3	1.6	3.3	3.1	.9	1.5	3.3	1.4
1800 - 1900	1.8	2.6	4.6	3.0	1.6	1.7	3.0	2.6
1900 - 2000	2.4	1.4	3.4	2.2	1.4	1.5	2.1	2.4
2000 - 2100	2.6	1.3	2.8	1.3	1.4	1.4	1.8	---

APPENDIX A (cont.)

TIDEWATER, VA.
JAN. 9, 1977

HOUR	SITE 1	2	3	4	5	6
0500 -0600	1.0	1.0	.9	1.5	1.0	.9
0600 -0700	1.2	1.5	1.2	1.8	1.1	1.0
0700 -0800	1.8	2.0	.9	2.8	1.3	2.4
0800 -0900	1.3	1.5	1.0	2.3	1.2	1.9
0900 -1000	1.1	1.1	1.0	1.3	.9	1.2
1000 - 1100	1.0	1.0	1.0	1.3	.9	1.2
1100 - 1200	.9	1.0	1.0	1.7	1.0	1.0
1200 - 1300	.9	1.0	1.0	1.4	.9	.9
1300 - 1400	.9	.9	1.0	.9	.8	.9
1400 - 1500	.9	1.0	1.0	.9	.7	.9
1500 - 1600	1.0	1.1	.9	1.0	.7	.8
1600 - 1700	1.1	1.3	1.2	1.2	1.1	.8
1700 - 1800	1.9	2.2	1.4	2.0	1.5	1.5
1800 - 1900	2.6	3.0	1.7	2.9	1.4	2.1
1900 - 2000	4.0	2.9	2.4	3.0	2.9	3.9
2000 - 2100	2.7	2.6	3.2	2.0	4.3	4.2

TIDEWATER, VA.
JAN. 10, 1977

HOUR	SITE 1	2	3	4	5	6
0500 -0600	1.8	1.6	1.4	1.4	2.0	1.2
0600 -0700	6.8	3.9	2.1	2.4	3.3	2.0
0700 -0800	8.8	6.2	2.6	6.0	4.5	4.2
0800 -0900	3.7	7.7	4.1	6.6	6.0	3.5
0900 - 1000	1.6	1.5	1.7	2.0	2.7	1.5
1000 - 1100	1.1	1.2	1.1	1.3	1.5	.8
1100 - 1200	.9	1.0	1.2	1.1	1.0	1.2
1200 - 1300	.8	.9	.9	1.1	.8	1.0
1300 - 1400	.8	.9	.8	.9	.9	1.0
1400 - 1500	.9	.9	.8	1.0	.9	.8
1500 - 1600	.8	.9	.8	1.1	.9	1.0
1600 - 1700	1.1	1.2	1.0	1.2	1.0	1.0
1700 - 1800	1.6	1.8	1.2	1.7	1.1	1.1
1800 - 1900	1.8	2.6	1.7	2.0	1.2	1.4
1900 - 2000	3.2	3.8	2.2	5.3	3.9	2.7
2000 - 2100	3.7	4.9	2.8	4.6	4.1	4.7

0346

APPENDIX B

RICHMOND WIND VELOCITY DATA

WS = Wind speed in mi/hr (1.0 mi/hr = 1.6 km/hr)

WD = Wind direction

Date	Hour	Playground		State Police Hdqrs.		Spencer Road		State Fair-grounds	
		WS	WD	WS	WD	WS	WD	WS	WD
12/12/77	0400	1	N	1	WNW	2	NNW	2	NNE
	0500	1	N	2	NW	2	NW	2	N
	0600	1	NNW	2	WNW	2	NW	2	NNW
	0700	1	N	1	SW	2	NW	3	NNW
	0800	4	WNW	3	WSW	4	SSW	4	SSE
	0900	8	W	5	WSW	7	SSW	8	SSW
	1000	8	SSE	7	WSW	8	SW	8	SSW
	1100	9	S	8	WNW	9	SW	8	SSW
	1200	9	SSE	8	WNW	10	SW	8	SSW
	1300	10	S	7	W	9	SW	8	SSW
	1400	10	S	6	WSW	9	SW	8	SSW
	1500	8	S	7	WSW	9	SW	8	SSW
	1600	7	S	7	WSW	8	SW	7	SSW
	1700	4	S	5	SW	5	SW	7	SSW
	1800	6	S	5	SW	4	SSW	7	SSW
	1900	6	SSW	6	WSW	6	SSW	7	SSW
	2000	6	S	5	SW	5	SW	8	SSW
12/13/77	0400	4	SSW	6	WSW	5	SW	7	SW
	0500	4	S	4	WSW	4	SW	5	SW
	0600	4	S	4	WSW	3	SW	6	SW
	0700	4	S	4	WSW	4	SW	7	SW
	0800	5	S	6	WSW	5	SW	7	SW
	0900	4	SSW	7	WNW	4	WSW	7	SW
	1000	4	S	6	W	3	SW	7	SW
	1100	5	SSW	5	W	4	SW	7	SW
	1200	6	S	7	W	5	SW	6	SW
	1300	9	SSW	7	W	8	WSW	8	SW
	1400	8	SSW	6	WNW	8	WSW	7	SW
	1500	8	SSW	9	WNW	5	WSW	7	WSW
	1600	8	SSW	9	W	9	WSW	8	WSW
	1700	5	SSW	6	WSW	5	SW	6	SW
	1800	4	S	6	SW	5	SSW	5	SSW
	1900	5	S	7	SW	5	SSW	6	SSW
	2000	4	SSE	6	SW	5	SSW	6	SSW

APPENDIX B (cont.)

Date	Hour	Playground		State Police Hdqrs.		Spencer Road		State Fair-grounds	
		WS	WD	WS	WD	WS	WD	WS	WD
12/14/77	0400	3	SSE	6	SSW	3	S	4	SW
	0500	2	SSE	6	SW	4	S	5	SSW
	0600	4	S	7	SW	6	SSW	5	SSW
	0700	6	S	8	SW	7	SSW	6	SW
	0800	7	S	7	SW	8	SSW	7	SW
	0900	8	S	9	SW	8	SSW	8	SW
	1000	10	S	9	SW	9	SSW	8	SW
	1100	6	S	8	SW	8	SSW	8	SW
	1200	7	S	9	SW	8	SSW	9	SW
	1300	9	S	9	SW	9	SSW	9	SW
	1400	8	S	9	SW	9	SSW	8	SW
	1500	6	S	7	SW	7	SSW	7	SW
	1600	3	S	6	SSW	4	S	5	SSW
	1700	1	SSE	2	SSW	3	S	2	S
	1800	1	SSE	2	SE	2	—	2	—
	1900	1	WSW	3	SSE	3	—	3	—
	2000	1	SW	2	W	3	—	3	—
12/15/77	0400	5	W	5	NW	5	WNW	7	WNW
	0500	3	NW	5	NNW	5	NW	6	NW
	0600	2	NW	5	NNE	3	NW	6	NW
	0700	1	NW	4	NNE	2	NW	5	NW
	0800	2	NW	4	N	3	NNW	4	NW
	0900	6	NNW	6	N	6	NNW	7	NNW
	1000	8	NW	8	N	6	NNW	8	NNW
	1100	7	NNW	7	NNE	7	NNW	7	NNW
	1200	6	NW	5	N	6	NNW	6	NNW
	1300	5	NW	5	N	5	NNW	6	NNW
	1400	6	NW	6	NNW	6	NNW	5	NNW
	1500	6	NW	6	NNW	5	NNW	5	NNW
	1600	4	NW	4	NNW	4	NNW	4	NNW
	1700	2	N	3	ENE	2	NE	3	NNE
	1800	3	NNE	3	ESE	3	ENE	4	NE
	1900	3	NE	3	ESE	2	ENE	2	ENE
	2000	2	NE	5	SSE	2	ESE	2	E

Date	Hour	Playground		State Police Hdqrs.		Spencer Road		State Fair-grounds	
		WS	WD	WS	WD	WS	WD	WS	WD
12/16/77	0400	2	NNE	3	ESE	1	ENE	1	NE
	0500	2	N	3	E	1	ENE	1	NE
	0600	1	NW	2	ENE	1	ENE	2	NE
	0700	2	WNW	2	NNE	1	ENE	2	NE
	0800	2	NNW	2	NE	2	ENE	2	NE
	0900	4	NE	4	S	3	E	5	E
	1000	3	E	4	SSE	4	ESE	7	ESE
	1100	4	S	4	S	4	ESE	6	ESE
	1200	4	S	4	SSW	4	—	3	—
	1300	2	NE	3	S	4	—	3	—
	1400	2	NE	3	SE	3	ESE	4	—
	1500	3	ENE	5	SSE	4	ESE	5	ESE
	1600	3	E	4	S	3	ESE	3	ESE
	1700	2	SE	3	S	2	SE	2	ESE
	1800	2	SE	4	S	2	SE	2	SE
	1900	3	SE	4	SSE	3	SE	4	SE
	2000	2	ESE	5	SSE	2	SE	3	SE

APPENDIX C

TIDEWATER WIND VELOCITY DATA

WS = Wind speed in mi/hr (1.0 mi/hr = 1.6 km/hr)

WD = Wind direction

Date	Hour	WS	WD
1/9/79	0400	9	N
	0500	8	N
	0600	8	NNW
	0700	8	NNW
	0800	7	NNW
	0900	9	N
	1000	9	NE
	1100	8	N
	1200	13	NE
	1300	5	E
	1400	6	ENE
	1500	7	ENE
	1600	7	ENE
	1700	5	E
	1800	4	SE
	1900	7	S
	2000	5	SSW
1/10/79	0400	6	SW
	0500	7	WSW
	0600	5	SW
	0700	7	W
	0800	5	WNW
	0900	6	N
	1000	7	N
	1100	5	NNE
	1200	9	N
	1300	8	NNE
	1400	9	NNE
	1500	7	E
	1600	7	ESE
	1700	6	ESE
	1800	4	ESE
	1900	1	ESE
	2000	5	SW

0352