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A Pilot Study on Dispersion Near Roadways

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A PILOT STUDY ON DISPERSION NEAR ROADWAYS

by

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AUTHOR'S AFFILIATION

The author, William B. Petersen, is on assignment with the U.S. Environmental Protection Agency from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

ABSTRACT

High frequency wind fluctuation data from the General Motors Sulfate Dispersion Experiment were used to estimate the dispersion near roadways. The standard deviations of the wind direction and the elevation angle were computed for six averaging times for three half-hour periods when the winds were nearly parallel to the test track. The EPA HIWAY model was modified to use these fluctuation statistics directly to estimate dispersion. Results from analysis show that model performance was improved for parallel wind conditions when the fluctuation statistics of the wind were used to estimate dispersion. The results also show that model estimates are most sensitive to the vertical dispersion parameter. Indeed, concentrations seem to be insensitive to the horizontal dispersion parameter.

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1. INTRODUCTION

This paper discusses the results of a pilot study on data obtained from the General Motors Sulfate Dispersion Experiment (Cadle et al. 1976). The purpose of this study is to investigate and develop methods for estimating dispersion near roadways. A major objective of this study is to investigate the performance of the EPA HIWAY model (Zimmerman and Thompson, 1975) using dispersion estimates from the fluctuation statistics of the wind.

The HIWAY model does not use the infinite line source approximation to estimate concentrations downwind of a line source. Concentration estimates are made by numerical integration of the Gaussian plume point source equation. Thus, concentration estimates are functions of the horizontal and vertical dispersion parameters (σ_y and σ_z). Pasquill (1976) stated that the horizontal dispersion parameters (Pasquill-Gifford (PG) dispersion curves) are most appropriate to a 3-minute sampling time. One would expect that for longer sampling times, say 1 hour, σ_y would increase and thus increase dispersion.

For the case where the wind is near perpendicular to the roadway, the infinite line source equation is a good approximation. The effects of crosswind dispersion are not important since the crosswind dispersion from one segment of the line is compensated by dispersion in the opposite direction from adjacent segments. However, when the winds are near parallel to the roadway, it is no longer appropriate to assume that the dispersion from one point is compensated by that of adjacent points. In the past it has been observed that HIWAY overestimates concentrations when the winds are near parallel to the road. If the overestimation of HIWAY is due to a conservative estimate of σ_y, it should be most noticeable during parallel wind conditions.

The General Motors (GM) Sulfate Dispersion Experiment provides an excellent data base for investigating dispersion near roadways. Not only was this a controlled roadway study, but also three components of the wind were measured and recorded every second at 20 locations across the test track. This high frequency wind data is the most valuable in estimating dispersion. The data used in this pilot study represent three half-hour periods during which the winds were nearly parallel with the the road. While the analysis of the data from the three periods gives valuable insight into the dispersion during parallel wind conditions, the major function of this paper is to set forth the techniques that will be used to analyze the whole data set. The entire data set consists of about 60 half-hour periods. A brief description of the GM data follows in the next section.

2. DATA BASE

The data used in this analysis is a small part of a data set collected at Milford Proving Ground by General Motors during the sulfate dispersion experiment. The experiment was performed during October 1975. The data used in this paper consists of three half-hour periods on October 24. A fleet of 352 catalyst-equipped automobiles were driven around a 10 km narrow oval track. At the sampling locations, about halfway down the track, the cross section simulated a 4-lane road with a median. Eight vehicles were equipped to release sulfur hexafluoride (SF_6) as a tracer. The SF_6 was sampled at 20 locations in the vicinity of the test track (see Figure 1). SF_6 samplers were located on towers 1 through 6 at heights of 0.5, 3.5, and 9.5 m. Samplers were also located on stands 7 and 8 at 0.5 m. Gill u-v-w anemometers were on towers 1 through 6 at heights of 1.5, 4.5, and 10.5 m. On stands 7 and 8 the anemometers were at 1.5 m. The meteorological data consisted of 1-second values of the u-v-w components of the wind from the 20 anemometers. The sampling time for SF_6 was 30 min. For a more detailed discussion of the experiment and the data set, see Cadle et al. (1976), and EPA (1976).

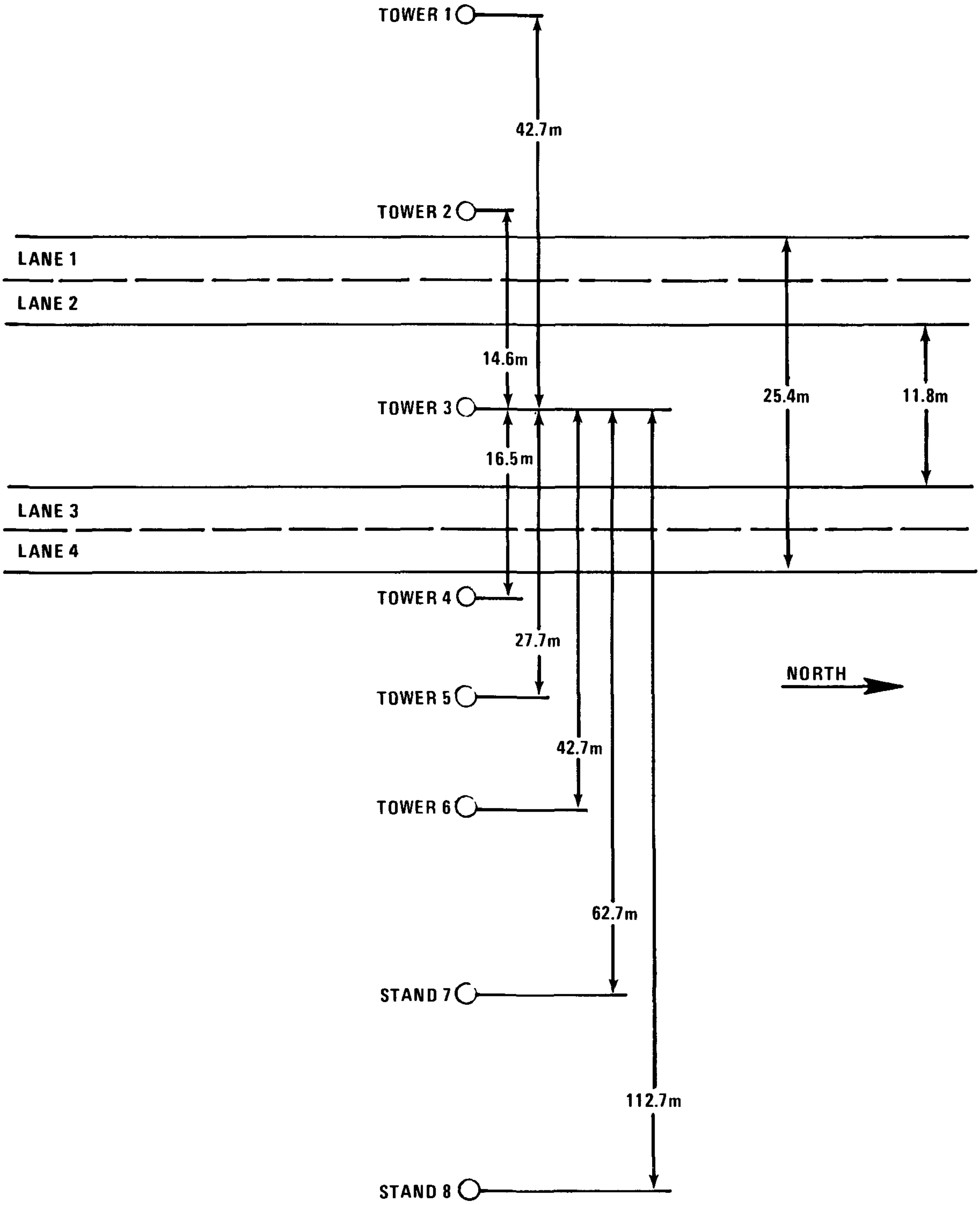

Figure 1. Orientation of test track and perpendicular distances of the meteorological towers from the center of the test track.

3. ANALYSIS OF THE DATA

The data chosen for this pilot study were three half-hour periods on October 24. These periods were chosen because the winds were within 5° of parallel to the test track. The fluctuation statistics σ_θ (standard deviation of the horizontal wind direction) and σ_ϕ (standard deviation of the vertical wind direction) were calculated from the wind data collected by the anemometer on Tower 1 at the 4.5 m level (see Figure 1).

The standard deviation of the wind direction was calculated from the u and v components of the Gill anemometer. The mean wind direction $\bar{\theta}$ is given by,

$$\bar{\theta} = \frac{\sum_{i=1}^{n} \theta_i}{n},$$

where $\theta_i = \arctan\left(\frac{u}{v}\right)$

To avoid the discontinuity at 360°, each θ_i was assumed to be a unit vector with components $\hat{u}$ and $\hat{v}$. $\bar{\theta}$ is now defined as,

$$\bar{\theta} = \arctan\left[\frac{\sum_{i=1}^{n} \hat{u}_i}{\sum_{i=1}^{n} \hat{v}_i}\right]$$

Defining $\bar{\theta}$ in this way eliminates the discontinuity problem and avoids the effect of the wind speed on the mean wind direction. σ_θ is now given as,

$$\sigma_\theta = \left[\frac{\sum_{i=1}^{n} (\Theta_i - \bar{\theta})^2}{n}\right]^{1/2}$$

It is apparent that the maximum deviation between θ_i and $\bar{\theta}$ is 180°. Therefore, if the absolute value (ABS) of the difference $(\theta_i - \bar{\theta})$ was greater than 180°, the deviation is equal to 360-ABS$(\theta_i - \bar{\theta})$.

The standard deviation of the vertical wind direction was computed from the three components of the wind field. The horizontal wind speed V_H is defined as,

$$V_H = (u^2 + v^2)^{1/2}$$

The mean elevation angle $\bar{\phi}$ is given as,

$$\bar{\phi} = \arctan \left[\frac{\sum_{i=1}^{n} \hat{w}_i}{\sum_{i=1}^{n} \hat{V}_{H_i}} \right]$$

where w is the vertical component of the wind. $\hat{w}$ and $\hat{V}_H$ are components of a unit vector. σ_ϕ is given as,

$$\sigma_\phi = \left[\frac{\sum_{i=1}^{n} (\phi_i - \bar{\phi})^2}{n} \right]^{1/2}$$

The relationship between the horizontal dispersion parameter, σ_y, and σ_θ was suggested by Hay and Pasquill (1957, 1959).

$$\sigma_y (x) = \sigma_{\theta_{\tau,s}} \; x, \qquad (1)$$

where; $x = \beta u s$

β = ratio of the Lagrangian to the Eulerian time scales,

u = mean wind speed,

s = averaging time,

τ = sampling time.

The relationship between σ_z and σ_ϕ is not as well understood as that for the horizontal dispersion. In this analysis the following relationship was used to estimate σ_z :

$$\sigma_z(x) = \sigma_{\phi_{\tau,s}} x. \qquad (2)$$

For each half-hour period σ_θ and σ_ϕ were calculated for different averaging times. Table 1 shows σ_θ and σ_ϕ for averaging times of 5, 10, 15, 30, 60 and 90-second. For example, in the first half-hour, σ_θ calculated from the 5-second averages would be indicated, using the notation in Equation (1), as $\sigma_{\theta_{1800,5}}$. The sampling time is 1800 seconds (half-hour), and the averaging time is 5 seconds. Then, 360 values of θ were determined by forming 5-second averages end-to-end from the 1800 values of the wind direction. $\sigma_{\theta_{1800,5}}$ is the standard deviation of the 360, 5-second averages. Similarly, values of σ_θ for the other averaging times were determined.

Using Equations (1) and (2), the dispersion parameters were determined as a function of downwind distance x (where $x = \beta us$; the value for β used in this analysis was 4 (Hay and Pasquill, 1959) for each half-hour period. Figure 2 shows σ_y and σ_z plotted as a function of downwind distance. The dotted lines indicate the PG dispersion curves. For small x, $\sigma_y(x)$ has a slope similar to the PG curves. Both plots indicate that the dispersion during these three half-hour periods is that typical of B-C stability.

The EPA HIWAY model was modified for this analysis to make concentration estimates from the dispersion parameters determined from σ_θ and σ_ϕ. Both σ_y and σ_z are assumed to have the form of ax^b, where a and b are constants determined from the data. For example, σ_θ is determined for six averaging times. σ_y and x are then calculated using Equation (1) for each of the six averaging times. σ_y is then known for six downwind distances. The constants a and b are calculated for each interval in the following way:

$$b_j = \frac{\ln \sigma_{y(j+1)} - \ln \sigma_{y(j)}}{\ln x_{(j+1)} - \ln x_{(j)}} \qquad a_j = \frac{\sigma_{y(j)}}{x_j^{\,b}}$$

TABLE 1. σ_θ AND σ_ϕ FOR DIFFERENT AVERAGING TIMES. σ_y AND σ_z (CALCULATED FROM σ_θ AND σ_θ) FOR DIFFERENT DOWNWIND DISTANCES, x.

	Averaging Time (seconds)					
	5	10	15	30	60	90
Number in Averages	(360)	(180)	(120)	(60)	(30)	(20)
Day Time 297/0804						
σ_θ (degrees)	8.10	6.99	6.15	5.13	3.92	3.14
σ_ϕ (degrees)	4.76	4.07	3.72	2.98	2.46	2.24
σ_y (meters)	7.05	12.16	16.05	26.77	40.92	49.17
σ_z (meters)	4.14	7.08	9.72	15.55	25.72	34.99
X (meters)	49.8	99.7	149.5	299.0	598.1	897.1
297/0834						
σ_θ (degrees)	9.86	8.71	7.80	6.52	4.89	4.20
σ_ϕ (degrees)	6.07	5.16	4.76	4.07	3.15	2.52
σ_y (degrees)	7.70	13.60	18.27	30.55	45.82	59.03
σ_z (meters)	4.74	8.05	11.14	19.06	29.53	35.43
X (meters)	44.7	89.5	134.2	268.4	536.9	805.3
297/0904						
σ_θ (degrees)	9.77	8.79	8.15	6.78	5.24	4.44
σ_ϕ (degrees)	5.10	4.41	3.84	3.44	2.87	2.46
σ_y (meters)	9.90	17.81	24.77	41.21	63.7	80.96
σ_z (meters)	5.17	8.94	11.67	20.89	34.83	44.92
X (meters)	58.0	116.1	174.1	348.2	696.5	1044.7

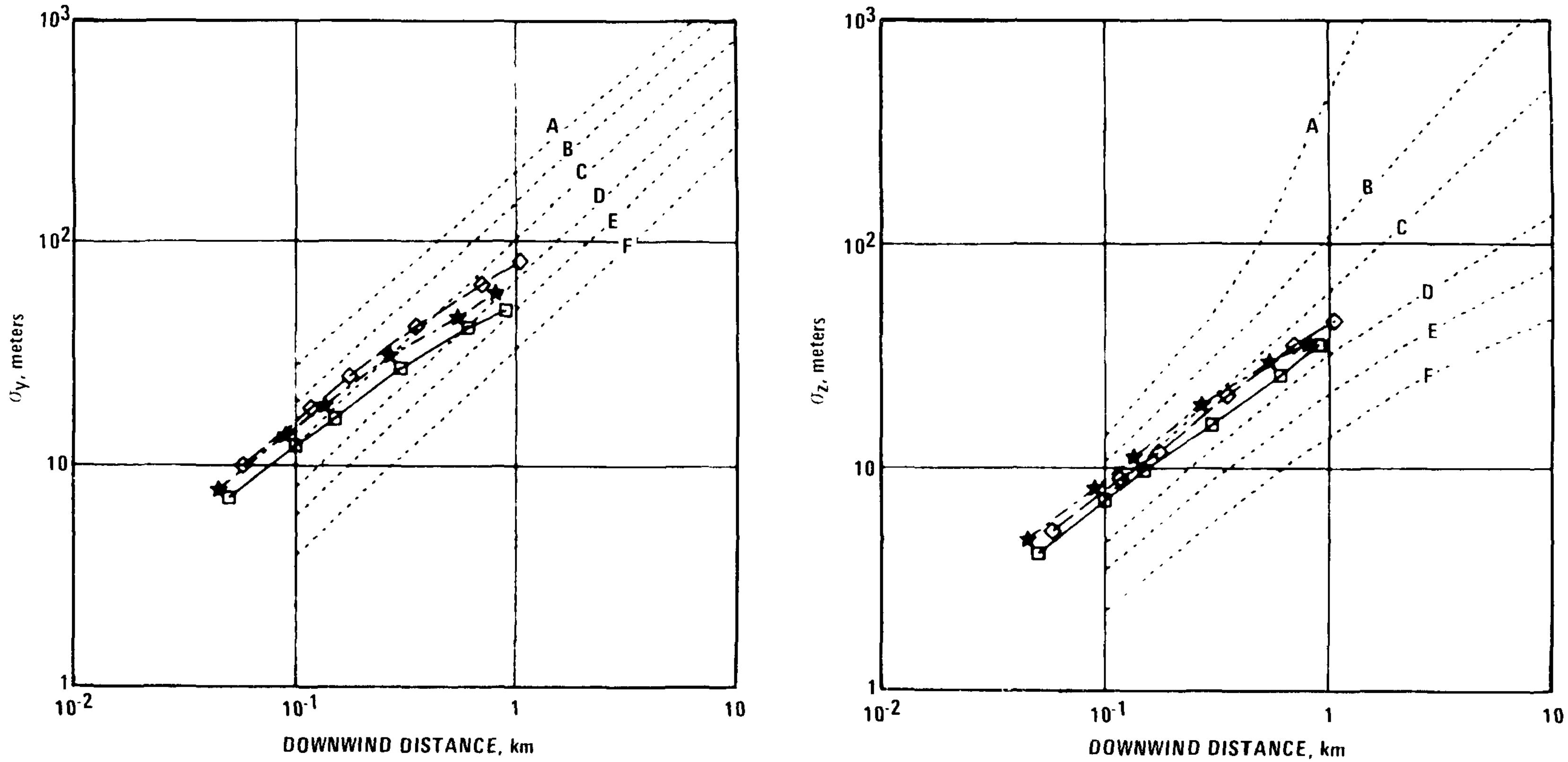

Figure 2. σ_y and σ_z computed from σ_θ and σ_ϕ respectively. Data from periods one through three are plotted as squares, stars and diamonds respectively.

a_j and b_j are used to determine σ_y when the downwind distance is between the intervals x_j and $x_{(j+1)}$. There are five intervals for which a and b are determined. For downwind distances less than that given by the 5-second averaging times, a_1 and b_1 are used to determine σ_y. For x greater than that given by the 90-second averaging time, a_5 and b_5 are used as the appropriate constants. Similarly, constants (c and d) are determined for $\sigma_z(x)$.

The initial dispersion parameters σ_{y_o} and σ_{z_o} used in the modified HIWAY model were not changed. The appropriate virtual distances necessary to account for the initial dispersion are:

$$x_y = \left[\frac{\sigma_{y_o}}{a_1}\right]^{\frac{1}{b_1}}, \qquad x_z = \left[\frac{\sigma_{z_o}}{c_1}\right]^{\frac{1}{d_1}},$$

Where:

$$\sigma_{y_o} = 3 \text{ m},$$

$$\sigma_{z_o} = 1.5 \text{ m}.$$

Finally, the equations used to estimate σ_y and σ_z are

$$\sigma_y\ (x_j) = a_j\ (x_y + x)^{b_j},$$

$$\sigma_z\ (x_j) = c_j\ (x_z + x)^{d_j},$$

where $x_j = x_y + x$ or $x_z + x$ in the j^{th} interval.

The modified HIWAY model was used to estimate SF_6 concentrations at the 20 sampler locations (See Figure 1). In Figure 3 are scatter plots of measured SF_6 concentrations versus model estimates for the three half-hour periods. Figure 3 also contains a composite of all the data for the three periods. The dashed lines on the plots are least squares fits to the data with the regression information in the upper left-hand corner of the plot. Table 2 shows that the mean wind speed and direction were steady during this time.

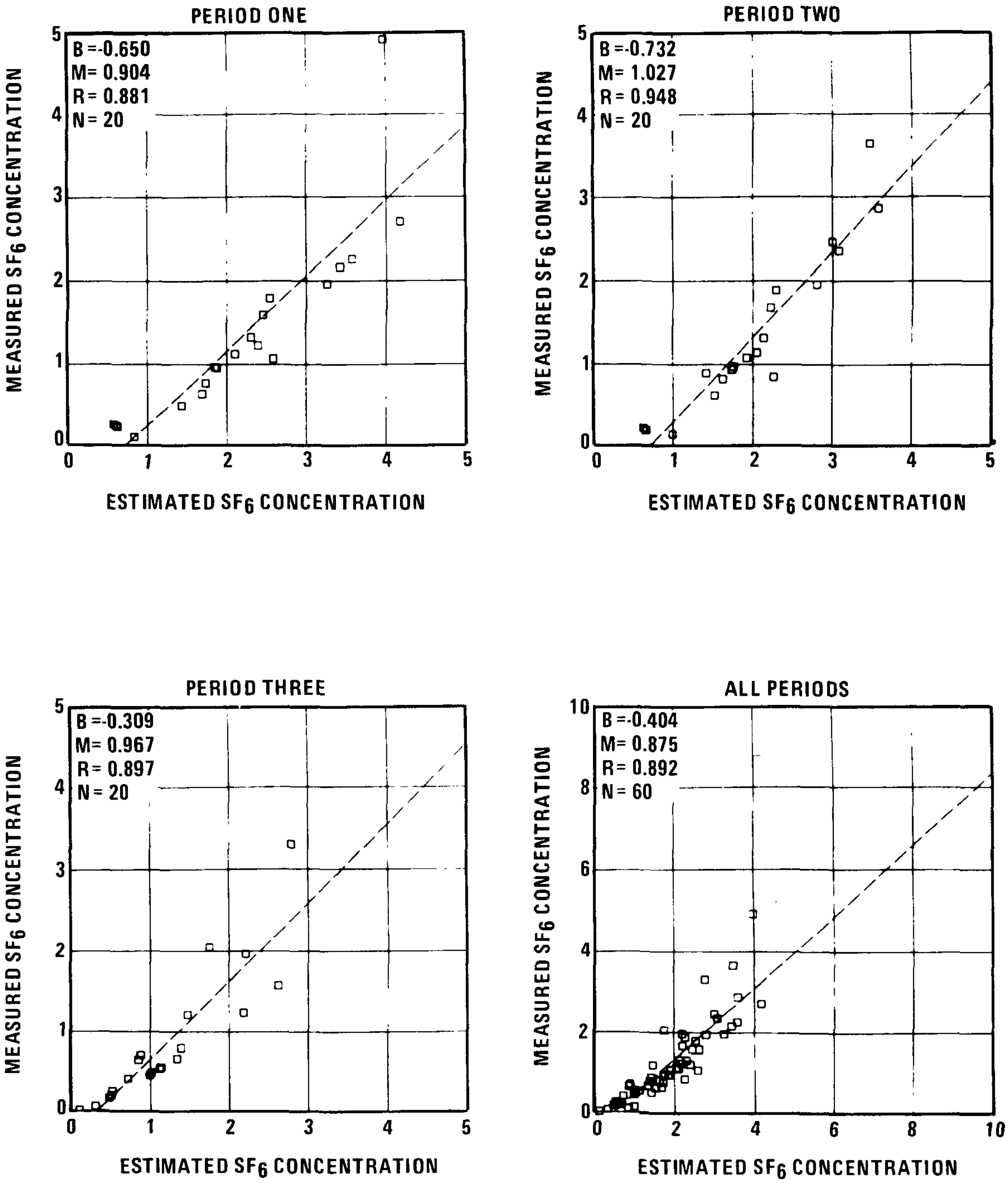

Figure 3. SF_6 concentrations (ppb). B, M, R, N in the plots are the intercept slope, correlation coefficient, and number of data points respectively.

TABLE 2. WIND DIRECTION AND WIND SPEED DURING THE THREE HALF-HOUR PERIODS

Half-hour periods	Wind direction	Wind speed)m sec^{-1})
1	182	2.5
2	183	2.2
3	175	2.9

The improvement in the performance of HIWAY can be shown by analyzing concentration estimates using three different approaches to estimating atmospheric dispersion. The approach described in Turner (1964) uses cloud cover, ceiling height, and wind speed to determine the stability class. The stability class for each half-hour period was determined using the wind speed at the experimental site and the observations of cloud cover and ceiling height at 3-hour intervals for Flint, Michigan (about 44 km north of the site). The Richardson Number measured at the site was used subjectively to determine how fast the atmospheric stability was changing. The stability was never allowed to change more than one class from one half-hour period to the next. Another approach used to determine the stability class was that suggested by Golder (1972). Golder showed an empirical relationship between the Richardson Number, roughness height and the stability class. Appendix A contains a more complete description of how Golder's technique was applied to this data set. The stability class for each half-hour period was determined by the two techniques mentioned above is shown in Table 3.

TABLE 3. STABILITY CLASS FOR EACH HALF-HOUR PERIOD

Stability class	Half-hour period		
determined from	First	Second	Third
Turner (1964)	E	D	D
Golder (1972)	F	F	F

Figure 4 is a scatter plot of measured SF_6 concentration versus model estimates using HIWAY with the three different techniques to estimate dispersion. For the data plotted as squares and stars, the stability class was determined from the Richardson Number and the Turner (1964) approach, respectively. In both cases σ_y and σ_z came from the PG curves once the stability class was determined. In the third data set, plotted as diamonds, the dispersion was estimated from σ_θ and σ_ϕ using Equations (1) and (2). Table 4 shows a summary of the regression analysis of the three sets of data. The slope of the regression line was significantly improved using on-site estimates of dispersion. However, the correlation coefficient was not improved.

Using two different sets of dispersion parameters in HIWAY, then analysing the results from model estimates, is analogous to using two different models. When two models are compared with the same measured concentrations, one has to be very careful about statistical statements concerning the regression results. For the case in which both models are compared with the same measured concentrations, the deviations from the regression lines could be correlated. Thus for the same measured concentrations, it is not appropriate to use a T-test, formed using a pooled variance in the standard way, to test the difference between the regression slopes from the two models. A suggested way to overcome this is to split the data into two sets (private communication from R. J. Hader, N. C. State University, 1977). The two data sets should have the same characteristics. One approach to insure that the range of concentration is the same for both data sets is to rank the measured concentrations and assign every other value to a different data set. One set would then be used for comparison by one model and the other set with the other model. A T-test could then be used to test for the significant difference between the two slopes. This approach was not used for this pilot study because of the limited size of the data set. However, this approach will be pursued with further analysis of the GM data.

Four data points (squares) were not plotted on Figure 4. Although the concentration estimates fell outside the boundaries of the plot, they were used in the regression analysis.

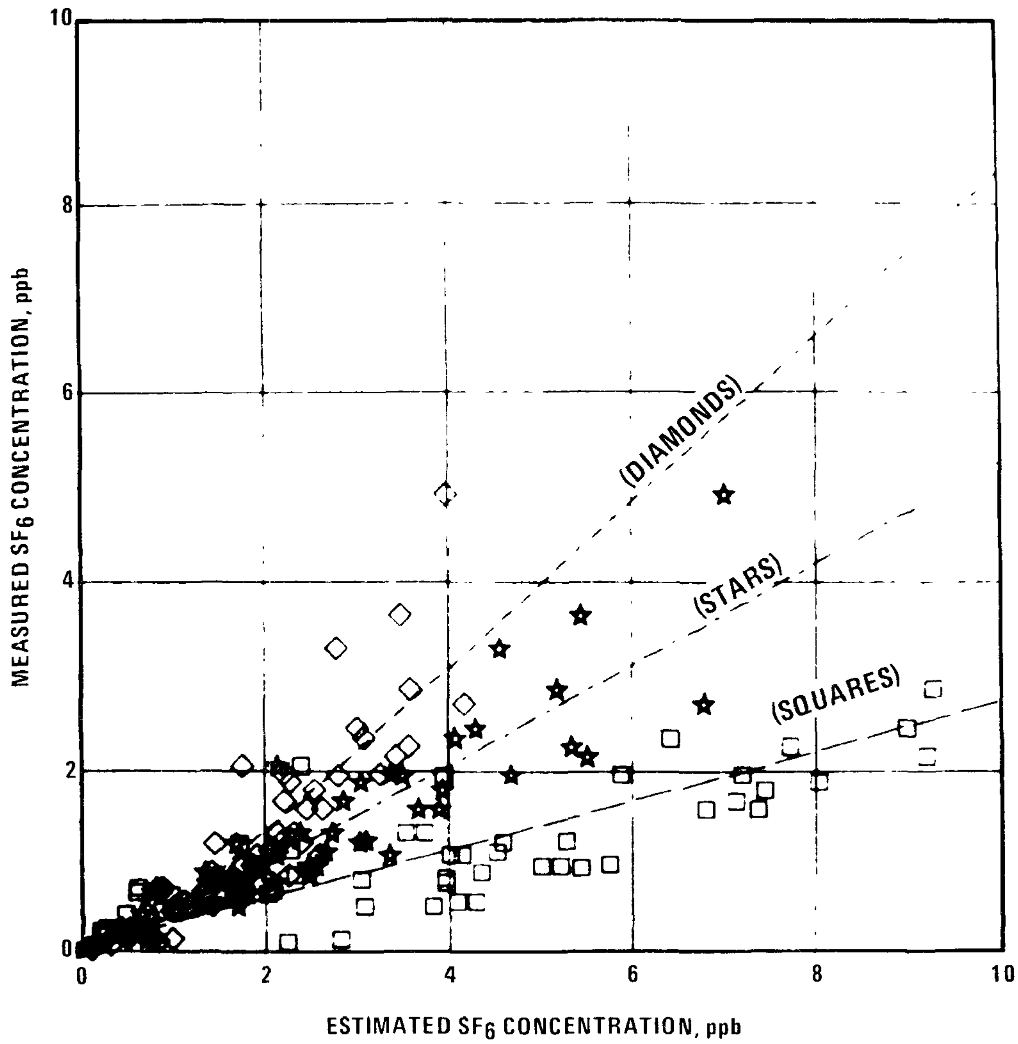

Figure 4. For the data plotted as squares the stability class for each half-hour period was determined from the Richardson Number. For the data plotted as stars the stability class was determined from the Turner (1964) classification scheme. For the data plotted as diamonds the dispersion parameters σ_y and σ_z were determined directly from σ_θ and σ_ϕ.

TABLE 4. REGRESSION ANALYSIS

Type of dispersion	Slope	Intercept	Correlation coefficient
Dispersion parameters from Equations 1 and 2	0.875	-0.404	0.892
PG curves stability class from Turner (1964)	0.536	-0.087	0.923
PG curves stability class from Richardson No.	0.268	0.065	0.890

As suggested in the introduction, concentrations in the vicinity of a line source should be most sensitive to crosswind dispersion when the winds are parallel to the line source. In order to investigate this, concentration estimates, using a modified HIWAY model, were made using σ_θ to estimate σ_y, and the PG curves to estimate σ_z, shown as squares in Figure 5. For the data plotted as stars, both σ_y and σ_z were determined from the PG curves. The regression analysis shows that there is essentially no difference between the two cases where the σ_z's were the same. Results from these data show that on the average concentrations downwind of a line source are not sensitive to variations in σ_y. Further investigation is needed to establish the effect of crosswind dispersion on the spatial distribution of concentration.

Conclusions drawn from such a limited data set are very preliminary. Nevertheless, the analysis of the data shows that the model performance, for parallel wind cases, was significantly improved by using dispersion parameters calculated from on-site fluctuation statistics. At the highest measured SF_6 concentrations, about 5 ppb, the model estimates calculated from the regression lines are shown in Table 5.

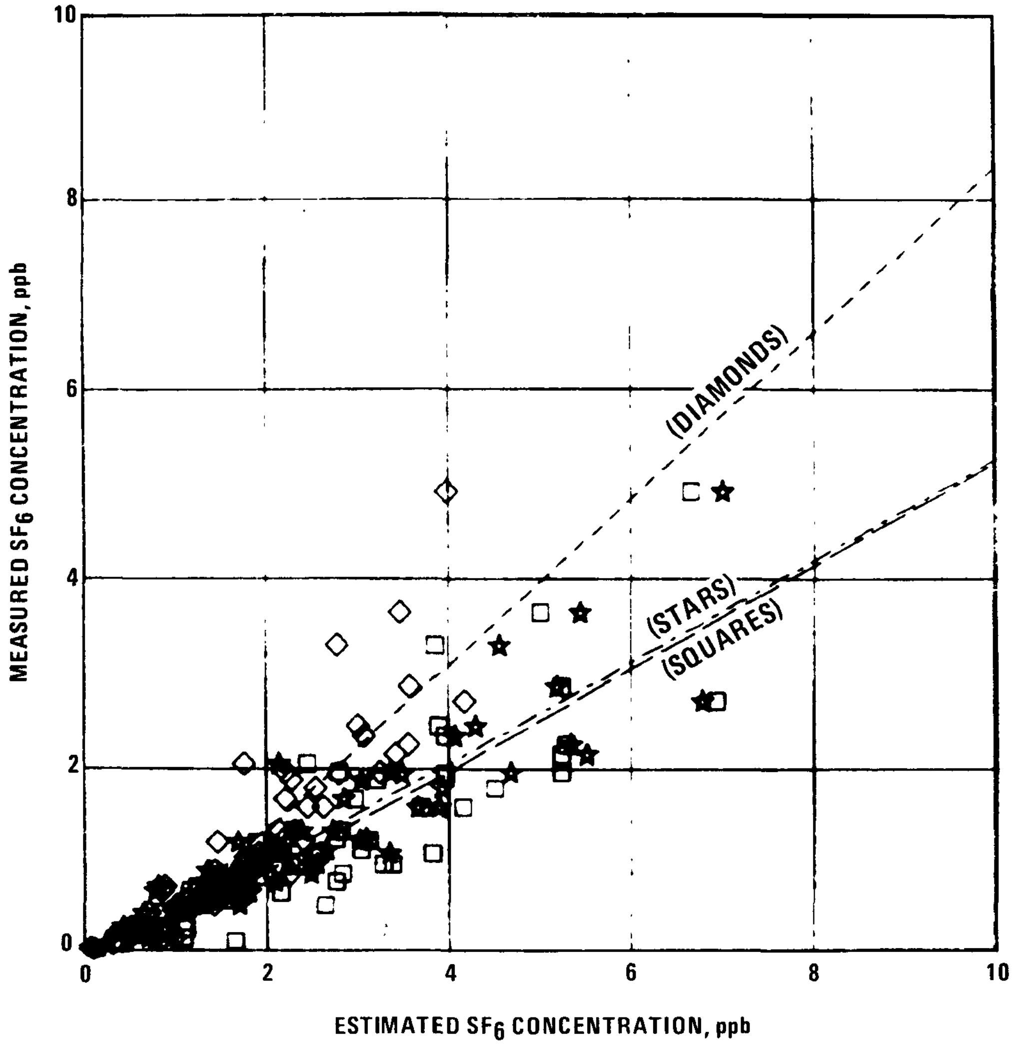

Figure 5. For the data plotted as squares σ_y was determined from σ_θ and σ_z from the PG curves. For the data plotted as stars σ_y and σ_z were determined from the PG curves. For data plotted as diamonds σ_y and σ_z were determined from σ_θ and σ_ϕ respectively.

TABLE 5. COMPARISON OF MODEL ESTIMATES

	Measured concentration (ppb)	Model estimate (ppb)	Ratio of model/measured
Stability class from Richardson No.	5	18.41	3.68
Stability class from Turner (1964)	5	9.49	1.90
Dispersion parameters from Equations (1)&(2)	5	6.18	1.24

4. SUMMARY

The major objectives of this pilot study were to develop the methodology to estimate the dispersion parameters from the fluctuation statistics of the wind using a small sample of the GM data, and to modify the HIWAY model to incorporate these dispersion parameters into the model computations. To that end the pilot study has been a success.

The following conclusions can be made as a result of the analysis of the data used in this pilot study: (1) during conditions when the winds are nearly parallel to the test track, concentrations are less sensitive to crosswind dispersion then expected; (2) dispersion parameters determined from the fluctuation statistics of the wind have a shape similar to the PG curves for downwind distances up to 500 m; (3) the fluctuation statistics of the wind indicate that the atmosphere near the ground was more dispersive than the stability class indicated; and (4) the performance of the model was significantly improved using the dispersion parameters determined from wind fluctuations.

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APPENDIX A.

DETERMINATION OF THE STABILITY CLASS FROM THE RICHARDSON NUMBER

The Richardson Number (Ri) was calculated for each half-hour period in the following way:

$$Ri = \frac{\frac{g}{T}\frac{\partial T}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2}$$

where g = gravitational acceleration,
T = absolute temperature,
z = height,
u = wind speed.

Wind speeds and temperatures used in the calculation of Ri were measured at 1.5 and 10.5 m. The appropriate height for z is given by the geometric mean of 1.5 and 10.5, equal to $(1.5 \times 10.5)^{\frac{1}{2}}$. For unstable atmospheric conditions, Pandolfo and Businger hypothesised that Ri is related to the Monin Obukhov length (L), (Paulson, 1970).

$$L^{-1} = \frac{Ri}{z} \qquad \text{(A-1)}$$

For stable air, an empirical relationship was found by McVehil (1964).

$$L^{-1} = \frac{Ri}{z\,(1-\beta Ri)} \qquad \text{(A-2)}$$

Golder (1972) showed an empirical relationship between L and the Turner stability types. Consistent with Golder, β was assigned a value of 7 in Equation (A-2). β is the reciprocal of the critical Ri (Binkowski, 1975). The figure below shows the Turner stability types as a function of L^{-1} and roughness height z_0. The roughness height typical of the terrain around the test track is 3 cm. Figure A-1 below is very similar to Figure 5 in the Golder paper.

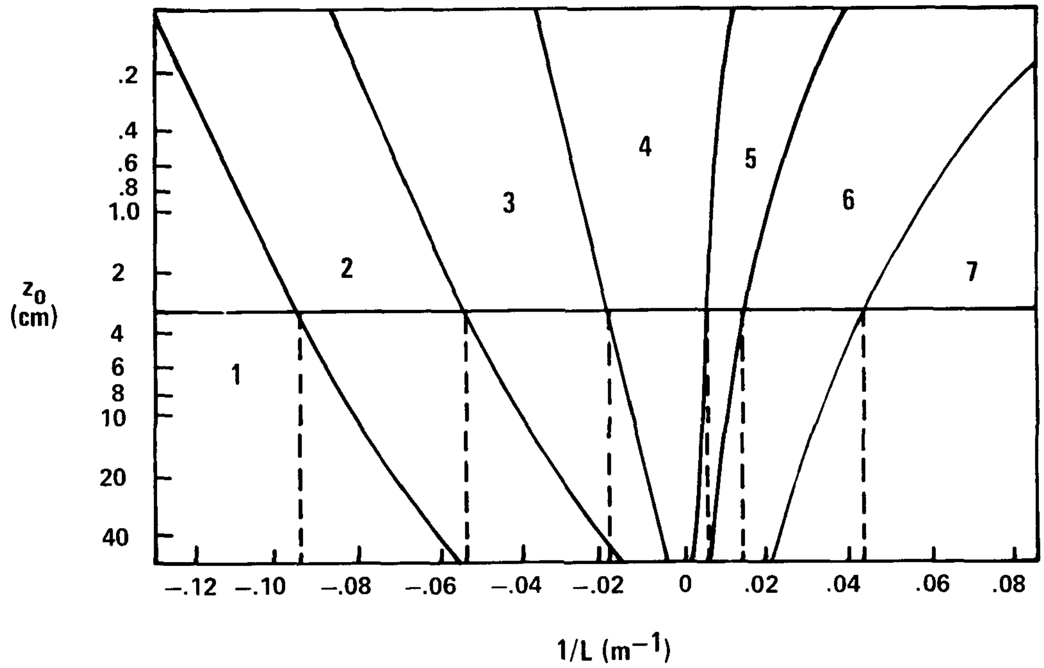

Figure A-1. Turner stability class as a function of L^{-1} and z_0.

If a horizontal line is drawn across the figure at z_0 = 3 cm, the stability classes are determined by the ranges of L^{-1} bounded by the dotted lines. For Ri greater than zero Equation (A-2) is used to calculate L^{-1}. For the Ri less than zero, Equation (A-1) is used to determine L^{1}. The following values were used to define each stability class.

TABLE A-1. STABILITY CLASS AS A FUNCTION OF L^{-1}

Range of L^{-1}	Stability Class
$L^{-1} \leq -0.095$	A
$L^{-1} \leq -0.055$ and > -0.095	B
$L^{-1} \leq -0.018$ and > -0.055	C
$L^{-1} \leq 0.005$ and > -0.018	D
$L^{-1} \leq 0.013$ and > 0.005	E
$L^{-1} > 0.013$	F

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TECHNICAL REPORT DATA

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

High frequency wind fluctuation data were used to estimate the dispersion near roadways. The standard deviations of the wind direction and the elevation angle were computed for six averaging times. The EPA HIWAY model was modified to use these fluctuation statistics directly to estimate dispersion. The data from the General Motors Sulfate Dispersion Experiment were used in this study. In particular, the data used in this pilot study were three half-hour periods when the winds were nearly parallel with the test track. Results from analysis show that model performance was improved for parallel wind conditions when the fluctuation statistics of the wind were used to estimate dispersion. The results also show that model estimates are most sensitive to the vertical dispersion parameter. Indeed, concentrations seem to be insensitive to the horizontal dispersion parameter.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
*Air pollution		13B
*Wind (meteorology)		04B
*Atmospheric diffusion		04A
*Roads		13B
*Mathematical models		12A

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