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An Overview of the General Motors Sulfate Dispersion Experiment

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The General Motors sulfate dispersion experiment was conducted in October 1975 at the General Motors Milford Proving Ground. The experiment simulated a four-lane freeway; 352 catalyst-equipped automobiles were driven at 80 km/h, resulting in a traffic volume of 5462 vehicles/h. The runs were conducted in the morning to obtain the most adverse conditions for pollutant dispersion. The maximum catalyst sulfate exposure near the roadway averaged 8 $\mu g/m^3$ for sixty-six 0.5-h runs. The average sulfate emission rate for each vehicle was 0.023 g/km. Near the roadway, mechanical mixing due to the traffic dominated the mixing caused by the ambient turbulence. At low cross-road winds, plume rise becomes important. The U.S. Environmental Protection Agency's HIWAY model was found to overestimate the concentrations at the pedestrian level under stable conditions. These overestimates become worse as the wind speed decreases, as the wind direction approaches parallel to the road, and as the distance from the road increases. A simple line-source model was constructed to remedy many of the limitations of the HIWAY model. The new model takes plume rise into account at low cross-road winds. It also avoids a cumbersome numerical integration required in the HIWAY model. An advection-diffusion model was also constructed in which the eddy diffusivity was determined from dynamic considerations. The influence of traffic was approximated by an additive component in the diffusivity tensor. Good agreements with observations were found, even when the off-diagonal terms of the diffusivity tensor were neglected. It is also expected that when the vehicle velocity is reduced, the extent of pollutant dispersion would also be reduced.

The General Motors sulfate dispersion experiment was conceived out of the concern about possible high sulfuric acid exposures near busy roadways. Such exposures would result from the conversion of sulfur dioxide (SO_2) in automobile exhaust to sulfur trioxide (SO_3) by the oxidation catalysts installed in most post-1974 automobiles. A further concern regarded the validity of the U.S. Environmental Protection Agency's (EPA) HIWAY dispersion model (1, 2), which had been used to predict sulfuric acid concentrations near roadways under adverse meteorological conditions. A controlled experiment simulating a busy highway provided a unique opportunity to study the influence of traffic on atmospheric dispersion, and thereby enabled the construction of more reliable dispersion models. The purposes of the General Motors sulfate dispersion experiment, therefore, were as follows:

1. To characterize the SO_4 exposures from a fleet of catalyst-equipped automobiles;
2. To assess the EPA's HIWAY model;
3. To study the influence of traffic on pollutant dispersion; and
4. To construct more reliable dispersion models.

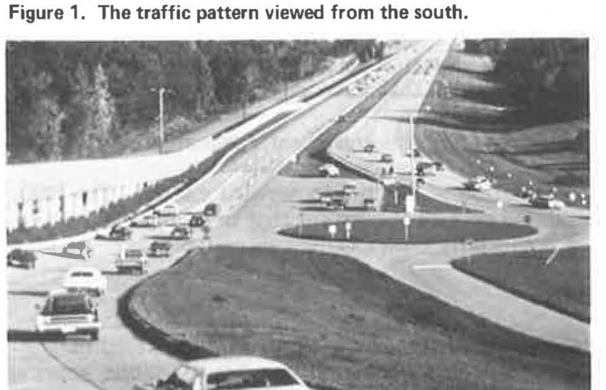
The experiment was conducted in October 1975 at the General Motors Milford Proving Ground.

EXPERIMENT

The proving ground is located in rural southeastern Michigan. The north-south straightaway at the proving ground was selected as the test track to simulate a 5-km long, 4-lane freeway. The terrain around the test track is relatively flat, especially at the sampling site. The automobiles driven in the experiment were provided by the four major domestic automobile manufacturers and equipped with catalysts and air pumps. After a lengthy preconditioning schedule (3), they were driven on 0.032 weight percent sulfur Amoco 91 gasoline during the experiment.

During the experiment, 352 automobiles were grouped into 32 packs. The packs were then grouped into parallel pairs, which occupied both lanes in each direction. The pairs were evenly spaced in both directions. The traffic speed was maintained at 80 km/h, resulting in a traffic density of 5462 vehicles/h. The traffic was controlled so that each pair of packs passed a fixed point every 29 s, thus maintaining a stationary flow. Figure 1 shows the traffic pattern during the experiment. A pickup truck is also visible in the figure. In fact, eight automobiles were replaced by pickup trucks, which were evenly distributed in the traffic and used to release a tracer gas, sulfur hexafluoride (SF_6), at a known emission rate.

Figure 1. The traffic pattern viewed from the south.



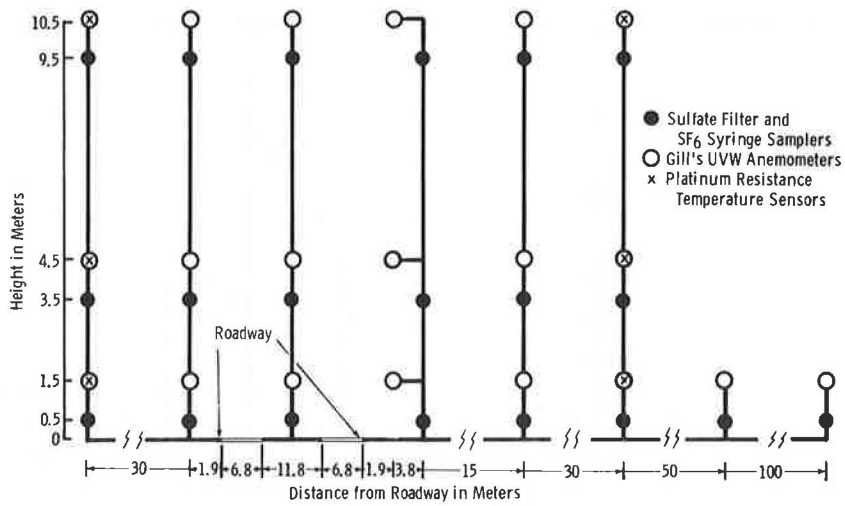


Figure 2. The instrument layout of the experiment viewed from the south.

Figure 3. A view of the instrument layout.

The sampling site was located in a level area 2.4 km from the south end of the track. Six towers and two stands were erected at different distances on a line across the track. Figures 2 and 3 show the instrument layout. Both sulfate particulates and SF_6 were collected continuously by the filter samplers and syringe samplers, respectively. The sampling duration for each run was 0.5 h. The particulate samples were analyzed for total soluble sulfate by the barium chloranilate method (4). The SF_6 samples were analyzed by electron-capture gas chromatography (5). Gill UVW anemometers recorded the wind field every second. Rosemount platinum-resistance thermometers measured the temperature every 5 s. They were calibrated to better than 0.01° C. The observed concentrations, temperatures, and wind vectors for each run represent an average over 0.5 h, unless otherwise specified.

Other measurements, including dew point, barometric pressure, visibility, particle size, and noble metal analyses were also made during the experiment. These results are reported elsewhere (6, 7).

Most runs were performed in the morning in an attempt to obtain the most adverse meteorological conditions possible. On a typical day, four consecutive runs of 30 min each were performed. A total of 62 runs was made during the month of October. Background sulfate concentrations were also measured before and after the driving period.

Catalyst Sulfate Exposure

Substantial background sulfate concentrations were observed during the course of the experiment. They ranged from 0.3 to 19.5 $\mu g/m^3$. Since the total sulfate concentration can only be measured with 10 percent precision, a high background concentration leads to greater uncertainty in the catalyst sulfate estimate.

The maximum sulfate increases over the background within each run were generally observed at the 0.5-m level either at the first tower downwind or in the median. Figure 4 shows a histogram of the maximum sulfate increases over the background. The average of these maximum increases was 8 $\mu g/m^3$. The spatial distribution of catalyst sulfate was very similar to that of SF_6. Obviously, the SF_6 concentrations were more reliable due to the absence of a background and the availability of very accurate measurement techniques.

Sulfate Emission Rate Determination

The sulfate particles emitted from the catalysts, at least in their initial stage near the roadway, ranged from 0.01 to 0.1 μm in diameter (7). In the presence of traffic turbulence, these sulfate particles are expected to disperse like a gas, and ground attachment will be small. This was supported by the high correlation coefficients between SF_6 and sulfate concentrations. The concentration ratio between the catalyst sulfate and SF_6 is, thus, equal to the ratio between the sulfate emission rate and the SF_6 emission rate. The SF_6 emission rate was known, so the sulfate emission rate could be determined. The sulfate emission rate fluctuated substantially. It tended to increase over time during each 2 h of driving.

There was no evidence of a systematic increase from day to day. Figure 5 shows the day-to-day variation of the 2-h means for the emission rates. The average of the 2-h means for each vehicle is 0.023 g/km. The standard deviation for each vehicle of the 2-h means from the average is 0.004 g/km.

Figure 4. Histogram of maximum sulfate increase.

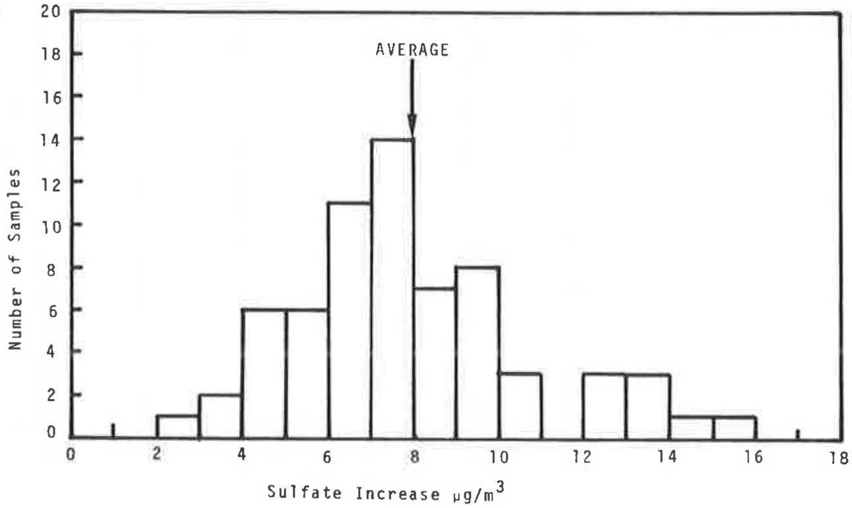
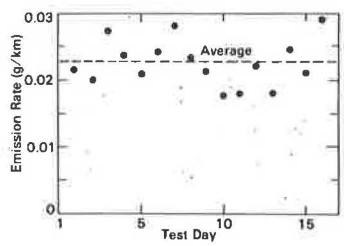


Figure 5. Day-to-day variation in sulfate emission rate.



EFFECTS OF TRAFFIC ON DISPERSION

Due to the vertical stratification of wind and temperature, the choice of a representative ambient wind and temperature was somewhat arbitrary. We chose the readings at the 4.5-m level, 30 m upwind of the road as our representative ambient measurements. The ambient Richardson number (Ri) was estimated from the measurements at the 1.5- and 4.5-m levels of the same tower.

Perhaps the most important physical parameter in describing the dispersion from a line source is the vertical velocity fluctuation (σ_w). Figures 6a and b show, respectively, the relations between σ_w and the ambient wind speed at the 4.5-m level, 30 m upwind and 30 m downwind of the road. The open circles are for stable conditions, and the closed circles are for unstable conditions. In the upwind region (Figure 6a), at a fixed wind speed, σ_w generally increases with decreasing stability. Furthermore, σ_w is proportional to the wind speed, in agreement with other observations (8). However, in the downwind region (Figure 6b), σ_w increases substantially over its upwind value for wind speeds less than ~2.5 m/s and does not have a clear dependence on stability. The influence of traffic is obvious. The vertical velocity fluctuation, and hence the vertical dispersion, is enhanced downwind of the road. In fact, mechanical mixing due to the traffic dominates the mixing due to ambient turbulence.

The traffic wake also caused some dispersion of pollutants upwind of the road. This dispersion was observed when the cross-road wind component was less than 1 m/s. In addition, when the ambient wind opposed the traffic direction on the upwind lanes, the resulting wind shear gave rise to a substantial dispersion upwind of the road. As shown in Figure 7, high ratios of the upwind-to-downwind roadside SF_6 concentrations at the 0.5-m level were evident when the ambient wind was ≥140° relative to the traffic direction on the upwind lanes. The dashed lines in the figure correspond to the constant cross-road wind speed.

The transport of heat correlated very well with the transport of concentration. We could, therefore, determine the heat emission rate from the vehicles in the experiment. It was 0.11 (MJ/vehicle)/s. This result is consistent with the estimated fuel consumption.

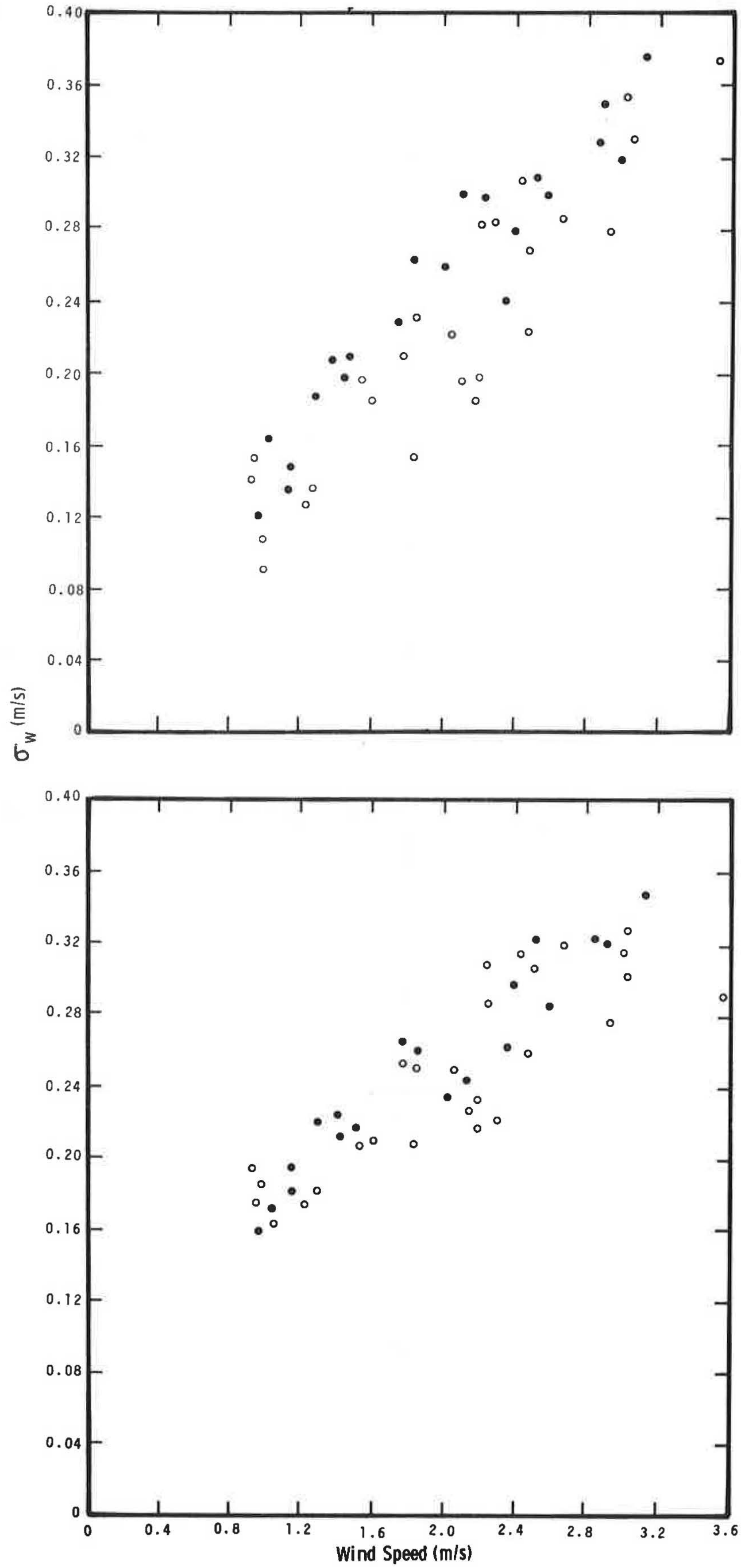
The effect of temperature, manifested in plume rise, was important at low wind speeds. As the cross-road wind component decreased, the concentrations at high sampling points increased relative to those at the 0.5-m level, even when the wind was within 45° of the perpendicular of the road. This is evidence of plume rise because the pollutants from the distant section of the road did not contribute much to the observed concentrations. Often at low cross-road winds, the concentrations at higher levels were actually higher than those at the 0.5-m level, 30 m downwind of the road. More details on the effects of traffic on the dispersion can be found elsewhere (9).

ASSESSMENT OF THE EPA'S HIWAY MODEL

EPA's HIWAY model is an empirical Gaussian model. It assumes that the concentration at a point is the sum of contributions from an infinite number of point sources that make up the line source. The concentration is assumed to be inversely proportional to the ambient wind speed. The vertical and horizontal dispersion parameters are those of Pasquill-Gifford (10) extrapolated to the emission source, where they are assumed to be 1.5 and 3 m, respectively. The model had not been rigorously tested in the past, especially under adverse meteorological conditions [stable atmospheres and low wind speeds (<1 m/s)] where the model was applied most frequently.

Case comparisons with observations were made. Some of them have been described previously (11). This type of comparison can reveal the accuracy of the predicted concentration distribution. Comparisons of predicted and observed concentrations at fixed locations were also made. They allow us to test the predictions as a function of wind speed, wind direction, and stability. Figure 8 shows the ratios of predicted to observed concentrations at the 0.5-m level, 30 m downwind of the road, for neutral to very stable conditions. The ratios

Figure 6. Vertical velocity fluctuation (σ_w) at the 4.5-m level as a function of wind speed.



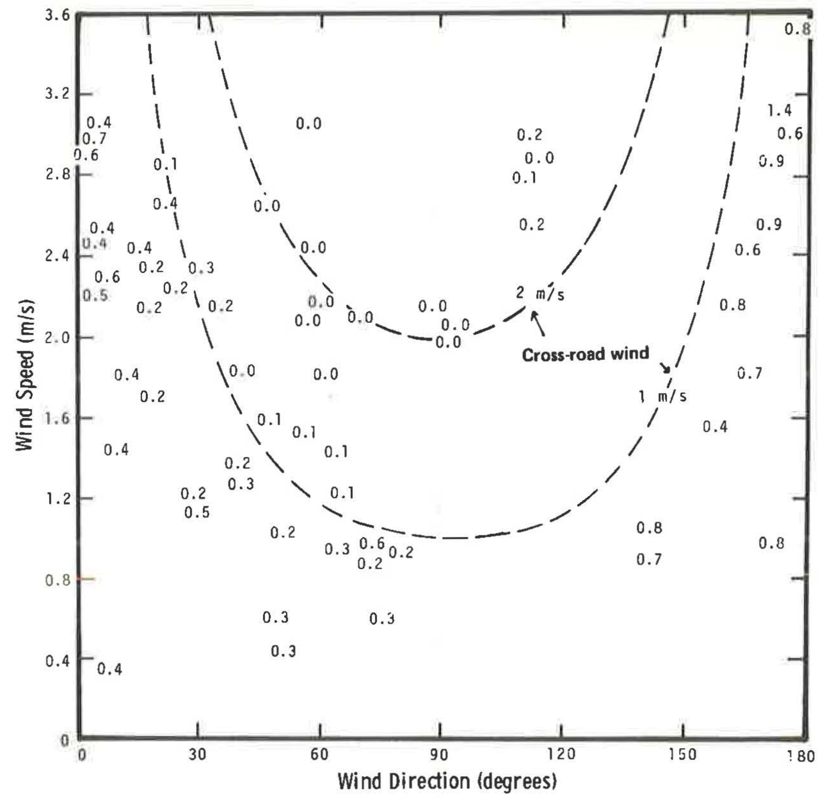


Figure 7. The upwind-to-downwind SF_6 concentration ratios for the 0.5-m level of the roadside towers, as a function of the ambient wind.

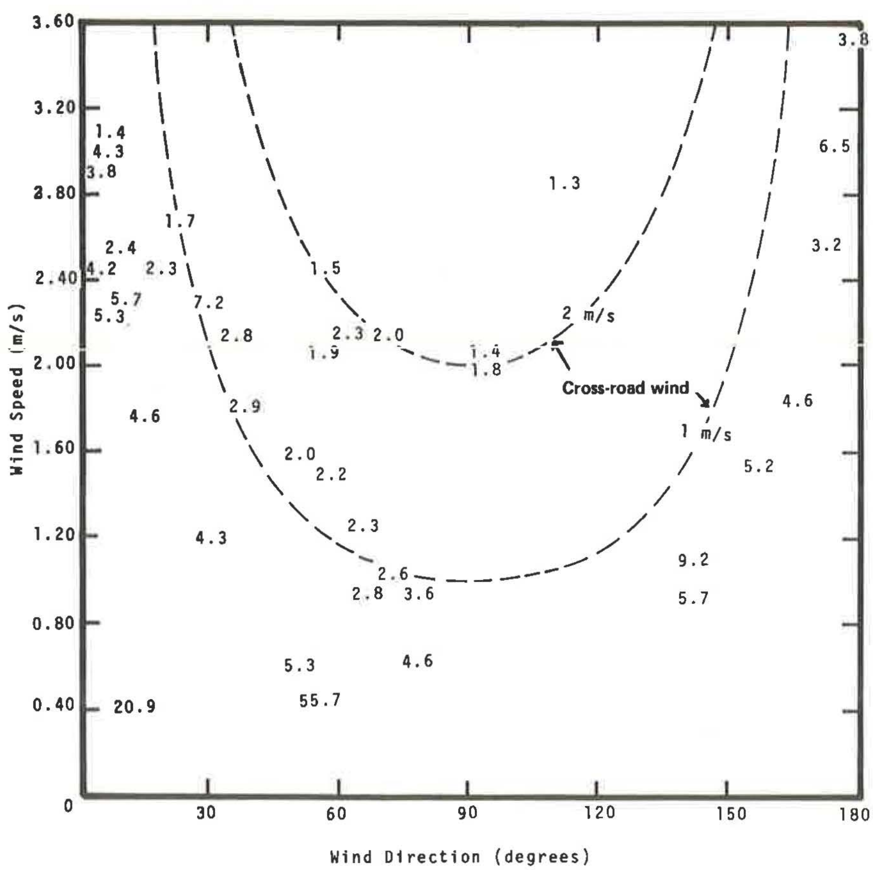


Figure 8. The predicted-to-observed SF_6 concentration ratios for the 0.5-m level, 30 m downwind of the road.

are generally high. The ratio of 55.7 in the figure corresponds to an extremely stable case with very low wind speeds. This could be characterized as a worst meteorological condition. The wind was variable at different heights and plume rise was observed.

The conclusions derived from the comparison with experiment can be summarized:

1. The HIWAY model is not applicable under the worst meteorological condition.
2. Downwind from the road, the model works relatively well for unstable conditions. For stable conditions it overpredicts at the pedestrian level and underpredicts at higher levels.
3. Upwind from the road the model is inapplicable.
4. The model overpredicts as wind speed decreases, as the wind direction approaches parallel to the road, and at low levels under stable conditions as the distance from the road increases.

A SIMPLE LINE-SOURCE MODEL

The experiment revealed many limitations of the HIWAY model. The model requires a cumbersome numerical integration: It would be useful, therefore, to develop a simple line-source model that would overcome the limitations and at the same time eliminate the necessity of a numerical integration. We have developed such a model, which is necessarily empirical so that the parameters are determined from the experiment.

This new, simple model is also a Gaussian model. However, in order to avoid many of the limitations of the HIWAY model, we redetermined the vertical dispersion parameter, allowed for plume rise, and introduced a wind speed correction term. The wind speed correction not only prevents the concentration from approaching infinity at low wind speeds, but it also plays the role of an effective advection due to the outward dispersion of pollutants generated by the traffic wake. In order to avoid the numerical integration, the vertical dispersion parameter was made wind-direction dependent. No lateral dispersion parameter was introduced. In addition, the superposition assumption inherent in the HIWAY model becomes unnecessary. The new model is not applicable to upwind dispersion. Thus, the effect of wind shear that causes dispersion upwind of the road is not taken into account. More details on the model can be found elsewhere (12).

An example of the simple line-source model's performance is given in Figure 9, which shows the predicted-to-observed concentration ratios for the 0.5-m height, 30 m downwind of the road. An improvement index, due to the inclusion of plume rise, is defined as ($|r_1-1| - |r_0-1|$) where r_0 and r_1 are the predicted-to-observed concentration ratios with and without plume rise, respectively. The indexes for the 0.5-m height, 30 m downwind from the road, are shown in Figure 10. Indexes less than 0.05 are not shown. These generally occurred when the cross-road wind was >1 m/s. The parameters were estimated from the sulfate dispersion experiment and can be further refined as other data become available.

AN ADVECTION-DIFFUSION MODEL

The simple line-source model is useful in estimating dispersion near roadways, but we also hoped to develop a physically more realistic model that satisfies conservation of mass and allows for the presence of wind shear, for the effects of traffic-induced turbulence, and for different boundary conditions. The simplest form of such a model is an advection-diffusion model, which in a stationary state can be written as:

$$\sum_j (\partial/\partial x_j)(U_j C) = \sum_{ij} (\partial/\partial x_i)[K_{ij}(\partial C/\partial x_j)] + S \quad (1)$$

where

C = the mean concentration,
U_j = the jth component of the mean velocity,
K_{ij} = the eddy-diffusivity tensor, and
S = the source and sink term.

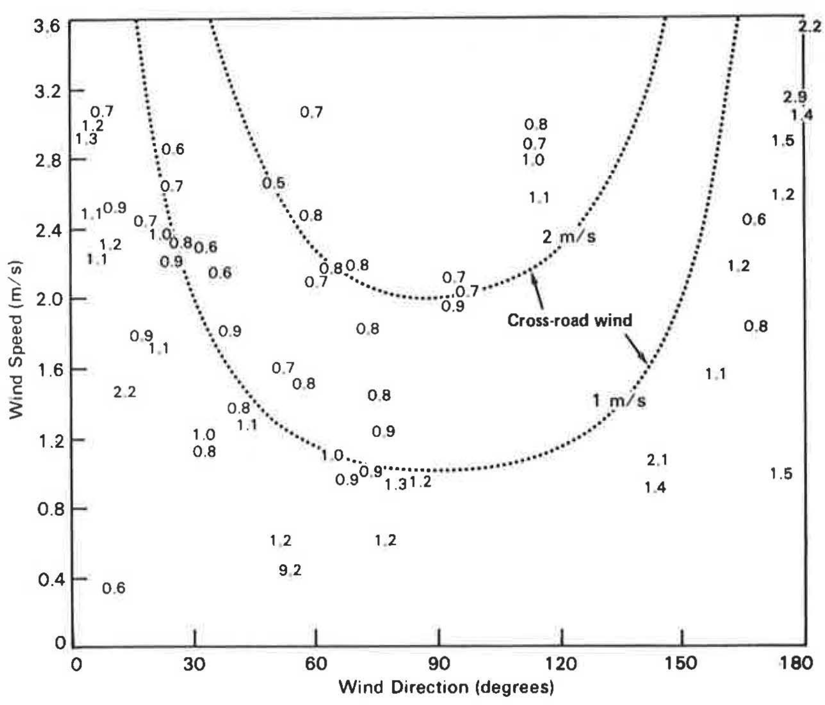


Figure 9. The predicted-to-observed SF_6 concentration ratios for the 0.5-m level, 30 m downwind of the road.

The difficulty with this model lies in the specification of the eddy-diffusivity tensor. Instead of parameter fitting, we made use of a second-order closure model to determine it. If spatial homogeneity can be assumed along the road direction, then only two spatial dimensions need be considered. They correspond to the horizontal component perpendicular to the road and the vertical component. The result of second-order closure modeling allows one to express the eddy diffusivity in terms of velocity correlations, velocity gradients, and temperature gradients. Using the lowest order approximation, the eddy-diffusivity was further assumed to be the sum of contributions from the ambient and traffic-induced components. The velocity correlations obtained during the experiment could be separated into an ambient part and a traffic part, provided that the interaction between the energy-containing eddies of the two parts was not large. This is not a bad approximation since the characteristic frequencies of both eddies were significantly different. The detailed description of the construction of the eddy-diffusivity tensor is given elsewhere (13).

A finite-element method was applied to solve the advection-diffusion equation. The predicted concentrations agree quite well with the observed concentrations. Figure 11 shows the predicted-to-observed concentration ratios for the 0.5-m height, 30 m downwind from the road. Good agreement was also evident when the off-diagonal elements of the eddy-diffusivity tensor were ignored. Thus, keeping only the diagonal elements of the eddy-diffusivity tensor appears adequate for modeling dispersion of pollutants from a roadway.

Finally, it is argued that the traffic component of the diffusivity scales with the wind and negative vehicle velocity. When the vehicle velocity is reduced, so the extent of the pollutant dispersion would also be reduced.

ACKNOWLEDGMENTS

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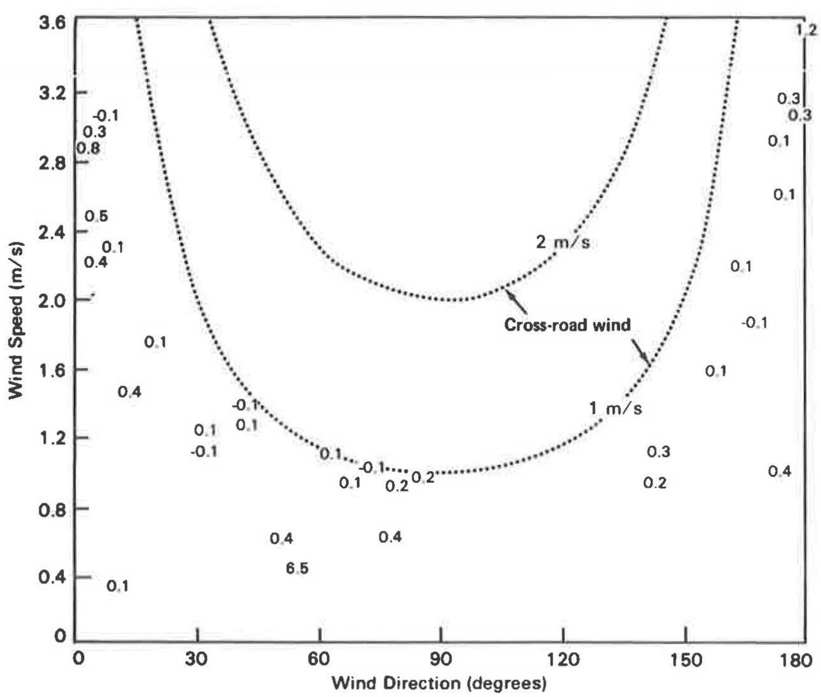

Figure 10. Improvement indices when plume rise is included in the simple line-source model.

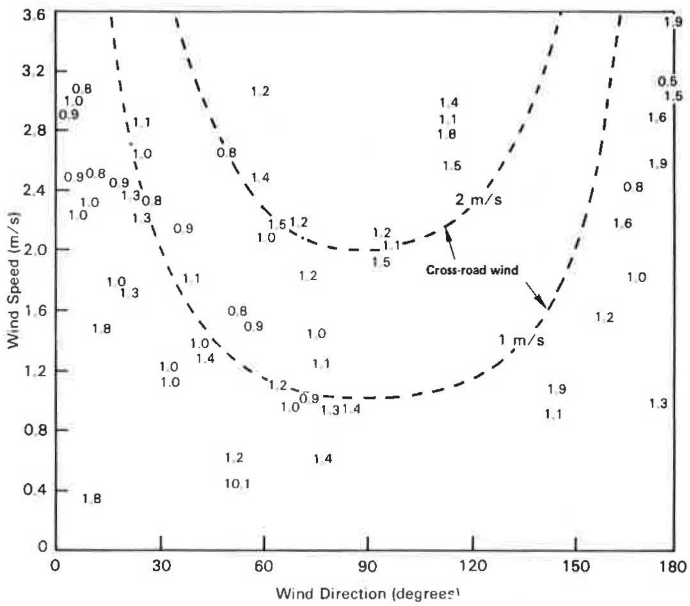

Figure 11. The predicted-to-observed SF_6 concentration ratio values from the advection-diffusion model.

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Atmospheric and Wind Tunnel Studies of Air Pollution Dispersion Near Highways

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Atmospheric and wind tunnel studies of gaseous dispersion near roadways have identified new concepts regarding the influence of roadway traffic and stimulated the development of a versatile yet simple simulation model, ROADMAP. Influences of site geometry and roadway configurations were observed and quantified. Two effects found to be particularly significant to microscale dispersion were (a) thermal turbulence and buoyancy caused by vehicular waste heat and (b) mechanical turbulence from highway traffic. ROADMAP simulates two-dimensional gaseous dispersion patterns for various roadway configurations including grade-level, vertical, and slant-wall cut, fill, and viaduct sections. Development of the model is first detailed for a uniform, grade-level freeway. Dispersion patterns were obtained up to heights of 14 m and to downwind distances of 100 m by a sampling array that measured meteorological conditions and concentrations of carbon monoxide and two artificial tracer gases released in the traffic. Comparison of equivalent field and wind-tunnel tests for grade-level roads shows good agreement except for acute wind-roadway angles. ROADMAP's capability for varied site geometries was evaluated by analyzing field and wind tunnel tests for 20 roadway configurations. Comparisons of ROADMAP to independent carbon monoxide data (i.e., data not used in developing the model) from the grade-level field tests resulted in high values of the linear correlation coefficient: 0.91 for neutral stability, 0.67 for stable atmospheric conditions, and 0.80 for unstable conditions. Values for the cut and elevated-section tests in the wind tunnel ranged from 0.69 to 0.93.

The air pollutants entrained and subsequently dispersed by highway traffic depend on the meteorological characteristics generally prevailing in the specified loca-